# CHROMIUM AND CHROMIUM ALLOYS

## 1. Introduction

Chromium [7440-47-3] is one of the “newer” elements, celebrating the 200th anniversary of its discovery in 1997. It was about 1760 when the chromium-bearing mineral crocoite from deposits in the Ural Mountains was recognized in Europe. However, it was not until 1797/98 that chromium was isolated by Nicolas-Louis Vauquelin, a professor of chemistry at the Paris Ecole des Mines. Chromium was discovered later than other metals because it does not appear terrestrially as a native metal, and it is strongly bonded in the minerals in which it occurs. The wide variety of colorful compounds derivable from crocoite led Vauquelin to name the newly discovered element chromium, a name derived from *chroma*, the Greek word for color. Crocoite, also called *Siberian red lead*, was found to produce a yellow pigment that became popular. Thus paint became the first commercial application of chromium. Chromium was soon discovered in chromite, a much more common mineral, also from the Ural Mountains.

Chromium is used primarily in the metallurgical industry as an alloying element in steel. Chromium confers properties on the alloy that are not achievable with base metals alone. The most common use of chromium is with iron to make stainless steel, an iron–chromium alloy. Chromium confers oxidation resistance to stainless steel, making it “stainless.” Stainless steel, in addition to being commonly found in home and commercial kitchens, is an important engineering alloy used throughout industry in machinery, containers, and pipes (see STEEL). Chromium is also used in chemicals for a variety of purposes. Chromite, the mineral from which chromium is extracted for use in the metallurgical and chemical industries, is used directly by the refractory industry to produce heat-, spalling-, corrosion-, and abrasion-resistant bricks for metallurgical and high-temperature industrial mineral processing applications. Chromite is not mined domestically; thus, the United States is 100% dependent on imports to meet domestic chromite demand. Domestic chromium demand is met by import of chromite ore; chromium ferroalloys, chromium metal, or chromite ore; and chemicals; and by recycling.

Chromium has a wide range of uses in metals, chemicals, and refractories. It is one of the nation's most important strategic and critical materials. The use of chromium to produce stainless steel and nonferrous alloys are two of its more important applications. Other applications are in alloy steel, plating of metals, pigments, leather processing, catalysts, surface treatments, and refractories.

The major commercially traded forms of chromium materials are chromite ore [1308-31-2] and ferrochromium [11114-46-8]. The United States was a significant world chromite ore producer before 1900. However, since that time, U.S. production has declined to nil. Ferrochromium is a product of smelting chromite ore in an electric-arc furnace. Ferrochromium is the major form of chromium used by the metallurgical industry. Historically, ferrochromium smelters developed in major steel-producing centers of the United States, Europe, and Japan. Since about 1970, the net effect of vertical integration in chromite producing nations' industry and the concomitant rationalization in developed steel-producing centers has resulted in the migration of ferrochromium production to chromite-producing countries. This trend is expected to continue. Thus the United States is a chromium importing nation. Chromium is subsequently exported from the United States in stainless-steel products.

Stainless steel was invented in the early 1900s. Soon thereafter electric furnaces evolved that could smelt chromite into ferrochromium. Before about 1960, ferrous alloys required the addition of as little carbon as possible because carbon could not be efficiently removed from molten steel. Thus, the production of low-carbon, high-chromium alloys (typically less than 0.1% carbon and more than 65% chromium) was the common practice. To make this ferrochromium, high chromium:iron ores were required (ratios greater than about 2:1).

Since 1960, major changes have occurred in the chromium industry because of changes in steelmaking technology. The development of ladle refining techniques (ie, processes that permit the chemical modification of liquid metal) such as argon–oxygen decarburization, permitted the steel industry to shift from the more costly low-carbon ferrochromium to the less costly high-carbon ferrochromium. This shift in ferrochromium grade has been accompanied by a shift in quantity of production among ferrochromium-producing countries. Since the 1970s, chromite ore–producing countries have developed their own ferrochromium production capacities. As a result, ferrochromium production has moved from the major stainless-steel-producing centers, Japan, the United States, and western Europe, to chromite-producing countries, Finland, India, the Republic of South Africa, Turkey, and Zimbabwe. With the exception of Japan, only minor ferrochromium production remains in the major stainless-steel-producing countries. In particular, the Republic of South Africa, whose ores have a chromium:iron ratio of about 1.5:1, has increased its high-carbon ferrochromium production dramatically. Significant, but declining, quantities of ferrochromium continue to be produced in Japan.

Because the United States has no chromite ore reserves and a limited reserve base, domestic supply has been a concern during every national military emergency since World War I. World chromite resources, mining capacity, and ferrochromium production capacity are concentrated in the Eastern Hemisphere. The National Defense Stockpile (NDS) contains chromium in various forms, including chromite ore, chromium ferroalloys, and chromium metal in recognition of that material is being disposed of the vulnerability of long supply routes during a military emergency.

The terms *chromium* and *chrome*, as used in the chemical industry, are synonymous. Similarly, the terms *dichromate* and *bichromate* are used interchangeably in the chemical industry.

Hargreaves and co-workers (1) reviewed the world minerals industry by mineral, country, and mining company. The composite world rank of chromium among most globally important strategic investment mineral commodities was found to be 10th out of 36. The composite world rank is an indexed composite of five factors: output by value, population and gross domestic product, resource demand, mineral reserve base, and country investment risk.

## 2. Occurrence

Many minerals contain chromium as a major element [see Table 1 (2)], and many minerals contain tens of percent chromium. However, only the mineral chromite occurs in large enough quantities to be a commercial source of chromium. Chromite can be found in many different rock types, but the host rocks for economically important chromite deposits are called *peridotite* and *norite*. These are distinctive rocks composed mainly of the minerals olivine and pyroxene (peridotite) and pyroxene and plagioclase (norite). These rocks occur primarily in two geologic settings: *layered intrusions*, which are large bodies of layered igneous rock that cooled very slowly in large underground chambers of molten rock; and *ophiolites*, which are large pieces of the oceanic crust and mantle that have been thrust over continental rocks by the same tectonic forces that cause continental drift. Because chromite deposits in layered intrusions tend to be tabular in form they are known as *stratiform deposits*, whereas those in ophiolites are typically podlike or irregular in form, are known as *podiform deposits* (see also MINERAL RECOVERY AND PROCESSING). Other sources of chromite are beach sands derived from chromite-containing rocks and laterites that are weathering products of peridotite. Laterites are more widely known as sources of nickel and cobalt. Beach sands and laterites historically have been a minor source of chromite.

Table 2 shows the reserves and resources of chromite worldwide.

The identified world resources of chromite are sufficient to meet conceivable demand for centuries. Current world demand is about 12 million metric tons per year. Reserves are that part of identified resources that are currently economic. The reserve base, which includes reserves, is that part of identified resources that are economic now and also may become economic with existing technology, depending on economic conditions and price of chromite.

### 2.1. Stratiform Deposits.

Most of the world's chromite resources occur as stratiform deposits in layered intrusions. The Bushveld Complex in South Africa contains over 8.5 billion tons of chromite while the remainder of the world's economic and subeconomic deposits have a little over 2.5 billion tons,

Table 1. **Terrestrial Minerals Containing Chromium as a Major Constituent**[a]

| Name | General formula | Wt % Cr |
|---|---|---|
| Barbertonite | $Mg_6Cr_2(CO_3)(OH)_{16}\cdot 4H_2O$ | 16 |
| Bentorite | $Ca_6(Cr,Al)_2(SO_4)_3(OH)_{12}\cdot 26H_2O$ | 5 |
| Bracewellite[b] | $CrO(OH)$ | 61 |
| Brezinaite | $Cr_3S_4$ | 47–50 |
| Carlsbursite | $CrN$ | 79 |
| Caswellsilverite | $NaCrS_2$ | 37 |
| Chromian diopside | $Ca(Mg,Fe,Cr)Si_2O_6$ | 0.1–8 |
| Chromian geikielite | $(Mg,Fe^{2+},Cr,Fe^{3+})(Ti,Cr,Fe^{3+})O_3$ | 0.5–8.5 |
| Chromian garnet | $(Cr,Mg)_3(Al,Cr)_2(SiO_4)_3$ | 0.1–13 |
| Chromite | $(Mg,Fe^{2+})(Cr,Al,Fe^{3+})_2O_4$ | 10–54 |
| Chromatite | $CaCrO_4$ | 33 |
| Chromian clinochlore | $(Mg,Fe^{2+})(Al,Cr)_2(Al_2,Si_2)O_{10}(OH)_8$ | 0.5–12 |
| Cochromite | $(Co,Ni,Fe^{2+})(Al,Cr)_2O_4$ | 34–37 |
| Crocoite | $PbCrO_4$ | 16 |
| Daubreelite | $Fe^{2+}Cr_2S_4$ | 36 |
| Deanesmithite | $Hg_2{}^{1+}Hg_3{}^{2+}Cr^{6+}O_5S_2$ | 4.3 |
| Dietzeite | $Ca_2(IO_3)_2(CrO_4)$ | 10 |
| Donathite | $(Mg,Fe^{2+})(Cr,Fe^{3+})_2O_4$ | 28–30 |
| Edoylerite | $Hg_3{}^{2+}Cr^{6+}O_4S_2$ | 6.6 |
| Embreyite | $Pb_5(CrO_4)(PO_4)_2\cdot H_2O$ | 7 |
| Eskolaite | $Cr_2O_3$ | 44–68 |
| Fornacite | $(Pb,Cu)_3[(Cr,As)O_4]_2(OH)$ | 6 |
| Fuchsite | $K(Al,Cr)_2(AlSi_3)O_{10}(OH)_2$ | 0.5–6 |
| Georgeericksenite | $Na_6CaMg(IO_3)_6(CrO_4)_2(H_2O)_{12}$ | 5 |
| Grimaldiite[b] | $CrO(OH)$ | 61 |
| Guyanaite[b] | $CrO(OH)$ | 61 |
| Heideite | $(Fe,Cr)_{1+x}(Ti,Fe)_2S_4$ | 0.1–18 |
| Hemihedrite | $Pb_{10}Zn(CrO_4)_6(SiO_4)_2F_2$ | 13–14 |
| Iranite | $Pb_{10}Cu(CrO_4)_6(SiO_4)_2(F,OH)_2$ | 10 |
| Knorringite | $Mg_3Cr_2(SiO_4)_3$ | 12–23 |
| Krinovite | $NaMg_2CrSi_3O_{10}$ | 14 |
| Lopezite | $K_2Cr_2O_7$ | 35 |
| Loveringite | $(Ca,Ce)(Ti,Fe^{3+},Cr,Mg)_{21}O_{38}$ | 0.5–10 |
| Macquartite | $Pb_3Cu(CrO_4)SiO_3(OH)_4\cdot 2H_2O$ | 6 |
| Manganochromite | $(Mn,Fe^{2+})(Cr,V)_2O_4$ | 41–62 |
| Mariposite | $K(Al,Cr)_2(Si_{3+x}Al_{1-y})O_{10}(OH)_2$ | 0.5–6 |
| McConnellite | $CuCrO_2$ | 35 |
| Mountkeithite | $(Mg,Ni)_{11}(Fe^{3+},Cr,Ni)_3(OH)_{24}(CO_3,SO_4)_{3.5}$ $(Mg,Ni)_2(SO_4)_2\cdot 11H_2O$ | 2.2–6 |
| Nichromite | $(Ni,CoFe^{2+})(Cr,Fe^{3+},Al)_2O\text{-}_4$ | 31–37 |
| Phoenicochroite | $Pb_2(CrO_4)O$ | 8–10 |
| Redingtonite | $(Fe^{2+},Mg,Ni)(Cr,Al)_2(SO_4)_4\cdot 22H_2O$ | 0.5–3 |
| Redledgeite | $Mg_4Cr_6Ti_{23}Si_2O_{61}(OH)_4$ | 11 |
| Rilandite | $(Cr,Al)_6SiO_{11}\cdot 5H_2O$ | 33 |
| Santanaite | $9PbO\cdot 2PbO_2\cdot CrO_3$ | 2 |
| Schreyerite | $(V,Cr,Al)_2Ti_3O_9$ | 0.7–3.6 |
| Shuiskite | $Ca_2(Mg,Al,Fe)(Cr,Al)_2[(Si,Al)O_4](Si_2O_7)(OH)_2\cdot H_2O$ | 10–17 |
| Stichtite | $Mg_6Cr_2(CO_3)(OH)_{16}.4H_2O$ | 6–19 |
| Tarapacaite | $K_2CrO_4$ | 27 |
| Ureyite | $NaCrSi_2O_6$ | 23 |
| Uvarovite | $Ca_3Cr_2(SiO_4)_3$ | 21 |
| Vauquelinite | $Pb_2Cu(CrO_4)(PO_4)(OH)$ | 7 |
| Vuorelaineite | $(Mn,Fe,^{2+})(V,Cr)_2O_4$ | 3.2–21 |
| Wattersite | $Hg_4{}^{1+}Hg^{2+}Cr^{6+}O_6$ | 4.5 |
| Yedlinite | $Pb_6CrCl_6(O,OH)_8$ | 4 |

[a] Modified from Lipin (2).
[b] Different crystal structures.

Table 2. **Chromite Reserves, Reserve Base, and Identified Resources in 1998**[a]

| Country | Deposit type | Reserves | Reserve base | Identified resources |
|---|---|---|---|---|
| Albania | podiform | 1,890 | 1,890 | 7,980 |
| Australia | stratiform | 0 | 56 | 1,830 |
| Brazil | stratiform | 4,450 | 7,140 | 9,060 |
| Canada | stratiform | 0 | 1,600 | 3,840 |
| China | podiform | 2,500 | 3,000 | 10,000 |
| Cuba | podiform | 739 | 739 | 1,970 |
| Finland | stratiform | 12,530 | 37,900 | 37,900 |
| Greece | podiform | NA | 380 | 785 |
| Greenland | stratiform | 0 | 0 | 26,000 |
| India | stratiform | 8,210 | 20,500 | 37,400 |
| Indonesia | laterite | 235 | 235 | 235 |
| Iran | podiform | 745 | 745 | 17,700 |
| Japan | podiform | 33 | 60 | 69 |
| Kazakstan | podiform | 126,000 | 126,000 | 301,000 |
| Madagascar | stratiform | 2,120 | 2,120 | 2,120 |
| Macedonia | podiform | NA | NA | NA |
| Oman | podiform | NA | 301 | 602 |
| Papua New Guinea | laterite | 0 | 0 | 2,890 |
| Philippines | podiform | 2,260 | 2,260 | 2,260 |
| Russia | podiform | 1,230 | 140,000 | 140,000 |
| South Africa | stratiform | 933,000 | 1,700,000 | 2,970,000 |
| Sudan | podiform | 513 | 513 | 513 |
| Turkey | podiform | 2,450 | 6,040 | 6,770 |
| USA | stratiform | 0 | 3,100 | 35,000 |
| United Arab Emirates | podiform | 64 | 64 | 64 |
| Venezuela | podiform | 0 | 0 | 713 |
| Zimbabwe | stratiform | 43,500 | 285,000 | 285,000 |
| *Total* | | *1,140,000* | *2,350,000* | *3,910,000* |

[a] Values are in 1000 t, gross weight normalized to 45% $Cr_2O_3$ content. (*Note*: Deposit type is predominant deposit type. In many countries, more than one deposit type occurs. Reserves are economically recoverable, demonstrated resources. Reserve base is economic, marginally economic, and, possibly, some currently uneconomic, demonstrated resources. Identified resources are resources whose location, grade, quality, and quantity are known or estimated from specific geologic evidence.) Data and total rounded independently; NA = not available.

and about half of that tonnage is in the Great Dyke in Zimbabwe, another layered intrusion (3). Clearly, chromite resources in layered intrusions are not evenly distributed worldwide. Other layered intrusions that produce or have produced chromite are Stillwater Complex, Montana, USA; Kemi Complex, Finland; Orissa Complex, India; Goias, Brazil; Andriamena, Befandriana, and Ranomena, Madagascar; and Mashaba, Zimbabwe.

Stratiform deposits are not evenly distributed over geologic time, either. While intrusions of the type of rock that carry chromite deposits appear over the spectrum of geologic time, only those of Precambrian age (older than ~540 million yr) are known to carry economic chromite deposits; the youngest of these deposits is the Bushveld, at about 2.066 billion yr. A possible exception to this might be the deposits in the central Ural Mountains, which may be a disrupted layered complex of Early Silurian age (about 440 million yr old).

**2.2. Podiform Deposits.** Although resources and reserves of podiform deposits are quite small compared to stratiform deposits, podiform deposits have been, and continue to be, important sources of chromite. This is because many of these deposits are large and rich enough to be economic. In addition, before certain advances in metallurgy, the composition of the chromite produced from podiform deposits was more suited for the metallurgical uses of chromite.

As stated above, podiform deposits occur in *ophiolites*, which are pieces of the oceanic crust and mantle thrust up over continental rocks. Many different rock types occur in an ophiolite, but the stratigraphically lowest of these is peridotite, which is the host for podiform chromite deposits. Podiform deposits are found in many places in the world and throughout geologic time. The most important historic sources of chromite from podiform deposits are Kempersai, Kazakstan; Perm district, Russia; Zambalas, Philippines; four districts, Albania; six districts, Turkey; Selukwe, Zimbabwe; New Caledonia; Troodos, Cyprus; and Vourinos, Greece.

Other production has come from the Appalachians in the United States, Australia, China, Cuba, the former Yugoslavia, Iran, New Guinea, Oman, Pakistan, Sudan, the coastal ranges in California and Oregon, the Shetland Islands in Scotland, and Vietnam.

Podiform and stratiform deposits have different chemical characteristics, which has determined how they are used. Industry has classified chromite ore as high-chromium, high-iron, and high-aluminum. Table 3 summarizes the relationship between these classifications, and major use. Table 4 (4) summarizes the range of chemical contents of chromite ores.

**2.3. Beach Sands.** Beach sands that contain chromite exist as a result of erosion. Chromite mined from hard rock deposits, either stratiform or podiform, are concentrations in the rock commonly at least 15 vol% chromite up to 100% massive chromite. Some of them are many millions of tons in size. However, all peridotites, even those that do not contain economic concentrations of chromite, contain chromite at low levels, between 1 and 5 vol% of the rock. In addition, peridotite can occur over many hundreds of square kilometers in ophiolites. The fact that chromite is ubiquitous in peridotite at low levels and peridotite can occur over large areas allows for the possibility of streams moving through peridotite to erode the rock and deposit chromite downstream. In addition, the fact that chromite is the most dense mineral in peridotite means that wave action will naturally concentrate the mineral in a beach environment.

Table 3. **Classification of Chromite by Composition, Type of Deposit, and Principal Uses**

| Class of ore | Composition, wt% | Type of deposit | Major use |
|---|---|---|---|
| high-Cr | $Cr_2O_3$ 46–55%<br>Cr/Fe>2:1 | podiform and stratiform | metallurgical |
| high-Fe | $Cr_2O_3$ 42–46%<br>Cr/Fe<2:1 | stratiform | metallurgical and chemical |
| high-Al | $Cr_2O_3$ 33–38%<br>$Al_2O_3$ 22–34% | podiform | refractory |

Table 4. **Range of Commercially Available Chromite Ore Chemical Characteristics Based on a Composite of Sources (in Percent)**[a,b]

| | Observed range of values | |
|---|---|---|
| Chemical compound | Lower | Upper |
| $Cr_2O_3$ | 30 | 57 |
| $SiO_2$ | 0.98 | 18 |
| Fe | 9 | 19.6 |
| $Al_2O_3$ | 6 | 22 |
| MgO | 8 | 28 |
| P | 0.002 | 0.01 |

[a] Reference 4; Although the composition limits shown here come from commercially available material, they do not as a group represent any specific material.
[b] Chromium:iron ratio varies from 1.4 to 4.2.

Such is the case in Oregon, where beach sands were mined during Word War II. Since 1988, some attempts have been made to mine sands on the island of Palawan in the Philippines. Other sand or placer chromite deposits occur in Indonesia, Papua New Guinea, Vietnam, and Zimbabwe.

**2.4. Laterites.** Laterite forms as the result of weathering of peridotite in a tropical or a forested, warm temperate climate. Laterite is a thick red soil derived from the rock below. It is red because of the high concentration of iron. The process of laterization leaches out most of the silicate minerals in the rock, leaving higher concentrations of elements that can fit in the structures of nonsilicate minerals. Thus laterites concentrate elements such as iron, nickel, cobalt, and chromium. In some laterites chromite is concentrated to economic concentrations. This is the case in Indonesia where chromite is being mined.

**2.5. Chromite.** The mineral chromite is jet black in color, has a submetallic luster, yields a brown streak, is generally opaque in thin section, and has no cleavage. The density ranges from about 3.8 to 4.9 $g/cm^3$ and has a Vickers hardness number between 5 and 6. Chromite is a solid solution mineral of the spinel group, has cubic symmetry and a closely packed crystal lattice, hence the high density of the minerals of the spinel group. The six end-member compositions that combine to form chromite (see Fig. 1) are hercynite ($FeAl_2O_4$), spinel ($MgAl_2O_4$), Fe–chromite ($FeCr_2O_4$), picrochromite ($MgCr_2O_4$), magnetite ($Fe_3O_4$), and magnesioferrite ($MgFe_2O_4$). Thus, the general formula is $(Mg, Fe)(Cr, Al)_2O_4$. At high temperatures ($>1200°C$) and low oxygen fugacity, the conditions under which chromite first forms, there is complete solid solution between Mg and Fe and between Cr and Al. Other elements found in lesser amounts are Ti, Zn, Ni, V, Mn, and Co. There are no formal rules for naming chromite; however, most geologists and people in the industry use the term *chromite* when the $Cr_2O_3$ content rises above 15 wt%. Because chromite is a solid solution, it has no fixed composition.

