U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Chromium

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Draft

HANDBOOK OF CHEMICAL INDUSTRY ECONOMICS, INORGANIC

Chromium Chapter

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Contents

Units and Abbreviations:

°C	Degrees Centigrade.
cgs	centigrade gram second
cm	centimeter.
eV	Electron volt.
J	Joule.
g	gram.
k	thousand.
K	Kelvin.
m	meter.
mol	mole.
ppm	parts per million.

Introduction and History

Chromium 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 name 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 primarily used 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. 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 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 and ferrochromium. 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 1900's. 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-to-iron ratio ores were required (ratios greater than about 2:1).

Since 1960, major changes have occurred in the chromium industry because of changes in steel making technology. The development of ladle refining techniques (i.e., 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 1970's, 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-to-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 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 dichromate are used interchangeably in the chemical industry.

Hargreaves et al. reviewed the world minerals industry by mineral, country, and mining company (Hargreaves et al., 1994). 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.

Occurrence

Many minerals contain chromium as a major element (see Table 1), 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 types of 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. Ophiolites 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***, while those in ophiolites are typically pod-like or irregular in form, are known as ***podiform deposits***. 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 have historically been a minor source of chromite.

Table 2 shows the reserves and resources of chromite worldwide.

INSERT TABLE 1 HERE.

INSERT TABLE 2 HERE.

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.

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 has a little over 2.5 billion tons, and about half of that tonnage is in the Great Dyke in Zimbabwe, another layered intrusion (Mineral Commodity Summaries, 1998). Clearly, chromite resources in layered intrusions are not evenly distributed worldwide. Figure 1 shows the distribution of chromite resources. 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

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 ~560 million years) are known to carry economic chromite deposits; the youngest of these deposits is the Bushveld at about 1.9 billion years. 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 years old).

INSERT FIGURE 1 HERE.

Figure 1. Geographic distribution of chromium resources. Chromite deposits are shown by geographic location, deposit size, and predominant deposit type. (Non)Producing determination made in 1997.

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 some 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, Kazakhstan

Perm district, Russia;

Zambalas, Philippines

Four districts, Albania

Six districts, Turkey

Selukwe, Zimbabwe

New Caledonia

Troodos, Cyprus

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 Coast Ranges in California and Oregon, the Shetland Islands in Scotland, and Vietnam.

Podiform and stratiform deposits have different chemical characteristics, which have 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 summarizes the range of chemical contents of chromite ores.

INSERT TABLE 3 HERE.

INSERT TABLE 4 HERE.

Beach Sands

Beach sands that contain chromite exist because of a series of geologic facts. Chromite mined from hard rock deposits, either stratiform or podiform, are concentrations in the rock commonly at least 15 volume percent chromite up to 100 percent 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 one and five volume percent of the rock. In addition, peridotite can occur over many hundreds of square miles 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. Such is the case in Oregon where beach sands were mined during Word War II. Over the last decade, 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.

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 non- silicate minerals. Thus lateritic deposits 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.

The Mineral 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 grams per cubic centimeter 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 figure 2 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^{0}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 weight percent. Because chromite is a solid solution, it has no fixed composition.

INSERT FIGURE 2 HERE.

Figure 2. Composition diagram for the spinel minerals. Each of the corners 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.

Terrestrial Chromium Abundance

Chromium is the 18th most abundant element in the Earth's upper crust at 35 ppm (Taylor and McLennen, 1985). Chromium is most concentrated in rocks that constitute the upper mantle, from which crustal rocks are evolved. Upper mantle rocks are almost exclusively peridotite in which the average chromium content is 3000 ppm (Shiraki, 1997). The granite-like 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 (Taylor and McLennen, 1985) and the concentration in the overall crust of the Earth is 100 ppm (Handbook of Chemistry and Physics, 66th Edition). Seawater contains 2×10^{-10} grams of chromium per gram of water while rivers average 1×10^{-9} grams of chromium per gram of water (Taylor and McLennen, 1985).

Table 1. Terrestrial minerals containing chromium as a major constituent.

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*	$CrO(OH)$	61
Brezinaite	Cr_3S_4	47-50
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
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*	$CrO(OH)$	61
Guyanaite*	$CrO(OH)$	61

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
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	$(Ni,CoFe^{2+})(Cr,Fe^{3+},Al)_2O_4$	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
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

*Different crystal structures

Source: Modified from Lipin, 1983.

Table 2. Chromite reserves, reserve base, and identified resources in thousands of metric tons, gross weight normalized to 45% Cr_2O_3 content.

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
Kazakhstan	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

NA Not Available.

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.

Table 3. Classification of chromite by composition, type of deposit, and principle uses.

Class of ore	Composition (wt %)	Type of deposit	Major use
High-Cr	Cr_2O_3 46-55%	Podiform and Stratiform	Metallurgical
	Cr/Fe>2:1		
High-Fe	Cr_2O_3 42-46%	Stratiform	Metallurgical and
	Cr/Fe<2:1		Chemical
High-Al	Cr_2O_3 33-38%	Podiform	Refractory
	Al_2O_3 22-34%		

Table 4. Range of Commercially Available Chromite Ore Chemical Characteristics Based on a Composite of Sources.[1] (Percent)

Chemical compound	Observed range of values: 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

[1] Chromium-to-iron ratio varies from 1.4 to 4.2.

Note: While the composition limits shown above come from commercially available material, they do not as a group represent any specific material.

Source: Papp, 1997.

Properties

The data in this properties section are taken from the 77th edition of the Handbook of Chemistry and Physics (1996-1997). 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 ^{0}C and its boiling point is 2671^{0}C. At 20^{0}C the specific gravity is 7.18 to 7.20 grams per cubic centimeter.

Chromium is one of the so-called transition elements, meaning 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, with the filling orbital being 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 weight percent 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.

Isotopes

Chromium has four naturally occurring isotopes, none of which is radiogenic. The following are their symbols, percent abundance, and atomic mass: $_{24}Cr^{50}$, 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.

Thermodynamic Properties

The thermodynamic properties of chromium are shown in table 5.

At various temperatures the heat capacities are (in J mol^{-1} K^{-1}): 200 K, 19.86; 250 K, 22.30; 300 K, 23.47; 350 K, 24.39; 400 K, 25.23; 500 K, 26.63; 600 K, 27.72.

Insert Table 5 here.

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, 0.385 at 10 K, 1.59 at 100 K, 1.11 at 200 K, 0.937 at 300K, 0.860 at 500 K, 0.654 at 1000 K, 0.556 at 1600 K, and 0.494 at 2000 K.
- Magnetic Susceptibility is $180x10^{-6}$ cgs at 273 K and $224x10^{-6}$ cgs at 1713 K.
- Hardness (Knoop value) is 1160.
- Ionic radii (in nanometers) are as follows: Cr^{2+} (6 coordination) is 0.73; Cr^{3+} (6 coordination) is 0.62; and Cr^{6+} (4 coordination) is 0.26.
- The electron affinity of the Cr-Cr bond is 0.666 eV.
- The strength of the Cr-Cr chemical bond at 298 K is 142.9 kJ mol^{-1}.
- The elastic constants 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.

Table 5. 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

Sources and Supply

Availability

The U. S. Geological Survey conducted an inventory of chromium resources (DeYoung, 1984). 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 Kazakhstan.

The former U.S. Bureau of Mines (USBM) studied the availability of chromium (Boyle et al., 1993). 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 (MEC's).

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.

Based on Cr_2O_3 content of in situ chromite ore, the ten MEC's 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; and the low-grade group, only 15.90% Cr_2O_3.

Table 6 shows the results of the USBM's analysis. Chromium material costs were calculated on a weighted average basis, free on board ship at the port of export. The chromite cost shown in Table 6 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. USBM's analysis shows that South Africa and Zimbabwe could produce about 78% of total metallurgical chromite ore, 93% of total chemical chromite ore, 85% of total refractory chromite ore, and 93% of total 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 break even 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.

INSERT TABLE 6 HERE.

Strategic Considerations

Supply Security.--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 ferrochromium, 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 stainless and some alloy steel production, which are in turn essential to both the domestic economy and to the production of military hardware.

Strategic Factors, Stockpile

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 US Government has maintained a stockpile since World War I. Industrial mobilizations resulting from World War I (1914-18), World War II (1939-45), and the Korean War (1950-52), 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 (1949-50) and of the United States against Rhodesia as a result of United Nations actions (1966-72) caused national defense planners to acquire and maintain a stockpile. The United States also implemented trade sanctions against South Africa (1986-94); however, chromium materials were exempt for those sanctions.

Critical and strategic materials were stockpiled. Critical materials are materials that are essential in a national security emergency due to their important end uses. Strategic materials are materials that are potentially in short supply during a national emergency. The Defense Logistics Agency, the manager of the National Defense Stockpile, define "strategic and critical materials" as materials that would both be needed to supply the military, industrial, and essential civilian needs of the United States during a national emergency, and are not found or produced in the United States in sufficient quantities to meet such need (U.S. Department of Defense, 1998). 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. Table 7 shows the United States chromium-specific supply and stockpiling historical experience. Figures 3, 4, and 5 show National Defense Stockpile chromite ore, chromium ferroalloy, and chromium metal inventory history for those years for which data are publicly available.

INSERT TABLE 7 HERE.

INSERT FIGURE 3 HERE.

INSERT FIGURE 4 HERE.

INSERT FIGURE 5 HERE.

Figure 3. National Defense Stockpile chromite ore inventory. Chemical, metallurgical, refractory grade ore inventory and total of all grades. The figure shows that inventory was built up over the 1940 to 1962

time period during most of which time (1947 through 1960) stockpile inventory information was confidential information. After 1962, inventory declined owing to sale, barter, and upgrading of materials. Most of the chromite ore disposed of during the 1984-94 time period went into an upgrading program to convert chromite ore into high-carbon ferrochromium in recognition of limited domestic resources necessary to carry out such a conversion promptly.

Figure 4. National defense stockpile ferrochromium inventory. The high- and low-carbon ferrochromium inventories were built up between 1940 and 1965, a time period during which stockpile information was confidential. After a small addition to inventory in 1970, the low-carbon ferrochromium inventory remained unchanged until the Defense Logistics Agency implemented an upgrading program to convert nonspecification-grade low-carbon ferrochromium to electrolytic chromium metal. The program lasted from 1990 through 1994. High-carbon ferrochromium inventory remained unchanged from 1965 until 1984 when inventory increased as a result to an upgrading program to convert chromite ore to high-carbon ferrochromium in recognition of limited domestic resources necessary to carry out such a conversion promptly. The program lasted from 1984 through 1994. High-carbon ferrochromium disposals overlapped the conversion program because payment for upgrading was made in material instead of cash. It was not until 1996 that high-carbon ferrochromium was made available for public sale.

Figure 5. National Defense Stockpile chromium metal and ferrochromiumsilicon inventory. Ferrochromiumsilicon inventory was unchanged from 1971 through 1995 when cash sales stated. Chromium metal inventory declined in the early 1970's after which it remained constant until the 1989-94 upgrading program to convert non-specification grade low-carbon ferrochromium to chromium metal caused the inventory to more than double.

The Defense Logistics Agency, Department of Defense, is currently responsible for National Defense Stockpile operations (U.S. Department of Defense, 1988). Chromium materials included in the National Defense Stockpile 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 to legislative mandate, DLA began modernizing chromium materials in the NDS by converting chromite ore to high-carbon ferrochromium (1984-94) and nonspecification-grade low-carbon ferrochromium into chromium metal (1989-94).

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

INSERT TABLE 8 HERE.

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.

Prices

Chromium materials are not traded in open market exchanges like 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.

Upon being imported into the United States, the value of imported material at the port of export is declared for the purpose of tax collection. This is called the FOB (free on board) 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 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 6 through 9 show the price or value of chromite ore, chromium ferroalloys, and chromium metal histories. Figure 9 shows the value history of chromium materials in units of dollars per metric ton of contained chromium.

INSERT FIGURE 6 HERE.

INSERT FIGURE 7 HERE.

INSERT FIGURE 8 HERE.

INSERT FIGURE 9 HERE.

Figure 6. Composite chromite ore average annual price and U.S. import value and the chromite ore average annual prices based on prices reported in trade journals and value based on trade data from which the composite price and value were calculated. Composite chromite ore price exceeds value over the entire time period for which there is data for each. The trend for each is the same except from 1992 through 1995 when composite price increased and value declined. Price and value peaks occurred in 1989 and 1996.

Figure 7. Composite ferrochromium average annual price and U.S. import value and the ferrochromium average annual prices based on prices reported in trade journals and value based on trade data from which the composite price and value were calculated. Composite ferrochromium price exceeds value over the entire time period for which there is data for each. Ferrochromium price and value trends are similar in their salient features. Price and value peaks occurred in 1988 and 1995. For both price and value, increases are faster than decreases.

Figure 8. Composite chromium metal average annual price and U.S. import value and the chromium metal average annual prices based on prices reported in trade journals and value based on trade data from which the composite price and value were calculated. Composite chromium metal price exceeds value throughout

the time period for which there is data for each. Chromium metal price and value trends are the same except for 1981 through 1989 during which time period value went through a significant dip while price went through a peak.

Figure 9. 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.

Figure 6 shows that 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 1988-90 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. The price peaks for ferrochromium shown in figure 7 correspond to increases in world stainless steel production. Those 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-1970's, the value of various ferrochromium grades were tightly grouped compared to the post mid-1970's 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 free on board (FOB) import value.

Figure 9 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 of contained chromium basis for recent years, the value of ferrochromium is about 5 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.)

Chemicals: Reported price in 1991 for sodium dichromate crystals was $0.60 per pound of sodium dichromate dihydrate equivalent content (for pricing purposes, sodium dichromate dihydrate equivalent content of crystals is 100%) and for sodium dichromate liquor was $0.55 per pound of sodium dichromate dihydrate equivalent content (typically the sodium dichromate dihydrate equivalent content of liquor ranges from 69% to 70%) (Chemical Marketing Reporter, 1991).

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. The United States is a major world chromium chemical producer.

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

INSERT FIGURE 10 HERE.

INSERT FIGURE 11 HERE.

INSERT FIGURE 12 HERE.

INSERT FIGURE 13 HERE.

Figure 10. U.S. chromite ore trade. U.S. chromite ore imports have exceeded exports by a large amount since such traded 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.

Figure 11. U.S. chromium ferroalloy trade. Since the mid-1970's, high-carbon ferrochromium imports have dominated chromium trade. The introduction of post-melting 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.

Figure 12. 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.

Figure 13. U.S. chromium material trade. Chromium material trade is dominated by imports. Before the early 1980's, chromite ore supplied most of the chromium consumed in the United States; however, after that time ferrochromium became the major source of chromium. This transition occurred as domestic ferrochromium smelters closed and foreign smelter capacity expanded, especially in chromite ore producing countries.

Figure 10 shows that chromite ore imports have always greatly exceeded exports. Imports grew rapidly after about 1939, when the National Defense Stockpile enabling legislation was passed, and peaked in the 1950's, at about the time that National Defense Stockpile reached its peak chromite ore inventory. Figure 11 shows that chromium ferroalloy imports greatly exceed exports and that high-carbon ferrochromium imports have dominated chromium ferroalloy imports since the mid-1970's when post melting 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-1970's. Figure 12 shows that chromium metal imports greatly exceed exports and that both imports and exports are growing. Figure 13 shows that, as a source of chromium to U.S. industry, chromite ore and ferrochromium imports dominate. The figure also shows that chromite ore was the predominant source of chromium until the 1980's time period when high-carbon ferrochromium displaced chromite ore.

As one would expect of a major world chromium chemical producing country, figures 14 and 15 show that, except for a brief period in the mid 1960's, the quantity of chromium chemical exports have been substantially larger than imports. Sodium dichromate makes up the major share of trade followed by chromic acid both of which show strong export growth in recent years.

INSERT FIGURE 14 HERE.

INSERT FIGURE 15 HERE.

Figure 14. U.S. major chromium chemical imports. The major chromium chemicals imported into the United States are sodium dichromate and chromate, chromic acid, and chrome yellow. The chromium chemical tariff system categories were affected by the transition from the Tariff Schedule of the United States to the Harmonized Tariff Schedule of the United States because the change redistributed major trade materials among new categories. Before 1989, sodium chromate and dichromate were in one category and chromic acid, another. After 1988, sodium chromate and chromic acid were combined in one category with sodium dichromate in a second one.