**2.6. Terrestrial Chromium Abundance.** Chromium is the 18th most abundant element in the earth's upper crust at 35 ppm (5). Chromium is most concentrated in rocks that constitute the upper mantle, from which crustal

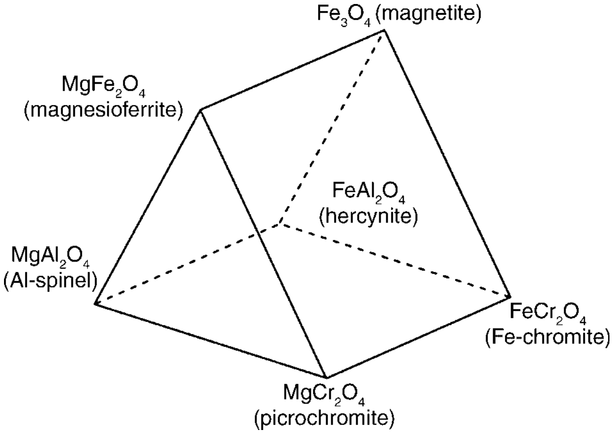

**Fig. 1.** Composition diagram for the spinel minerals. Each corner represents an end-member composition in a complex solid solution that involves all the end members. As a result, the corners represent the purest forms of the named minerals of this group. A naturally occurring chromite mineral composition would lie within the bounds of the prism defined by these end members.

rocks are evolved. Upper-mantle rocks are almost exclusively peridotite in which the average chromium content is 3000 ppm (6). The granitelike compositions that dominate the upper crust, and erode to form sedimentary rocks, tend to exclude chromium. The lower crust, which contains rocks that are somewhat closer in composition to the upper mantle, contains ~235 ppm (5) and the concentration in the overall crust of the Earth is 100 ppm (7). Seawater contains $2\times10^{-10}$ g of chromium per gram of water, while rivers average $1\times10^{-9}$ g of chromium per gram of water.

## 3. Properties

The data in this properties section are taken from the Ref. 8. The chemical symbol for chromium is Cr, and it has an atomic weight of 51.966 and atomic number of 24. Its melting point is 1907°C and its boiling point is 2671°C. At 20°C the specific gravity is 7.18–7.20 g/cm$^3$.

Chromium is one of the so-called transition elements, meaning that it has valence electrons in two shells instead of one. Chromium exists as a metal and in three valence states, $2^+$, $3^+$, and $6^+$, when combined with other elements—all of which can occur naturally. However, the di- and trivalent forms are most prevalent in nature. The electron shell configuration of chromium is 2, 8, 13, 1, and the filling orbital is $3d5$.

Chromium is a steel gray metal, has cubic symmetry, and is very hard. It is soluble in $H_2SO_4$, HCl, $HNO_3$, and aqua regia. Chromium resists corrosion and oxidation. When used in steel at greater that 10 wt% it forms a stable oxide surface layer, which makes it particularly useful in making stainless steel and other specialty steels to ward off the corrosive effects of water. The ability of chromium to resist corrosion and accept a high polish has made it almost ubiquitous as a coating on household water faucets. See Table 5 for physical properties of chromium.

Chromium has four naturally occurring nonradiogenic isotopes. Their symbols, percent abundance, and atomic mass are as follows: ${}_{24}Cr^{50}$, 4.35%, 49.946046; ${}_{24}Cr^{52}$, 83.79%, 51.940509; ${}_{24}Cr^{53}$, 9.50%, 52.940651; ${}_{24}Cr^{54}$, 2.36%, 53.938882.

Table 5. **Physical Properties of Chromium**

| Property | Value |
|---|---|
| at no. | 24 |
| at wt | 51.996 |
| isotopes | |
| mass | 50525354 |
| relative abundance, % | 4.3183.769.552.38 |
| crystal structure | bcc |
| lattice parameter, $a_o$, nm | 0.2888–0.2884 |
| density at 20°C, g/mL | 7.19 |
| mp, °C | 1875 |
| bp, °C | 2680 |
| vapor pressure, at 1610°C, Pa[a] | 130 |
| heat of fusion, kJ/mol[b] | 14.6 |
| latent heat of vaporization at bp, kJ/mol[b] | 305 |
| specific heat at 25°C, J/(mol·K)[b] | 23.9 |
| linear coefficient of thermal expansion at 20°C, $K^{-1}$ | $6.2\times10^{-6}$ |
| thermal conductivity at 20°C, W/(m·K) | 91 |
| electrical resistivity at 20°C, $\mu\Omega\cdot m$ | 0.129 |
| superconducting transition temperature, K | 0.08 |
| antiferromagnetic (Néel) transition temperature, K | 311 |
| specific magnetic susceptibility at 20°C | $3.6\times10^{-6}$ |
| total emissivity at 100°C[c] | 0.08 |
| reflectivity, $R$, % | |
| at 30 nm | 67 |
| at 50 nm | 70 |
| at 100 nm | 63 |
| at 400 nm | 88 |
| refractive index, $\alpha$, for $\lambda = 257-608$ nm | 1.64–3.28 |
| standard electrode potential, V | |
| $Cr \longrightarrow Cr^{3+} + 3\,e^-$ | −0.74 |
| $Cr^{4+} \longrightarrow Cr^{6+} + 2\,e^-$ | +0.95 |
| ionization potential, V | |
| 1st | 6.74 |
| 2nd | 16.6 |
| half-life of ${}^{51}Cr$ isotope, days | 27.8 |
| thermal neutron scattering cross section, $m^2$ | $6.1\times10^{-28}$ |
| elastic modulus, GPa[d] | 250 |
| compressibility[e] at 10–60 TPa | $70\times10^{-3}$ |
| hardness (Knoop value) | 1.160 |
| electron affinity of Cr–Cr bond, eV | 0.666 |

[a] To convert Pa to mm Hg, multiply by 0.0075.

[b] To convert J to cal, divide by 4.184.

[c] Nonoxidizing atmosphere.

[d] To convert GPa to psi, multiply by 145,000.

[e] 99% Cr; to convert TPa to megabars, multiply by 10.

Table 6. **Standard Thermodynamic Properties of Chromium at 298.15 K**

| Phase | Enthalpy of formation, kJ mol$^{-1}$ | Gibbs energy of formation, kJ mol$^{-1}$ | Entropy, J mol$^{-1}$ K$^{-1}$ | Heat capacity, J mol$^{-1}$ K$^{-1}$ |
|---|---|---|---|---|
| solid | 0.0 | | 23.8 | 23.4 |
| liquid | | | | |
| gas | 396.6 | 351.8 | 174.5 | 20.8 |

**3.1. Thermodynamic Properties.** The thermodynamic properties of chromium are shown in Table 6. At various temperatures the heat capacities are (in J mol$^{-1}$ K$^{-1}$): at 200 K, 19.86; at 250 K, 22.30; at 300 K, 23.47; at 350 K, 24.39; at 400 K, 25.23; at 500 K, 26.63; at 600 K, 27.72.

**3.2. Other Properties.** The following is a list of other properties of chromium.

- Thermal conductivity (in watts cm$^{-1}$ K$^{-1}$) at selected temperatures is 0.402 at 1 K, 0. 3.85 at 10 K, at 100 K, 1.11 at 200 K, 0.937 at 300 K, 0.860 at 500 K, 0.654 at 1000 K, 0.556 at 1600 K, and 0.494 at 2000 K.
- Magnetic Susceptibility at 273 K is $180\times10^{-6}$ cgs, at 1713 K is $224\times10^{-6}$ cgs.
- Ionic radii (in nanometers) are as follows: $Cr^{2+}$ (6 coordination) is 0.73; $Cr^{3+}$ (6 coordination) is 0.62; $Cr^{6+}$ (4 coordination) is 0.260.
- The elastic constant of a single crystal of chromium are as follows (in units of $10^{11}$ Newtons M$^{-2}$): $C_{11}$=3.398; $C_{12}$=0.586; $C_{44}$=0.990.
- Electrical resistivity at various temperatures (in $10^{-8}$ ohm m): 100 K = 1.6; 200 K = 7.7; 273 K = 7.7; 298 K = 12.6; 400 K = 15.8; 600 K = 24.7; 800 K = 34.6; 900 K = 39.9.

## 4. Mining and Processing

Exploration has nontechnologic aspects, including general and commodity-specific economic factors, and politics. Exploration requires investment, which, in turn, requires economic decisions. The first step in the exploration process is deposit discovery and description, followed by cross-correlation of deposit information. Deposit descriptions covering many important and less well-known deposits have been published and analyzed. Government and academic geologists have correlated geologic aspects of chromite deposits, defining the general geologic conditions that are consistent with known chromite deposits.

Both stratiform and podiform deposits are associated with ultramafic rocks even though the origins of these two types of chromite deposits differ. For stratiform deposits, the regular layering can be used to locate chromite deposits concealed by faulting or segmentation. Podiform deposits cannot be reliably inferred. So far, no consistently reliable geophysical or geochemical exploration technique has been found for podiform deposits. Without chromite-specific physical indicators, the traditional methods of ore body location, outcrop analysis, trenching, and drilling remain the most reliable way to locate chromite deposits. Drilling and drifting are used to locate or extend underground deposits. When an ore body has been located, structural analysis may be used to locate deposit extensions if they exist.

**4.1. Beneficiation.** A wide variety of mining technology is applied to the surface and subsurface mining of chromite ore. Most ore comes from large mechanized mines. However, small labor-intensive mining operations contribute to world supply. Recovery includes surface and underground mining using unmechanized to mechanized methods.

Beneficiation to marketable chromite products varies from hand sorting to gravimetric and electromagnetic separation methods. The amount of beneficiation required and the techniques used depend on the ore source and end-use requirements. When the chromite is clean and mossive, only hand sorting of coarse material and gravity separation of fine material may be required. When the ore is lumpy and mixed with other minerals, heavy-media separation may be used. When the chromite mineral occurs in fine grains intermixed with other minerals, crushing may be used in conjunction with gravity separation and magnetic separation. Processing of chromite to produce chromium products for the refractory, chemical, and metallurgical markets includes crushing and grinding and size sorting by pneumatic and hydraulic methods, kiln roasting, and electric furnace smelting (see Fig. 2). Labeling of material as it moves from the earth to the consumer is not uniform. The terms *chromite* and *chromite ore* are used here to refer to material in the ground, run-of-mine ore (ie, material removed from the ground), or material supplied to the marketplace. For the purpose of trade, imports are called *chromite ore* and *concentrate made therefrom*. This description is frequently abbreviated to chromite ore and concentrate, chromite ore, or simply chromite. Some sources use chromite ore to refer to material in the ground

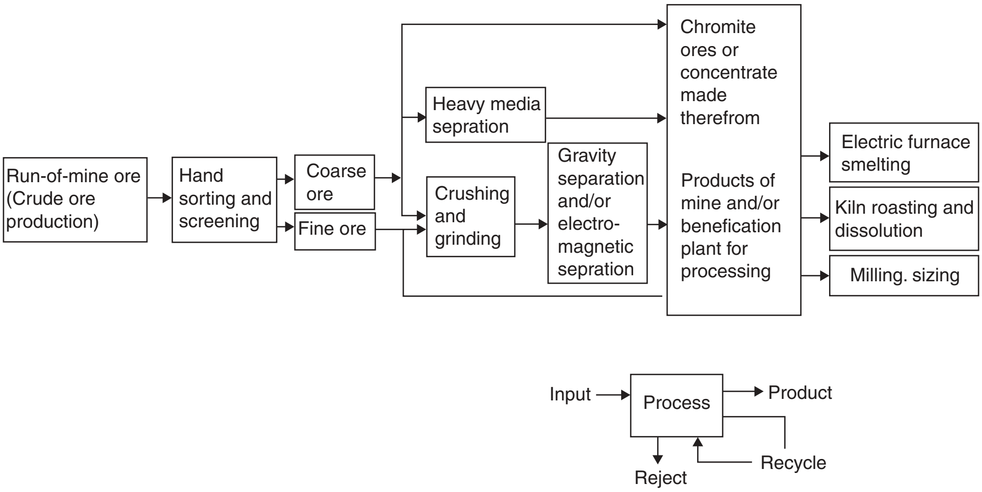

**Fig. 2.** Chromite material flow process from the mine to conversion to industrial products. Not shown are reject and recycle fractions that are associated with most processes as shown in box at lower right of the figure.

and material removed from the ground before processing. The term *chromite products* is then used to refer to material supplied to the marketplace. Historically, mining operations supplied minimally processed material. Beneficiation and processing shown in Figure 2 may be carried out at the mine site, at a plant that serves several mines in one geographic area, or at a plant associated with end users. This variety in processing further complicates labeling of material. Today, quality control leads consumers to seek chromite supplies that do not vary significantly in physical or chemical properties over time. As a result, chromite ore is typically beneficiated to produce a physically and chemically uniform product before it reaches the marketplace.

Mining methods are carefully chosen to meet the characteristics of a deposit, including the ore and its environment. Since both small and large, podiform and stratiform, high-grade and low-grade, subsurface and near surface, massive and disseminated chromite deposits are exploited, a variety of mining methods are used. Since, typically, surface mining is less expensive than underground mining and ore bodies are found by their outcrops, surface mining at an outcrop precedes underground mining.

The purpose of beneficiation is to increase desirable ore attributes and decrease undesirable ones. For example, depending on end use, increasing chromic oxide content, chromium:iron ratio, or alumina content is desirable. Reducing silica or other minerals associated with chromite is desirable. Depending on end use, certain sizes may be selected or rejected. The techniques used to accomplish these tasks depend on the physical properties and sizes of the minerals present. Beneficiation does not change the chemical characteristics of the chromite mineral. However, since chromite ore is a mixture of minerals, the characteristics of the ore can be changed by altering its mineral mix. A deposit producing lumpy ore in which the chromite is easily distinguished may require only hand sorting and screening. When the chromite cannot easily be distinguished visually from associated minerals and the ore is lumpy, then heavy-media separation can be used. A deposit that yields an ore of chromite thoroughly intermixed with other minerals, however, may require milling and sizing followed by gravimetric and/or electromagnetic separation methods to produce marketable chromite products.

Beneficiation may also be selected to process tailings once sufficient quantities have been stockpiled and the technology of beneficiation and processing has been established.

**4.2. Ferrochromium.** The smelting of chromite ore to produce ferrochromium requires electric-arc furnace technology. Early electric furnaces having power ratings in the kilovolt-ampere range have developed into modern furnaces having power ratings of about 50 MV·A. Closed and partially closed electric-arc furnaces replaced open furnaces in the 1970s to improve pollution control, efficient furnace operation, and safety.

*Ferrochromium* is produced from chromite ore by smelting a mixture of the ore, flux materials (eg, quartz, dolomite, limestone, and aluminosilicates), and a carbonaceous reductant (wood, coke, or charcoal) in an electric-arc furnace. If the ore is lumpy, it can be fed directly into the furnace. However, if the ore is not lumpy, it must be agglomerated before it is fed into the furnace. Efficient operations recover chromium lost to furnace fume by collecting and remelting the dust

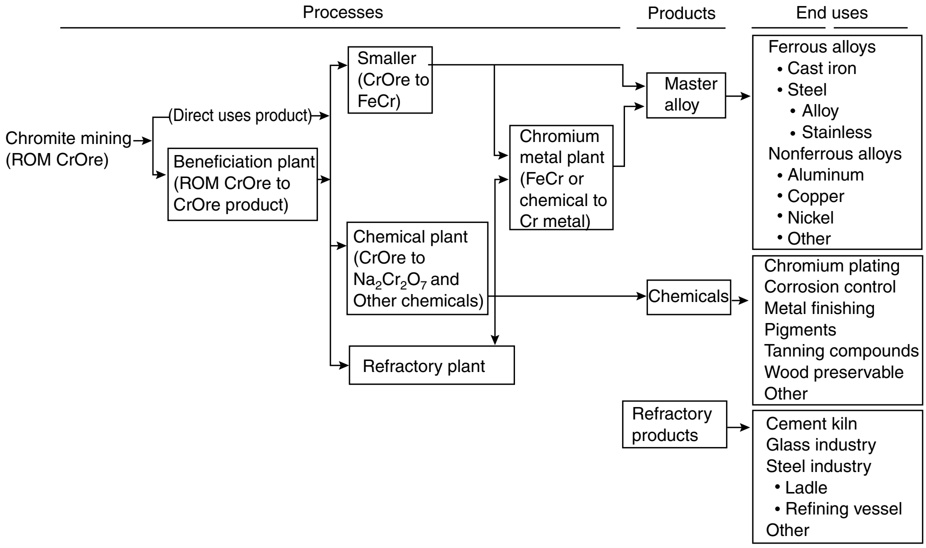

**Fig. 3.** Chromium material flow from mining through processing by the chemical, metallurgical, and refractory industries, to primary industrial products and the end uses in which those primary industrial products are used. CrOre = chromite ore; FeCr = ferrochromium; $Na_2Cr_2O_7$ = sodium dichromate and ROM = run-of-mine. Mining includes screening and hand sorting. Benefication includes crushing, grinding, and separation techniques including gravimetric, heavy media, magnetic, and spiral. Master alloy is an alloy used as a feed stock to produce other alloys.

and recover chromium lost to slag by crushing and beneficiating the slag. The chromium content of the ferrochromium is determined by the chromium:iron ratio of the chromite ore.

The shift from high-chromium, low-carbon ferrochromium to low-chromium, high-carbon ferrochromium, commonly called *charge-grade ferrochromium*, permitted the use of low-chromium:iron ore for smelting to ferrochromium. The Republic of South Africa is the most abundant and low-cost source of such ore. Unfortunately, this ore is friable (breaks easily into small pieces), and the finer fractions of such ore are blown out of a furnace before it can be smelted. Agglomeration technology has been developed to permit the use of fine chromite ore in the electric arc furnace. Both briquetting and pelletizing are practiced. Efficient production technology uses prereduced and preheated pelletized furnace feed. Industry is developing new production technologies using high-temperature plasmas or using alternatives to electrical power supply. The new production technologies are expected to be more cost-competitive than traditional production technology under some conditions. Advanced smelting technologies that use abundant friable ore have been and are being developed. Plasma processes, including both transferred and nontransferred arc processes, have been applied to ferrochromium production. The kiln roasting prereduction process is being applied to ferrochromium production.

**4.3. Chromium Metal Production.** Chromium metal is produced primarily through one of two production processes: electrodeposition process to produce electrolytic chromium metal and the reduction of chromic oxide with aluminum powder to produce aluminothermic chromium metal. The aluminothermic reduction process is more widely used and more easily installed or expanded. A wide variety of variations of reductants for the exothermic reduction process and of feed materials and electrolytes for the electrowinning process resulted in the current commercial production processes: aluminothermic reduction of chromic oxide to produce aluminothermic chromium metal and electrolytic deposition from a chromium–alum electrolyte made from high-carbon ferrochromium to produce electrolytic chromium metal. The aluminothermic process was used first. The electrolytic process was developed to provide a higher-purity chromium metal than could be obtained by the aluminothermic process. The processes from chromite ore mining to chromium metal product are shown in Figure 3.

Commercial grades of chromium metal have been produced in the United States in bulk quantities by Eramet Marietta, Inc. using the electrolytic process and by Shieldalloy Corp. using the aluminothermic process. Shieldalloy suspended production in 1990, leaving Eramet as the sole U.S. producer.

## 5. Sources and Supply

### 5.1. Availability.

The U.S. Geological Survey conducted an inventory of chromium resources (9). They found that, by far, the world's major resources are centered in the Bushveld Complex deposit in Republic of South Africa and in the Great Dyke deposit in Zimbabwe. Other significant deposits were identified in the Cuttack district of Orissa State in India and in the Kempirsai district of Kazakstan.

The former U.S. Bureau of Mines (USBM) studied the availability of chromium (10). The USBM analyzed for the simultaneous availability of chromium contained in chromium ferroalloy products and in exportable chromite products (metallurgical, chemical, refractory, and foundry sands) in 10 market economy countries (MECs).

A total of about 874 million tons gross weight of *in situ* material containing about 203 million tons of chromium was analyzed. Extraction and beneficiation of this material was estimated to result in about 475 million tons of chromite products, of which 289 million tons would be available for export, and the remaining 187 million tons would be smelted in the country in which it was mined to produce about 80 million tons of chromium ferroalloys. The chromium ferroalloys would then be available for use in the country of production or for export. The 80 million tons of chromium ferroalloy included about 74 million tons of high-carbon ferrochromium, 4 million tons of low-carbon ferrochromium, and 2 million tons of ferrochromium–silicon.

The countries of South Africa and Zimbabwe held about 80% of the *in situ* contained chromium. India and Finland accounted for an additional 11% of the contained chromium; another 8% of the contained chromium was fairly evenly divided among Brazil, the Philippines, Turkey, and the United States; the remainder was in Greece and Madagascar.

Table 7. **Availability Based on Cost of Production of Chromite and Chromium Ferroalloys from 10 Market Economy Countries**[a]

| Chromium materials | Quantity available, $\times 10^6$ tons, gross weight | Cost,[b], \$/t | |
|---|---|---|---|
| | | Weighted average | Range |
| chromite | | | |
| chemical grade | 64.3 | 53 | 35–174 |
| foundry sand grade | 16.4 | 49 | 39–83 |
| refractory grade | 26.8 | 87 | 54–180 |
| metallurgical grade | | | |
| primary product | 145.4 | 101 | 42–705 |
| secondary product | 35.6 | 54 | 33–117 |
| *Subtotal* | *181.0* | *92* | *33–705* |
| refractory grade | 26.8 | 87 | 54–180 |
| *Total* | *288.5* | | |
| chromium ferroalloys | | | |
| ferrochromium | | | |
| high-carbon ferrochromium | 74.3 | 473 | 417–1,286 |
| low-carbon ferrochromium | 3.9 | 937 | 635–1,309 |
| ferrochromium-silicon | 2.0 | 737 | 578–814 |
| *Total* | *80.2* | | |

[a] Ref. 10.

[b] Cost of production for 0% discounted cash flow rate of return in Jan. 1989 dollars per metric ton, gross weight, of product.

Based on $Cr_2O_3$ content of *in situ* chromite ore, the 10 MECs split into two groups: a high-grade group and a low-grade group. The *high-grade group*, those with ore grades ranging from 33.96 to 43.01% $Cr_2O_3$, included the countries of India, Madagascar, South Africa, Turkey, and Zimbabwe. The *low-grade group*, those with ore grades ranging from 9.16 to 26.65% $Cr_2O_3$, included the countries Brazil, Finland, Greece, the Philippines, and the United States. The grade differences between the two groups resulted in a wide disparity in the respective weighted average $Cr_2O_3$ contents. The high-grade group averaged 38.76% $Cr_2O_3$; the low-grade group, only 15.90% $Cr_2O_3$.

Table 7 shows the results of the USBM analysis. Chromium material costs were calculated on a weighted average basis, free-on-board (fob) ship at the port of export. The chromite cost shown in Table 7 includes mining and beneficiating the ore (including mine capital and operating costs and taxes) and transportation of ore and products to port facilities. Chromium ferroalloy cost includes chromite ore but excludes smelter capital cost. The USBM analysis shows that, measured on the basis weight of production from South Africa and Zimbabwe to weight of production from all sources at the respective sources break even cost as measured in their study, South Africa and Zimbabwe could produce about 78% of metallurgical chromite ore, 93% of chemical chromite ore, 85% of refractory chromite ore, and 93% of foundry chromite ore. South Africa and Zimbabwe could also produce about 69% of the high-carbon ferrochromium, 89% of the low-carbon ferrochromium, and 100% of ferrochromium–silicon that could be produced at their respective estimated breakeven cost. The product breakdown between chromium ferroalloy and chromite and among the grades within those product categories was based on mine and smelter production capacities and known operating relationships circa the 1987/88 time period.

**5.2. Strategic Considerations.** There is no production of chromite ore in the United States; primary consumption of chromium by U.S. industry is by companies that use chromite ore to produce chromium chemicals and chromite refractories and by chromium metal producers that use ferrochromium. World reserves of chromite ore are abundant, ensuring adequate long-term supply. However, major supply sources are few and remote from the United States, making supply vulnerable to disruption. The problem for the United States is one of national security. Ferrochromium is essential to production of stainless and some alloy steel, which are, in turn, essential to both the domestic economy and to the production of military hardware.

It has been the policy of the Federal Government of the United States to maintain a National Defense Stockpile of critical and strategic materials for use in the event of a national defense emergency. The U.S. government has maintained a stockpile since World War I. Industrial mobilizations resulting from World War I (1914–1918), World War II (1939–1945), and the Korean War (1950–1952), along with politically motivated peacetime supply embargoes of the former Union of Soviet Socialist Republics against the United States as a result of the Berlin crisis (1949–1950) and of the United States against Rhodesia as a result of United Nations actions (1966–1972), caused national defense planners to acquire and maintain a stockpile. The United States also implemented trade sanctions against South Africa (1986–1994); however, chromium materials were exempt for those sanctions.

Critical and strategic materials were stockpiled. *Critical materials* are essential in a national security emergency because of their important end uses. *Strategic materials* are potentially in short supply during a national emergency. The Defense Logistics Agency, the manager of the National Defense Stockpile, defines "strategic and critical materials" as materials that (*1*) would be needed to supply the military, industrial, and essential civilian needs of the United States during a national emergency and (*2*) are not found or produced in the United States in sufficient quantities to meet such need (11). Critical and strategic materials for the purpose of inclusion in the National Defense Stockpile are materials Congress directs the administration to include in the stockpile by act of Congress. So, pragmatically, critical and strategic materials are those defined to be so by Congress.

The Defense Logistics Agency, Department of Defense, is currently responsible for National Defense Stockpile operations (12). Chromium materials included in the National Defense Stockpile (NDS) are chromite ore (metallurgical, chemical, and refractory grades), chromium ferroalloys (high- and low-carbon ferrochromium and ferrochromium-silicon), and chromium metal. The purpose of the NDS is to supply military, essential civilian, and basic industrial needs of the United States during a national defense emergency, and by law the stockpile cannot be used for economic or budgetary purposes.

Changes in industrial capacity and new manufacturing and technological developments have rendered selected chromium materials in the NDS inventory obsolete, either in quality or form or both, and in need of upgrading. Subsequent

Table 8. **U.S. Government Stockpile Year-End Inventories, (metric tons, gross weight)**[a]

| Material | 1995 | 1996 | 1997 |
|---|---|---|---|
| chromite | | | |
| chemical | 219,914 | 219,914 | 217,110 |
| metallurgical | 772,587 | 644,957 | 564,799 |
| refractory | 328,107 | 321,966 | 309,406 |
| chromium ferroalloys | | | |
| ferrochromium-silicon | 52,941 | 52,687 | 52,688 |
| high-carbon ferrochromium | 737,694 | 717,627 | 689,226 |
| low-carbon ferrochromium | 282,735 | 282,735 | 282,735 |
| chromium metal | | | |
| aluminothermic | 2,667 | 2,667 | 2,667 |
| electrolytic | 5,018 | 5,054 | 5,054 |

[a] Inventories includes specification- and nonspecification-grade materials.

to legislative mandate, DLA began modernizing chromium materials in the NDS by converting chromite ore to high-carbon ferrochromium (1984–1994) and nonspecification-grade low-carbon ferrochromium into chromium metal (1989–1994).

As result of the dissolution of the Soviet Union in 1991, NDS planners have reduced material goals and implemented inventory reduction programs. Material disposal from the NDS takes the form both of direct sales and material used in payment for service. Table 8 shows National Defense Stockpile inventory levels (for 1995–1997).

In addition to private and government stocks, there exists a large unreported inventory of chromium contained in products, trader stocks, and scrap. The amount of these stocks varies with demand and material price. Under price pressures resulting from primary chromium shortages, recycling of consumer materials could add to the supply.

**5.3. Prices.** Chromium materials are not traded in open-market exchanges such as gold, silver, nickel, and some other metals. As a result, chromite ore, chromium ferroalloys, and chromium metal do not have an easily identifiable price. The price of these chromium materials is usually negotiated between buyer and seller and is known only to them. Price speculation is, of course, a very popular activity because of the great impact of prices on both producers and consumers. As a service to their readers, some periodicals report a composite price based on surveys of sellers and buyers. Included among these are American Metal Market, Industrial Minerals, Metal Bulletin, Metals Price Report, Platt's Metals Week, and Ryan's Notes. Unfortunately, the volume of trade at the reported price is unknown.

When material is imported into the United States, its value at the port of export is declared for the purpose of tax collection. This is called the free on board (fob) value. Using this value, a value history for chromium materials by import category was constructed. This value history averages reported import values over sources of supply weighted by quantity of material supplied. Using reported prices, an annual average price for chromium materials has been generated using sources that report prices in the United States. Since reported prices are

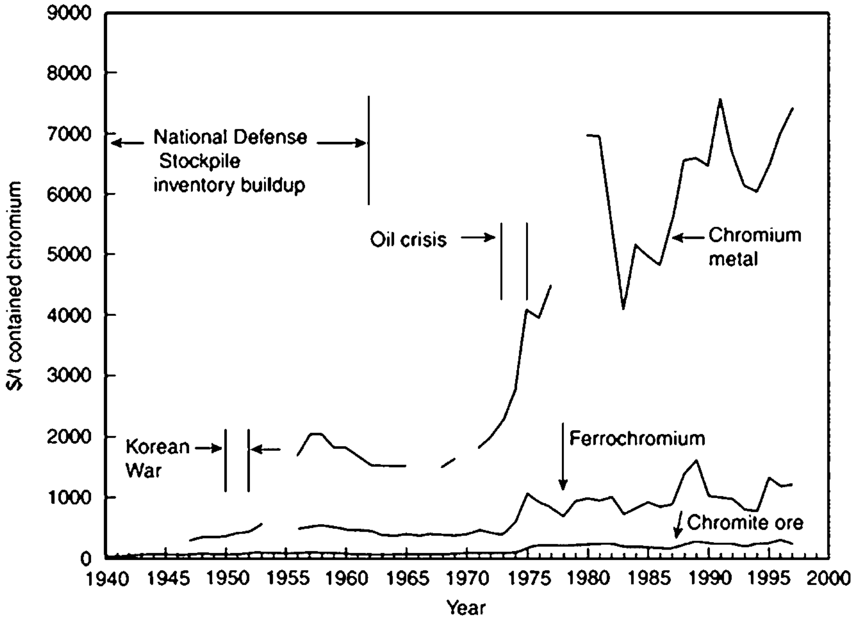

**Fig. 4.** Composite chromite ore, ferrochromium, and chromium metal value. The value of chromium metal exceeds that of ferrochromium by a factor of 5 and that of chromite ore by a factor of 25.

source sensitive, an annual average including all sources was calculated. Chromite ore price reported in dollars per metric ton, gross weight, can vary by nearly a factor of 2 depending on the origin and quality of the material. Ferrochromium price reported in dollars per metric ton of contained chromium shows similar variation based on material grade. Figure 4 shows the value history of chromium materials in units of dollars per metric ton of contained chromium. The value of chromite was relatively stable through about 1970, when the value started to rise. The value of chromite declined from 1982 to 1988, the time period during which steel production in general and stainless steel production in particular was weak. Strong stainless steel recovery in the 1988–1990 time period resulted in short supply of ferrochromium. The shortage nearly doubled the price of ferrochromium and stimulated capacity expansion in that industry, primarily in South Africa. The price of chromite ore rose following that of ferrochromium. Additional chromite production capacity was added to meet the anticipated additional demand from added ferrochromium production capacity, primarily in South Africa and India. When adjusted for inflation, each material is found to be less expensive today than it has been in the past. Price peaks for ferrochromium correspond to increases in world stainless steel production. The increases resulted in demand for ferrochromium in excess of material available from active production capacity and stocks.

Ferrochromium values show greater variation than those of chromite ore. Before the mid-1970s, the value of various ferrochromium grades were tightly grouped compared to the post mid-1970s time period, when the value of low-carbon ferrochromium was about double that of high-carbon ferrochromium except for a couple of years when ferrochromium shortages drove the prices together. This value differentiation shows the advantage of post-melting refining technology—it permits the use of lower cost materials. The figure also shows that reported price generally exceeded fob import value.

Figure 4 shows the value relationship among chromium materials. These values show that as chromite ore is processed to ferrochromium and to chromium metal, the added value is quite large. On a per unit scale of contained chromium basis for recent years, the value of ferrochromium is about five times that of chromite ore; the value of chromium metal is about 30 times that of chromite ore. Variations of the value of ore are shown to follow those of ferrochromium, indicating values of chromite ore change in response to demand, with ferrochromium value first to reflect demand changes. (Because chromite ore price changes may lag those of ferrochromium by only a few weeks, the tables may show peak average annual values occurring in the same year.)

**5.4. Trade.** The United States is 100% import dependent for chromite ore. Chromium import dependence is lessened by the supply of some chromium through recycling. The United States imports chromite ore, chromium ferroalloys, chromium chemicals, and chromium metal. Chromium ferroalloys, metal, and chemicals and chromite-containing refractories are manufactured in the United States. These materials are also exported from the United States, but in quantities smaller than those imported (except for chemicals). The United States is a major world chromium chemical producer.

The harmonized tariff schedule categories distinguish chromium-containing materials from chromium-free materials well except for chromite-containing refractories, which are included with chromite-free materials. The change from

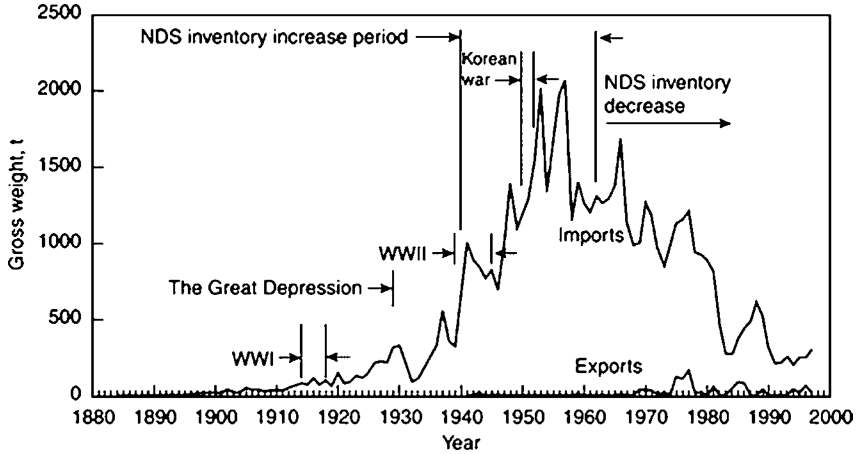

**Fig. 5.** U.S. chromite ore trade. U.S. chromite ore imports have exceeded exports by a large amount since such trade has been reported. At the end of World War II, U.S. chromite ore imports represented most of world chromite ore production. Part of the imports between 1939 and 1962 went into the National Defense stockpile, which reached its peak chromite ore inventory of about 8 million tons in 1962. Between 1945 and 1962, the United States imported nearly 24 million tons of chromite ore. The post-1965 decline in U.S. chromite ore imports results from declining chromite ore use in the metallurgical and refractory industries.

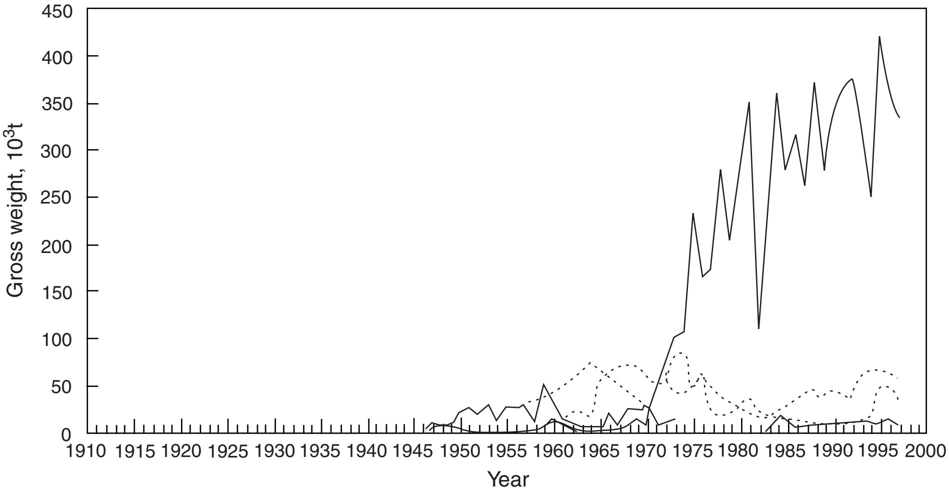

**Fig. 6.** U.S. chromium ferroalloy trade. Since the mid-1970s, high-carbon ferrochromium imports have dominated chromium trade. The introduction of postmelting refining processes in the steel industry after 1960 followed by rationalization of most of domestic ferrochromium production industry and strong growth in the ferrochromium consumption industry resulted in increased imports of high-carbon ferrochromium. ——, High-carbon ferrochromium imports; – –, low-carbon ferrochromium imports; - - - -, ferrochromiumsilcon imports; and ▬, exports, composite of various grades.

the Tariff Schedule of the United States to the Harmonized Tariff Schedule of the United States resulted in many category changes. As a result, comparison of statistics across the 1988/89 boundary may result in the comparison of inconsistent materials.

Figure 5 shows that Chromite ore imports have always greatly exceeded exports. Imports grew rapidly after about 1939, when the NDS-enabling legislation was passed, and peaked in the 1950s, at about the time that the NDS reached its peak chromite ore inventory. Figure 6 shows that chromium ferroalloy imports greatly exceed exports and that high-carbon ferrochromium imports have dominated chromium ferroalloy imports since the mid-1970s, when postmelting refining technology permitted high-carbon ferrochromium to replace low-carbon ferrochromium in the production of steel. The figure shows that high-carbon ferrochromium imports have been growing since the mid-1970s. Figure 7 shows that chromium metal imports greatly exceed exports and that both imports and exports are growing. As a source of chromium to U.S. industry, chromite ore and ferrochromium imports dominate. Chromite ore was the predominant source of chromium until the 1980s, when high-carbon ferrochromium displaced chromite ore.

## 6. Manufacturing and Production

Chromite ore mining and chromium material manufacturing is an international industry. The major industries associated with chromium are chemical,

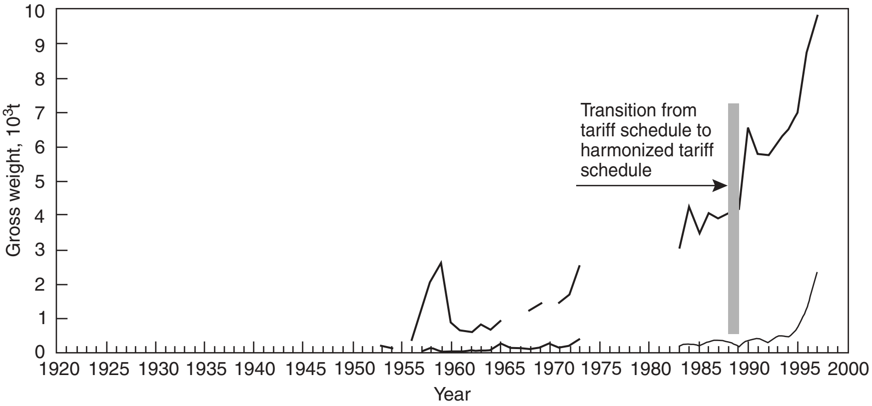

**Fig. 7.** U.S. chromium metal trade. Chromium metal trade is dominated by exports. The United States is both a major world chromium metal producer and consumer. ▬, imports; —, exports.

metallurgical, mining, and refractory. Mining is, of course, the first to process chromium in the form of chromite ore. The chemical industry processes chromite ore by kiln roasting to produce sodium dichromate initially and then other chromium chemicals. The metallurgical industry processes chromite ore mostly by electric-arc furnace smelting to produce ferrochromium. It also processes chromic oxide from the chemical industry and ferrochromium from the metallurgical industry into chromium metal. Ferrochromium and chromium metal are then incorporated into ferrous and nonferrous alloys. The refractory industry processes chromite ore into chromite-containing refractory materials. It also processes chromic oxide [1308-38-9] from the chemical industry into refractory materials (see also REFRACTORIES).

Production data are available for chromite ore, ferrochromium, and stainless steel by country because there are usually sufficient numbers of producers per country to maintain confidentiality of data about plants or companies. Chromium chemical and metal production and chromite-containing refractory producers are substantially fewer in number than are chromite ore, ferrochromium, and alloy producers, making it difficult to report those industries' products by country while maintaining confidentiality. Since nations are the largest grouping for which data are collected and published, production from these industries is simply not publicly available.

World chromite ore production is shown in Figure 8. The figure shows that world production has been dominated by South Africa and Kazakstan (reported as USSR before 1991) with a large number of smaller producers grouped close together. About 15 countries make up the "Other" category. Production from the most recent years indicate that South Africa, Turkey, and India are developing their chromite production potential. The decline in production from Kazakstan was substantial.

Figure 8 shows that there have been two major (i.e., >1 million tons per year) chromite ore producers over the time period shown: South Africa and Kazakhstan. (Kazakstani production was the larger share of USSR production,

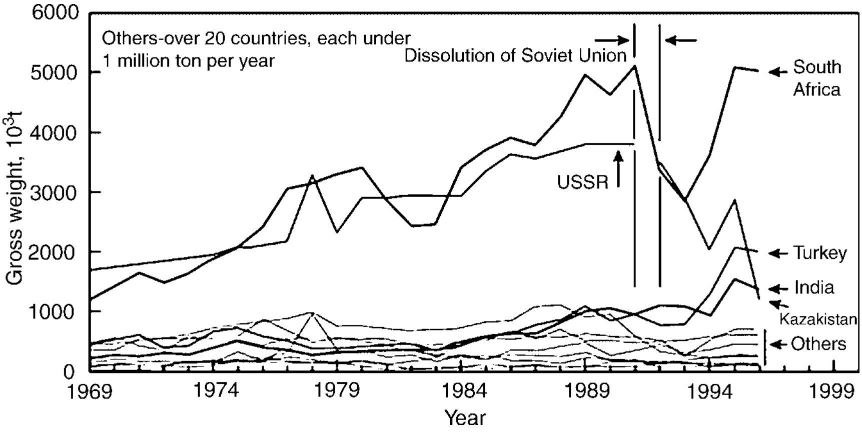

**Fig. 8.** World chromite ore production by country. Over most of the time period shown, South Africa and the former Soviet Union, most of which was from Kazakhstan, dominated world production. Since the dissolution of the Soviet Union in 1991, production from Kazakhstan has been displaced by increased production from India and Turkey. In any given year there are over 20 producers of chromite ore, most of which produce under one million tons per year. An immediate effect of the dissolution of the former Soviet Union was to stimulate exports of chromite ore to Western consumers traditionally supplied from Western sources. The impact was a major reduction in production by South Africa, the traditional supplier of chromium to Western consumers.