Figure 15. U.S. major chromium chemical exports. Sodium chromate and dichromate and chromic acid dominate U.S. chromium chemical exports. Since the United States is a major world chromium chemical producer, U.S. exports are greater than imports by a factor of about 2 while for the primary chemical product, sodium dichromate, exports exceed imports by a factor of 3 to 4.

Figure 14 and Figure 15 show U.S. trade in chromium chemicals. Sodium dichromate and chromic acid accounted for the largest volume of exports and of imports. On average over the time period 1989 through 1997, chromium chemical exports have exceeded imports by about 51% in terms of weight and by about 36% in dollar value.

Table 6. Availability based on cost of production of chromite and chromium ferroalloys from ten market economy countries.

Chromium materials	Quantity available (million metric tons, gross weight)	Cost[1] (Dollars per metric ton) 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		

[1]Cost of production for zero percent discounted cash flow rate of return in January 1989 dollars per metric ton, gross weight, of product.

Source: Boyle, 1993.

Table 7. U.S. chromium supply historical experiences.

1827.......... Chromite ore discovered.

1892.......... 10% of world supply from U.S. (2,000 tones)

1914 - 18... WWI. Steel industry finds chromite ore supply critical.

1929 .... Start of the Great Depression.

1939.......... Strategic Materials Act. Stockpile enabling legislation.

1939 - 45... WWII. Raw materials shortages.

1946 - 62 ... Post WWII. Stockpile buildup continues.

1949 - 50... Berlin Crisis (USSR embargoes chromite ore).

1950 - 52... Korean War. Raw materials shortages.

1952 - 72... Industry experiences tight supply.

1966 - 72... Rhodesian Sanctions (U.S. embargoes Rhodesian chromium products).

1966 - 77... Sales of defense stockpile (Cr) materials.

1973 - 75 .. Oil Crisis

1973.......... Industry experiences tight supply.

1984 - 94 .. National Defense Stockpile upgrades chromite ore to high-carbon ferrochromium.

1986 - 94 .. South African Sanctions (chromium products excluded).

1988 - 89 .. U.S. shifts from Tariff System of the USA to the Harmonized Tariff System of the USA

1989 - 94 .. Upgrade chromite ore to ferrochromium.

1989 - 94 .. National Defense Stockpile upgrades ferrochromium to chromium metal.

1991 .... Dissolution of the former USSR

1992 - 94 .. Upgrade ferrochromium to chromium metal in the National Defense Stockpile.

1994 - ?? . . Sale of material excess to goals in the National Defense Stockpile.

Table 8. U.S. Government stockpile yearend inventories. (Metric tons, gross weight)

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

Note:

Inventories include specification- and nonspecification-grade materials.

Uses and Market Demand

International

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% (Granville and Statham, 1989). 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% (Boyle et al., 1993). It was estimated in 1995 that 80% of chromite ore went into ferrochromium and 10% each into refractory and chemical use (Price, 1995). The 80% of chromite that went into ferrochromium was estimated to have supplied 40% to 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. In 1996, chromite ore consumption was estimated by end use industry at follows: metallurgical industry, 80%; refractory industry, 11%, and chemical industry, 9% (Maliotis, 1996). 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% (India Bureau of Mines, 1997). In 1998, the nonmetallurgical uses of chromite ore in 1995 were found to have been 55% by the chemical industry, 20% each to the refractory and foundry industry, and the remaining 5% to chromite flour for ceramic and glass use (O'Driscoll, 1998).

Domestic

On average (from 1983 through 1992), U.S. chromium use, by end-use industry, has been: metallurgical, 87%; chemical, 10%; and refractory, 3% (Papp, 1994). 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% (Papp, 1991). Stainless steel, by definition, contains at least 10.5% chromium but may contain as much as 36% chromium.

INSERT TABLE 9 HERE.

Chromium in the Chemical Industry

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 major 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 is 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. The Federal Government, both in civilian and military applications, uses chromate metal primers extensively.

Annual chromite ore consumption by the chemical industry at the end of the 1940-85 time period was nearly double that of the beginning of the period, yielding an average annual growth rate of about 1.4% over the period. The United States has the world's second largest chromium chemicals production capacity (second to Russia), and is a major producer, consumer, and world supplier of chromium chemicals. Other major world producing countries include Japan, Kazakhstan, Russia, and the United Kingdom. German production is in the process of being displaced by South African production. World production capacity in 1996 was about 316,000 tons, contained chromium, or about 907,000 tons sodium dichromate dihydrate equivalent. (These are nameplate capacities. Actual production can be substantially less than nameplate capacity.) Of the countries producing chromium chemicals, only Kazakhstan is a significant chromite ore producer, with about 10% of world chromite production. South Africa, which accounts for in excess of 39% of world chromite ore production and whose ore is generally recognized as suited to chemical industry processing, is constructing chromium chemical production capacity.

INSERT TABLE 10 HERE.

Chromium chemical markets were reviewed in 1991 (Chemical Marketing Reporter, 1991). U.S. demand for sodium dichromate was reported to have been 130,200 tons in 1990 and was projected to be 130,800 tons in 1991 and 133,400 tons in 1995. The domestic chromium chemicals market showed -0.7% growth from 1981 through 1990 and was expected to show a positive 1% growth from 1991 through 1995. Sodium dichromate was used as follows: chromic acid, 55%; chromium oxide, 10%; leather tanning, 8%; pigments, 7%; wood preservatives, 2%; drilling mud additives, 2%; other uses (including metal finishing, water treatment, textiles, and catalysts), 3%. About 13% of demand was exports. Environmental concerns were seen as driving the chromium chemicals markets.

Chromic acid was consumed for the production of wood preservatives, metal finishing, and chromium dioxide production. In 1991, wood preservation accounted for about 70% of chromic acid demand and was expected to increase even though chromium chemicals account for about 70% of the U.S. wood treatment market. Environmental restrictions on the use of creosote (in marine pilings) and pentachlorophenol (in utility poles) were expected to result in greater use of chromic acid for wood preservation. The most widely used chromium-containing wood preservative is chromium copper arsenate (CCA). CCA-treated wood is resistant to decay and termite attack, and wood treated with CCA is easier to paint than wood treated with oil-based formulations. CCA-treated wood thus finds use in roofing, outdoor decks, house foundations, and marine applications. Metal finishing accounted for about 27% of chromic acid demand. Metal finishing includes chromium plating, aluminum anodizing, and other metal treatments. No growth was anticipated for metal finishing. The remaining 3% of chromic acid consumption included the production of chromium dioxide, a growth market that included the production of magnetic particles for use in magnetic recording media (audio tapes and videotapes and computer disks).

Chromium chemical markets were again reviewed in 1994 (Chemical Marketing Reporter, 1994a). They reported U.S. demand for sodium dichromate was about 132,000 tons in 1993. Industry sources suggest that U.S. demand was about 125,000 tons while North American demand was about 132,000 tons in 1993. U.S. production had been growing at about 1% per year and was expected to continue at that rate. Sodium dichromate was used to make chromic acid (64%), leather tanning chemicals (12%), chromic oxide (10%), and other end uses including wood preservatives, drilling mud additives, metal treatments, and textile chemicals (8%). Chromic acid demand in 1994 was about 53,000 tons (Chemical Marketing Reporter, 1994b). Its U.S. production has been growing at about 1% per year and was expected to continue to do so. Chromic acid was used for wood preservatives (68%), metal finishing (22%), and other uses (10%) including water treatment, magnetic particles, and catalysts. Demand for wood preservatives and magnetic particles for the recording industry had been growing. World demand for chromium chemicals had been declining resulting in facility closure and capacity rationalization. Closures and rationalizations were attributed to reduced demand owing to more stringent environmental regulations, general over capacity, and collapse of the Russian economy.

A review of lead chromate pigments in 1994 found that owing to restrictions on lead, use of lead chromate pigments is declining and may be nil by 2010 (Chemical Marketing Reporter, 1994c). Chrome yellow is a lead chromate pigment. The major use of chrome yellow is in coatings and plastics. As a coating, chrome yellow is used to color paint for highway center stripes. In plastics, chrome yellow is used to tint engineering resins. Chrome yellow was found to dominate the market for traffic paint but was losing market share to organic pigments (American Paint and Coatings, 1995).

The domestic chemical industry has restructured over the years. In 1951, demand distribution among major end uses was leather tanning and metal finishing, 25% each; pigments, 35%; and other, 15%. Today, demand distribution among major end uses is: wood preservation, 42%; metal finishing, 14%; pigments, 13%; leather tanning, 9%; and other, 22%. Sales during the time period were estimated to have grown by 20%. Demand is expected to continue the same slow growth rate (Barnhart, 1997). In 1996, the end uses of sodium dichromate were estimated to have been chromic acid, 64%; leather tanning, 12%; chromic oxide, 10%; chrome pigments, 5%; wood preservative, 3%; miscellaneous, 6% (Mannsville Chemical Products Corp., 1997); however, other industry analysts report that this chrome pigments estimate is low and the wood preservative estimate is high by about 2 points.

Estimations of chemical market performance are shown from various sources in Table 11. Domestic production of chromium chemicals is reported in the Manufacturing section of this report.

INSERT TABLE 11 HERE.

Table 9. World and domestic chromium demand by end use.

	World			Domestic	
Industry	1989	1990	1992-1996	1973-1982	1983-1992
Chemical	13%	14%	--	12%	10%
Metallurgical	79%	77%	79%	79%	87%
Refractory	8%	9%	--	9%	3%

Sources:

1989. Granville and Statham, 1989.

1990. Boyle and others, 1993.

1973-1982, 1983-1992. Papp, 1994. Chromium Life Cycle.

1992-1996. Papp, 1997. Chromium Annual Review 1996.

Table 10. World annual chromium chemical production capacity 1997.

	Capacity	
	Thousand metric tons per year	
	Sodium dichromate	Contained
Country	dihydrate	chromium
Argentina	16	6
China	62	21
Germany	70	24
India	23	8
Iran	6	2
Japan	50	17
Kazakhstan	120	42
Macedonia	15	5
Pakistan	9	3
Poland	8	3
Romania	25	9
Russia	170	60
South Africa[1]	(70)	(24)
Turkey	30	10
United Kingdom	150	52
United States	153	53
Total	907	316

[1] Capacity under construction in 1997.

Table 11. US demand and consumption of sodium dichromate.

	1951	1991	1993	1994	1995	1996	1997
Demand (metric tons)	--	130,200	132,000	--	110,000	--	155,000
Distribution of demand (percent):							
Chromic acid	--	55	64	--	45	64	66
Chromic oxide	--	10	10	--	--	10	9
Leather tanning	25	8	12	9	--	12	13
Pigments	35	7	6	13	--	5	6
Wood preservation	2	2	iwo	42	--	3	iwo
Drilling mud additive	--	2	iwo	--	--	--	iwo
Metal finishing	25	--	--	14	--	--	--
Other	13	16	8	22	--	6	6

iwo Included with other.

Notes:

In 1951, Other included 1% refractory and less than 1% catalyst and magnetic tape.

In 1991, Other included 13% attributed to exports.

In 1993, Other included wood preservation, drilling mud additives, metal treatment, and textiles.

In 1994, Other included 8% refractory and 8% catalyst and magnetic tape.

Sources:

1951, 1994 Barnhart, 1997. Note that distribution over end uses ignores chemical form (i.e., sodium dichromate or chromic acid).

1991, 1994, 1995, 1997 Chemical Marketing Reporter.

1996 Manville, 1997.

Manufacturing, Production, and Shipment

Exploration and Mining

Exploration has non-technologic aspects, including general and commodity-specific economic factors, and politics. Exploration requires investment, which in turn, requires economic decisions. Exploration is the first step to increasing supply. Before taking this step, the developer and investor must expect demand sufficient to support the new supply. Since the time between mineral discovery and production can be on the order of years to decades, developers try to estimate the balance of supply and demand over this time period. Politics may encourage or discourage exploration within specific geographic areas by certain exploration teams, or may proscribe or prescribe commodities sought by these teams.

Knowing the minerals in which chromium appears as an ore, the rock types that contain them, and the tectonic setting and conditions under which the ore deposits formed, geologists can combine this information with knowledge of the geologic history of the earth and deposit formation processes to enhance the likelihood of further discoveries. The first step in this exploration process is deposit 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.

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.

World Production

Chromite ore mining and chromium material manufacturing is an international industry. The major industries associated with chromium are chemical, 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 first to produce sodium dichromate 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 from the chemical industry into refractory materials.

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 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 16. The figure shows that world production has been dominated by South Africa and Kazakhstan (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 indicates that South Africa, Turkey, and India are developing their chromite production potential. The decline in production from Kazakhstan was substantial.

INSERT FIGURE 16 HERE.

Figure 16. 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.

Figure 16 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. (Kazakhstan production was the larger share of USSR production, 1969-91.) The figure 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-year time period 1992-96, the major producing countries accounted for about 80% of production.

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.

World ferrochromium production is shown in figure 17. The figure shows that

INSERT FIGURE 17 HERE.

Figure 17. 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 tons per year. 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.

Figure 17 shows that, over most of the time period, there have been two major producers (> 500,000 tons per year). 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 tons per year) 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 over the 5-year time period 1992-1996, South Africa accounted for about 30% of world 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 economies. 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, and Turkey. Moderate-scale plant development to displace production in Germany is underway in South Africa. Small-scale local producers operate in China and India.

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, and 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.

Chromite Consumption

Reported chromite consumption in the United States over the 5-year period from 1993-97 averaged about 328,000 tons annually, a decline from the 1970's time period 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. US chromite consumption is shown in Figure 18, by weight, and Figure 19, by percent of total consumption.

INSERT FIGURE 18 HERE.

Figure 18. U.S. chromite ore consumption by end use industry. Composite chromite ore consumption, the sum of consumption by end use industries, peaked in the mid-1950's driven by metallurgical industry consumption. Until the early 1980's metallurgical use dominated domestic chromite consumption followed by refractory and chemical industry use. Metallurgical industry consumption shows greater volatility than that of the refractory industry, which, in turn shows greater volatility than that of the

chemical industry. U.S. chromite ore consumption has declined from a peak value of about 1.5 million tons per year in the mid-1950's to its current value of about under one-half million tons per year. Most of that decline is from reduced metallurgical industry consumption; however, declining refractory industry consumption has contributed too. Only the chemical industry has shown increased chromite ore consumption over the time period. As a result of declining numbers of chromite ore consumers and in order to protect company proprietary information, the U.S. Geological Survey combined chemical and metallurgical industry consumption for the purpose of reporting in 1986 and refractory industry information was combined with the other two in 1995.

INSERT FIGURE 19 HERE.

Figure 19. Distribution of U.S. chromite ore consumption by industry. Metallurgical industry chromite ore consumption accounted for more than half of chromite ore consumption until 1982. Refractory industry chromite ore consumption accounted for one-fourth to one-third of consumption over most of the same period.

Figure 18 shows an increase in U.S. chromite use from 1940 to the mid-1950s, and declining use since then. Both metallurgical and refractory industry chromite ore use declined since the mid-1950s. The largest changes have been in the metallurgical industry. Refractory industry use appears to have reached a plateau from about 1950 to 1965, after which it slowly declined. Chemical industry use increased slowly from 1940 to 1985. Declining chromite use in the metallurgical industry resulted from declining domestic ferrochromium production. Over the time period in which the metallurgical, chemical, and refractory industry data were reported separately (i.e., 1940-1985), the metallurgical industry accounted for 56% of reported chromite consumption; refractory industry, 27%; and chemical industry, 18%. More recently (from 1976-85) metallurgical industry chromite use has decreased to 51% while refractory use declined to 18% and chemical use increased to 31%.

Figure 18 shows that the metallurgical industry dominated domestic chromite consumption from 1940 to 1980. The pattern of total chromite consumption is similar to that of metallurgical consumption over that time period. More recently, the number of metallurgical chromite consumers has fallen below the minimum three companies required by the U.S. Geological Survey to report collected data and ensure the confidentiality of respondents. As a result, in 1986, metallurgical and chemical industry chromite consumers were combined into a single group for the purpose of reporting chromite consumption. The dramatic drop in metallurgical consumption of chromite ore in 1980-83 resulted in chemical industry consumption surpassing that of the metallurgical industry for the first time since 1940. The decline of metallurgical market share is shown in Figure 19.