1969–1991). The figure also shows that when former Soviet markets merged with Western markets after 1991, it was South African production that declined to accommodate new chromite ore supply. When the Eastern and Western markets merged, production and capacity in the East was unchanged while Eastern demand declined rapidly. Political change in Kazakhstan appears to have negatively affected chromite ore production because, except for a one-year recovery in 1995, Kazakhstani production has declined since 1991. South Africa, on the other hand, appears to have benefited from political change over the same time period because South African, as well as Turkish and Indian production has increased. Both India and Turkey have also experienced changes in their national political paradigms in the same time period; but, with lesser impact on their national economies than have been experienced in Kazakhstan and South Africa. Increasing demand for chromium and declining production in Kazakhstan has resulted in both India and Turkey joining the major producer category in 1989 and 1994, respectively. On average over the 5-yr time period 1992–1996, the major producing countries accounted for about 80% of production.

World ferrochromium production is shown in Figure 9. The figure shows that, over most of the time period, there have been two major producers (>500,000 t/yr). However, since 1991, South Africa has stood alone as the world's largest ferrochromium producer with production over double that of the next-largest producer. Other moderate producers (200,000 to 500,000 t/yr) include China, Finland, Japan, Kazakhstan, and Zimbabwe, of which China and Japan do not have domestic ore supplies to support their ferrochromium production. On average during 1992–1996, South Africa accounted for about 30% of world

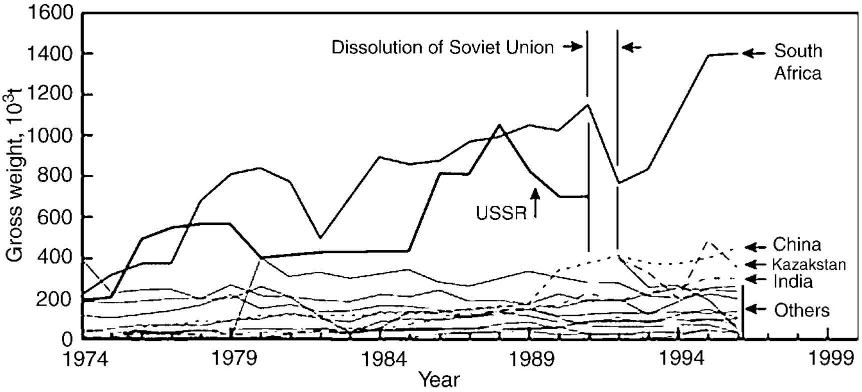

**Fig. 9.** World production of ferrochromium by country. World production of ferrochromium has been dominated by South Africa and the former Soviet Union, most of which came from Kazakhstan, over the time period shown. Since the dissolution of the Soviet Union in 1991, production from Kazakhstan has been displaced by increased production from China and India. In any given year there are over 20 producers of ferrochromium most of which produce under about 200,000 t/yr. An immediate effect of the dissolution of the former Soviet Union was to stimulate exports of ferrochromium to Western consumers traditionally supplied from Western sources. The impact was a major reduction in production by South Africa, the traditional supplier of chromium to Western consumers. Others includes over 15 producers each under 200,000 t/yr.

production while the moderate producers accounted for about 55%. Compared to the chromite ore industry, moderate-size producers account for a grater share of production in the ferrochromium industry.

Chromium chemical production is geographically concentrated in developed economy countries. Major producing countries where large plants (capacity in excess of 100,000 tons per year of sodium dichromate) operate include Kazakhstan, Russia, the United Kingdom, and the United States. Moderate-sized production facilities are located in Brazil, China, Japan, Romania, South Africa, and Turkey. Small-scale local producers operate in China and India.

**6.1. Chromium and Chromite.** Chromite is used in the metallurgical, chemical, and refractory industries. In the metallurgical industry, chromite is processed into ferrochromium or chromium metal, then is used as an alloying metal to make a variety of ferrous and nonferrous alloys. The major end use is in stainless steel, a ferrous alloy made resistant to oxidation and corrosion by the addition of chromium. Chromite is used in the chemical industry to make sodium dichromate which is both a chemical industry product and an intermediate product used to make other chromium chemicals. Chromium chemicals find a wide variety of end uses, including pigments, and plating and surface finishing chemicals. Chromite is used in the refractory industry to produce refractory materials, including shapes, plastics, and foundry sands. These refractory materials are then used in the production of ferrous and nonferrous alloys, glass, and cement. Chromite is useful in the refractory industry because it retains its physical properties at high temperatures and is chemically inert.

**6.2. Chromite Consumption.** Reported chromite consumption in the United States over the 5-year period from 1993 to 1997 averaged about

328,000 tons annually, indicating a decline from the 1970s, when annual production regularly exceeded 1 million tons annually. Virtually all of this chromite was imported. The chromite was used to make chromium ferroalloys and chemicals, and chromite refractory materials, including casting sand. The major reason for declining domestic chromite use is the shift from domestic to foreign ferrochromium supply as the source of chromium units for the metallurgical industry. Contributing to reduced chromite ore consumption is the decline in chromite-containing refractory use.

**6.3. Metallurgical.** The metallurgical industry consumed chromite ore to produce chromium ferroalloys and metal.

**6.4. Refractory.** Refractory materials resist degradation when exposed to heat. Chromite is a refractory material. Unlike the chemical and metallurgical industries, where chromite is processed to extract its chromium content, chromite is used chemically unmodified in the refractory industry. Chromic oxide, a chemical industry product, is also used to make refractories for the glass industry. Chromic oxide refractories are used in glass contact areas of glass melting furnaces to achieve long furnace life.

Refractories are broadly categorized according to their material composition into clay and nonclay refractories. The predominant nonclay refractory material is silica. Nonclay refractory materials also include alumina (bauxite), carbon (graphite), chromite, dolomite, forsterite, magnesia (magnesite), mullite, pyrophylite, silicon carbide, and zirconia (zircon). Basic refractories are a type of nonclay refractory, so called because they behave chemically as bases. Basic refractories are made of chromite, dolomite, magnesite, or various combinations of magnesite and chromite. In the refractory industry, chromite-containing refractories are called chrome refractories. Chrome–magnesite refractories are those in which more chromite than magnesite is used. Magnesite–chrome refractories are those in which more magnesite than chromite is used. The terms chrome and magnesite are used in association with refractories to indicate that the refractory was made with chromite ore and magnesia.

Refractories are further categorized by the form in which they are supplied as shaped or unshaped. *Shaped refractories* are manufactured to fit together to form a desired geometric structure, like building blocks. *Unshaped refractories* include mortars (materials used to hold shaped refractories together), plastics (materials that may be formed into whatever shape is desired), and gunning (material that may be sprayed onto a surface). In the refractory industry, the term *monolithics* is commonly used to describe refractories that are not shaped. The units used to report shipments of shaped and unshaped refractories differ. Shaped refractories have been reported in thousand 9-in. (22.86-cm) brick equivalents; unshaped refractories, in tons. A 9-in. (22.86-cm) brick equivalent is a solid volume of 0.165919 $m^3$, used in the United States as a “standard unit” for refractory bricks.

Chromite-containing refractory producers are shown in Table 9 along with refractory industry products and the end users and uses of those products. The major end users for chromite refractories are in the cement, copper, glass, nickel, and steel industries. Basic refractories are used in copper and nickel furnaces. In the glass industry, chromite refractories are used in glass tank regenerators and chromic oxide refractories are used in melting furnaces for the production of

Table 9. **U.S. Chromite and Chromic Oxide Refractory Producers, Products, and End-Use Markets**

| Producers in 1998 | Products | End users and uses |
|---|---|---|
| General Refractories Co. | bricks and shapes | steel industry |
| U.S. Refractories Division | mortar | AOD vessels |
| 600 Grant Street Room 3000 | plastic | barrel |
| Pittsburgh, PA 15219 | gunning | trunnion and tuyere area |
| | | bottom |
| | | electric-arc furnaces |
| | | sidewall |
| Harbison-Walker | | slagline |
| Refractories | | |
| a subsidiary of Global | | steel ladles |
| Industrial Technologies | | |
| One Gateway Center | | |
| Pittsburgh, PA 15222 | | ladle metallurgical furnaces |
| | | slagline |
| | | sidewall and bottom |
| | | vacuum degassers |
| National Refractories and | | sidewall |
| Minerals Corp. | | |
| 1825 Rutan Drive | | snorkel |
| Livermore, CA 94550 | | open-hearth furnace |
| | | backwalls |
| | | endwalls |
| | | lower walls |
| North American Refractories Co. Ltd. | | roofs |
| 500 Halle Building | | furnace ports |
| 1228 Euclid Avenue | | copper–nickel industry |
| Cleveland, OH 44115 | | electric-arc furnaces |
| | | slagline |
| | | bottom |
| | | flash furnaces |
| Corhart Refractories | | roof and sidewall |
| RR 6, Box 82 | | bottom |
| Buckhannon, WV 26201-8815 | | Pierce–Smith converters |
| Phone: (304)-473-1239 (voice) | | tuyere areas |
| (304)-473-1287 (fax) | | barrel and endwall |
| | | Top-blown rotary converters |
| | | upper cone |
| | | bottom and barrel |
| | | anode furnace |
| | | barrel and endwall |
| | | fire refining and secondary furnaces |
| | | bottom |
| | | sidewall and endwall |
| | | cement–lime industry |
| | | rotary kilns |
| | | burning zone |
| | | upper transition zone |
| | | lower transition zone |
| | | glass industry |
| | | glass furnace regenerators |
| | | checker |
| | | wall |
| | | crown |
| | | fiberglass furnace |
| | | melting furnace |

reinforcing glass fibers and textiles. In the cement industry, chromite refractories are used primarily in the transition zones of cement kilns. Basic refractories are typically used in open-hearth and electric-arc steelmaking furnaces.

Chromite refractories were used heavily in steel production using the open-hearth furnace method. Contemporary steelmaking processes that use the basic oxygen furnace or the electric-arc furnace use much less chromite-containing refractories. Whereas open-hearth furnaces used about 30 kg of refractories per ton of steel, the basic oxygen furnace uses about 1 kg/t and the electric-arc furnace uses in the range of 1–2 kg/t. As a result, the steel industry demand for basic refractories has declined dramatically as open-hearth furnace steelmaking has been phased out.

The general decline in refractory use results, at least in part, from the more cost-efficient use of refractories. Longer lasting refractories result in lower labor cost to change the refractories and higher production equipment availability because of less down time for relining. A specific reason for the decline in chromite-containing refractory use results from changes in steel industry production practice. The major end use for basic chrome refractories was in the production of steel in open-hearth furnaces. As steel production technology has shifted away from open-hearth furnace steel making, chromite refractory use has declined. Steel is no longer produced in open hearth furnaces in the United States.

**6.5. Foundry Sand.** Foundry sand use of chromite is a modern application. Sand is used to contain molten metal in a desired shape until the metal has solidified. Sand used in the foundry industry is washed, graded, and dried. Since silica sand is common and inexpensive, it is the most commonly used mineral. However, when physical or chemical conditions dictate, other sands are chosen, such as zircon, olivine, or chromite. Chromite foundry sand is used in the ferrous and copper casting industries.

Casting sands are defined by function and by processing. Mold and core sands are designed for the exterior and interior of a casting, respectively. Facing sand is used on the surface of a core or mold. Flour or paint may be applied to the facing sand. As indicated by its name, flour is finer in size than sand. Before casting, sand is naturally or chemically bonded. There are a variety of methods for bonding sand before casting. Chromite sand is compatible with the commonly used methods. After casting, foundry sand is reclaimed.

Chromite sand is compatible with steel castings. It is typically used as facing sand in heavy section (>4 t) casting and enjoys a technical advantage over silica sand in casting austenitic manganese steel. Chromite sand does not react with the manganese in the steel. Chromite and zircon, each having a higher melting point than silica, are chosen when casting temperatures exceed those acceptable for silica sand. U.S. foundry sand producers, products, and end-use industries are shown in Table 10. Chromite sand is also used in copper-base nonferrous casting.

Chromite sand casting was developed in South Africa, where chromite fines are readily available as an inexpensive grade of chromite associated with chemical, refractory, and metallurgical chromite production. After satisfactory results in South Africa in the late 1950s, use expanded in the 1960s to include the United Kingdom followed closely by the United States. Use of chromite sand was facilitated first by a shortage of zircon sand supply and then by the higher

Table 10. **U.S. Foundry Sand Producers, Products, and End Uses**

| Producers | Products | End Uses |
|---|---|---|
| American Colloid Co. | chromite flour | architectural brick |
| 1500 W. Shure Drive | chromite sand | brake shoes |
| Arlington Heights, IL 6004-1434 | | casting facing sand |
| | | ceramic |
| American Minerals Inc. | | colorant |
| 901 East Eighty Avenue, Suite #200 | | glass |
| King of Prussia, PA 19406 | | mold coating |

price of zircon sand. The foundry characteristics that make chromite sand desirable include good thermal stability, good chill properties, good moisture resistance, resistance to metal penetration, high degree of refraction, and imperviousness to chemical reaction. Its disadvantages, compared with the zircon sand it replaces, include higher thermal expansion, occasional presence of hydrous mineral impurities, and different bonding practice with some binders.

Chromite sand for U.S. foundry use was estimated to have increased from about 20,000 t in 1965 to about 36 000 t in 1971. Industry sources estimate U.S. chromite foundry sand use in 1989 and 1990 to have been about 40,000 t annually.

Reclamation is an integral part of the foundry industry. It includes mechanical, pneumatic, wet, and thermal processes, and combinations thereof. Using these processes, as much as 90% of chemically bonded foundry sand (average over all minerals used) can be reclaimed (13). Chromite sand is adaptable to these processes. After casting, chromite sand, typically used as facing sand, becomes mixed with the bulk sand (silica). Since chromite sand has a size distribution similar to that of silica sand, mechanical separation is not applicable. Hydraulic spiral separation and magnetic separation are effective at separating chromite sand from silica and zircon sand. Silica and zircon sands are nonmagnetic. Some chromite sand was found to degrade during use. However, degraded sand tends to adhere to the castings, so it does not become part of the reclaimed sand. Reclaimed chromite sand was found to be interchangeable with new chromite sand. The actual amount of chromite sand reclaimed, like the amount used, is unknown. However, Sontz estimated that about half of the foundry industries chromite demand could be met by reclaimed chromite sand (14).

## 7. Shipment

Chromite ore is typically transported by trackless truck or conveyor belt from the mine face to storage or processing facilities on the mine site. From there, it is transported by truck from the mine site to the local railhead. It is then transported by rail to ports or to smelters. Smelters that do not have associated loading and unloading facilities for ships transport their product by rail to ports. Following transport by ship to consumer countries, chromium materials are typically hauled by barge, truck, or rail to end users who have no loading and unloading facilities for ships.

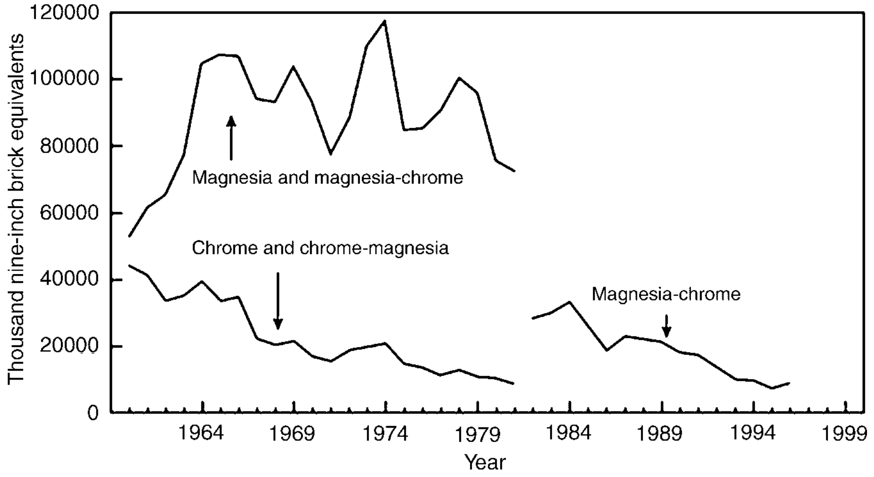

**Fig. 10.** U.S. chromium-containing shaped refractory shipments. Chromite ore is combined with magnesia to produce chrome–magnesia or magnesia–chrome refractories. The major end use for these refractories was in open-hearth steelmaking furnaces, which have been displaced by more efficient steelmaking methods in most of Western countries.

The historical trends of chromite-containing refractory shipments are shown in Figures 10 and 11. These figures show shipments of chromite-containing refractories since 1960. Basic refractory shipments trends shown in these figures indicate trends for chromite refractory shipments as well. Since the chrome and chrome–magnesite refractories are predominantly chromite, at least half of their content represents chromite consumed in refractories. The American Society for Testing and Materials sets specifications for the identification of chrome, chrome–magnesite, and magnesite–chrome brick. Chrome brick is identified as a refractory brick manufactured substantially or entirely of chrome ore. Chrome–magnesite and magnesite–chrome brick are classified by nominal and

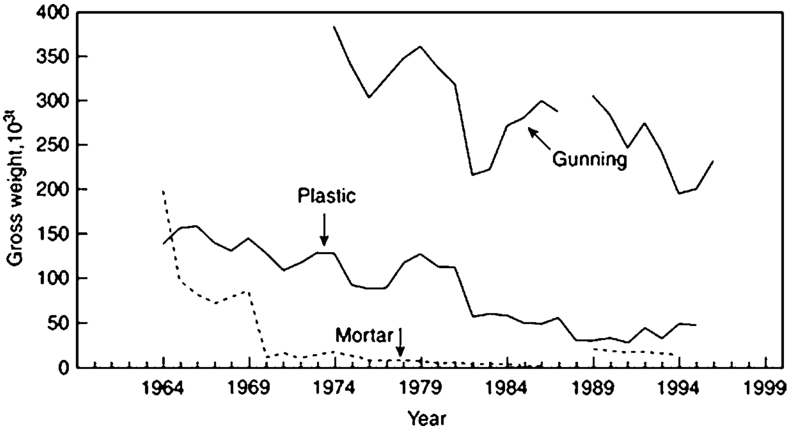

**Fig. 11.** U.S. chromite-containing unshaped refractory shipments.

minimum magnesia (MgO) content. Nominal MgO content ranges from 30 to 80%, so the chromite content of magnesite–chrome refractories is over 20%. However, the distribution between magnesite and magnesite–chrome within the magnesite and magnesite–chrome category is unknown.

Basic unshaped refractories may include chromite, dolomite, forsterite, magnesite, or zircon. Thus, these shipments data should be viewed as indicative of the performance of a segment of the refractory industry of which chromite is a part.

Figure 10 shows shipments of chromite-containing shaped refractories. The figure clearly shows a downward trend in chrome and chrome–magnesite refractory shipments from 1960 through 1981 when the data series was discontinued. Over the same time period the number of chrome and chrome–magnesite refractory producers fell from 9 to 7. Since 1981, the number of chromite refractory producers has fallen from 7 to 4, a trend indicative of declining production and use. Magnesite and magnesite–chrome refractories showed growth from 1960 through 1965, after which large variations in shipments occurred. The magnesite–chrome refractories shipments trend from 1982 through 1990 declined 28 to 18 million 9-in. (22.86-cm) brick equivalents. The chrome and chrome–magnesite curves are based on reported shipments. The magnesite and magnesite–chrome and the magnesite–chrome curves are composites of reported shipments data.

The trend in shipments of basic unshaped refractories is shown in Figure 11. Mortar shipments show a rapid decline from 1964 to 1970, followed by a very slow decline until 1986, when the series was discontinued. Plastic shipments show a slow decline, as does gunning. The data are not sufficiently discriminating to show trends among different materials used to make basic unshaped refractories.

In 1985, shapes started to be reported in tons, also. No specific conversion factor is applicable because the weight equivalent of the volume of shipments is dependent on the distribution of minerals used to make the bricks. From 1985 to 1990, the weight per volume of magnesite–chrome refractories averaged 4.7 kt per million 9-in. (22.86-cm) brick equivalents (kt/M9be), with a range of 4.3–5.0 kt/M9be.

## 8. Economic Aspects

**8.1. Chromite Ore.** Operations and transportation are the two major components of chromite ore cost in the market place. Operating cost includes mining (the production of run-of-mine ore) and beneficiation (the production of marketable chromite ore or concentrate from the run-of-mine ore). Mining cost is typically in the range of 70–90% of operating cost but exceeds 90% in some cases. Labor cost is the major component of mining and of beneficiation cost. Labor cost is typically in the range of 20–70% of mining cost and from 25–90% of beneficiation cost, but can be higher.

**8.2. Ferrochromium.** Excluding the delivered cost of chromite ore, electrical energy, other raw materials, and labor are the major components of smelting (ie, production of ferrochromium from chromite ore) cost. (Note that smelting cost excludes the cost of chromite ore feed material.) Electrical energy cost is in the range of 20–55% of smelting cost; raw materials (excluding chromite ore), 15–35%; and labor, 10–30%.

Ferrochromium production is electrical energy intensive. Charge-grade ferrochromium requires 3800–4100 kWh per ton of product, with efficiency varying with ore grade, operating conditions, and production process. Thus, ferrochromium plant location reflects a cost balance between raw materials and electrical energy supply.

**8.3. Stainless Steel.** Analysis of the stainless-steel industry based on historical performance and announced production capacity increases indicated that from 1987 to 1996, world annual stainless-steel production grew from 12 to 16 million tons, compound annual growth rate of 2.9%. Western stainless-steel production showed double-digit percentage growth in 1994 and 1995. Planned expansions in 1996 by nine countries (Brazil, China, India, Indonesia, Malaysia, the Republic of Korea, South Africa, Taiwan, and Thailand) were expected to add 4 million tons of crude stainless steel production capacity (3.66 million tons, rolled product) by 2000 (15).

Price for stainless steel is demand-sensitive, and an important part of it is the cost of nickel (about 70% of stainless-steel production requires nickel). Nickel availability and cost have been viewed as potential limitations to increased stainless-steel production. The discovery and development of new nickel deposits, projected to produce at nearly one-half the cost of that of currently exploited deposits, mitigate this potential limitation to stainless steel production growth.

**8.4. Chromium Metal.** Tosoh, the Japanese electrolytic chromium metal producer, ceased production in 1995, leading to an anticipated restructuring of the chromium metal industry. It was not until December 1996 that the company finally sold off its stocks. To a degree, Tosoh stocks have become consumer stocks. Restructuring of the chromium metal supply market started in earnest in 1997, with the remaining electrolytic producers (Russia and the United States) competing with the major aluminothermic producers (France and the United Kingdom) for the Japanese market. Both aluminothermic producers are in a position to expand production having brought new production capacity on line in 1996. The price of chromium metal was expected to increase as raw material (chromic oxide) price increases implemented in 1995 and 1996 are passed on to metal consumers. The price of low-grade chromium metal relative to ferrochromium in Japan during 1996 permitted stainless-steel producers to substitute chromium metal for ferrochromium. This substitution is expected to be curtailed as metal prices increase.

**8.5. Chromite Foundry Sand.** At last count, about 3100 foundries were active in the United States. These foundries tend to be small, independent operations. Chromite sand found a place in the casting industry in the 1960s when it substituted for zircon sand, which was in short supply. Since then, chromite sand has gained recognition as being technically suited to manganese steel and stainless steel casting because it produces a finish superior to that of zircon sand. Performance of the foundry industry is tied to that of the general economy, which has been strong and is expected to so continue. The automotive industry is a major demand sector for castings. Demand was good, stable, and expected to grow moderately. The use of nonmetallic materials could displace demand for metallic castings in the long term (16).

**8.6. Tariffs and Taxes.** Domestic producers were subject to a tax on chromium, potassium dichromate, and sodium dichromate under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (also known as CERCLA or Superfund). The tax amounted to $4.91/t on chromium, $1.86/t on potassium dichromate, and $2.06/t on sodium dichromate. The tax expired in 1995.

Import tariffs are typically imposed to protect the domestic industry. Where there is no domestic industry, such as chromite ore production in the United States, there is no tariff. In some cases, such as ferrochromium imports to the European Community, import tariffs are used with import quotas; that is, a duty-free quota is allocated to member countries. The quotas may be revised as necessary to meet the needs of domestic consumers and producers. Only in a few cases, such as ferrochromium exports from China and certain grades of chromite ore exports from India, are export duties applied.

Chromium materials are categorized by the Harmonized Tariff System that was implemented in 1989 into the following broad areas: chromite ore, chromium ferroalloys, chromium metal, and chromium chemicals.

The trend to supply chromium in the form of ferrochromium by chromite mining countries is expected to continue. With new, efficient ferrochromium production facilities and excess capacity in chromite-producing countries, production and capacity are expected to diminish in traditional nonore-, but ferrochromium-producing countries. Production by small, less efficient producers, except where domestic industries are protected by quotas and tariffs is also expected to decline. Further upward integration of the chromium industry is expected as countries that produce chromite expand ferrochromium or stainless steel production capacity.

China has emerged as a potential major factor in the world chromium market. Because China produces only a minor amount of chromite ore, it is primarily a processor and consumer of chromium and supplies substantial quantities of ferrochromium and chromium metal to world markets. Continued industrial growth in China could result in increased demand for stainless steel there because its use is characteristic of the larger and more technologically developed economies.

For the same reasons as for China, India, too, has the potential to grow as a chromium consumer in the near future. Unlike China, India is a major chromite producing country with a vertically integrated chromium industry from chromite mining through stainless steel production; however, stainless steel production remains small.

**8.7. Energy Requirements.** Electric-arc furnace ferrochromium production is an electrical energy intensive process (requiring about 3500–3800 kWh per ton of ferrochromium produced) that produces similar volumes of ferrochromium and slag. However, heat recovery can reduce energy requirements. Energy-efficient processes using preheating can reduce the energy requirements to about 2500–2800 kWh ton of ferrochromium produced. Typically, all the energy required to smelt chromite is supplied in the form of electricity. Electrical energy requirements can be reduced by preheating or prereducing charge material using alternative energy sources such as coal, natural gas, or fuel oil or by recycling gases generated in the smelting furnace. Advanced production technology permits the use of liquid or gas fuel to substitute for part of the energy required. Alternative production technology is being developed that would permit nonelectrical energy sources to supply a significant fraction of the energy required to smelt chromite ore.

**8.8. International Markets.** In 1989, it was estimated that, on average internationally, the metallurgical industry used about 79% of chromium; the chemical industry, 13%; and the refractory industry, 8% (17). Of the chromium used in the metallurgical industry, about 60% was used in stainless steel. Thus, stainless-steel production accounted for about 50% of the chromium used internationally. In 1993, it was estimated that, on average internationally within market economy countries, the metallurgical industry used about 77% chromium; the chemical industry, 14%; and the refractory industry (including foundry sand), 9% (18). It was estimated in 1995 that 80% of chromite ore went into ferrochromium and 10% each into refractory and chemical use (19). The 80% of chromite that went into ferrochromium was estimated to have supplied 40–70% of the chromium units required by the steel (alloy plus stainless) industry. The remainder of the steel industries demand was satisfied by scrap. Of the chromium units going into the steel industry, it was estimated that 80% went into stainless steel and the remaining 20% went into alloy steel. A comparison of world production of chromite ore, ferrochromium, and stainless steel as reported in contained chromium showed that, on average, from 1992 through 1996, chromium contained in ferrochromium was about 79% of chromium contained in ore production and about 87% of that in stainless steel production. India reported its distribution of chromite ore consumption to have been: chemical, 5%; metallurgical, 88%; and refractory, 7% (20).

**8.9. U.S. Markets.** On average (from 1983 through 1992), U.S. chromium utilization, by end-use industry, has been as follows: metallurgical, 87%; chemical, 10%; and refractory, 3% (21). About 70% of metallurgical industry chromium use is as feed material for stainless steel production. Thus, stainless-steel production accounts for about 60% of the chromium used in the United States. The remainder of metallurgical industry use is for the production of other ferrous and nonferrous alloys. Some chemical and refractory products are used in steel production. The average chromium content of stainless steel produced in the United States from 1962 through 1983 was 17% (22). Stainless steel, by definition, contains at least 10.5% chromium but may contain as much as 36%

Table 11. **World and Domestic Chromium Demand by End Use,** %

| | World | | | Domestic | |
|---|---|---|---|---|---|
| Industry | 1989[a] | 1990[b] | 1992–1996[c] | 1973–1982[d] | 1983–1992[d] |
| chemical | 13 | 14 | — | 12 | 10 |
| metallurgical | 79 | 77 | 79 | 79 | 87 |
| refractory | 8 | 9 | — | 9 | 3 |

[a] Ref. 17.
[b] Ref. 18.
[c] Ref. 23.
[d] Ref. 23.

chromium. For domestic demand for chromium by end use, see the two rightmost columns in Table 11 (17,18,21,23).

## 9. Grades, Specifications, and Quality Control

**9.1. Government and Industry Organization Specifications.** U.S. industry sets chemical and physical specifications for chromium materials through the American Society for Testing and Materials (ASTM). Other organizations also make specifications for chromium materials. The Defense Logistics Agency (DLA), in cooperation with the Department of Commerce, maintains purchase specifications for chromium materials contained in the National Defense Stockpile (NDS). The Treasury Department, in cooperation with the Department of Commerce and signatories to the General Agreement on Tariffs and Trade, maintains definitions of chromium materials for the purpose of recording trade and applying tariff duties. Chromium material specifications reported by ASTM are shown in Table 12.

For the purpose of trade, the U.S. government has categorized chromium materials. The import category "chromite ore and concentrates made therefrom" is subdivided by chromic oxide content as follows: containing not more than 40% chromic oxide, containing more than 40% and less than 46% chromic oxide, and containing 46% or more chromic oxide. Producers of chromite ore and concentrate typically specify chromic oxide content; chromium:iron ratio; and iron, silica, alumina, magnesia, and phosphorous contents. They also specify the size of the ore or concentrate. Typically, chromic oxide content ranges from 36 to 56%; values in the 40–50% range are most common. Chromium:iron ratios typically range from about 1.5:1 to about 4.0:1, with typical values of about 1.5:1–3.0:1. In trade, the chromite ore is also called chromium ore, chromite, chrome ore, and chrome.

Not more than 3% carbon was further subdivided in 2000 to more than 0.5% carbon but not more than 3% carbon and not more than 0.5% carbon.

The import category "chromium ferroalloys" is subdivided into ferrochromium and ferrochromium–silicon. Ferrochromium–silicon, also called *ferrosilicon–chromium* and *chromium silicide*, is not further classified. Ferrochromium is classified by its carbon content as containing not more than 3% carbon, more than 3% but not more than 4% carbon, or more than 4% carbon. Producers of ferrochromium typically classify their material as low- or high-carbon or charge-grade ferrochromium. Charge-grade ferrochromium is also called *charge chrome*. Producers of chromium ferroalloys typically specify chromium, carbon, silicon, phosphorous, and sulfur contents and material size. Ferrochromium–silicon typically contains 24–40% chromium, 38–50% silicon, and 0.05–0.1% carbon. Ferrochromium typically contains 50–75% chromium and 0.05–8% carbon. Low-carbon ferrochromium typically contains 55–75% chromium and 0.02–0.1% carbon. High-carbon ferrochromium typically contains 60–70% chromium and 6–8% carbon. Charge-grade ferrochromium typically contains 50–55% chromium and 6–8% carbon.

Table 12. **Composition of Typical Chromium Ferroalloys and Chromium Metal (Composition in Percentage)**[a]

| Material[b] | Grade | Chromium[c] | Carbon[d] | Silicon[d] | Sulfur[d] | Phosphorus[d] | Nitrogen[d] |
|---|---|---|---|---|---|---|---|
| Ferrochromium | | | | | | | |
| High-carbon | A | 51.0–56.0 | 6.0–8.0 | 6.0 | 0.040 | 0.030 | 0.050 |
| | B | 56.0–62.0 | 6.0–8.0 | 8.0–14.0 | 0.050 | 0.030 | 0.050 |
| | C | 62.0 max | 6.0–8.0 | 3.0 max | 0.050 | 0.030 | 0.050 |
| low-carbon | A | 60.0–67.0 | 0.025 | 1.0–8.0 | 0.025 | 0.030 | 0.12 |
| | B | 67.0–75.0 | 0.025 | 1.0 | 0.025 | 0.030 | 0.12 |
| | C | 67.0–75.0 | 0.050 | 1.0 | 0.025 | 0.030 | 0.12 |
| | D | 67.0–75.0 | 0.75 | 1.0 | 0.025 | 0.030 | 0.12 |
| vacuum low-carbon | | | | | | | |
| | E | 66.0–70.0 | 0.015 | 2.0 | 0.030 | 0.030 | 0.050 |
| | G | 63.0–68.0 | 0.050 | 2.0 | 0.030 | 0.030 | 5.0–6.0 |
| nitrogen-bearing | — | 62.0–70.0 | 0.050 | 1.0 | 0.025 | 0.030 | 1.0–5.0 |
| ferrochromium–silicon | A | 34.0–38.0 | 0.060 | 38.0–42.0 | 0.030 | 0.030 | 0.050 |
| | B | 38.0–42.0 | 0.050 | 41.0–45.0 | 0.030 | 0.030 | 0.050 |
| chromium metal | A | 99.0 | 0.050 | 0.15 | 0.030 | 0.010 | 0.050 |
| | B | 99.4 | 0.050 | 0.10 | 0.010 | 0.010 | 0.020 |

[a] *1996 Annual Book of ASTM Standards*.

[b] In addition to the chemical specifications listed here, American Society for Testing Materials (ASTM) lists supplementary chemical requirements and standard sized and tolerances.

[c] Minimum, except where range of values indicating minimum and maximum appears or where noted otherwise.

[d] Maximum, except where range of values indicating minimum and maximum appears.

The Harmonized Tariff Schedule of the U.S. names and numbers for chromite ore and concentrate, chromium ferroalloys and metal, and chromium chemicals and pigments are shown in the "Economic Aspects" section of this article.

**9.2. Commercial Specifications.** Domestic and foreign companies supply imported chromite ore, chromium ferroalloys, chromium metal, chromium chemicals, and chromium containing refractories to U.S. consumers. Chemical specification of these materials varies among consumers and producers. Typically, consumers do not reveal detailed specification. However, producers do make typical specifications available to prospective customers. Typical chemical specifications for a variety of chromite ores, ferrochromium, and chromium metal products available to U.S. consumers have been assembled here. The chemical specifications of several chromite ores are shown in Table 13; (21) ferrochromium, in Table 14; chromium metal, in Table 15.

Domestically produced chromium chemicals and chromium-containing refractories are supplied to U.S. consumers. The chemical and physical specifications of these materials vary among consumers and producers. Consumers rarely reveal detailed purchase specifications. However, producers make typical specifications available to prospective customers. Typical chemical and physical specifications for a variety of chromium chemical and refractory products are available from U.S. producers and suppliers to the U.S. market. See the "Manufacturing, Production, and Shipments" section of this article for more details.

**9.3. By-Products and Coproducts.** Chromite ore is a by-product only of platinum mining of the UG-2 layer of the Bushveld complex. No coproducts or by-products are associated with chromite mining operations. Here, by-product or coproduct is assumed to mean a mineral product that is different from the primary product and not different grades of the primary mineral product. A single mining operation is likely to produce more than one grade of its product. Grades of chromite products are distinguished by ore size and chemistry.

Chromite recently became a by-product of platinum mining in South Africa. MINTEK, South Africa's mining research organization, has demonstrated smelting of beneficiated chromite-containing waste material from certain platinum mines. Platinum has been mined from the Merensky Reef, a chromite-free seam of the Bushveld Complex. As those platinum mines deplete their reserves, platinum mining is expected to move to the chromite-containing UG-2 seam, generating more chromite-containing tailings. UG-2 seam platinum mining has started. MINTEK has also demonstrated the feasibility of recovering platinum from tailings resulting from chromite mining of the LG-6 chromitite layer. The by-product chromite ore yields a ferrochromium of under 50% chromium content produced and used in South Africa for stainless-steel production.

## 10. Analytical Methods

Procedures for the analysis for total chromium of chromite ore and ferrochromium slags were developed at the Albany Research Center of the Department of Energy (formerly of the U.S. Bureau of Mines) as part of the study of domestic chromite ore deposits and the processing of that ore. They developed procedures to analyze for chromium content in the range of a fraction of a percent to 30% and

Table 13. **Chromite Ore Chemical Specifications**[a,b]

| Company and Grade | $Cr_2O_3$ | $Fe_2O_3$ | FeO | $SiO_2$ | $Al_2O_3$ | MgO | MnO | $TiO_2$ | $T_2O_5$ | $V_2O_5$ | CaO | P | S | Cr:Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Albchrome Ltd.* | | | | | | | | | | | | | | |
| 40–42% $Cr_2O_3$ | 40–42 | — | 11.8 | 11.5 | 8 | 23.5 | — | 0.160 | — | 0.110 | 0.31 | — | — | 3 |
| 36–38% $Cr_2O_3$ | 36–38 | — | 12.5 | 15 | 7 | 23 | — | 0.160 | — | 0.020 | 0.50 | — | — | 2.7 |
| 30–34% $Cr_2O_3$ | 30–34 | — | 10.0 | 18 | 7 | 27 | — | 0.160 | — | 0.060 | 0.15 | — | — | 2.6 |
| concentrates 48–50% | 48–50 | — | 13.93 | 7 | 9.37 | 17.94 | — | 0.160 | — | 0.060 | 0.14 | — | — | 3 |
| concentrates 45–47% | 45–47 | — | 13.93 | 9 | 9.37 | 18.2 | — | 0.160 | — | 0.060 | 0.14 | — | — | 3 |
| *Advanced Mining Works Co. Ltd.* | | | | | | | | | | | | | | |
| metallurgical | 50.1 | — | 10.26 | 7.35 | 6.24 | 17.96 | | | | | | 0.003 | 0.001 | 3.341 |
| *Benguet Corporation-Masinloc Chromite Operation* | | | | | | | | | | | | | | |
| concentrates | 32 | — | 11 | 5.5 | 27.5 | 18 | — | — | — | — | 0.45 | — | — | 1.9 |
| refractory | 32 | — | 11 | 5.5 | 27.5 | 18 | — | — | — | — | 0.45 | — | — | 1.8 |
| foundry sand | 31 | — | 14.19 | 4.4 | 27 | 16 | — | — | — | — | 0.70 | — | — | 1.9 |
| *Bayer (Pty.) Ltd.* | | | | | | | | | | | | | | |
| metallurgical | 40.1 | — | 23.4 | 5.72 | 15.84 | 10.7 | — | — | — | — | 0.57 | 0.004 | 0.005 | 1.52 |
| chemical | 46.05 | — | 25.79 | 1.10 | 14.80 | 9.75 | — | 0.62 | — | — | 0.25 | 0.003 | 0.001 | 1.57 |
| foundry sand | 46.50 | — | 25.8 | 0.55 | 14.50 | 10.10 | — | 0.60 | — | — | 0.20 | 0.003 | 0.003 | 1.56 |
| *Bilfer Madencilik A.S. (Bilfer Mining Inc.)* | | | | | | | | | | | | | | |
| concentrates | | | | | | | | | | | | | | |
| refractory | 53 | — | 18 | 1.7 | 16 | 17 | — | — | — | — | 0.12 | <0.007 | — | >2.5 |
| metallurgical | 48 | — | 15 | 5 | 19 | 18 | — | — | — | — | 0.5 | <0.007 | — | >2.7 |
| metallurgical | | | | | | | | | | | | | | |
| high alumina | 38–40 | — | 15 | 8–9 | 18 | 18 | — | — | — | — | 0.5 | <0.007 | — | >2.5 |
| standard grade | 34–42 | — | 14 | 12–15 | 8 | 21 | — | — | — | — | 0.6 | <0.007 | — | >2.8 |
| refractory | | | | | | | | | | | | | | |
| fines | 36–40 | — | 15 | 6–9 | 18 | 17 | — | — | — | — | 0.5 | <0.007 | — | >2.5 |
| lumps | 38–41 | — | — | 4–6 | — | — | — | — | — | — | — | — | — | — |
| foundry sand | 52–54 | — | 19 | 1.2 | 15 | 16 | — | — | — | — | 0.05 | — | — | — |
| *Birlik Madencilik Dis Tic. Insaat San. ve Tic. A.S.* | | | | | | | | | | | | | | |
| metallurgical | 32–46 | — | | 8–13 | 6–10 | 16–24 | — | — | — | — | — | 0.005–0.008 | 0.005–0.007 | 2.2–3.0 |