Over the 9-year time period from 1986-94, refractory use has declined further to 9% of chromite use, while chemical and metallurgical use was 91% of reported consumption.

Metallurgical

The metallurgical industry consumed chromite ore to produce chromium ferroalloys and metal. Figure 20 shows domestic ferrochromium production.

INSERT FIGURE 20 HERE.

Figure 20. U.S. production of chromium ferroalloys and metal. High-carbon ferrochromium evolved as the major chromium material produced in the early 1960's as a result of the installation of post-melting refining technology (e.g., argon-oxygen decarburization) in the stainless steel industry. Before post-melting refining, low-carbon ferrochromium played a greater role in steel production. As a result of declining numbers of chromium ferroalloy producers and in order to protect company proprietary information, the U.S. Geological Survey combined high- and low-carbon ferrochromium production data and ferrochromiumsilicon and other production data for the purpose of reporting in 1980. Both of these categories had to be combined for the same reason in 1990.

Chemical

In the chemical industry, the terms chromium and chrome are used in the chemical industry and mean the same, the element chromium. Similarly, the terms dichromate and dichromate are used interchangeably in the chemical industry. Historically, the term chrome was used more commonly than chromium. Thus many chemical products, namely pigments, have chrome in their name. To be consistent with the chemists' convention for naming compounds, dichromate would be used instead of dichromate. However, in trade and commerce, the term dichromate is used.

Chromite is used in the chemical industry to produce sodium dichromate from which other chromium chemicals are manufactured. Chromite ore is pulverized and mixed with soda ash (sodium carbonate) and a diluent. The diluent could be lime (calcium oxide) or recycled material from the production processes. The mixture is roasted in a rotary kiln to produce a compound containing sodium chromate, which is leached out and treated with acid to produce sodium dichromate and then purified. Sodium chromate and dichromate are produced by this process in the United States. The major commercial product is sodium dichromate dihydrate. Table 12 lists several primary chromium chemicals produced by US chemical companies that produce chromium chemicals from chromite. Many other chromium chemicals are manufactured from sodium dichromate. The primary chromium chemicals and their end uses are shown in Figure 22.

INSERT TABLE 12 HERE.

INSERT FIGURE 22 HERE.

Figure 22. U.S. chromium pigment production. Lead chromate, also know as chrome yellow, has accounted for most of chromium pigment production throughout the time period. Chrome colors, calculated as the sum of the chrome colors individually reported. Chrome colors reported is that reported by the Department of Commerce. Comparing chrome colors calculated with chrome colors reported suggests the decline in chrome colors calculated after 1976 resulted from the elimination of reporting categories instead of from declining production.

Chromite ore consumption by the chemical industry is shown in Figure 18 and chemical industry chromite market share is shown in Figure 19. Figure 18 shows that chemical industry chromite consumption has been increasing slowly since 1940. The radical increase of chemical industry market share in 1982 shown in Figure 19 resulted from the decrease in metallurgical industry chromite consumption and not from a major increase in consumption by the chemical industry.

Figure 21 shows production of major domestically produced chromium chemicals as reported by the Department of Commerce; sodium dichromate, chromic acid, and chromium pigments. Sodium dichromate production was reported until 1985, when production was about 120,000 tons. Chromic acid production was reported until 1973, when production peaked at about 27,000 tons. The sodium dichromate and chromic acid production data shown in Figure 21 are reported, whereas the chromium pigments production shown is a composite of the reported production of several chromium pigments from 1958 through 1990. In 1990, chrome colors reported production became available. The production of those chromium pigments, including chrome yellow and orange, chrome molybdate orange, chrome oxide green, zinc yellow, and chrome green, are shown in Figure 23. Chromium pigment production was by far the greatest for chrome yellow and orange followed by chrome molybdate orange. In both cases, production appears to have peaked in the 1973-77 time period and declined since then. Chrome yellow and orange annual production has declined from about 34,000 tons to the current level of about 15,000 tons, while chrome molybdate orange has declined from about 12,000 tons in the 1974-77 time period to about 750 tons in 1996. Zinc yellow annual production declined from 7,000 tons in the 1965-67 time period to about 1,000 tons in 1987 when the series was discontinued. Chrome oxide green annual production appears to have remained between about 4,000 and 8,000 tons until reporting was discontinued in 1985. Chrome green annual production varied between about 2,500 and 4,000 tons until reporting was discontinued in 1972. Chromium pigment production appears from the composite chrome pigment production curve to have declined; however, that appears to have been a result of increasingly withheld pigment production data. When the U.S. Census Bureau started reporting production of chromium colors in 1990, production was about that which preceded the decline in the composite chromium pigments curve. Chromium pigment production is about 40,000 tons annually.

INSERT FIGURE 21 HERE.

Figure 21. U.S. chromium chemical production. Sodium dichromate is the first commercial chromium chemical product. Chromic acid, chrome colors, and other chromium chemicals are produced from sodium dichromate.

The number of producers of selected chromium chemicals (sodium dichromate and chromate, chrome yellow and orange, and chrome molybdate orange) are shown in Figure 24. Figures 23 and 24 show the number of producers has declined while quantity of production has not. The number of sodium dichromate and chromate producers has also declined. However, production of chromium chemicals has not declined, suggesting that in the United States production has consolidated with the remaining producers. That is, fewer producers are manufacturing about the same amount of material. Reported sodium dichromate and chromate production was more erratic than reported chemical industry chromite ore consumption.

INSERT FIGURE 23 HERE.

Figure 23. Material flow from chromite ore through chemical industry products to end-uses. Chromite ore is roast in a rotating kiln with soda ash and lime to produce sodium dichromate, which is subsequently processed to produce the other chromium chemicals shown. These chemicals are used in a wide variety of industrial end uses.

INSERT FIGURE 24 HERE.

Figure 24. Number of U.S. chromium chemical and pigment producers. While chromite ore consumption by the chemical industry has been increasing slowly, the number of chemical industry consumers (sodium dichromate) has been declining. This suggests that the remaining plants have been getting larger. The same appears to have been happening for chromium pigments.

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 names 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-inch brick" equivalents; unshaped refractories, in tons. A "9-inch brick" equivalent is a solid volume of 0.165919 cubic meters, used in the United States as a "standard unit" for refractory bricks.

Chromite-containing refractory producers are shown in Table 13 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 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 steel-making furnaces.

INSERT TABLE 13 HERE.

Chromite refractories were used heavily in steel production using the open-hearth furnace method. Contemporary steel-making 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/ton and the electric arc furnace uses in the range of from 1 to 2 kg/ton. As a result, the steel industry demand for basic refractories has declined dramatically as open-hearth furnace steel making has been phased out.

The historical trends of chromite-containing refractory shipments are shown in Figure 25 and Figure 26. 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 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 25 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 from 28 to 18 million "9-inch 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.

INSERT FIGURE 25 HERE.

Figure 25. 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 steel making furnaces that have been displaced by more efficient steel making methods in most of Western countries.

The trend in shipments of basic unshaped refractories is shown in Figure 26. 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.

INSERT FIGURE 26 HERE.

Figure 26. U.S. chromite-containing unshaped refractory shipments.

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 upon the distribution of minerals used to make the bricks. From 1985-90, the weight per volume of magnesite-chrome refractories averaged 4.7 kt per million "9-inch brick" equivalents (kt/M9be), with a range of from 4.3 to 5.0 kt/M9be.

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.

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 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 (greater than 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. US foundry sand producers, products, and end use industries are shown in Table 14. Chromite sand is also used in copper-base nonferrous casting.

INSERT TABLE 14 HERE.

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 then by the higher price of zircon sand. The foundry characteristics that make chromite sand desirable include: good thermal stability, good chill properties, not easily wetted, resistant to metal penetration, highly refractory, and chemically unreactive. 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 US foundry use was estimated to have increased from about 20,000 tons in 1965 to about 36 000 tons in 1971. Industry sources estimate US chromite foundry sand use in 1989 and 1990 to be about 40,000 tons 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 (Heine). 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.

Table 12. Primary U.S. chromium chemical producers and their chromium chemical products.

	Product	
Producer	Formula	Name
Elementis Chromium LP	CrO_3	Chromic acid
Buddy Lawrence Drive	Cr_2O_3	Chromic oxide
P. O. Box 9912	$Cr_2(SO_4)_3$	Basic chromium sulfate
Corpus Christi, TX 78469	$Cr_2O_3{\bullet}2H_2O$	Chromium hydrate
	$K_2Cr_2O_7$	Potassium dichromate
	Na_2CrO_4	Sodium chromate anhydrous
	$Na_2Cr_2O_7$	Sodium dichromate anhydrous
	$Na_2Cr_2O_7{\bullet}2H_2O$	Sodium dichromate dihydrate
Occidental Chemical Corporation	CrO_3	Chromic acid
Occidental Tower, 5005 LBJ Freeway	$K_2Cr_2O_7$	Potassium dichromate
P. O. Box 809050	Na_2CrO_4	Sodium chromate anhydrous
Dallas, TX 75380-9050	$Na_2Cr_2O_7{\bullet}2H_2O$	Sodium dichromate dihydrate
	$Na_2CrO_4{\bullet}4H_2O$	Sodium chromate tetrahydrate

Table 13. U.S. chromite and chromic oxide refractory producers, products, and end use Markets.

Producers	Products	End users and uses
General Refractories Company	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 Refractories		Slagline
a subsidiary of Global Industrial Technologies		Steel ladles
One Gateway Center		
Pittsburgh, PA 15222		Ladle metallurgical furnaces
		Slagline
		Sidewall and bottom
		Vacuum degassers
National Refractories and Minerals Corp.		Sidewall
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 and Nickel Industry
Cleveland, OH 44115		Electric furnaces

Corhart Refractories

RR 6, Box 82

Buckhannon, WV 26201-8815

Phone: 304 473 1239 (voice)

304 473 1287 (Fax)

- Slagline
- Bottom

Flash furnaces

- Roof and sidewall
- Bottom

Pierce Smith converters

- Tuyere areas
- 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 and Lime Industry

Rotary kilns

- Burning zone
- Upper transition zone
- Lower transition zone

Glass Industry

Glass furnace regenerators

- Checker
- Wall
- Crown

Fiberglass Furnace

Melting furnace

Table 14. U.S. foundry sand producers, products, and end uses.

Producers	Products	End uses
American Colloid Company	Chromite flour	Architectural brick
1500 W. Shure Drive		Brake shoes
Arlington Heights, IL 6004-1434	Chromite sand	Casting facing sand
		Ceramic
American Minerals Inc.		Colorant
901 East Eighty Avenue Suite #200		Glass
King of Prussia, PA 19406		Mold coating

Processing

Beneficiation and Processing

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, only hand sorting of coarse material and gravity separation of fine material may be required. When the ore is lumpy and mixed with host rock, heavy-media separation may be used. When the chromite mineral occurs in fine grains intermixed with host rock, 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 Table 15 and Figure 27.) 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 (i.e. material removed from the ground), or material supplied to the market place. 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 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 27 may be carried out at the mine site, at a plant which 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.

INSERT TABLE 15 HERE.

INSERT FIGURE 27 HERE.

Figure 27. Chromite material flow process from the mine to conversion to industrial products.

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 amount and kind of beneficiation required depends on the ore deposit characteristics and mining technique. An operation where miners can extract only high-grade ore and avoid host rock (a massive deposit) may require only hand sorting and screening. Beneficiation is necessitated by geologic conditions that result in intermixing of chromite with other minerals or the use of mechanized mining methods that are nonselective.

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-to-iron ratio, or alumina content is desirable. Reducing silica or other host rock 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.

Ferrochromium Production

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 megavolt-amperes. Closed and partially closed electric arc furnaces replaced open furnaces in the 1970's to improve pollution control, efficient furnace operation, and safety.

Ferrochromium is produced from chromite ore by smelting a mixture of the ore, flux materials (e.g., 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 and recover chromium lost to slag by crushing and beneficiating the slag. The chromium content of the ferrochromium is determined by the chromium-to-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-to-iron ratio 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.

Chromium Chemical Production

Chromite is used in the chemical industry to produce sodium dichromate from which other chromium chemicals are manufactured. Chromite ore is pulverized and mixed with soda ash (sodium carbonate) and a diluent. The diluent could be lime (calcium oxide) or recycled material from the production processes. The mixture is roasted in a rotary kiln to produce a compound containing sodium chromate, which is leached out and treated with acid to produce sodium dichromate and then purified. Sodium chromate and dichromate are produced by this process in the United States. The major commercial product is sodium dichromate dihydrate. Several primary chromium chemicals produced by U.S. chemical companies that produce chromium chemicals from chromite include sodium dichromate anhydrous and sodium dichromate dihydrate; sodium chromate anhydrous and sodium chromate tetrahydrate; chromic acid; chromic oxide; and potassium dichromate. Elementis Chromium LP and Occidental Chemical Corp. are the primary chromium chemical producers in the United States. Many other chromium chemicals are manufactured from sodium dichromate and these other primary chromium chemicals.

Two industry process trends have been evolving, chromium recovery from slag in the ferrochromium industry and supply of still melted ferrochromium for stainless steel production. Both of these trends improve chromium recovery efficiency.

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 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 28.

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

INSERT FIGURE 28 HERE.

Figure 28. Chromium material flow 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.

Table 15. Factors used to characterize chromite deposits and mining, beneficiation, and processing methods applied to chromite deposits.

Mineral	Mineral Appearance in ore	Deposit types	Host rock	Mining method	Beneficiation method	Processing method
Chromite (a spinel structure oxide mineral)	Massive (spinel mineral of varying chemistry)	Stratiform (bedded)	Mafic	Surface	Hand sorting	Sizing
	Disseminated (spinel mineral intermixed with other minerals)	Podiform (lenticular)	Ultramafic	Subsurface	Screening	Roasting and dissolution
					Gravity concentration	Smelting
					Electromagnetic separation	
					Heavy Media separation	

Economic Aspects

Chromite Ore

Operating 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% to 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% to 70% of mining cost and from 25% to 90% of beneficiation cost, but can be higher. (Boyle, 1993)

Ferrochromium

Excluding the delivered cost of chromite ore, electrical energy, other raw materials, and labor are the major components of smelting (i.e., 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% to 55% of smelting cost; raw materials (excluding chromite ore), 15% to 35%; and labor, 10% to 30%.

Ferrochromium production is electrical energy intensive. Charge-grade ferrochromium requires from 3,800 to 4,100 kilowatt-hours 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.

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, a 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 (Mole and Armitage, 1996).

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.

Chromium Chemicals

Chromium chemical production capacity 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 national production capacity is located in China, Germany (in process of closing in 1998), India, Japan, South Africa (under construction in 1998), and Turkey.

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.

Chromite Foundry Sand

At last count, about 3,100 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 1960's 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 (Bolger, 1996).

Tariffs and taxes

Domestic producers were subject to a tax on chromium, potassium dichromate, and sodium dichromate under Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (also known as CERCLA or Superfund). The tax amounted to $4.91 per metric ton on chromium, $1.86 per metric ton on potassium dichromate, and $2.06 per metric ton 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 Harmonized Tariff Schedule number, material name, and tariff rate are shown in Table 16.

INSERT TABLE 16 HERE.

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 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.

Energy Requirements

Electric arc furnace ferrochromium production is an electrical energy intensive process (requiring about 3,500 to 3,800 kilowatt-hours 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 2,500 to 2,800 kilowatt-hours per ton of ferrochromium produced. Typically, all of 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.

Table 16. U.S. import duties for chromium-containing materials in 1997.

Item	Harmonized Tariff Schedule No.	Most favored nation (MFN)	Non-MFN[1]	Special MX[2]	Special A, CA, E, IL, J[3]
Chromite ores and concentrates therefrom:					
Not more than 40% Cr_2O_3	2610.00.0020	Free	Free	NA	NA.
More than 40% and less than 46% Cr_2O_3	2610.00.0040	Do.	do.	NA	NA.
Not less than 46% Cr_2O_3	2610.00.0060	Do.	do.	NA	NA.
Chromium oxides and hydroxides:					
Chromium trioxide	2819.10.0000	3.7% ad valorem	25% ad valorem	Free	Free.
Other	2819.90.0000	Do.	do.	do.	Do.
Sulfates; alums; peroxosulfates (persulfates):					
Other sulfates: of chromium	2833.23.0000	Do.	do.	do.	Do.
Salts of oxometallic or peroxometallic acids:					
Chromates of zinc and of lead	2841.20.0000	Do.	do.	do.	Do.
Sodium dichromate	2841.30.0000	2.4% ad	8.5% ad	do.	Do.