Table 13 (*Continued*)

| Company and Grade | $Cr_2O_3$ | $Fe_2O_3$ | FeO | $SiO_2$ | $Al_2O_3$ | MgO | MnO | $TiO_2$ | $T_2O_5$ | $V_2O_5$ | CaO | P | S | Cr:Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| chemical | 40–48 | — |  | 8–10 | 7–10 | 18–21 | — | — | — | — | — | 0.005–0.008 | 0.005–0.007 | 2.4–2.8 |
| refractory |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| lump and fines | 44–56 | — |  | 3–4 | 9–11 | 16–18 | — | — | — | — | — | 0.005–0.008 | 0.005–0.007 | 2.8–3.3 |
| concentrate | 48–50 | — |  | 5–7 | 7–10 | 16–18 | — | — | — | — | — | 0.005–0.008 | 0.005–0.007 | 2.4–2.6 |
| chrome ore briquettes | 42–48 | — |  | 6–7 | 7–10 | 16–19 | — | — | — | — | — | 0.005–0.008 | 0.005–0.007 | 2.4 |
| *Blue Nile Mines Co. Ltd.* |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| metallurgical | 48–56 | — | 9–18 | 0.6–10 | 7–12 | 15–17 | — | — | — | — | 0.1–0.3 | Traces | Traces | 3:1 |
| *Chromecorp Holdings Ltd.* |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| metallurgical |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| lumpy | 38 | — | 24 | 8.4 | 15.5 | 11.6 | — | — | — | — | 1.9 | 0.002 | 0.005 | 1.5 |
| fines | 44 | — | 24.9 | 2.5 | 15. 6 | 10.6 | — | — | — | — | 1.4 | 0.002 | 0.005 | 1.52 |
| chemical | >46 | — | 25.7 | <1 | 15.4 | 10.3 | — | — | — | — | 0.8 | 0.002 | 0.004 | 1.54 |
| *Consolidated Metallurgical Industries Ltd. (CMI)* |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| metallurgical | 45.5 | — | 26 | 2 | 15 | 11 | — | 0.6 | — | 0.3 | 0.3 | 0.003 | 0.01 | 1.55 |
| chemical | 46.3 | — | 26 | 1 | 15 | 11 | — | 0.6 | — | 0.3 | 0.2 | 0.003 | 0.01 | 1.57 |
| *Dedeman Madencilik, Turizm, San. ve Tic. A.S.* |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| lumpy | 38–40 | — | 10 | 9–10 | 10–11 | 21–22 | — | — | — | — | 0.3–0.4 | 0.002 | 0.009 | 2.6–2.8 |
| fines | 38–40 | — | 9–10 | 9–11 | 10–11 | 21–22 | — | — | — | — | 0.3–0.4 | 0.002 | 0.009 | 2.6–2.8 |
| high-grade |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| lump | 46–48 | — | 13.0 | 6 | 12–13 | 16–18 | — | — | — | — | 0.2–0.4 | 0.002 | 0.007 | 2.9–3.1 |
| fines | 48–50 | — | 13–14 | 6–7 | 12–13 | 18 | — | — | — | — | 0.2–0.3 | 0.002 | 0.004 | 2.9–3.0 |
| concentrate | 48 | — | 13 | 6 | 11–12 | 17 | — | — | — | — | 0.2–0.3 | 0.002 | 0.004 | 2.9–3.0 |
| refractory |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| hard, lumpy | 50–52 | — | 13–14 | 3 | 15–16 | 16 | — | — | — | — | 0.1–0.3 | 0.002 | 0.007 | 3.1–3.2 |
| super concentrate | 54–56 | — | 11–12 | 1–1.5 | 14–15 | 16 | — | — | — | — | 0.2–0.3 | 0.002 | 0.007 | 3.2 |
| jig grade |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| pebbles | 46–48 | — | 12–13 | 6 | 12–13 | 18 | — | — | — | — | 0.2–0.3 | 0.002 | 0.004 | 2.9–3.0 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| concentrate | 48–50 | — | 12–13 | 6 | 12–13 | 18 | — | — | — | — | 0.2–0.3 | 0.002 | 0.004 | 3.0–3.1 |
| *Ege Metal Endüstri A.S.* |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| orhaneli |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| concentrates | 47.84 | — | 15.82 | 6.53 | 7.98 | 17.60 | — | 0.03 | — | 0.01 | 0.42 | 0.002 | 0.01 | 2.66 |
| jig fines | 39.69 | — | 13.58 | 9.93 | 7.81 | 20.96 | — | 0.03 | — | 0.01 | 0.61 | 0.002 | 0.01 | 2.57 |
| metallurgical | 39.72 | — | 12.43 | 11.27 | 7.48 | 21.67 | — | 0.03 | — | 0.01 | 0.59 | 0.002 | 0.01 | 2.81 |
| chemical | 45.49 | — | 18.48 | 7.37 | 6.43 | 18.79 | — | 0.03 | — | 0.01 | 0.77 | 0.002 | 0.01 | 2.17 |
| eskisehir |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| concentrates | 48.03 | — | 15.54 | 4.95 | 11.38 | 15.30 | — | 0.03 | — | 0.01 | 0.42 | 0.002 | 0.01 | 2.72 |
| jig fines | 38.57 | — | 12.30 | 11.32 | 8.72 | 21.84 | — | 0.03 | — | 0.01 | 0.72 | 0.00 | 0.01 | 2.76 |
| metallurgical | 38.03 | — | 11.82 | 11.02 | 9.71 | 23.15 | — | 0.03 | — | 0.01 | 0.61 | 0.002 | 0.01 | 2.83 |
| refractory concentrates | 53.13 | — | 15.94 | 1.85 | 8.55 | 16.20 | — | 0.03 | — | 0.01 | 0.66 | 0.002 | 0.01 | 2.93 |
| lump | 50.91 | — | 15.12 | 3.65 | 9.27 | 16.63 | — | 0.03 | — | 0.01 | 0.74 | 0.002 | 0.01 | 2.96 |
| kop |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| jig fines | 38.13 | — | 14.88 | 10.05 | 7.96 | 21.13 | — | 0.03 | — | 0.01 | 0.42 | 0.002 | 0.01 | 2.26 |
| metallurgical | 38.18 | — | 14.42 | 10.90 | 7.95 | 20.97 | — | 0.03 | — | 0.01 | 0.51 | 0.002 | 0.01 | 2.33 |
| *Etibank General Management* |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| concentrates | 37–47 | — | 12–15 | 7–11 | 10–12 | 18–23 | — | 0–0.01 | — | — | 0.3–1 | 0–0.01 | 0–0.04 | 2.9 |
| metallurgical | 42–48 | — | 12–15 | 5–9 | 12–14 | 14–19 | — | 0–0.01 | — | — | 0.3–1 | 0–0.01 | 0–0.04 | 2.9 |
| refractory | 46 | — | 14 | 3–5 | 16 | 16–17 | — | — | — | — | 0.2 | — | — | 2.9 |
| *Faryab Mining Co.* |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| metallurgical | 35–55 | — |  | 1.5–10 | 7–11 | 15–21 |  |  |  |  |  |  |  | 3.0–3.5 |
| *Ferro Alloys Corporation Ltd. (FACOR)* |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| boula |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| concentrates | 39–42 | — | 24–26 | 8–10 | 4–8 | 10–14 | — | Traces | Traces | — | 1.1–1.3 | Traces | Traces | 1.4–1.6 |
| metallurgical | 38–47 | — | 14–19 | 8–18 | 7–10 | 10–14 | — | Traces | Traces | — | 0.2–0.3 | 0.003–0.004 | Traces | 1.8–2.9 |
| kathpal metallurgical | 40–46 | — | 11–13 | 5–10 | 7–8 | 10–13 | — | Traces | Traces | — | 0.2–0.3 | 0.001 | Traces | 2.4–2.5 |
| ostapal metallurgical | 42–45 | — | 23–24 | 8–11 | 6–10 | 10–13 | — | Traces | Traces | — | 0.6–1.0 | 0.010 | Traces | 1.6–2.0 |
| *Hayri Ögelman Mining Co. Ltd.* |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| orhaneli concentrates | 47.36 | — | 16.73 | 10.33 | 8.29 | 14.16 | — | 0.16 | — | — | — | 0.01 | — | 2.83 |
| others | 48–52 | — | — | — | — | — | — | — | — | — | — | — | — | — |
| concentrates, refractory | 48–53 | — | 14.66 | 4.11 | 7.13 | 17.63 | — | — | — | — | 0.83 | — | — | 3.19 |

Table 13 (*Continued*)

| Company and Grade | $Cr_2O_3$ | $Fe_2O_3$ | FeO | $SiO_2$ | $Al_2O_3$ | MgO | MnO | $TiO_2$ | $T_2O_5$ | $V_2O_5$ | CaO | P | S | Cr:Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Hernic Ferrochrome (Pty.) Ltd.* | | | | | | | | | | | | | | |
| lumpy/chips | 38–40 | — | 23 | 9 | 15.5 | 11.8 | — | 0.65 | — | 0.45 | 2.2 | 0.003 | 0.004 | 1.48 |
| concentrates | 44–46 | — | 26.5 | 1–3 | 15.5 | 10.5 | — | 0.64 | — | 0.44 | 0.28 | 0.003 | 0.004 | 1.50 |
| metallurgical | 44–45 | — | 26.5 | 2.5 | 15.5 | 10.5 | — | 0.64 | — | 0.44 | 0.3 | 0.003 | 0.004 | 1.50 |
| chemical | 45–46 | — | 26.5 | <1 | 15.5 | 10.5 | — | 0.64 | — | 0.44 | 0.26 | 0.003 | 0.004 | 1.52 |
| foundry sand | 45–46 | — | 26.5 | <1 | 15.5 | 10.5 | — | 0.64 | — | 0.44 | 0.26 | 0.003 | 0.004 | 1.52 |
| *Ingessana Chromite Mines (of AMW Co. Ltd.)* | | | | | | | | | | | | | | |
| metallurgical | 50% | — | — | — | — | — | — | — | — | — | — | — | — | — |
| *Japan Chrome Industry Co. Ltd.* | | | | | | | | | | | | | | |
| refractory | 33.1 | — | 4.0 | 4.1 | 25.8 | 21.4 | — | — | — | — | — | — | — | — |
| *Kraomita Malagasy (Kraoma)* | | | | | | | | | | | | | | |
| metallurgical | | | | | | | | | | | | | | |
| concentrate | 48 | — | 17–18 | 6 | 13–16 | 12–14 | — | — | — | — | — | 0.0090 | — | 2.4 |
| lumpy | 42 | — | 13–16 | 12–14 | 13–16 | 17–20 | — | — | — | — | — | 0.0070 | — | 2.5 |
| friable | 48 | — | 17 | 7 | — | — | — | — | — | — | — | 0.0090 | — | 2.4 |
| fines | 49 | — | 21 | 6 | — | — | — | — | — | — | — | 0.0070 | — | 2 |
| Krominco Inc. | | | | | | | | | | | | | | |
| metallurgical | 46 | — | NA | NA | NA | NA | — | NA | — | NA | NA | — | NA | 2.9 |
| concentrates | 48 | — | NA | NA | NA | NA | — | NA | — | NA | NA | — | NA | 2.6 |
| *Magnesita S.A.* | | | | | | | | | | | | | | |
| concentrates | 45.05 | 17.00 | — | 6.50 | 16.50 | 13.50 | 0.15 | 0.27 | — | — | 0.53 | — | — | 2.59 |
| metallurgical | 41.32 | 14.92 | — | 9.01 | 16.8 | 16.05 | 0.12 | 0.31 | — | — | 1.46 | 0.0109 | 0.0016 | 2.71 |
| refractory | 49.09 | 17.89 | — | 2.71 | 16.58 | 13.15 | 0.16 | 0.29 | — | — | 0.13 | 0.0048 | 0.0023 | 2.68 |
| chemical grade | 44.55 | 17.00 | — | 7.00 | 16.50 | 13.50 | 0.15 | 0.27 | — | — | 0.53 | — | — | 2.56 |
| foundry sand | 45.55 | 17.00 | — | 6.00 | 16.50 | 13.50 | 0.15 | 0.27 | — | — | 0.53 | — | — | 2.62 |
| *Outokumpu Chrome Oy* | | | | | | | | | | | | | | |
| metallurgical | | | | | | | | | | | | | | |
| concentrates | 44.1 | — | 24.3 | 3.5 | 13.6 | 10.8 | — | 0.53 | — | 0.21 | 0.4 | 0.0014 | 0.005 | 1.62 |
| lumpy | 36.0 | — | 18.3 | 10.9 | 12.4 | 15.0 | — | 0.45 | — | 0.18 | 1.4 | 0.003 | 0.003 | 1.76 |
| foundry sand | 46.7 | — | 25.8 | 1.5 | 13.9 | 9.2 | — | 0.56 | — | 0.21 | 0.1 | 0.0007 | 0.004 | 1.62 |
| *PT. Palmabim Mining–PT. Bituminusa* | | | | | | | | | | | | | | |
| concentrates | 41–43 | — | 21.6–23 | 0.8–1.2 | 19–20 | 19–20 | — | 0.8–1 | — | — | 0.02 | 0.009 | 0.004 | 1.63 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Rustenburg Minerals Development Company* | | | | | | | | | | | | | | |
| concentrates | 44 | — | 24.2 | 4 | 14.1 | — | — | 0.46 | — | — | 0.26 | 0.005 | 0.004 | 1.60 |
| metallurgical | 42 | — | 23.3 | 6 | 14.2 | — | — | 0.47 | — | — | 0.28 | 0.005 | 0.004 | 1.59 |
| *Samancor Ltd.* | | | | | | | | | | | | | | |
| metallurgical | 45.0 | — | 25.5 | 2.0 | 15.60 | 10.5 | — | 0.5 | — | — | 0.25 | <0.003 | <0.002 | 1.54 |
| refractory | 46.3 | — | 26.3 | 0.7 | 14.5 | 9.6 | — | 0.6 | — | 0.2 | 0.13 | <0.001 | <0.001 | 1.55 |
| chemical | 46.3 | — | 26.3 | 0.7 | 14.5 | 9.6 | — | 0.6 | — | 0.2 | 0.13 | <0.001 | <0.001 | 1.55 |
| foundry sand | 46.5 | — | 26.0 | 0.6 | 14.5 | 10.3 | — | 0.6 | — | 0.2 | 0.13 | <0.001 | <0.001 | 1.57 |
| *The Orissa Mining Corporation Limited. (OMC)* | | | | | | | | | | | | | | |
| metallurgical, chemical | | | | | | | | | | | | | | |
| friable | 40–56 | — | 10–18 | 3–8 | 10–18 | 8–15 | — | — | — | — | — | 0.005–0.007 | 0.007–0.010 | 1.6–3.5 |
| lumpy | 40–56 | — | 10–18 | 3–8 | 10–16 | — | — | — | — | — | — | — | — | 1.6–3.6 |
| refractory | | | | | | | | | | | | | | |
| lumpy ore | 46–56 | — | 10–15 | 3–7 | 10–14 | — | — | — | — | — | — | 0.007 | — | 1.8–3.6 |
| concentrate | 45–49 | — | — | 5–6 | 12–13 | — | — | — | — | — | — | 0.005–0.007 | 0.007–0.03 | 2.1–2.4 |
| *The Tata Iron and Steel Co. Ltd. (TISCO): (India)* | | | | | | | | | | | | | | |
| metallurgical | | | | | | | | | | | | | | |
| friable ore | 40–58 | — | 9–20 | 1–6 | 10–14 | 9.5–14.0 | — | — | — | — | 0.2–0.41 | 0.005–0.007 | 0.005–0.007 | 1.6–3.5 |
| lumpy ore | 36–45 | — | 9–15 | 9–14 | 7–11 | — | — | — | — | — | 0.4–0.6 | 0.005–0.007 | 0.005–0.007 | 2.1–2.9 |
| refractory | | | | | | | | | | | | | | |
| lumpy | 45–55 | — | 8.5–12.5 | 3–9 | — | — | — | — | — | — | — | — | — | 2.8–3.9 |
| concentrate | 50–54 | — | 10–13 | 1.0–2.5 | 11–12 | — | — | — | — | — | — | 0.005–0.007 | 0.01 max | 2.4–3.5 |
| *Velore Mining Corp.* | | | | | | | | | | | | | | |
| concentrates | 43–53 | — | 9–23 | 3–5 | — | — | — | — | — | — | — | — | — | 1.5–2.4 |
| metallurgical | 30–45 | — | 10–12 | 9–17 | 11–15 | — | — | — | — | — | 0.8 | 0.004 | 0.01–0.03 | 2.4–2.8 |
| *Zimasco (Pvt. ) Ltd.* | | | | | | | | | | | | | | |
| concentrates | 42–46 | — | 11–14 | 10–13 | 10–14 | 15–17 | — | 0.20 | — | — | 3.00 | — | 0.20–0.3 | 2.5–2.9 |

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[a] Ref. 24.

[b] *Key*:—data not reported; Na, not available.

Table 14. **Chromium Ferroalloy Chemical Specifications and Physical Specifications**[a,b]

| Company and grade | Chemical Composition, wt% | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Cr | C | P | Si | S | Ti | Al | Size |
| Albchrome Ltd. | | | | | | | | |
| HCFeCr | 60–65 | 6–9 | 3 | 0.04 | 0.04 | 0.04 | | <10, 10–150, >150 |
| *Chelyabinsk Electrometallurgical Integrated Plant* | | | | | | | | |
| HCFeCr 1 | 55–60 | 9.1 | 1.19 | 0.04 | 0.034 | | | |
| HCFeCr 2 | 60–65 | 9.06 | 4.84 | 0.04 | 0.05 | | | |
| HCFeCr 3 | >65 | 10.5 | 4.38 | 0.05 | 0.06 | | | |
| LCFeCr 1 | 60–65 | 0.5 | 2.8 | 0.044 | 0.01 | | | |
| LCFeCr 2 | 65–70 | 0.5 | 2.7 | 0.044 | 0.01 | | | |
| FeCrSi | 28–31 | 0.1 | 46–52 | | 0.02 | | | |
| *Chrome Resources (Pty.) Ltd.* | | | | | | | | |
| ChCr | 50–53 | 6–8 | 2.5–7.0 | 0.04 | 0.05 | | | |
| *Cia. de Ferro Ligas da Bahia - FERBASA:* | | | | | | | | |
| ChCr | 54.69 | 7.59 | 3.35 | 0.026 | 0.014 | | | |
| LCFeCr | 55.86 | 0.044 | 0.93 | 0.030 | 0.002 | | | |
| FeCrSi | 31.95 | 0.060 | 47.87 | 0.030 | 0.002 | | | |
| ChCr 1 | 50–55 | 6–8 | 1–5 | 0.020 | 0.04 | | | 20–100 lumps, 5–50 granular |
| ChCr 2 | 50–52 | 6–7 | 2–6 | 0.020 | 0.035 | | | 20–150 |
| *Dalmacija Ferro-Alloys Works* | | | | | | | | |
| HCFeCr | 65 | 6–8 | 1.5 | 0.035 | 0.08 | | | 10–200 |
| *Darfo s.r.l* | | | | | | | | |
| HCFeCr 1 | 60–65 | 4–6 | 1–2 | 0.02 | 0.04 | | | |
| HCFeCr 2 | 60–65 | 6–8 | 1–2 | 0.02 | 0.04 | | | |
| *Elektrowerk Weisweiler GmbH* | | | | | | | | |
| LCFeCr | 65–82 | 0.5 | 1.5 | 0.03 | 0.01 | | | |
| *Elkem a/s* | | | | | | | | |
| HCFeCr | 60–65 | 4–8 | 1–5 | 0.03 | 0.040 | | | |
| *Etibank General Management* | | | | | | | | |
| HCFeCr | 62 | 8 | 1.5–4.0 | 0.04 | 0.06 | | | 10–200 |
| LCFeCr | 68–72 | 0.20 | 1.5 | 0.03 | 0.03 | | | 10–50, 10–80, 10–100, 10–200 |
| *Faryab Mining Co. - Abadan Ferroalloys Refinery* | | | | | | | | |
| HCFeCr | 70 | 8 | 2 | 0.04 | 0.04 | | | |
| *Feralloys Ltd.* | | | | | | | | |
| ChCr | 55 | 6–7 | 4 | 0.02 | 0.05 | | | |
| *Ferro Alloys Corporation Ltd. (FACOR)* | | | | | | | | |
| ChCr | 55–60 | 6–8 | 4 | 0.025–0.03 | 0.03 | | | 4–150 |
| HCFeCr 1 | 60–70 | 6–8 | 2 | 0.03–0.05 | 0.035 | | | 10–150 |
| HCFeCr 2 | 60–70 | 6–8 | 2–4 | 0.03–0.05 | 0.035 | | | 10–150 |
| HCFeCr 3 | 60–70 | 6–8 | 4–6 | 0.03–0.05 | 0.035 | | | 10–150 |
| MCFeCr | 60–70 | 2–4 | 2–4 | 0.03–0.05 | 0.035 | | | 10–150 |
| LCFeCr 1 | 60–70 | 0.03 | 1.50 | 0.035–0.05 | 0.025 | | 0.10 | 10–150 |
| LCFeCr 2 | 60–70 | 0.05 | 1.50 | 0.035–0.05 | 0.025 | | 0.10 | 10–150 |
| LCFeCr 3 | 60–70 | 0.10 | 1.50 | 0.035–0.05 | 0.025 | | 0.10 | 10–150 |
| LCFeCr 4 | 60–70 | 0.20 | 1.50 | 0.035–0.05 | 0.025 | | 0.10 | 10–150 |

Table 14 (*Continued*)

| Company and grade | Chemical Composition, wt% | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Cr | C | P | Si | S | Ti | Al | Size |
| Albchrome Ltd. | | | | | | | | |
| *Ferrochrome Philippines Inc.* | | | | | | | | |
| HCFeCr | 60 | 8 | 3 | 0.03 | 0.04 | | | 10–50, 10–80, 0–10 |
| *GMR Vasavi Industries Ltd.* | | | | | | | | |
| HCFeCr | 60–70 | 6–8 | 1.5–4.0 | 0.03 | 0.05 | | | |
| *Hernic Ferrochrome (Pty.) Ltd.* | | | | | | | | |
| ChCr | 50–54 | 6–7 | 3–7 | 0.025 | 0.050 | | | |
| *Hi-Tech Electrothermics (P) Ltd.* | | | | | | | | |
| HCFeCr | 60–65 | 4–6 | 2 | 0.05 | 0.05 | | | 25–150 |
| *Huta "Laziska"* Ferroalloy Plant | | | | | | | | |
| HCFeCr | 60–75 | 6–10 | 1–5 | 0.05 | 0.04 | | | |
| *Indian Metals and Ferro Alloys Ltd. (IMFA)* | | | | | | | | |
| HCFeCr | 50–75 | 6–8 | 1.5–6.0 | 0.020–0.05 | 0.025–0.05 | | | 10–150 |
| *Integrated Chrome Corp.* | | | | | | | | |
| ChCr | 50–55 | 6–8 | 3.5 | 0.025 | 0.03 | | | 10–150 |
| *Ispat Alloys Ltd.* | | | | | | | | |
| HCFeCr | 60–64 | 6–8 | 4 | 0.03–0.035 | 0.04 | | | 10–100 |
| *Jiangyin Ferroalloy Factory* | | | | | | | | |
| HCFeCr | 62–72 | 6–10 | 1–3 | 0.04 | 0.04 | | | |
| *Jilin Ferroalloy Works* | | | | | | | | |
| HCFeCr | 60–70 | 6–9 | 1.5–3.0 | 0.04 | 0.04 | | | |
| MCFeCr | 60–70 | 0.3–1.0 | 1.5–3.0 | 0.03 | 0.03 | | | |
| LCFeCr | 60–70 | 0.01–0.15 | 1–2 | 0.03 | 0.03 | | | |
| FeCrSi | 30–40 | 0.02–1.0 | 35–45 | 0.03 | 0.01 | | | |
| *Jindal Ferro Alloys Ltd.* | | | | | | | | |
| HCFeCr | 60–65 | 6–8 | 4 | 0.03 | 0.05 | | | |
| *Klutchevsk Ferroalloy Plant* | | | | | | | | |
| LCFeCr | 68–75 | 0.03 | 0.3 | 0.02 | 0.005 | | | |
| *Macalloy Corp.* | | | | | | | | |
| HCFeCr | 68 | 6.2 | 2 | 0.025 | 0.05 | | | |
| *Mandsaur Ferro Alloys Ltd.* | | | | | | | | |
| HCFeCr | 60–70 | 6–8 | 2–4 | 0.035 | 0.03 | | | 10–150 |
| *Monnet Industries Ltd.* | | | | | | | | |
| HCFeCr 1 | 60–70 | 6–8 | 2–4 | 0.050 | 0.050 | | | 10–50 |
| HCFeCr 2 | 60 | 6–8 | 2–4 | 0.050 | 0.050 | | | 3–10 |
| HCFeCr 3 | 60 | 6–8 | 3–6 | 0.045 | 0.035 | | | 1–3 |
| HCFeCr 4 | 58–68 | | | | | | | 100/60-mesh powder |
| *Nanjing Ferroalloy Plant* | | | | | | | | |
| HCFeCr 1 | 62.0 | 9.5 | 3.0 | 0.03 | 0.04–0.06 | | | <15-kg lumps, <20 |
| HCFeCr 2 | 52.0–60.0 | 10 | 3.0–5.0 | 0.04–0.06 | 0.04–0.06 | | | <15-kg lumps, <20 |
| HCFeCr 3 | 60.0 | 8.5 | 3.0 | 0.03 | 0.04 | | | <15-kg lumps, <20 |

Table 14 (*Continued*)

| Company and grade | Chemical Composition, wt% | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Cr | C | P | Si | S | Ti | Al | Size |
| Albchrome Ltd. | | | | | | | | |
| *Nav Chrome Ltd.* | | | | | | | | |
| HCFeCr | 64 | 7.5 | 2–4 | 0.05 | 0.05 | | | 25–100 |
| *Nava Bharat Ferro Alloys Ltd.* | | | | | | | | |
| HCFeCr | 64 | 6–8 | 4 | 0.04 | 0.035 | | | |
| *Nippon Denko Co., Ltd.* | | | | | | | | |
| HCFeCr | 65–70 | 6.0 | 1.5 | 0.04 | 0.08 | | | |
| *NKK Corp.* | | | | | | | | |
| HCFeCr | 60–65 | 8.0 | 6.0 | 0.04 | 0.04 | | | |
| LCFeCr | 60–65 | 0.1 | 1.0 | 0.04 | 0.03 | | | |
| *Oravske Ferozliatinarske Zavody (OFZ)* | | | | | | | | |
| HCFeCr 1 | 68 | 7.5 | 1.0 | 0.03 | 0.04 | 0.04 | | 10–50,<br>10–80,<br>10–100,<br>10–150,<br>10–250 |
| HCFeCr 2 | 68 | 6 | 0.8 | 0.03 | 0.03 | | | 10–50,<br>10–80,<br>10–100 |
| HCFeCr 3 | 67 | 5.6 | 0.8 | 0.025 | 0.015 | 0.02 | | 10–50,<br>10–80,<br>10–100 |
| HCFeCr 4 | 68 | 8.5 | 1 | 0.03 | 0.04 | | | 10–50,<br>10–80,<br>10–100,<br>10–150,<br>10–250 |
| ChCr | 62 | 7.5 | 5 | 0.03 | 0.02 | | | 10–80,<br>10–150,<br>10–100 |
| LCFeCr 1 | 69 | 2.5 | 0.8 | 0.03 | 0.01 | | | 10–50,<br>10–80,<br>10–100 |
| LCFeCr 2 | 70 | 0.35 | 0.8 | 0.03 | 0.004 | | | 10–50,<br>10–80,<br>10–100 |
| FeCrSi | 30 | 0.05 | 49 | | | | | 10–40,<br>10–50,<br>10–80,<br>10–100,<br>10–150;<br>granules<br>0–5, 0–7 |
| *Outokumpu Chrome Oy* | | | | | | | | |
| ChCr | 52 | 6–8 | 3–5 | 0.03 | 0.05 | | | 10–150 |
| *Philippine Minerals & Alloy Corp.* | | | | | | | | |
| HCFeCr | 60–70 | 6–8 | 1.5–3.0 | 0.05 | 0.05 | | | 10–150 |
| *S. C. Ferom S.A.* | | | | | | | | |
| HCFeCr | 60–65 | 8 | 4 | 0.04 | 0.06–0.08 | | | 10–100 |

Table 14 (*Continued*)

| Company and grade | Chemical Composition, wt% | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Cr | C | P | Si | S | Ti | Al | Size |
| Albchrome Ltd. | | | | | | | | |
| MCFeCr | 65 | 1–4 | 1 | 0.02–0.05 | 0.05 | | | 10–100 |
| LCFeCr | 65 | 0.04–0.5 | 0.8–2.0 | 0.02–0.04 | 0.02 | | | 10–100 |
| FeCrSi | 55–60 | 6 | 10–18 | 0.04 | 0.03 | | | 10–100 |
| *Samancor Ltd.* | | | | | | | | |
| ChCr 1 | 50–55 | 6–8 | 3–6 | 0.025 | 0.050 | | | 10 × 150, 10 × 80, 3 × 12, <3 mm, granules |
| ChCr 2 | 50–55 | 8–9 | 1–2 | 0.01 | 0.023 | | | 10 × 150, 10 × 80, 3 × 12, <3 mm |
| MCFeCr | 52–58 | 1.5–4.0 | 0.5 | 0.028 | 0.025 | | | Granules |
| LCFeCr | 58–60 | 0.03–0.10 | 1–2 | 0.03 | 0.02 | | | 10 × 100, 50 × 75, 25 × 50, 3 × 10, <3 mm |
| *Serov Ferroalloys Plant* | | | | | | | | |
| HCFeCr | 60–65 | 8–9.5 | 2 | 0.025–0.03 | 0.04–0.06 | | | |
| MCFeCr | 60–65 | 1–2 | 1.5–2.0 | 0.02–0.03 | 0.002 | | | |
| LCFeCr | 60–65 | 0.02–0.50 | 1.5 | 0.02–0.03 | 0.002 | | | |
| FeCrSi | 28 | 0.1 | 52 | 0.03 | 0.002 | | | |
| *Showa Denko K.K.* | | | | | | | | |
| ChCr | 50–55 | 8.5 | 3.0 | 0.04 | 0.06 | | | <35 mm |
| LCFeCr 1 | 60–65 | 0.06 | 1.0 | 0.03 | 0.03 | | | 10–200, 10–100, or 5–50 |
| LCFeCr 2 | 60–65 | 0.10 | 1.0 | 0.03 | 0.03 | | | 10–200, 10–100, or 5–50 |
| LCFeCr 3 | 60–65 | 0.01 | 1.0 | 0.03 | 0.03 | | | 10–200, 10–100, or 5–50 |
| LCFeCr 4 | 60–65 | 0.03 | 1.0 | 0.03 | 0.03 | | | 10–200, 10–100, or 5–50 |
| LCFeCr 5 | 65–70 | 0.10 | 1.0 | 0.03 | 0.03 | | | 10–200, 10–100, or 5–50 |
| LCFeCr 6 | 60–65 | 0.03 | 0.40 | 0.03 | 0.03 | | | 10–200, 10–100, or 5–50 |
| LCFeCr 7 | 85–92 | 0.10 | 1.0 | 0.020 | 0.020 | | | 10–70, 2–10, <250 mm, <104 μm |

Table 14 (*Continued*)

| Company and grade | Chemical Composition, wt% | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Cr | C | P | Si | S | Ti | Al | Size |
| Albchrome Ltd. | | | | | | | | |
| LCFeCr 8 | 70 min | 0.03 | 1.0 | 0.03 | 0.03 | | | 10–70,<br>2–10, or<br><250 mm |
| *Shri Girija Smelters Ltd.* | | | | | | | | |
| HCFeCr 1 | 60–70 | 6–8 | 2–4 | 0.03–0.05 | 0.05 | | | 25–150 |
| HCFeCr 2 | 60–70 | 6–8 | 2–4 | 0.03–0.05 | 0.05 | | | 10–120 |
| *Srinivasa Ferro Alloys Ltd.* | | | | | | | | |
| HCFeCr 1 | 60–70 | 6–8 | 2–4 | 0.03–0.05 | 0.05 | | | 25–150 |
| HCFeCr 2 | 60–70 | 6–8 | 2–4 | 0.03–0.05 | 0.05 | | | 10–120 |
| *Standard Chrome Ltd.* | | | | | | | | |
| HCFeCr | 65–68 | 7–8 | 2 | 0.02 | 0.02 | | | |
| *The Tata Iron and Steel Company Ltd. (TISCO)* | | | | | | | | |
| HCFeCr | 64 | 6–8 | 4 | 0.025 | 0.030 | | | |
| ChCr | 60 | 6–8 | 4 | 0.025 | 0.030 | | | |
| *Tovarna Dusika Ruse - Metalurgija d.o.o.* | | | | | | | | |
| HCFeCr | 60–70 | 6–8 | 1.5 | 0.03 | 0.06 | | | |
| LCFeCr | 63–70 | 0.05–0.10 | 1.5 | 0.02 | 0.01 | | | |
| *V. K. Ferro Alloys Private Ltd.* | | | | | | | | |
| HCFeCr | 60–70 | 6–8 | 0.5–4.0 | 0.03 | 0.05 | | | |
| *Vargön Alloys AB* | | | | | | | | |
| HCFeCr 1 | 65–67 | 4–6 | 1.5 | 0.02 | 0.08 | 0.04 | | |
| HCFeCr 2 | 65–67 | 6–8 | 1.5 | 0.02 | 0.08 | 0.04 | | |
| ChCr 1 | 55–60 | 6–8 | 1–3 | 0.025 | 0.05 | 0.5 | | |
| ChCr 2 | 55–60 | 6–8 | 3–6 | 0.025 | 0.05 | 0.5 | | |
| *VBC Ferro Alloys Ltd.* | | | | | | | | |
| HCFeCr | 60–70 | 6–8 | 2 | 0.03 | 0.05 | | | |
| *Yermakovsky Ferroalloy Plant* | | | | | | | | |
| HCFeCr | 65–68 | 8–9 | 2.0 | 0.03–0.05 | 0.04–0.08 | | | 10–80,<br>10–50,<br>0–10 |
| FeCrSi | 28 | 0.1 | 45 (min) | 0.03 | 0.02 | | | 10–80,<br>10–50,<br>0–10 |
| *Zimasco (Private) Ltd.* | | | | | | | | |
| HCFeCr | 65 | 8 | 2.5 | 0.02 | 0.06 | | | 10–150 |
| *Zimbabwe Alloys Ltd.* | | | | | | | | |
| LCFeCr | 64 | 0.06 | 1.2 | 0.025 | 0.01 | | | 3–100 |
| FeCrSi | 35 | 0.05 | 42 | 0.03 | 0.005 | | | 10–100 |

[a] *Key*: FeCrSi, ferrochromiumsilicon; HCFeCr, high-carbon ferrochromium; LCFeCr, low-carbon ferrochromium; ChCr, charge-grade ferrochromium; —, not reported.

[b] Cr is minimum except where range is specified unless noted otherwise. Al, C, Si, P, S, and Ti are maximum except where range is specified unless noted otherwise. Size in millimeters unless noted otherwise.

Table 15. **Chromium Metal Chemical Specifications**[a,b]

| | | Delachaux | | | Elkem (Vacuum-Grade) | | | Metallurg | | Nippon Denko | | Tula | ASTM | Polema | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Element | | Vacuum | DDB | Powder | Plate | Pellets | Powder | Standard | Vacuum Refining | Standard | Request | Flake | Grade A | Grade B | EX | ERX-1 | ERX-2 | ERX-3 |
| chromium | Cr | 99.5 | 99.7 | 99.8 | 99.1 | 99.5 | 99.0 | 99.2 | 99.4 | 99.0 | 99.0 | 66.6 | 99.0 | 99.4 | 99.95 | 99.95 | 99.95 | 99.95 |
| aluminum | Al | 0.1 | 0.01 | 0.01 | 0.01 | 0.005 | 0.01 | 0.15 | 0.10 | 0.3 | | 0.004 | 0.30 | 0.10 | 0.006 | 0.006 | 0.006 | 0.006 |
| antimony | Sb | 0.0005 | 0.0005 | | | | | | | | | 0.001 | 0.005 | 0.003 | | | | |
| arsenic | As | 0.0001 | 0.0001 | | | | | | | | | 0.001 | 0.005 | 0.003 | | | | |
| barium | Ba | 0.00003 | 0.00003 | | | | | | | | | | | | | | | |
| bismuth | Bi | 0.00005 | 0.00005 | | | | | | | | 0.0006 | 0.003 | 0.001 | | | | | |
| boron | B | 0.00001 | 0.00001 | | | | | | | | | | 0.005 | 0.003 | | | | |
| cadmium | Cd | 0.0002 | 0.0002 | | | | | | | | | | | | | | | |
| carbon | C | 0.01 | 0.04 | 0.01 | 0.02 | 0.05 | 0.02 | 0.03 | 0.03 | 0.04 | 0.02 | 0.0010 | 0.050 | 0.050 | 0.020 | 0.008 | 0.008 | 0.008 |
| cobalt | Co | | | | | | | | | | | 0.0003 | 0.003 | 0.001 | | | | |
| columbium | Nb | | | | | | | | | | | | 0.050 | 0.050 | | | | |
| copper | Cu | 0.002 | 0.001 | | | | | | | | | 0.0003 | 0.01 | 0.01 | 0.003 | 0.003 | 0.003 | 0.003 |
| hydrogen | H | 0.0001 | 0.0001 | | 0.01 | 0.002 | 0.02 | | | 0.0007 | 0.0007 | | 0.01 | 0.003 | | | | |
| iron | Fe | 0.2 | 0.15 | 0.12 | 0.20 | 0.25 | 0.25 | 0.025 | 0.25 | 0.5 | 0.5 | 0.002 | 0.35 | 0.35 | 0.008 | 0.008 | 0.008 | 0.012 |
| lead | Pb | 0.0005 | 0.0005 | | 0.003 | 0.001 | 0.01 | | | | | 0.002 | 0.003 | 0.001 | 0.001 | Trace | Trace | Trace |
| magnesium | Mg | 0.001 | 0.001 | | | | | | | | | | | | | | | |
| manganese | Mn | 0.0015 | 0.0015 | | 0.01 | 0.010 | 0.01 | | | | | 0.002 | 0.01 | 0.01 | | | | |
| molybdenum | Mo | | | | | | | | | | | 0.0003 | 0.050 | 0.01 | | | | |
| nickel | Ni | | | | | | | | | | | 0.001 | | | 0.005 | 0.005 | 0.005 | 0.007 |
| nitrogen | N | 0.02 | 0.008 | 0.005 | 0.05 | 0.010 | 0.05 | 0.01 | 0.02 | 0.030 | 0.030 | | 0.050 | 0.020 | 0.020 | 0.005 | 0.007 | 0.010 |
| oxygen | O | 0.1 | 0.045 | 0.045 | 0.50 | 0.05 | 0.60 | 0.15 | 0.1 | 0.046 | 0.046 | 0.334 | 0.50 | 0.10 | 0.600 | 0.005 | 0.008 | 0.020 |
| phosphorus | P | 0.002 | 0.001 | 0.001 | 0.005 | 0.002 | 0.005 | 0.005 | 0.001 | 0.05 | 0.003 | | 0.010 | 0.010 | | | | |
| selenium | Se | 0.0002 | 0.0002 | | | | | | | | | | | | | | | |
| silicon | Si | 0.1 | 0.05 | 0.04 | 0.005 | 0.02 | 0.01 | 0.15 | 0.10 | 0.2 | 0.2 | 0.020 | 0.15 | 0.10 | 0.010 | 0.010 | 0.010 | 0.012 |
| silver | Ag | 0.00005 | 0.00005 | | | | | | | | | 0.003 | 0.003 | 0.001 | | | | |
| sulfur | S | 0.01 | 0.004 | 0.005 | 0.030 | 0.010 | 0.04 | 0.005 | 0.01 | 0.05 | 0.05 | 0.0140 | 0.030 | 0.010 | 0.010 | 0.002 | 0.002 | 0.005 |
| tantalum | Ta | | | | | | | | | | | | 0.050 | 0.003 | | | | |
| tellurium | Te | 0.0002 | 0.0002 | | | | | | | | | | | | | | | |
| thallium | Tl | 0.0002 | 0.0002 | | | | | | | | | | | | | | | |
| tin | Sn | 0.0005 | 0.0005 | | | 0.001 | | | | | | 0.0001 | 0.001 | 0.001 | | | | |
| titanium | Ti | | | | | | | | | | | | 0.050 | 0.003 | | | | |
| vanadium | V | | | | | | | | | | | 0.0003 | 0.050 | 0.050 | | | | |
| zinc | Zn | 0.0005 | 0.0005 | | | | | | | | | 0.0001 | 0.005 | 0.003 | | | | |
| zirconium | Zi | | | | | | | | | | | | 0.050 | 0.003 | | | | |

[a] Ref. 2.

[b] Blank space, not reported.

to address the difficulty of dissolving samples that contain chromite. A procedure found to work is fusion with sodium peroxide followed by persulfate oxidation and titration with ferrous iron (26).

The Environmental Protection Agency (EPA) (27) has an interest in the analysis for chromium because it is classified as a toxic material, and waste materials are analyzed for chromium content. The required treatment of waste is affected by its leachable chromium content. EPA has published analysis methods for chromium and for hexavalent chromium. The analysis method for chromium is atomic absorption including direct aspiration (Method 7190) and furnace (Method 7191) techniques. The analysis methods for hexavalent chromium include coprecipitation (Method 7195), colorimetric (Method 7196A), chelation/extraction (Method 7197), and differential pulse polarography (Method 7198) techniques. The coprecipitation, colorimetric, and chelation/extraction techniques are recommended for extracts and groundwaters.

## 11. Environmental Concerns

In recognition of the development of environmental concerns about chromium worldwide and in response to a European Commission review of chromium occupational exposure limits, the International Chromium Development Association published industry guidelines on health, safety, and environment. The guidelines take account of extensive international changes and developments in legislation and regulation of chromium materials and is intended to help companies implement appropriate workplace practices and procedures for environmental protection.

Environmental concerns about chromium have resulted in a wide variety of studies to determine chemical characteristics, natural background levels, sources of environmental emission, movement of chromium in the environment, interaction of chromium with plants and animals, effect of chromium on plants and animals, measurement methods, and recovery technology. A broad review of many environmental factors and the role of chromium, among other metals, in the environment was published.

In the United States, the Environmental Protection Agency (EPA) regulates chromium releases into the environment. The Occupational Safety and Health Administration (OSHA) regulates workplace exposure.

The EPA regulates and monitors industrial impact on the environment. As part of its monitoring activity, EPA collects data on toxic chemicals. That information is made available in the Toxic Release Inventory (TRI). TRI is mandated under Title III of the Superfund Amendments and Re-authorization Act (SARA) of 1986. The Pollution Prevention Act of 1990 resulted in the addition of recycling activities to the material management categories covered under TRI reporting.

### 11.1. Environmental Regulations.

Chromium and chromium compounds are regulated by the EPA under the Clean Air Act (CAA), the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (also known as CERCLA or Superfund), National Primary Drinking Water Regulations (NPDWR), the Clean Water Act (CWA), and the Resource Conservation and Recovery Act (RCRA).

*Effluent.* Chromium in water effluents is manageable. The solubility of trivalent chromium compounds in neutral water usually results in a chromium concentration below that required by EPA for drinking water (0.1 ppm). Thus, when water is neutralized, chromium can be removed by filtration. If hexavalent chromium compounds are present, they must first be reduced to trivalent, a technically manageable operation.

*Emissions.* Congress enacted the Clean Air Act Amendments Law of 1990 (Public Law 101-549), completely revising the Air Toxics Program. Congress identified 189 hazardous air pollutants to be regulated. Chromium compounds—defined as any chemical substances that contain chromium as part of their structure—were included among those hazardous air pollutants. Under the revised Air Toxics Program, Congress instructed EPA to regulate hazardous air pollutants by regulating the source of those pollutants. Congress required EPA to identify pollution sources by November 1991, then to set emission standards for those sources. EPA eliminated the use of chromium chemicals in comfort cooling towers and regulated chromium releases from the electroplating and anodizing industries.

*Solid Waste.* EPA regulates solid waste generated by the chemical industry in the production of sodium chromate and dichromate. Chromium-containing treated residues from roasting and/or leaching of chrome ore is regulated under Subtitle D of the Resource Conservation and Recovery Act. EPA found no significant danger associated with treated residue from roasting and/or leaching of chrome ore based on waste characteristics, management practices, and damage case investigations.

**11.2. Resource Conservation and Recovery Act.** The Resource Conservation and Recovery Act (RCRA) brought waste from the extraction, beneficiation, and processing (smelting and refining) of ores and minerals under the regulatory control of EPA. EPA listed emissions from the production of ferrochromium–silicon (RCRA waste number K090) and ferrochromium (RCRA waste number K091) as hazardous waste. EPA regulates treated residue from roasting and leaching of chromite ore under Section D of RCRA. EPA was directed in 1988 by a court order to restrict the scope of exclusion to large volume, low hazard waste. An EPA study determined that treated residue from roasting and leaching of chromite ore does not pose an actual or potential danger to human health and the environment. EPA therefore decided to regulate treated residue from roasting and leaching of chromite ore under Section D of RCRA.

EPA regulates refractory material solid waste containing chromium. EPA determined that chromium-containing wastes exhibit toxicity. Therefore, they have established a policy that—if the extract from a representative waste sample contains chromium at a concentration greater than or equal to 5.0 mg/L (total chromium) as measured by a specified toxicity characteristics leaching procedure—it is hazardous. EPA promulgated a treatment standard for chromium-containing refractory brick wastes based on chemical stabilization. (Stabilization is a process that keeps a compound, mixture, or solution from changing its form or chemical nature.) EPA determined that some chromium-containing refractory brick wastes can be recycled as feedstock in the manufacture of refractory bricks or metal alloys.