[1] The following countries were non-MFN in 1997; Afghanistan, Cuba, Laos, North Korea, and Vietnam.
[2] North American Free Trade Agreement (Goods of Mexico).
[3] A-Generalized System of Preferences, CA-North American Free Trade Agreement (Goods of Canada), E-Caribbean Basin Economic Recovery Act, IL-United States-Israel Free Trade Area Implementation Act of 1985, J-Andean Trade Preference Act.

		valorem	valorem		
Potassium dichromate	2841.40.0000	1.5% ad valorem	3.5% ad valorem	do.	Do.
Other chromates and dichromates; peroxochromates	2841.50.0000	3.1% ad valorem	25% ad valorem	do.	Do.
Carbides, whether or not chemically defined:					
Other: of chromium	2849.90.2000	4.2% ad valorem	do.	do.	Do.
Pigments and preparations based on chromium:					
Chrome yellow	3206.20.0010	3.7% ad valorem	do.	do.	Do.
Molybdenum orange	3206.20.0020	Do.	do.	do.	Do.
Zinc yellow	3206.20.0030	Do.	do.	do.	Do.
Other	3206.20.0050	Do	do.	do.	Do.
Metal and alloys: Ferroalloys:					
Ferrochromium:					
More than 4% carbon	7202.41.0000	1.9% ad valorem	7.5% ad valorem	1.1% ad valorem	Free.
More than 3% and not more than 4% carbon	7202.49.1000	Do.	do.	do.	Do.
Other (i.e., not more than 3% carbon)	7202.49.5000	3.1% ad valorem	30% ad valorem	1.8% ad valorem	Do.
Ferrosilicon chromium	7202.50.0000	10% ad valorem	25% ad valorem	Free.	Do.
Other base metals; cermets; articles thereof:					
Chromium:					

Waste and scrap	8112.20.3000	Free	Free	Free.	NA.
Other	8112.20.6000	3.3% ad valorem	30% ad valorem	Free	Free.

NA Not applicable.

Source: U.S. International Trade Commission and U.S. Geological Survey.

Grades, Specifications, and Quality Control

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 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 17.

INSERT TABLE 17 HERE.

For the purpose for trade, the U.S. 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-to-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%, with values in the 40% to 50% range being most common. Chromium-to-iron ratios typically range from about 1.5:1 to about 4.0:1, with typical values of about 1.5:1 to 3.0:1. In trade, the chromite ore is also called chromium ore, chromite, chrome ore, and chrome.

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% to 40% chromium, 38% to 50% silicon, and 0.05% to 0.1% carbon.

Ferrochromium typically contains 50% to 75% chromium and 0.05% to 8% carbon. Low-carbon ferrochromium typically contains 55% to 75% chromium and 0.02% to 0.1% carbon. High-carbon ferrochromium typically contains 60% to 70% chromium and 6% to 8% carbon. Charge-grade ferrochromium typically contains 50% to 55% chromium and 6% to 8% carbon.

Harmonized tariff schedule of the United States 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 report.

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 18; ferrochromium, in Table 19; chromium metal, in Table 20.

INSERT TABLE 18 HERE.

INSERT TABLE 19 HERE.

INSERT TABLE 20 HERE.

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. Typically, consumers do not reveal detailed purchase specification. 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 chapter for more details.

Byproducts and Coproducts

Chromite ore is a byproduct only of platinum mining of the UG-2 layer of the Bushveld complex. No coproducts or byproducts are associated with chromite mining operations. Here, byproduct 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 byproduct 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 byproduct chromite ore yields a ferrochromium of under 50% chromium content produced and used in South Africa for stainless steel production.

Table 17.--Composition of typical chromium ferroalloys and chromium metal. (Composition, percentage)

Material[1]	Grade	Chromium[2]	Carbon[3]	Silicon[3]	Sulfur[3]	Phosphorus[3]	Nitrogen[3]
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

Source: 1996 Annual Book of ASTM Standards.

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

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

3 Maximum, except where range of values indicating minimum and maximum appears.

Table 18. Chromite ore chemical specifications.

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% Cr2O3	40-42	-	11.8	11.5	8	23.5	-	0.160	-	0.110	0.31	-	-	3
36-38% Cr2O3	36-38	-	12.5	15	7	23	-	0.160	-	0.020	0.50	-	-	2.7
30-34% Cr2O3	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 -	0.005 -	2.2-
												0.008	0.007	3.0

Chemical	40-48	-		8-10	7-10	18-21	-	-	-	-	-	0.005 - 0.008	0.005 - 0.007	2.4- 2.8
Refractory:														
Lump & 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-	0.002	0.009	2.6-
											0.4			2.8
Fines	38-40	-	9-10	9-11	10-11	21-22	-	-	-	-	0.3-	0.002	0.009	2.6-
											0.4			2.8
High grade :														
Lump	46-48	-	13.0	6	12-13	16-18	-	-	-	-	0.2-	0.002	0.007	2.9-
											0.4			3.1
Fines	48-50	-	13-14	6-7	12-13	18	-	-	-	-	0.2-	0.002	0.004	2.9-
											0.3			3.0
Concentrate	48	-	13	6	11-12	17	-	-	-	-	0.2-	0.002	0.004	2.9-
											0.3			3.0
Refractory:														
Hard lumpy	50-52	-	13-14	3	15-16	16	-	-	-	-	0.1-	0.002	0.007	3.1-
											0.3			3.2
Super	54-56	-	11-12	1-1.5	14-15	16	-	-	-	-	0.2-	0.002	0.007	3.2

concentrate											0.3			
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 Company:														
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-	traces	traces	1.4-
											1.3			1.6
Metallurgical	38-47	-	14-19	8-18	7-10	10-14	-	traces	traces	-	0.2-	0.003-	traces	1.8-
											0.3	0.004		2.9
Kathpal	40-46	-	11-13	5-10	7-8	10-13	-	traces	traces	-	0.2-	0.001	traces	2.4-

Metallurgical											0.3			2.5
Ostapal	42-45	-	23-24	8-11	6-10	10-13	-	traces	traces	-	0.6-	0.010	traces	1.6-
Metallurgical											1.0			2.0
Hayri Ögelman Mining Co. Ltd.:														
Orhaneli	47.36	-	16.73	10.33	8.29	14.16	-	0.16	-	-	-	0.01	-	2.83
Concentrates														
Others	48-52	-	-	-	-	-	-	-	-	-	-	-	-	-
Concentrates														
Refractory	48-53	-	14.66	4.11	7.13	17.63	-	-	-	-	0.83	-	-	3.19
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	-	n.a.	n.a.	n.a.	n.a.	-	n.a.	-	n.a.	n.a.	-	n.a.	2.9
Concentrates	48	-	n.a.	n.a.	n.a.	n.a.	-	n.a.	-	n.a.	n.a.	-	n.a.	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):														
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-	11-12	-	-	-	-	-	-	0.005 -	0.01	2.4-
				2.5								0.007	max	3.5
Velore Mining Corporation:														
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-	2.4-
													0.03	2.8
Zimasco (Pvt.) Ltd.:														
Concentrates	42-46	-	11-14	10-13	10-14	15-17	-	0.20	-	-	3.00	-	0.20-	2.5-
													0.3	2.9

- Data not reported. n.a. not available.

Source: International Chromium Development Association. Chromium Industry Directory. September 1966, p. 1-1 through 1-194.

Table 19. Chromium ferroalloy chemical specifications and physical specifications.

	Chemical composition (weight percent)							
Company and grade	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
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 Corporation:									
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 Corporation:								
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

Nav Chrome Limited:								
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 Corporation:								
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, 10-80, 10-100
								10-150, 10-250
HCFeCr 2	68	6	0.8	0.03	0.03	-	-	10-50, 10-80, 10-100
HCFeCr 3	67	5.6	0.8	0.025	0.015	0.02	-	10-50, 10-80, 10-100
HCFeCr 4	68	8.5	1	0.03	0.04			10-50, 10-80, 10-100
								10-150, 10-250
ChCr	62	7.5	5	0.03	0.02	-	-	10-80, 10-150, 10-100
LCFeCr 1	69	2.5	0.8	0.03	0.01	-	-	10-50, 10-80, 10-100

LCFeCr 2	70	0.35	0.8	0.03	0.004	-	-	10-50, 10-80, 10-100
FeCrSi	30	0.05	49					10-40, 10-50, 10-80 10-100, 10-150 Granules 0-5 & 0-7
Outokumpu Chrome Oy:								
ChCr	52	6-8	3-5	0.03	0.05	-	-	10-150
Philippine Minerals & Alloy Corporation:								
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
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 x 150, 10 x 80, 3 x 12, < 3 mm, Granules
ChCr 2	50-55	8-9	1-2	0.01	0.023	-	-	10 x 150, 10 x 80, 3 x 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 x 100, 50 x 75, 25 x 50, 3 x 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 µm, <104 µm

LCFeCr 8	70 min	0.03	1.0	0.03	0.03	-	-	10-70, 2-10, or <250 µm
Shri Girija Smelters Limited:								
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, 10-50, 0-10
FeCrSi	28	0.1	45 (min)	0.03	0.02	-	-	10-80, 10-50, 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

- not reported.

Al Aluminum. Cr Chromium. C Carbon. P Phosphorus. Si Silicon. S Sulfur. Ti Titanium. FeCrSi Ferrochromiumsilicon. HCFeCr High-carbon ferrochromium. LCFeCr Low-carbon ferrochromium. ChCr Charge grade ferrochromium. µm Micrometer. kg Kilograms. mm Millimeter. < Less than.

Note: 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 notes otherwise. Size in millimeters unless otherwise noted otherwise.

Table 20. Chromium metal chemical specifications.

		Delachaux			Elkem (Vacuum grade)			Metallurg	
Element		Vacuum	DDB	Powder	Plate	Pellets	Powder	Standard	Vacuum Refining
Chromium	Cr	99.5	99.7	99.8	99.1	99.5	99.0	99.2	99.4
Aluminum	Al	0.1	0.01	0.01	0.01	0.005	0.01	0.15	0.10
Antimony	Sb	0.0005	0.0005	--	--	--	--	--	--
Arsenic	As	0.0001	0.0001	--	--	--	--	--	--
Barium	Ba	0.00003	0.00003	--	--	--	--	--	--
Bismuth	Bi	0.00005	0.00005	--	--	--	--	--	--
Boron	B	0.00001	0.00001	--	--	--	--	--	--
Cadmium	Cd	0.0002	0.0002	--	--	--	--	--	--
Carbon	C	0.01	0.04	0.01	0.02	0.05	0.02	0.03	0.03
Cobalt	Co	--	--	--	--	--	--	--	--
Columbium	Nb	--	--	--	--	--	--	--	--
Copper	Cu	0.002	0.001	--	--	--	--	--	--
Hydrogen	H	0.0001	0.0001	--	0.01	0.002	0.02	--	--
Iron	Fe	0.2	0.15	0.12	0.20	0.25	0.25	0.025	0.25
Lead	Pb	0.0005	0.0005	--	0.003	0.001	0.01	--	--
Magnesium	Mg	0.001	0.001	--	--	--	--	--	--
Manganese	Mn	0.0015	0.0015	--	0.01	0.010	0.01	--	--
Molybdenum	Mo	--	--	--	--	--	--	--	--
Nickel	Ni	--	--	--	--	--	--	--	--
Nitrogen	N	0.02	0.008	0.005	0.05	0.010	0.05	0.01	0.02
Oxygen	O	0.1	0.045	0.045	0.50	0.05	0.60	0.15	0.1
Phosphorus	P	0.002	0.001	0.001	0.005	0.002	0.005	0.005	0.001
Selenium	Se	0.0002	0.0002	--	--	--	--	--	--
Silicon	Si	0.1	0.05	0.04	0.005	0.02	0.01	0.15	0.10

Silver	Ag	0.00005	0.00005	--	--	--	--	--	--
Sulfur	S	0.01	0.004	0.005	0.030	0.010	0.04	0.005	0.01
Tantalum	Ta	--	--	--	--	--	--	--	--
Tellurium	Te	0.0002	0.0002	--	--	--	--	--	--
Thallium	Tl	0.0002	0.0002	--	--	--	--	--	--
Tin	Sn	0.0005	0.0005	--	--	0.001	--	--	--
Titanium	Ti	--	--	--	--	--	--	--	--
Vanadium	V	--	--	--	--	--	--	--	--
Zinc	Zn	0.0005	0.0005	--	--	--	--	--	--
Zirconium	Zi	--	--	--	--	--	--	--	--

Source: Papp, John F. Chromium Metal. U.S. Bureau of Mines Information Circular 9430, 64 pp, 1995.

Table 20. (Continued) Chromium metal chemical specifications.

		Nippon Denko		Tula	ASTM		Polema			
Element		Standard	Request	Flake	Grade A	Grade B	EX	ERX-1	ERX-2	ERX-3
Chromium	Cr	99.0	99.0	66.6	99.0	99.4	99.95	99.95	99.95	99.95
Aluminum	Al	0.3	--	0.004	0.30	0.10	0.006	0.006	0.006	0.006
Antimony	Sb	--	--	0.0005	0.005	0.003	--	--	--	--
Arsenic	As	--	--	0.001	0.005	0.003	--	--	--	--
Barium	Ba	--	--	--	--	--	--	--	--	--
Bismuth	Bi	--	--	0.0006	0.003	0.001	--	--	--	--
Boron	B	--	--	--	0.005	0.003	--	--	--	--
Cadmium	Cd	--	--	--	--	--	--	--	--	--
Carbon	C	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	--	--	0.0003	0.01	0.01	0.003	0.003	0.003	0.003
Hydrogen	H	0.0007	0.0007	--	0.01	0.003	--	--	--	--
Iron	Fe	0.5	0.5	0.002	0.35	0.35	0.008	0.008	0.008	0.012
Lead	Pb	--	--	0.002	0.003	0.001	0.001	Trace	Trace	Trace
Magnesium	Mg	--	--	--	--	--	--	--	--	--
Manganese	Mn	--	--	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	0.030	0.030	--	0.050	0.020	0.020	0.005	0.007	0.010
Oxygen	O	0.046	0.046	0.334	0.50	0.10	0.600	0.005	0.008	0.020
Phosphorus	P	0.05	0.003	--	0.010	0.010	--	--	--	--
Selenium	Se	--	--	--	--	--	--	--	--	--

Silicon	Si	0.2	0.2	0.020	0.15	0.10	0.010	0.010	0.010	0.012
Silver	Ag	--	--	0.0003	0.003	0.001	--	--	--	--
Sulfur	S	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	--	--	--	--	--	--	--	--	--
Thallium	Tl	--	--	--	--	--	--	--	--	--
Tin	Sn	--	--	0.0001	0.001	0.001	--	--	--	--
Titanium	Ti	--	--	--	0.050	0.003	--	--	--	--
Vanadium	V	--	--	0.0003	0.050	0.050	--	--	--	--
Zinc	Zn	--	--	0.0001	0.005	0.003	--	--	--	--
Zirconium	Zi	--	--	--	0.050	0.003	--	--	--	--

Source: Papp, John F. Chromium Metal. U.S. Bureau of Mines Information Circular 9430, 64 pp, 1995.

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 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. (Baker and Siple,1990).

The Environmental Protection Agency 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. (USEPA.) The coprecipitation, colorimetric, and chelation/extraction techniques are recommended for extracts and ground waters.

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 are 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 emissions, 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 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.

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).

Effluents: 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 the Environmental Protection Agency (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.

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 feed stock 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.

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 5,000 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 1,540 hard chromium electroplaters, 2,800 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 1,000 for large hard plating operations. The regulation specifies emission limits, work practices, initial performance testing, ongoing compliance monitoring, record keeping, 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.

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 through 39. EPA's collection authority 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 use 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 chapter for more details.

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 milligram per liter. 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 being a carcinogenic hazard. EPA set the chromium III and chromium VI MCLG based on the reference dose concept. The safe dose to which EPA refers is the National Academy of Sciences recommended daily intake of 50 to 200 micrograms 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.

Recycling and Disposal

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 percent of chromium demand.

U.S. apparent consumption of chromium is primary production (i.e., chromium contained in domestic mine production of chromite ore) plus secondary production (i.e., chromium contained in recycled scrap) plus net trade (i.e., imports minus exports) in chromium materials (including chromite ore, chromium ferroalloys and metal, and selected chromium chemicals) plus domestic consumer 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 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 like continuous casting reduces prompt scrap generation and permits a higher product yield per unit of raw material feed (Staff, 1993).

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 can not 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 industrial 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 constitutes about 20% of current apparent consumption. In the year 2000, secondary chromium is expected to rise to 25% of apparent consumption because of recycling growth and decline in non-recycling uses. See figure 29.

INSERT FIGURE 29 HERE.

Figure 29. 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.

Disposal

The Environmental Protection Agency surveys domestic industry for quantity and method of disposal (i.e., releases plus transfers) and reports that information annually in the Toxics Release Inventory Public Data Release. Disposals are shown in figure 30. Figure 30 shows that 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 31. Figure 31 shows 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 to the 17 priority chemicals targeted by EPA as part of the 33/50 Program. A program in which industries voluntarily try 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% (EPA, 1995), 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 (Papp, 1998). 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.

INSERT FIGURE 30 HERE.

Figure 30 Chromium disposals (i.e., releases plus transfers) by industry. The major sources of chromium disposals are the same as 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.

INSERT FIGURE 31 HERE.

Figure 31 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.

Health and Safety Factors

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 to 200 micrograms. 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.

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 about chromium chemicals include whether the compound is synthetic or naturally occurring. Synthetic 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 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.

Under some conditions chromium compounds cause systemic damage to the human body. Because experimentation on human subjects is morally unacceptable, most toxicity data results from workplace, coincidental, or accidental human exposure or animal experimentation. EPA concluded that there is sufficient evidence in animals and humans for the carcinogenicity of chromium (VI) compounds, while evidence for the carcinogenicity of chromium (III) compounds in humans and animals is largely nonpositive. The acute toxicity of chromium (III) compounds is low whereas the acute toxicity of chromium (VI) compounds is in the high to moderate range. Chronic toxicity of chromium (III) is considered low.

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.

Health and Safety Factors

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 21 shows the exposure limits set by OSHA.

INSERT TABLE 21 HERE.

Table 21. Occupational Safety and Health Standards for workspace exposure to airborne chromium.

Air contaminant	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 (III) compounds	0.5 mg/ m^3

Note:

Acceptable ceiling concentration cannot be exceeded.

Limit for air contaminant shall not exceed the stated amount measured as an 8-hour time-weighted average during any 8-hour work shift of a 40-hour workweek.

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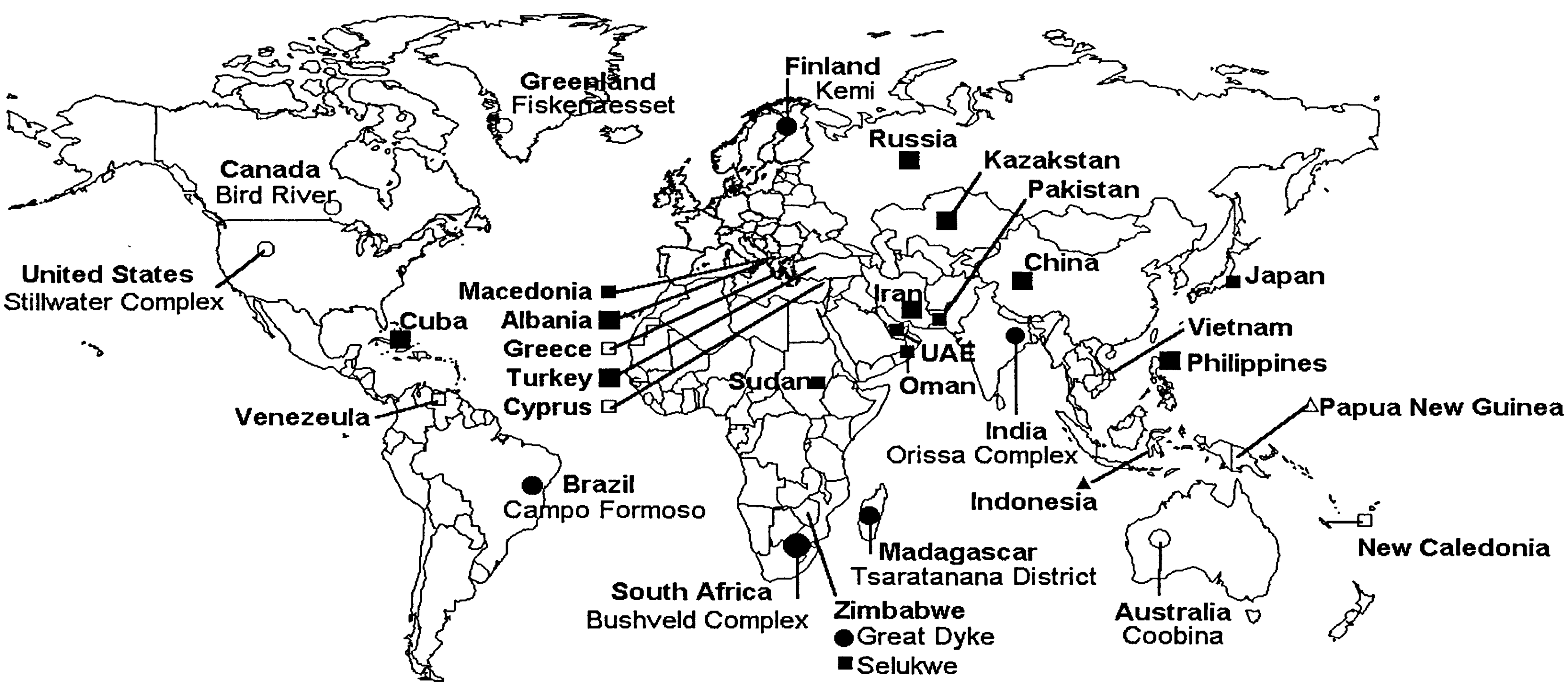
Geographic Distribution of Chromium Resources



Source: U.S. Geological Survey

Explanation
Geologic Deposit Type

Stratiform			Podiform			Laterite		
Symbol		Resources	Symbol		Resources	Symbol		Resources
Nonproducing	Producing	(Metric tons)	Nonproducing	Producing	(Metric tons)	Nonproducing	Producing	(Metric tons)
None	●	$>10^9$	None	None	$>10^9$	None	None	$>10^9$
○	●	10^6-10^9	□	■	10^6-10^9	△	None	10^6-10^9
None	None	$<10^6$	□	■	$<10^6$	△	▲	$<10^6$

Figure 1 (BA)

Composition diagram for the spinel minerals

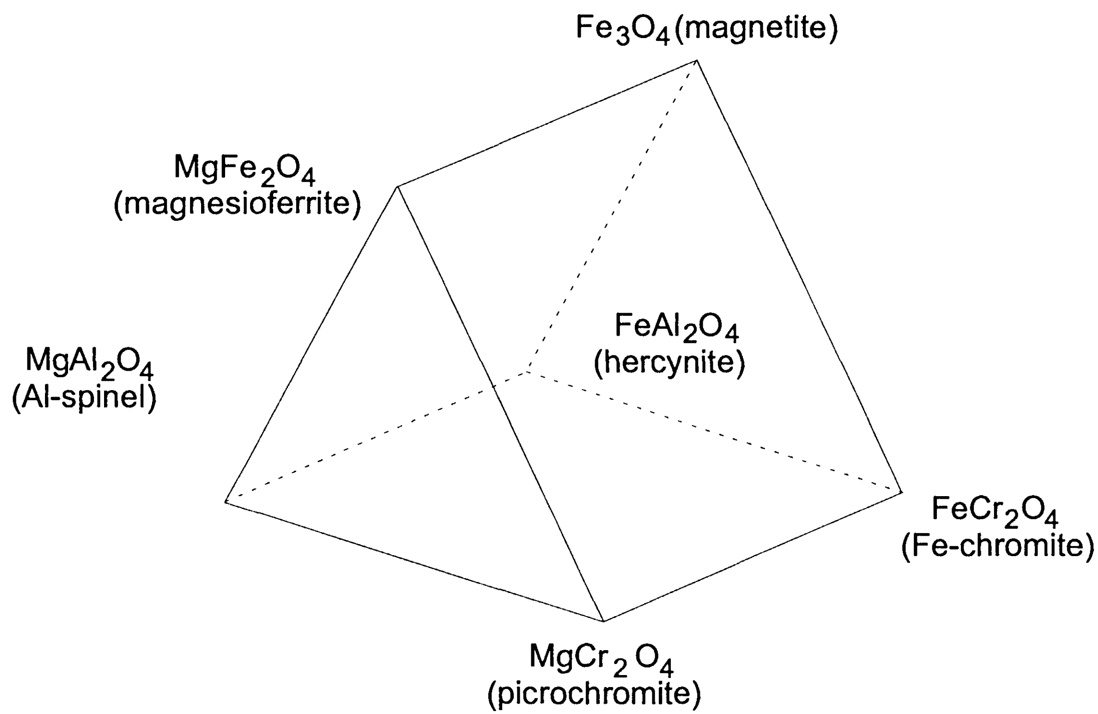


Figure 2 (BB)

National Defense Stockpile chromite ore inventory

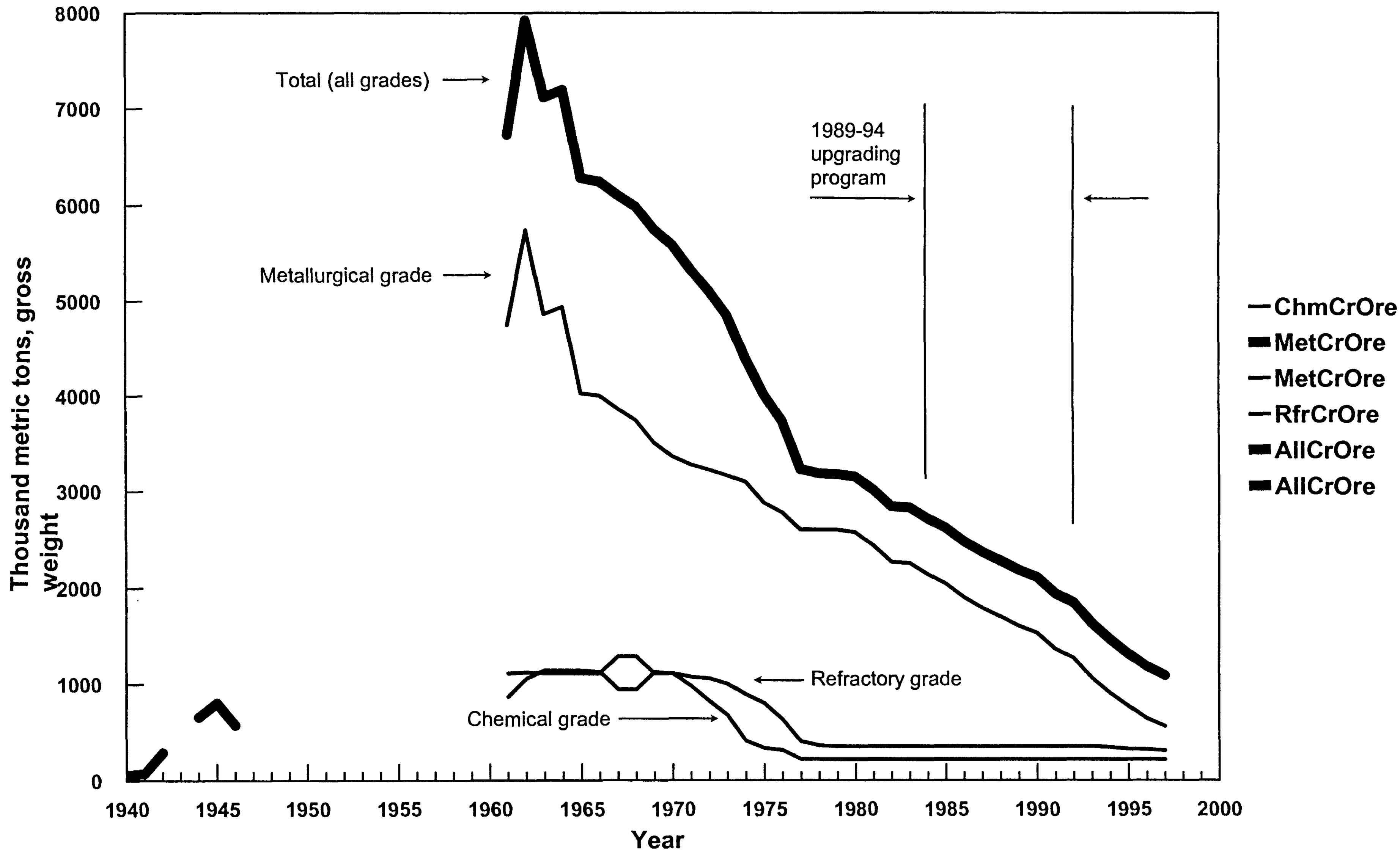


Figure 3 (DA)

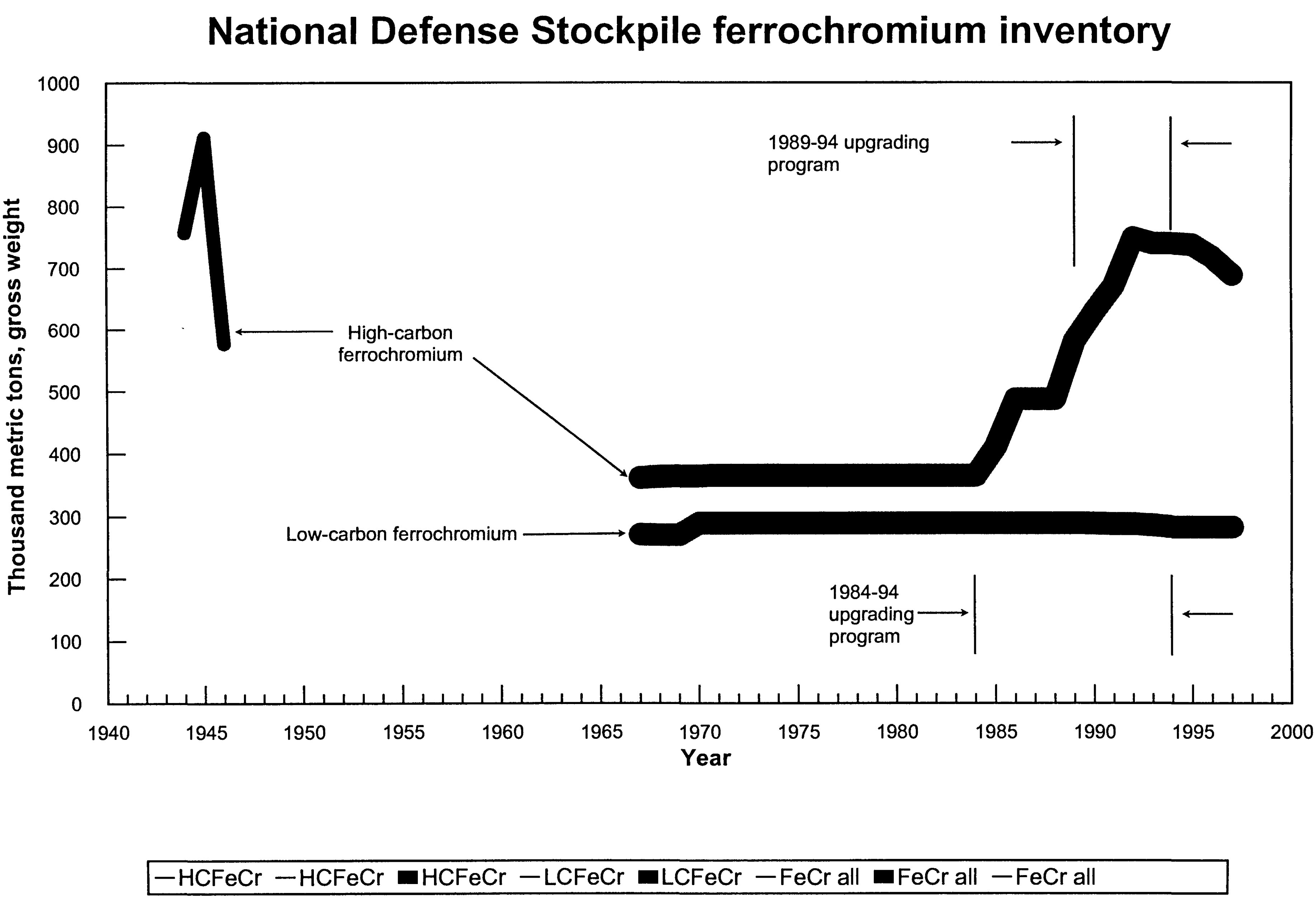

National Defense Stockpile ferrochromium inventory
Thousand metric tons, gross weight
0
100
200
300
400
500
600
700
800
900
1000
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
High-carbon ferrochromium
Low-carbon ferrochromium
1989-94 upgrading program
1984-94 upgrading program
—HCFeCr —HCFeCr ■HCFeCr —LCFeCr ■LCFeCr —FeCr all ■FeCr all —FeCr all