EPA regulates the wood preservation industry. As a result of the Resource Conservation and Recovery Act (1988), EPA promulgated regulations on the wood preserving industry (1990) to control inorganic preservatives containing chromium labeled F035 by EPA. In the *Code of Federal Regulations* (*CFR*), EPA specified standards for drip pad design, operation, inspection, and closure, specifically in 40 *CFR* 262, 264, and 265. In effect, EPA required wood preservers to upgrade their drip pad or build new ones to meet EPA standards.

EPA regulates the emission of chromium from toxic waste incinerators. The Resource Conservation and Recovery Act (1976) made EPA responsible for managing hazardous waste disposal. EPA regulates particulate emissions from incinerators. However, EPA found that the particulate standard may not provide sufficient protection if a substantial fraction of the particulate emissions were regulated metals, leading EPA to promulgate separate regulations for toxic waste incinerators. Incineration is a desirable method of toxic waste disposal because organic waste is destroyed, leaving no future cost to society. EPA proposed regulation of chromium emission from devices burning hazardous waste in 1987 and promulgated regulations in 1990. Regulation involves control of chromium (contained in the waste stream) feed rates, chromium emission limits, and site-specific risk assessment. Based on field studies, the emission limits of chromium were complicated by the fact that stainless steel (a chromium-containing alloy) was used in the production and transportation processes.

Chromium leaching behavior in soil derived from the kiln roasting and leaching of chromite ore was reported. It was found that (*1*) leaching was highly sensitive to pH and that the most chromium leached out at soil pH between 4 and 12 and (*2*) the presence of organic matter in the soil reduced the amount of chromium leached out.

**11.3. Clean Air Act.** In 1992, EPA identified chromium electroplaters and anodizers as an area source of hazardous air pollutants that warrant regulation under Section 112 of the Clean Air Act and described that source's adverse impact. It was estimated that over 5000 facilities nationwide, which were collectively emitting about 175 tons of chromium per year, would be required by regulation to reduce their emission by 99%. The chromium electroplating industry includes hard chromium platers (usually a thick chromium coating on steel for wear resistance of hydraulic cylinders, zinc diecastings, plastic molds, and marine hardware), decorative chromium platers (usually over a nickel layer on aluminum, brass, plastic, or steel for wear and tarnish resistance of auto trim, tools, bicycles, and plumbing fixtures), and surface-treatment electroplaters or anodizers (usually a chromic acid process to produce a corrosion-resistant oxide surface on aluminum used for aircraft parts and architectural structures subject to high stress and corrosive conditions). EPA estimated that 1540 hard chromium electroplaters, 2800 decorative electroplaters, and 680 chromic acid anodizers nationwide are affected. EPA estimated that electroplaters collectively emit 175 tons of chromium per year, most of which is hexavalent and carcinogenic in humans. EPA estimated that the resulting U.S. nationwide population risk is an additional 110 cases of cancer per year resulting from that emission. EPA estimated the resulting individual risk in the proximity of particular facilities ranged from less than 2 chances per 100,000 for small chromic acid anodizing operations to 5 chances per 1000 for large hard plating operations. The regulation specifies emission limits, work practices, initial performance testing, ongoing compliance monitoring, recordkeeping, and reporting requirements. The EPA reported on chromium emissions from electroplating operations and chromium recovery from electroplating rinse waters.

In 1994, EPA banned the use chromium chemicals for industrial process water-cooling towers for corrosion inhibition. It was reported that 90% of industrial cooling-tower operators had eliminated the use of chromium chemicals in anticipation of such an EPA ban. However, the remaining 800 operations were given 18 months within which to comply with the new ruling.

**11.4. Toxic Release Inventory.** Under the Toxic Release Inventory program, EPA collected environmental release information since 1987 from manufacturing facilities that employ 10 or more persons and used a threshold amount of chromium contained in chromium compounds. (A *manufacturing facility* is one whose product is included in Standard Industrial Classification Division E (SIC) Codes 20–39. EPA was expanded in 1997 to cover additional SIC codes. Reporting under the new set of SIC codes was expected to start for the 1998 reporting year.) The threshold amount decreased from 1987 to 1989, after which time it remained constant. The threshold limit for a facility that manufactured or processed chromium compounds was about 34 tons of contained chromium in 1987, about 23 tons in 1988, and about 11 tons in 1989 and subsequent years. The threshold limit for facilities that otherwise used chromium compounds has been and remains about 5.4 tons. (Note that EPA has definitions for the terms manufacture, process, and otherwise use for the purpose of reporting releases.) When reporting chromium releases, a facility must add up the chromium released from all sources that exceed a de minimis amount. The de minimis amount for chromium compounds is 0.1%. Facilities report the amount of chromium released to the air, water, and earth environment; the amount of chromium recovered on site; and the amount transferred to offsite locations. The data are collectively referred to as the Toxic Release Inventory (TRI).

EPA denied a petition to remove chromium III compounds and chromic oxide in particular from the chemicals covered by the Emergency Planning and Community Right-to-Know Act of 1986, in particular from the section 313 list of toxic chemicals. The petition to remove chromium III compounds was based on the contention that chromium III compounds are considered nonhazardous wastes under the Resource Conservation and Recovery Act (RCRA). EPA denied the petition based on EPA's determination that the conversion of chromium(III) to chromium(VI) has been demonstrated to occur in soils and in water-treatment processes that use chlorine.

EPA started the 33/50 Program, a voluntary program to reduce environmental release and transfer of 17 toxic chemicals, including chromium and chromium compounds. The program is so named because its objective is the voluntary one-third reduction of chromium and chromium compound releases and transfers by 1992 and one-half reduction by 1995. Reductions are to be measured against 1988 TRI data. See the "Recycling and Disposal" section of this article for more details.

**11.5. Water and Effluents.** EPA promulgated its final rule on chromium contained in primary drinking water in 1991. EPA set the maximum contaminant level goal (MCLG) and the maximum contaminant level for chromium contained in primary drinking water at 0.1 mg/L. EPA identified the best available technologies to remove chromium(III) compounds to be coagulation with filtration, ion exchange, lime softening, and reverse osmosis. EPA identified the best available technologies to remove chromium(VI) compounds to be coagulation with filtration, ion exchange, and reverse osmosis. EPA concluded that chromium contained in drinking water should be minimized in recognition of its biological reactivity, including its potential for posing a carcinogenic hazard. EPA set the chromium(III) and chromium(VI) MCLG on the basis of the reference dose concept. The safe dose to which EPA refers is the National Academy of Sciences recommended daily intake of 50–200 μg per day.

The EPA published a retrospective study on effluent guidelines, leather tanning, and pollution prevention. The report found that industry met the chromium limitations by modifying the tanning process to get more chromium out of the tanning wastewater and into the leather. By changing chromium formulations, raising process temperature and time, and reducing bath water, industry increased chromium fixation from about 50% to about 90%. Recycling was also done to meet guidelines.

## 12. Recycling and Disposal

**12.1. Recycling.** Stainless steel, superalloys, and chromium metal are produced primarily in Europe, Japan, and the United States. Stainless steel represents about 1% of steel production domestically and worldwide. It is a specialized, small part of the steel market serving the need for durable, corrosion-resistant steel. Yet stainless steel accounts for about 50% of chromium demand.

U.S. apparent consumption of chromium is primary production (ie, chromium contained in domestic mine production of chromite ore) plus secondary production (ie, chromium contained in recycled scrap) plus net trade (ie, imports minus exports) in chromium materials (including chromite ore, chromium ferroalloys and metal, and selected chromium chemicals) plus domestic consumer, government, and producer stock changes of chromite ore and chromium ferroalloys and metal.

Chromium contained in stainless steel and other metal scrap is recycled. Both new and old scrap are collected by scrap processors and returned to stainless-steel manufacturers. Secondary production is calculated as chromium contained in reported stainless-steel scrap receipts.

Recycling (qv) is the only domestic supply source of chromium. Stainless-steel and superalloys are recycled, primarily for their nickel and chromium contents. As much as 50% of electric furnace stainless-steel production can result from recycled stainless-steel scrap. Advanced stainless-steel production technology such as continuous casting reduces prompt scrap generation and permits a higher product yield per unit of raw material feed (28).

Industry practice is to sort scrap for recycling. Chromium-containing stainless steel is collected, processed, and returned to stainless steel manufacturers for reuse. Processing may include changing the physical form of the scrap. Large pieces may be cut to smaller size, common sizes may be bundled for easier handling, and smaller-sized pieces may be melted and cast into larger sizes.

Some materials require cleaning or sorting before they can be recycled. Some processors melt and combine several alloys to produce master alloy castings that meet stainless steel or other alloy manufacturers' chemical requirements. Superalloy (nickel- and cobalt-based alloys used in the aerospace industry) reuse is carried out by certified recycling companies in cooperation with alloy producers and product manufacturers. Superalloy scrap that cannot be reused is recycled in other alloys. Small quantities of chromium metal waste and scrap are also traded.

The price of chromium-containing stainless-steel scrap is sensitive to the price and availability of its constituents from primary sources. Stainless steel is composed of two major categories: austenitic and ferritic stainless steel. Austenitic stainless steel requires nickel and chromium. Ferritic stainless steel requires only chromium. The price of austenitic stainless steel is driven mostly by the higher-valued nickel contained in the scrap.

Chromium recycling is expected to increase, driven by environmental regulations mainly in the industrialized countries. Stainless-steel use has been growing, so the availability of stainless steel obsolete scrap as well as the scrap generated as a result of processing that material should continue to increase.

Recycled chromium constituted about 20% of current apparent consumption. According the year 2000, secondary chromium was expected to rise to 25% of apparent consumption because of recycling growth and decline in nonrecycling uses (see Figure 12).

**12.2. Disposal.** The Environmental Protection Agency surveys domestic industry for quantity and method of disposal (ie, releases plus transfers) and reports that information annually in the Toxics Release Inventory Public Data

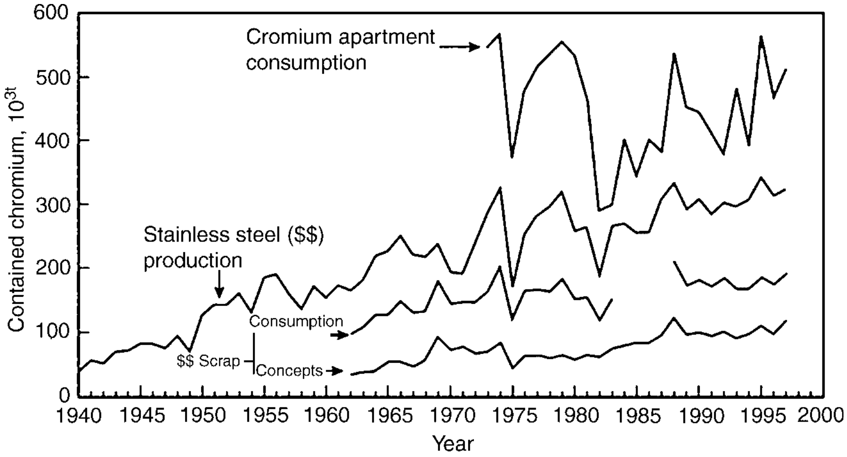

**Fig. 12.** U.S. chromium apparent consumption, and stainless-steel production, scrap receipts and consumption. For the purpose of calculating chromium apparent supply, secondary supply is estimated as stainless-steel scrap receipts. The trend of stainless-steel scrap receipts and consumption follow that of stainless steel production. Stainless-steel scrap consumption exceeds that of receipts by scrap generated within the consuming plant. The general trend to chromium apparent consumption is similar to that of stainless-steel production.

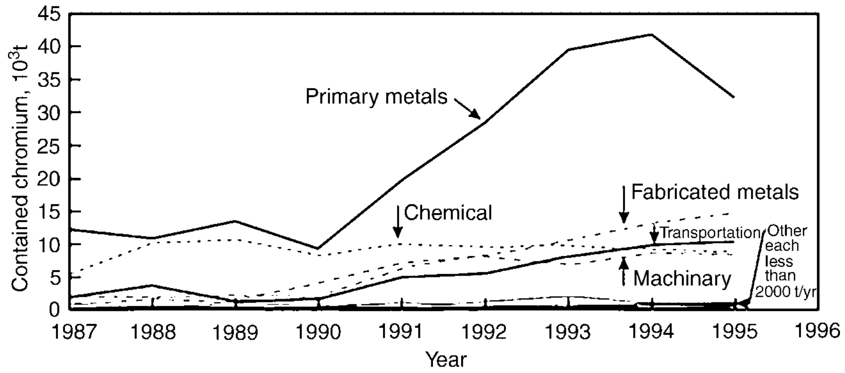

**Fig. 13.** Chromium disposals (ie, releases plus transfers) by industry. The major sources of chromium disposals are the same as those in the primary consuming industries: metallurgical and chemical. The major source of disposals from the metallurgical industry is primary metals, that portion that produces metal alloys in a variety of shapes for industrial consumers. Fabricated metals and machinery categories follow primary metals. Others include food, tobacco, textile, apparel, lumber, furniture, paper, printing, petroleum, rubber, leather, stone, electrical, instruments, miscellaneous other.

Release. Disposals are shown in Figure 13. Out of 20 specific categories, one—primary metals—dominates releases and transfers reflecting the fact that the major end use of chromium is in the metallurgical industry. Four other industries (fabricated metals, transportation, chemical, and machinery) account for a second tier of disposals. The remaining fifteen industries form a third tier in which each constituent accounts for less than 2.5% of total disposals. The rapid rise in disposal in fabricated and primary metals and transportation from 1990 to 1991 follows a similar rise in transfers by mode shown in Figure 14. This shows

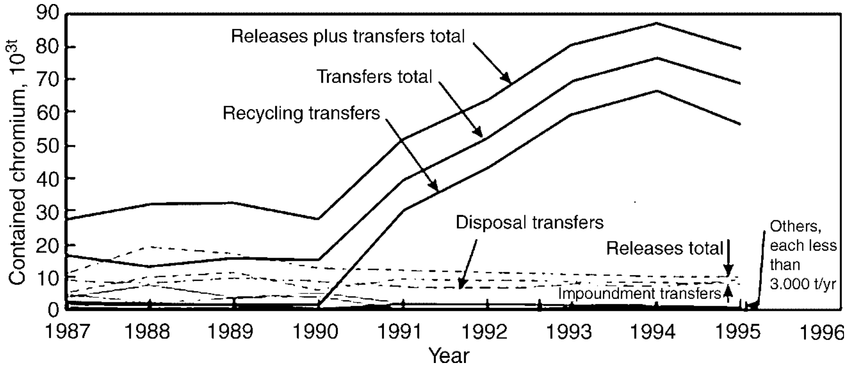

**Fig. 14.** Chromium releases and transfers by mode. It was in 1991 that the Environmental Protection Agency introduced "recycling transfers" as a material management category. Before 1991, "releases and transfers" were of comparable magnitude. Since 1991, the large volume of chromium contained in alloys transferred for recycling has both raised disposal (releases plus transfers) appreciably and caused both "transfers" and "disposals" to be dominated by recycling transfers. The next-largest disposal categories are "disposal transfers" and "impoundment transfers". "total releases" have declined slowly yet steadily since 1988.

that transfers exceed releases, that the difference increased from 1991 to 1994 mostly as a result of increasing transfers. Releases started to decline in 1988 and have continued to do so since then. The curves clearly show that the increase in total transfers results from the increase in recycling transfers. In 1994 and 1995, recycling accounted for in excess of 70% of releases and transfers. These increases occurred because recycling was not required to be reported until 1991.

Chromium and chromium compounds are one of the 17 priority chemicals targeted by EPA as part of the 33/50 Program, a program in which industries voluntarily tried to reduce releases with respect to those of 1988 by 33% in 1992 and by 50% in 1995. When adjusted for the change in reporting requirements from 1988 to 1992, chromium releases declined by 39%; transfers, by 43%. When adjusted for the change in reporting requirements from 1988 to 1995, chromium releases declined by 45%; transfers, by 22% (24), so the goal was not quite met, but these numbers should not be taken to mean that the program was unsuccessful. The measurement is relative to the base year, 1988, without regard to the level of industrial activity in each year. More industrial activity, even with more efficient material handling, could result in greater disposals. U.S. apparent consumption of chromium, a measure of national industrial activity, in 1988 was 537,000 tons; in 1992, 378,000 tons; and in 1995, 565,000 tons (30). The 30% decline in industrial chromium-related activity between 1988 and 1992 as indicated by the change in chromium apparent consumption between those two years likely enhanced apparent decline in chromium releases while the 5% increase from 1988 to 1995 likely diminished the apparent change in chromium releases. In other words, measuring changes in releases and/or transfers from one year to another without regard for changes in industrial activity may not be a valid way to measure industry performance at reducing releases and transfers. To measure industry performance, one should measure changes in releases and/or transfers relative to material processed. Of course, from the point of view of the environment, what matters is only how much material was released or transferred.

## 13. Health and Safety Factors

**13.1. Health and Nutrition.** Chromium is a trace mineral required by the human body. As such, the National Research Council recommends a daily intake in the range of 50–200 μg. Chromium is a cofactor for insulin, a hormone that participates in carbohydrate and fat metabolism. A cofactor is a material that acts with the material. The dietary chemical form of chromium is as trivalent compounds. Because humans cannot convert trivalent chromium to hexavalent chromium, the carcinogenicity of hexavalent chromium compounds bears no relevance to the nutritional role of trivalent chromium.

**13.2. Toxicity.** The effect of an element on the human body depends on several factors. These factors include the chemical or class of chemical, the route of exposure, the quantity and duration of exposure, and characteristics of the exposed subject.

The chemical distinctions typically made with respect to chromium chemicals include whether the compound is synthetic or naturally occurring. Synthetic

Table 16. **Occupational Safety and Health Standards for Workplace Exposure to Airborne Chromium**[a]

| Air contaminant | Limit |
|---|---|
| | Acceptable ceiling concentration |
| chromic acid and chromates | 1 mg/10 $m^3$ |
| | Limit for air contaminant |
| chromium metal and insoluble salts, as chromium | 1 $mg/m^3$ |
| chromium(II) and chromium(III) compounds | 0.5 $mg/m^3$ |

[a] *Note*: Acceptable ceiling concentration cannot be exceeded. Limit for air contaminant shall not exceed the stated amount measured as an 8-h time-weighted average during any 8-h work shift of a 40-h work week.

chromium compounds are typically classified by their oxidation state. Trivalent and hexavalent chromium compounds are two such classifications. Exposure to chromium compounds could typically occur through one or more of three routes: skin contact, ingestion, or inhalation. Exposure can also vary in intensity (concentration of the chemical) and duration (length of time for which exposure occurs). Response to chemical exposure is dependent on such human characteristics as age, sex, general health, and chemical sensitivity. The effect of chemical exposure on the human body can be good or bad. Chromium is one of those elements that is both essential to good health and detrimental to good health. The detrimental effects of chemical exposure are classified as acutely toxic when small amounts of the chemical cause significant damage in a short time, chronically toxic when exposure over a long time causes measurable damage, and carcinogenic when exposure can result in cancer.

Chromium generally forms chemical compounds in which chromium has either the hexavalent or trivalent oxidation state. Hexavalent chromium compounds are generally recognized as toxic. Chronic occupational exposure to hexavalent chromium has been associated with an increased incidence of bronchial cancer. The toxic status of trivalent chromium compounds is not clear. However, trivalent chromium compounds are less toxic than hexavalent chromium compounds. Chemical compounds containing chromium in lower valence states are generally recognized as benign.

The Food and Drug Administration, Department of Health and Human Services, was in the process of amending its regulations to add chromium to labeling for reference daily intakes and to add chromium to the factors in determining whether a substitute food is inferior.

The Occupational Safety and Health Administration (OSHA) regulated workplace exposure to chromium metal, soluble chromium salts, insoluble chromium salts, and chromic acid and chromates. Table 16 shows the exposure limits set by OSHA.

## 14. Uses

In the United States, most sodium dichromate is converted to chromic acid; some, however, is used directly by several industries. Chromium was first used in pigments and tanning compounds. Chromium plating, the electrodeposition of chromium from a solution of chromic acid, started in the early 1900s. A more recent use for chromium is in wood preservation. Chromium–copper–arsenate (CCA) impregnated wood can be protected from weathering, insects, and rotting for 40 years. Today, major end-use markets for sodium dichromate—drilling mud for the oil-and-gas industry, leather tanning, metal finishing, and wood preservation—are mature markets showing slow growth. Chromium chemicals are also used to make biocides, catalysts, corrosion inhibitors, metal plating and finishing chemicals, refractories, and printing chemicals. End uses showing declining use include chromate pigments, corrosion-control agents, and water-treatment chemicals. Newer, faster-growing markets include magnetic recording media and catalysts, and represent a small part of the market. In Europe, leather tanning is a major end use. In Japan, electroplating and metal finishing are principal end uses.

A chromium chemical end use with which many people are familiar is pigments. Chromium containing pigments are broadly classified as oxides or chromates. A rainbow of colors are produced by the pigment industry using a variety of mixed metal oxides with chromium. Oxides comprise chromic oxide green, copper chrome black, and hydrated chromium oxide green. Chromates comprise chrome green, lead chromate, and molybdate orange. Chromic oxide green pigment is used in camouflage because it has desirable infrared reflectance properties. Copper–chrome pigment is used in the black coating found on outdoor grills and wood-burning stoves. Hydrated chromium oxide green finds use in cosmetics and body soap. A variety of pigments are based on lead chromate including medium chrome yellow, lemon or primrose chrome yellow, molybdate orange, and chrome orange. Medium chrome yellow pigment is used in traffic marking yellow paint found on all major streets and highways. An important use of chromium pigments is in anticorrosion coatings. Chromium pigments that are used for corrosion control include lead, zinc, and strontium chromates. Chromate metal primers are used extensively by the federal government, in both civilian and military applications.

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