Figure 4 (DB)

National Defense Stockpile chromium metal and ferrochromiumsilicon inventory

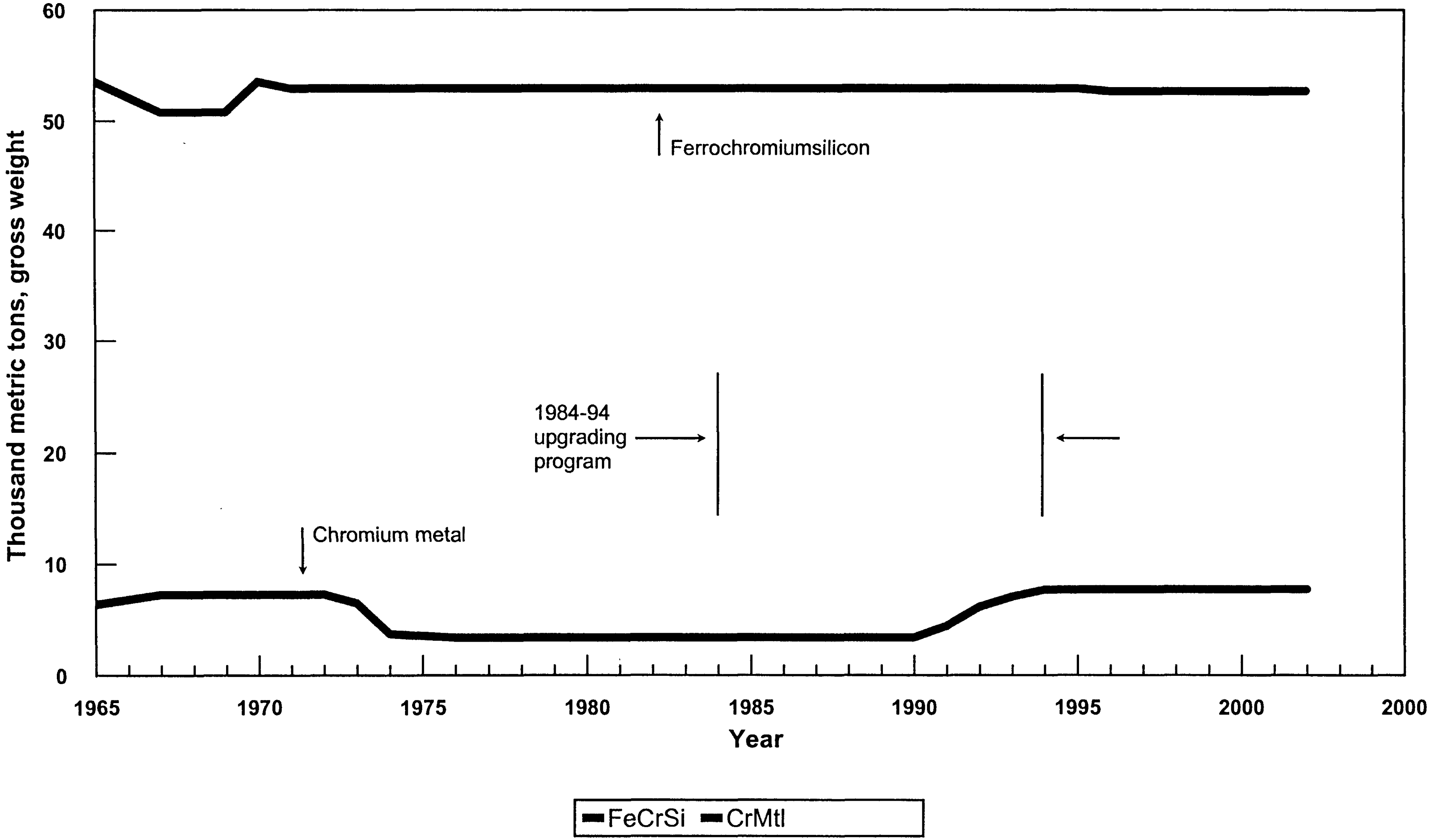


Figure 5 (DC)

Composite chromite ore average annual price and U.S. import value

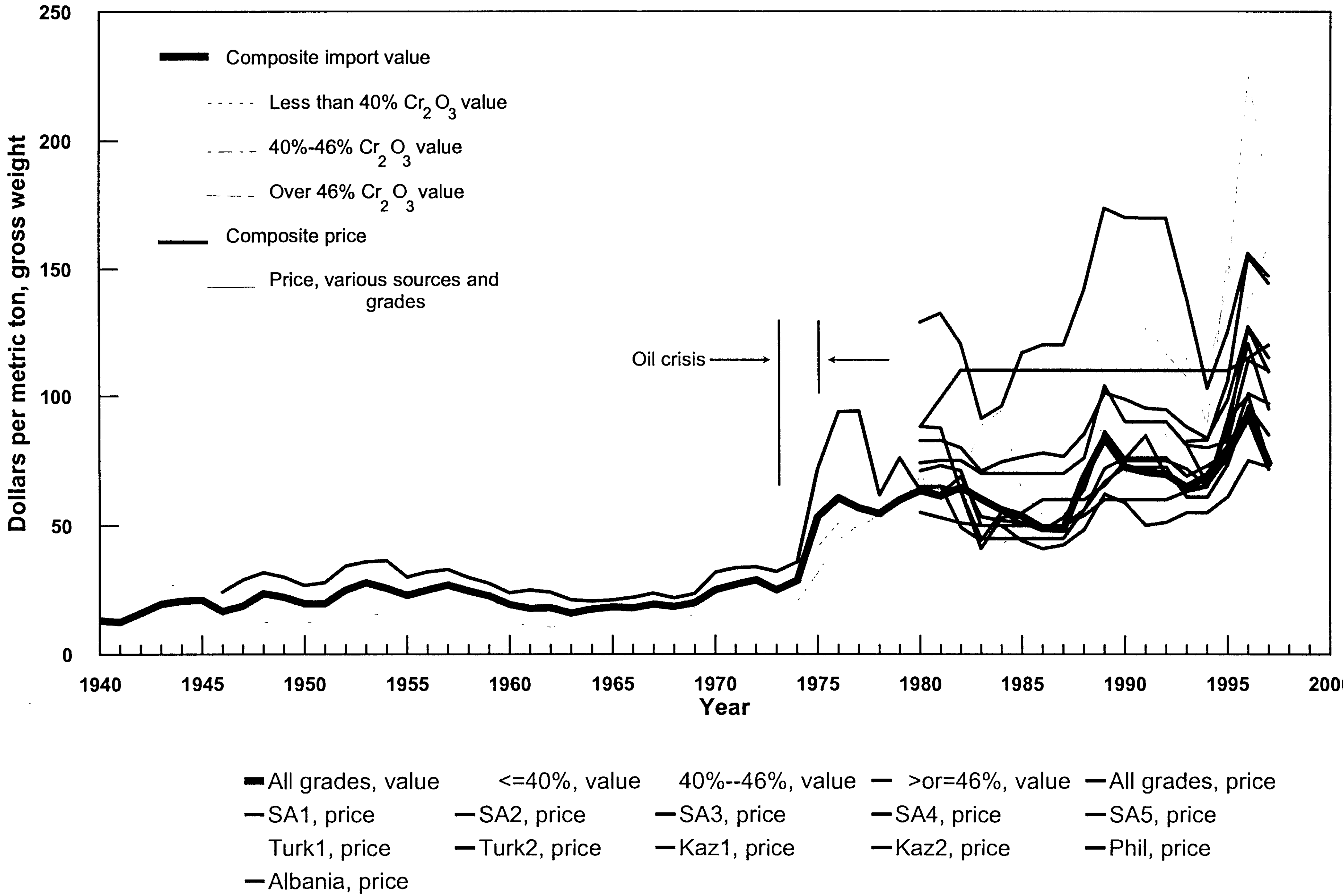


Figure 6 (DD)

Composite ferrochromium average annual price and U.S. import value

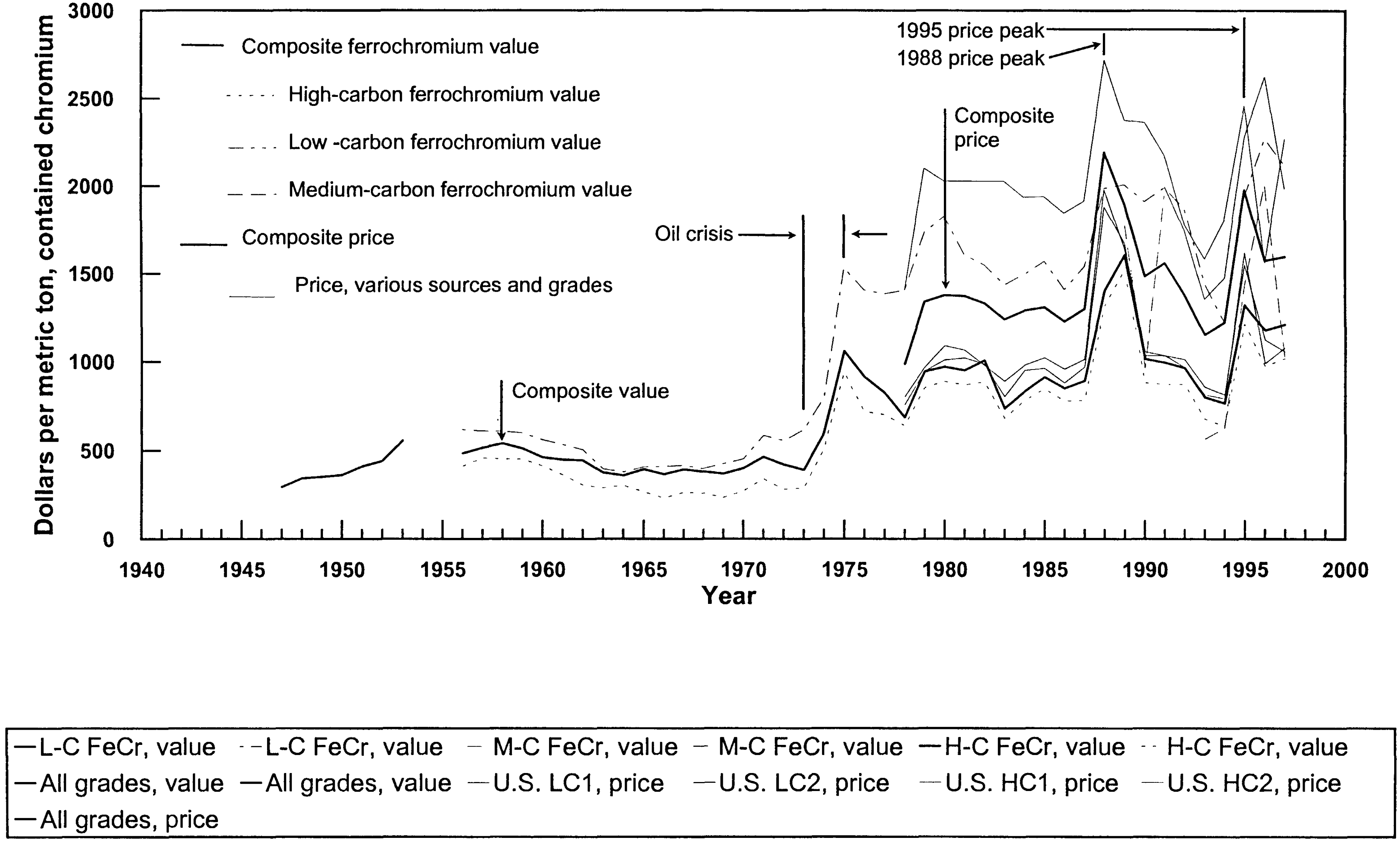


Figure 7 (DE)

Composite chromium metal average annual price and U.S. import value

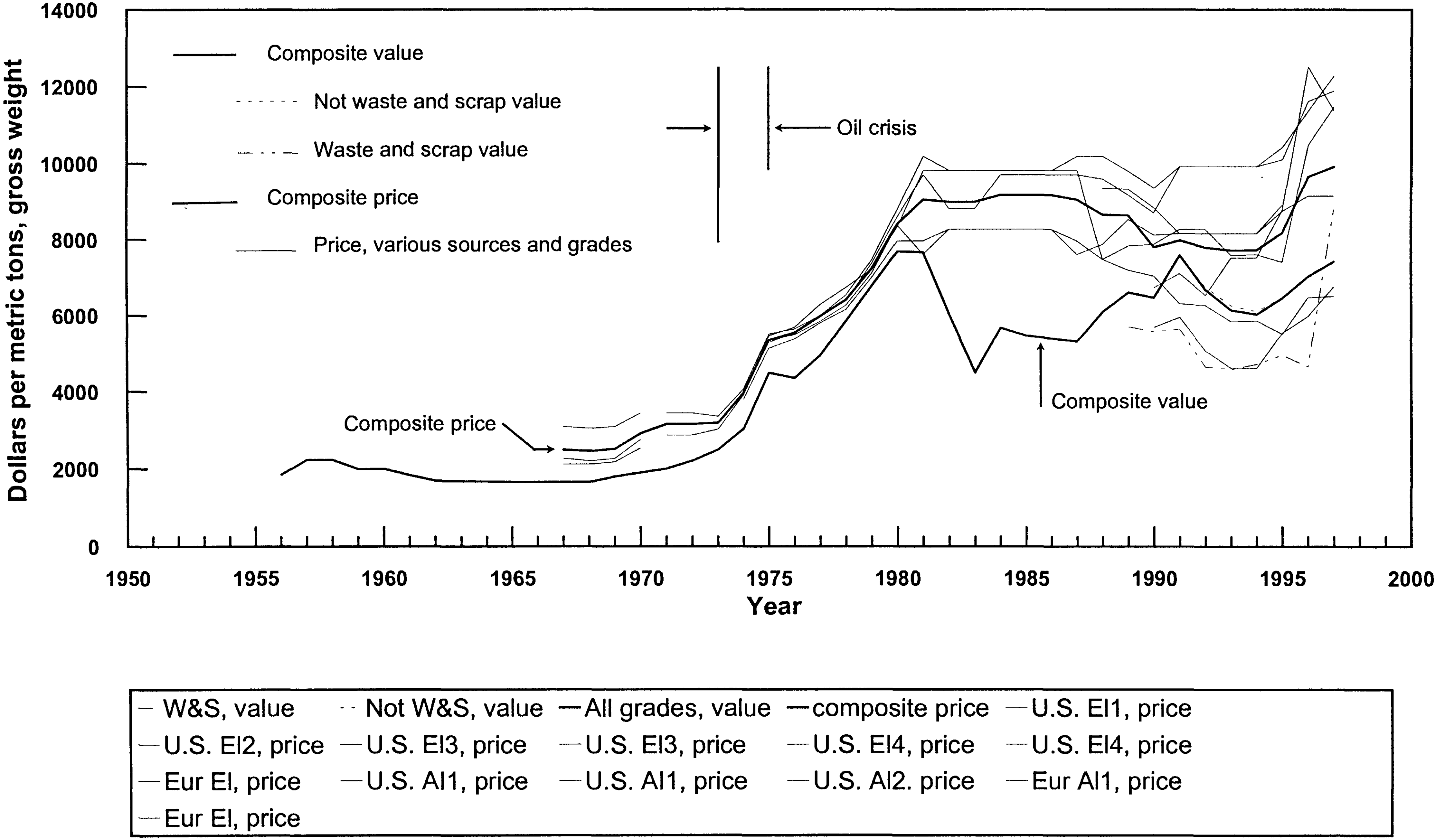


Figure 8 (DF)

Composite chromite ore, ferrochromium, and chromium metal value

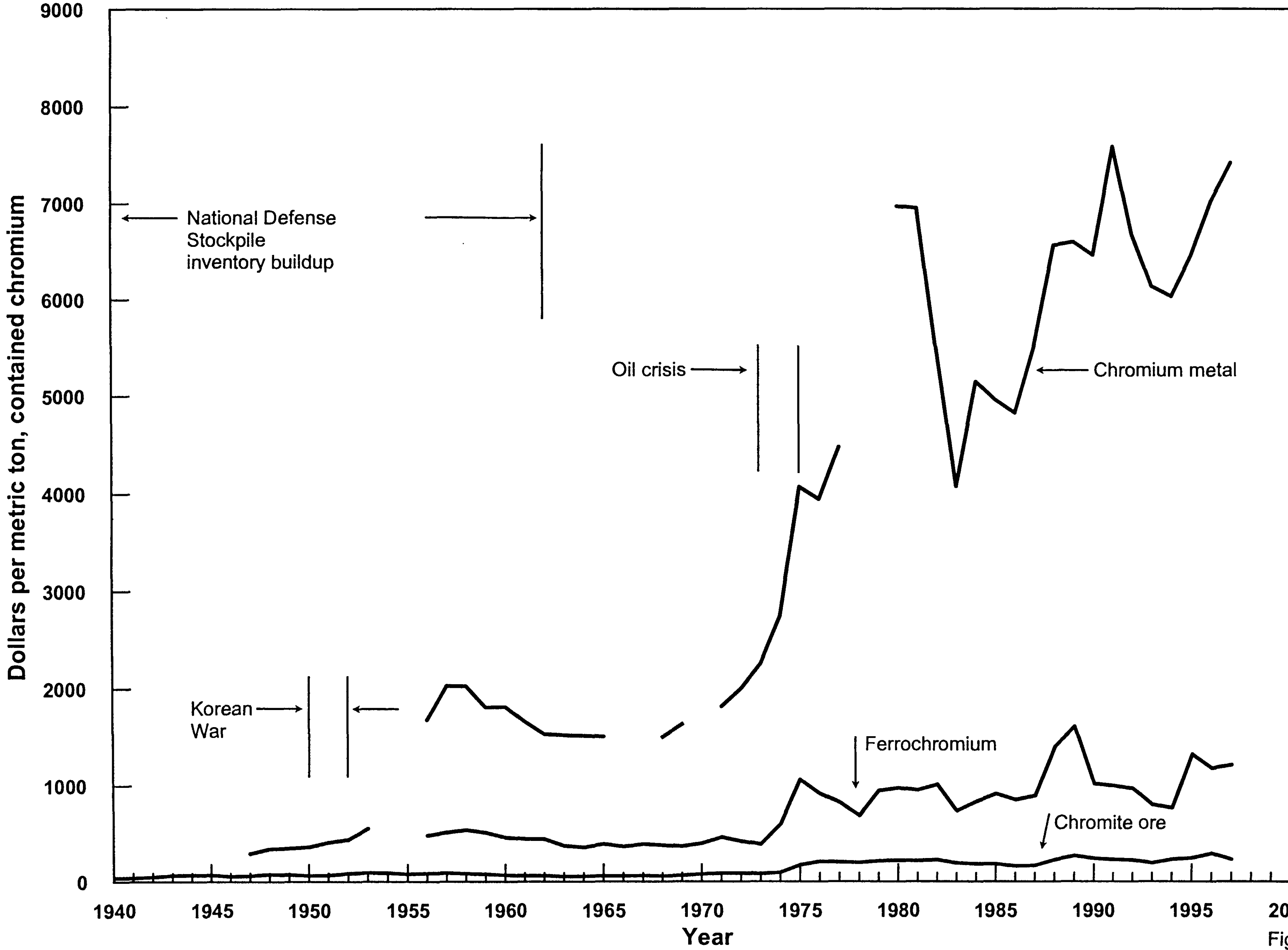


Figure 9 (DG)

U.S. chromite ore trade

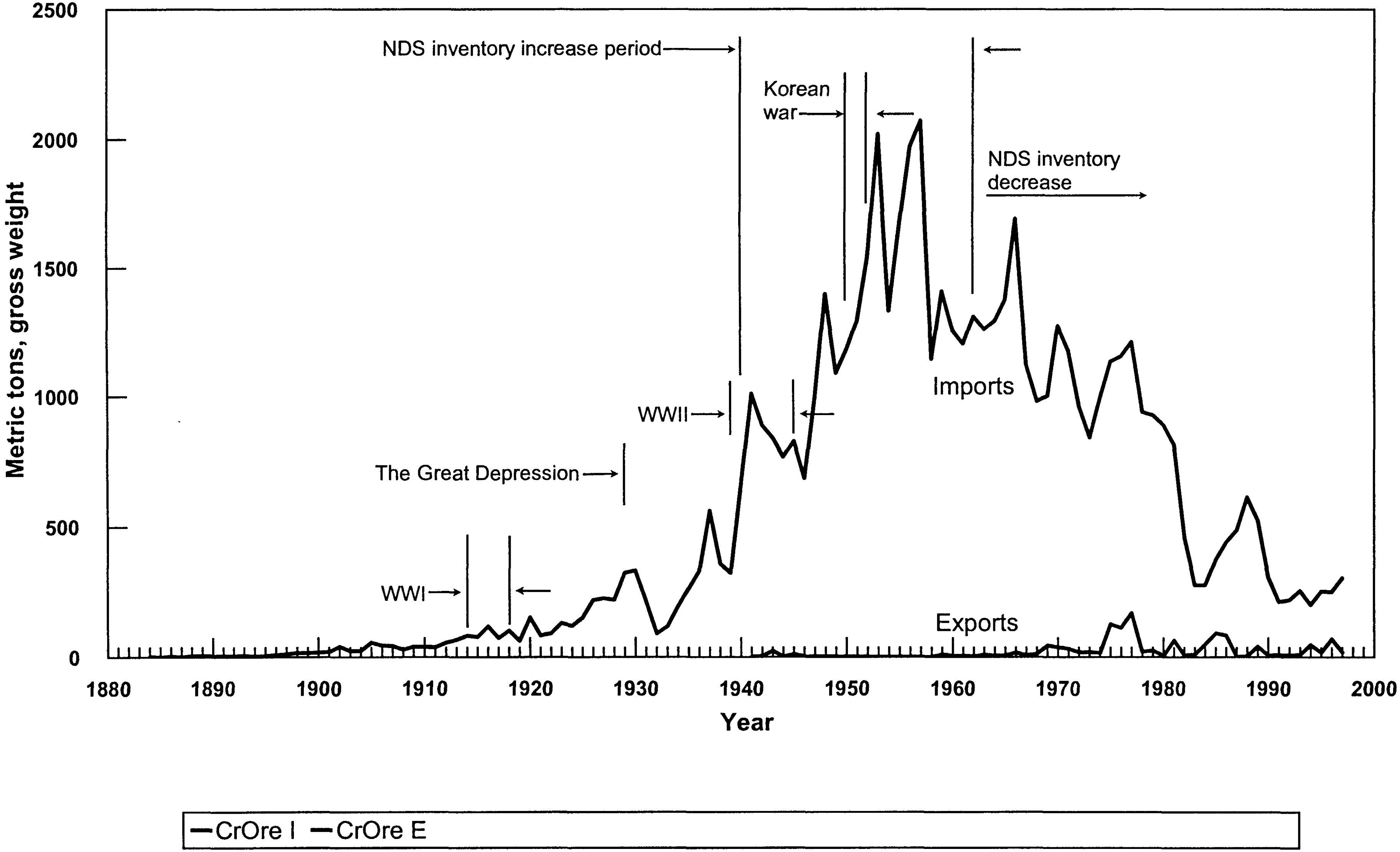


Figure 10 (DH)

U.S. chromium ferroalloy trade

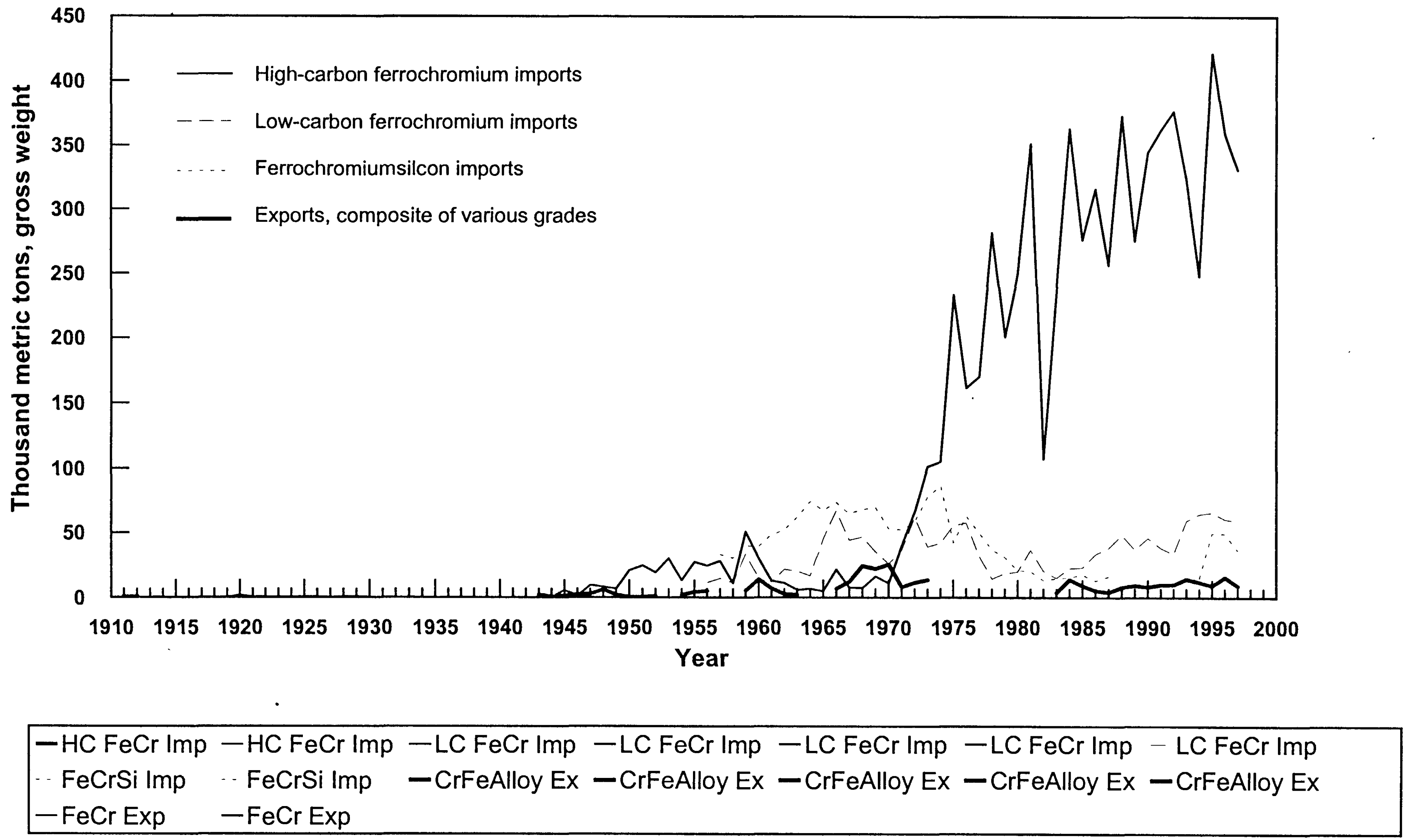


Figure 11 (DI)

U.S. chromium metal trade

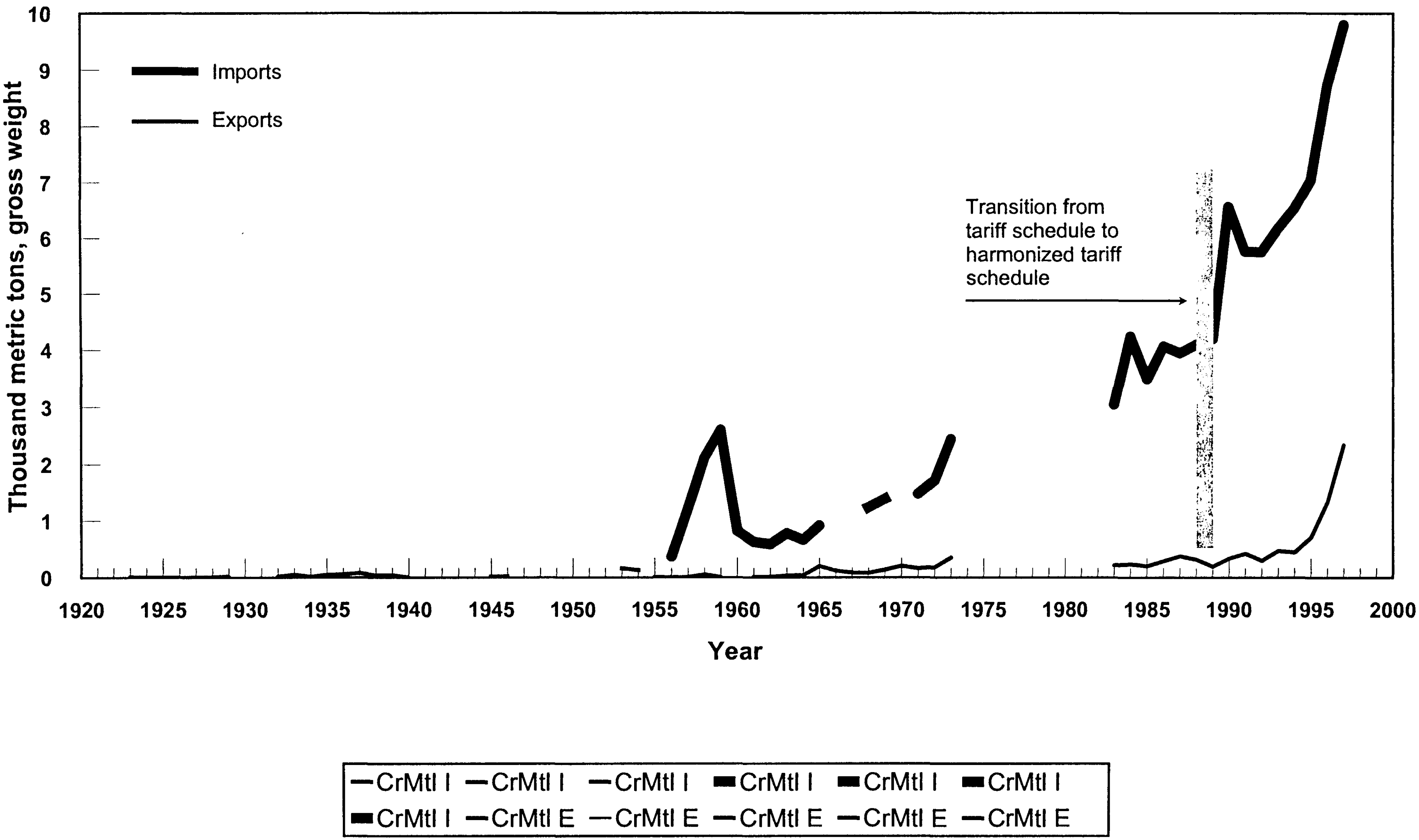


Figure 12 (DJ)

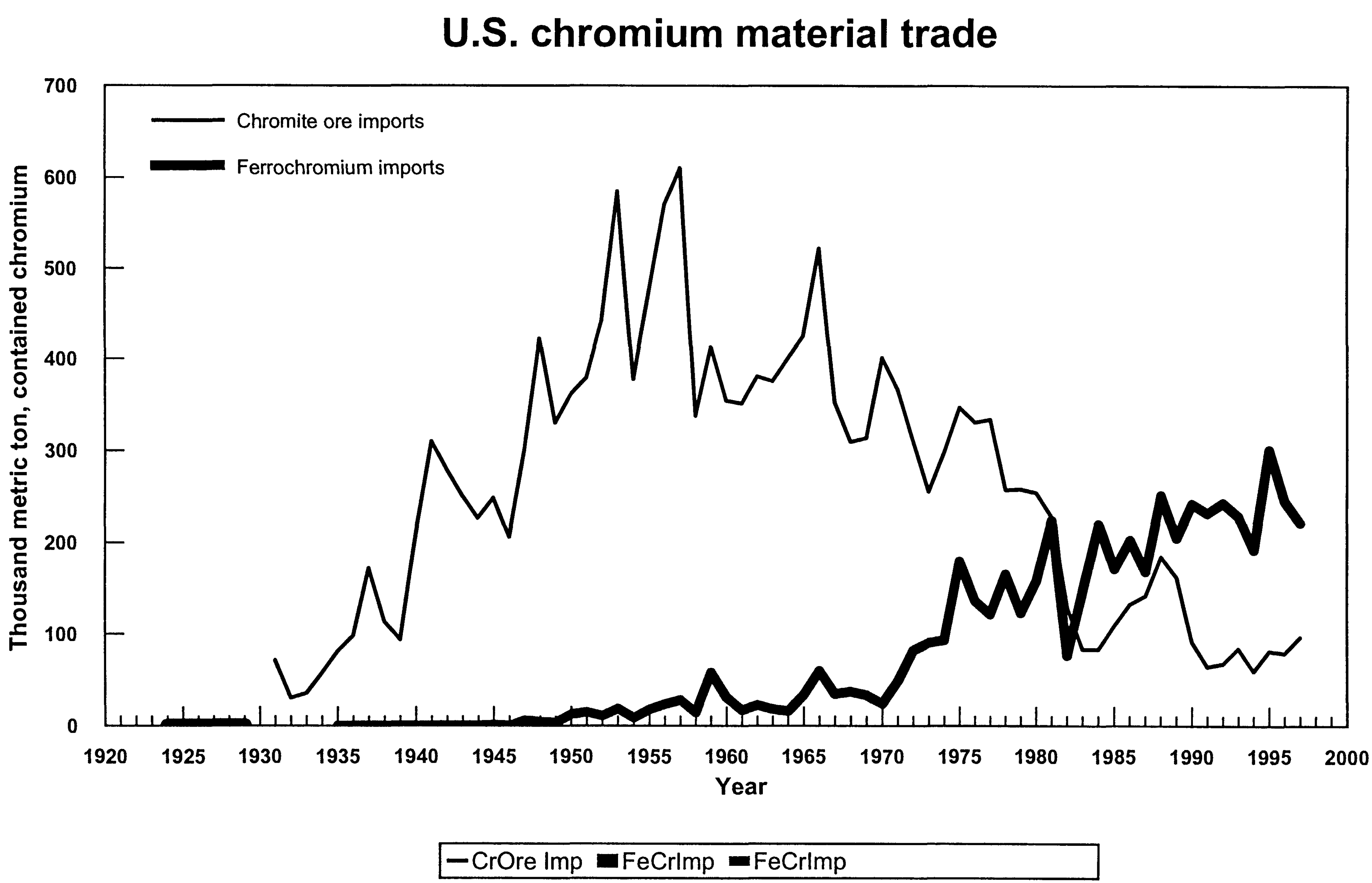

U.S. chromium material trade
Chromite ore imports
Ferrochromium imports
Thousand metric ton, contained chromium
700
600
500
400
300
200
100
0
1920
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
—CrOre Imp ■FeCrImp ■FeCrImp

Figure 13 (DK)

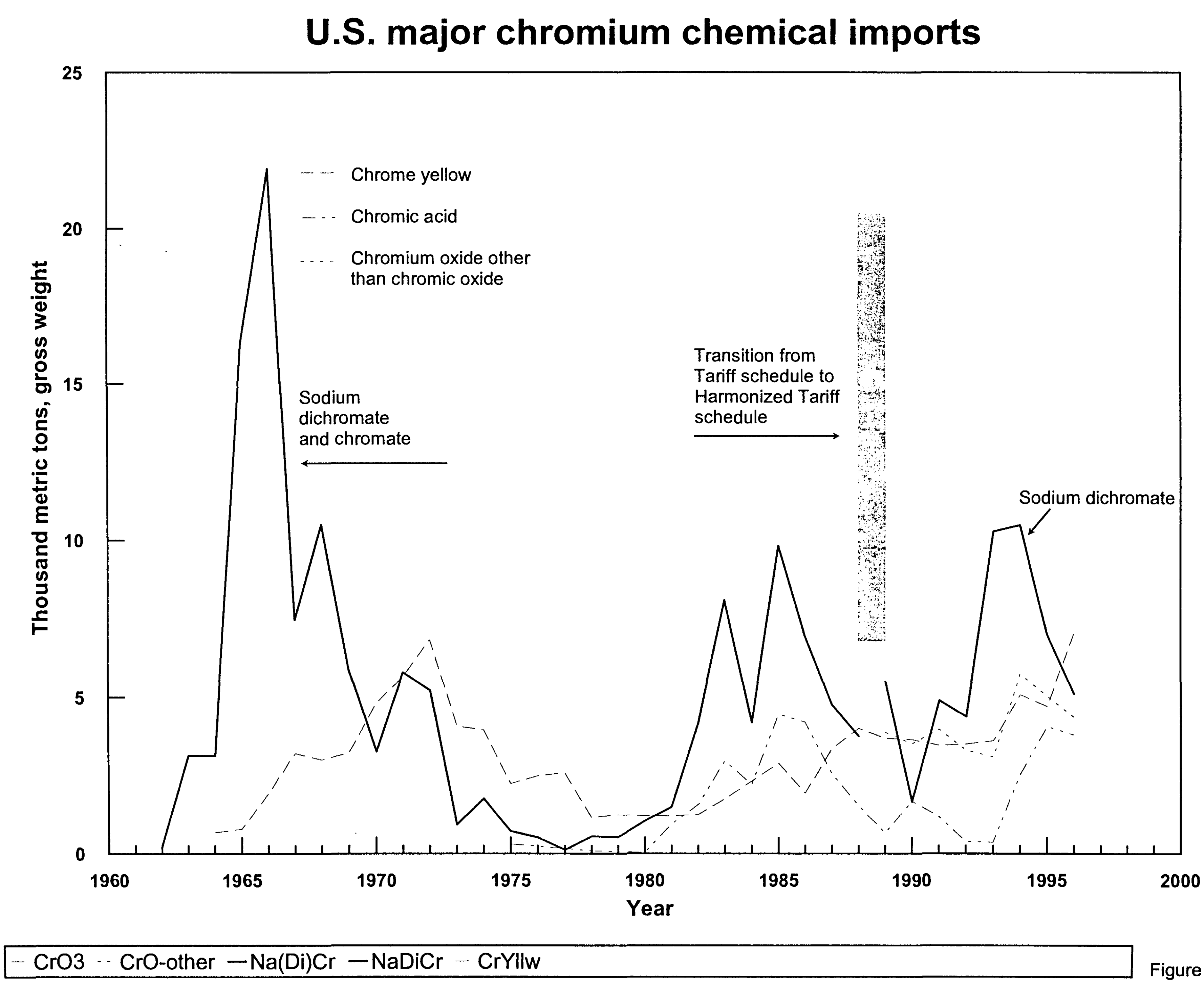

U.S. major chromium chemical imports
Chrome yellow
Chromic acid
Chromium oxide other than chromic oxide
Sodium dichromate and chromate
Transition from Tariff schedule to Harmonized Tariff schedule
Sodium dichromate
Thousand metric tons, gross weight
0
5
10
15
20
25
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
CrO3
CrO-other
Na(Di)Cr
NaDiCr
CrYllw

Figure 14 (DL)

U.S. major chromium chemical exports

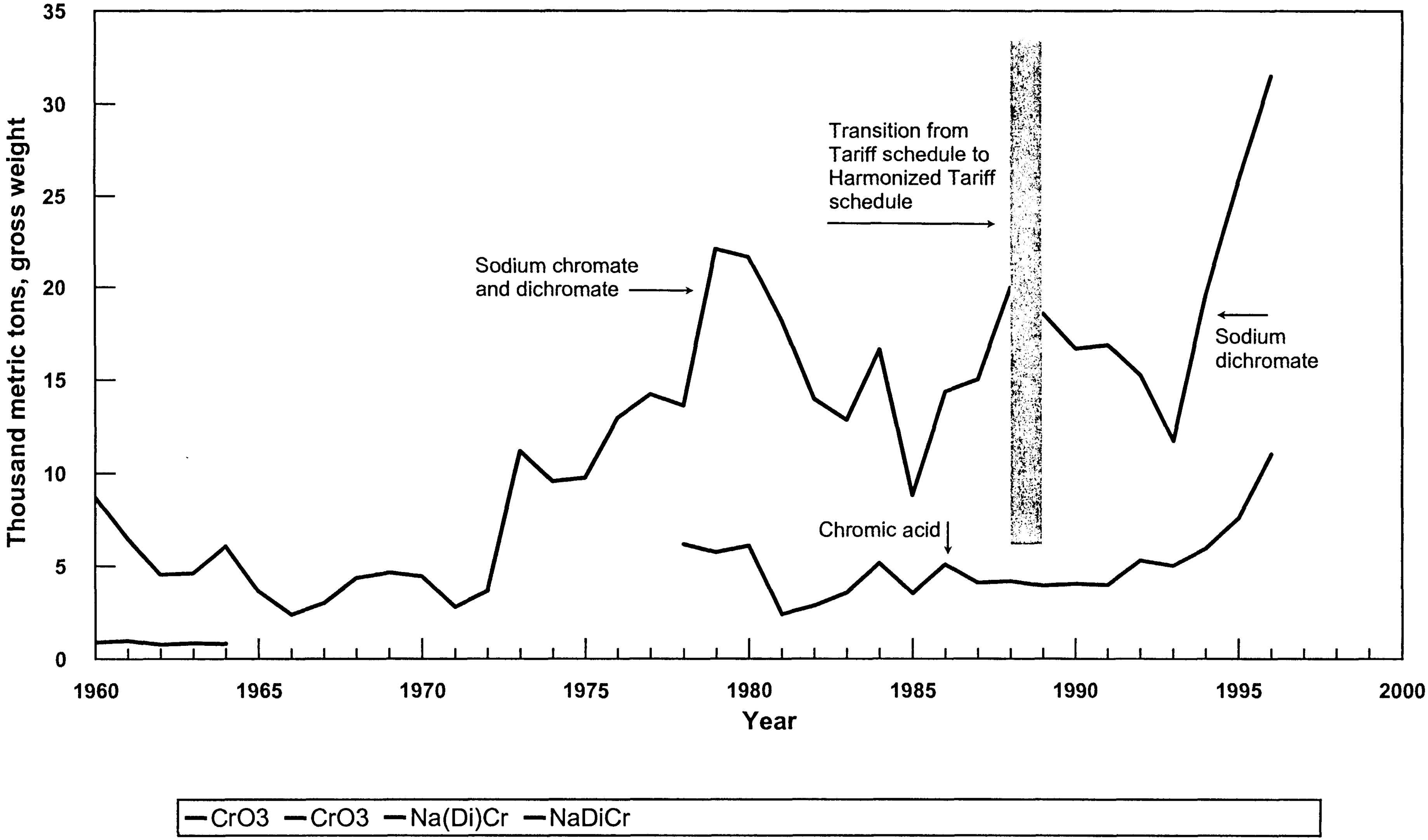


Figure 15 (DM)

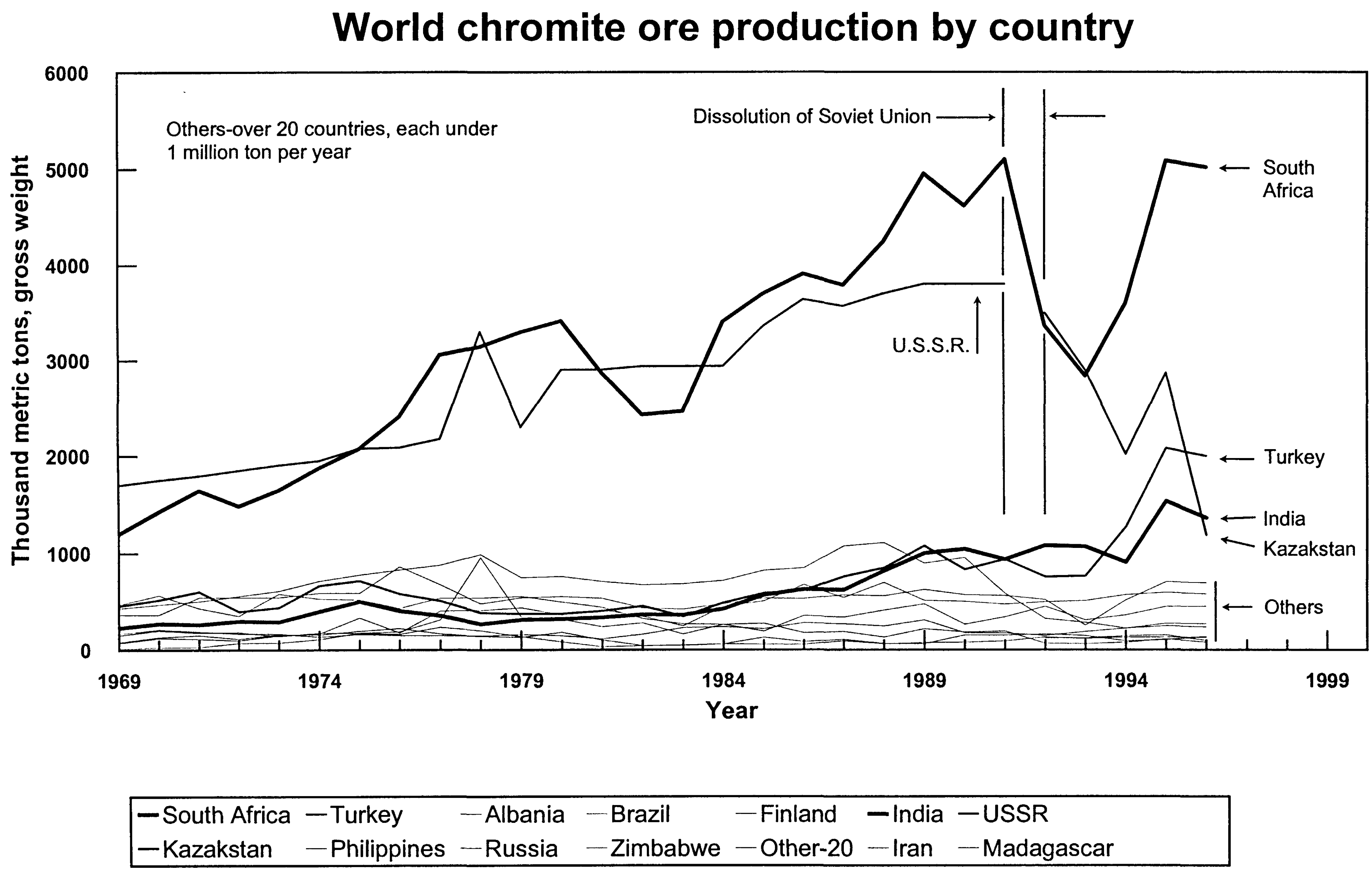

World chromite ore production by country
Thousand metric tons, gross weight
6000
5000
4000
3000
2000
1000
0
Others-over 20 countries, each under
1 million ton per year
Dissolution of Soviet Union
U.S.S.R.
South
Africa
Turkey
India
Kazakstan
Others
1969
1974
1979
1984
1989
1994
1999
Year
South Africa
Turkey
Albania
Brazil
Finland
India
USSR
Kazakstan
Philippines
Russia
Zimbabwe
Other-20
Iran
Madagascar

Figure 16 (FA)

World ferrochromium production by country

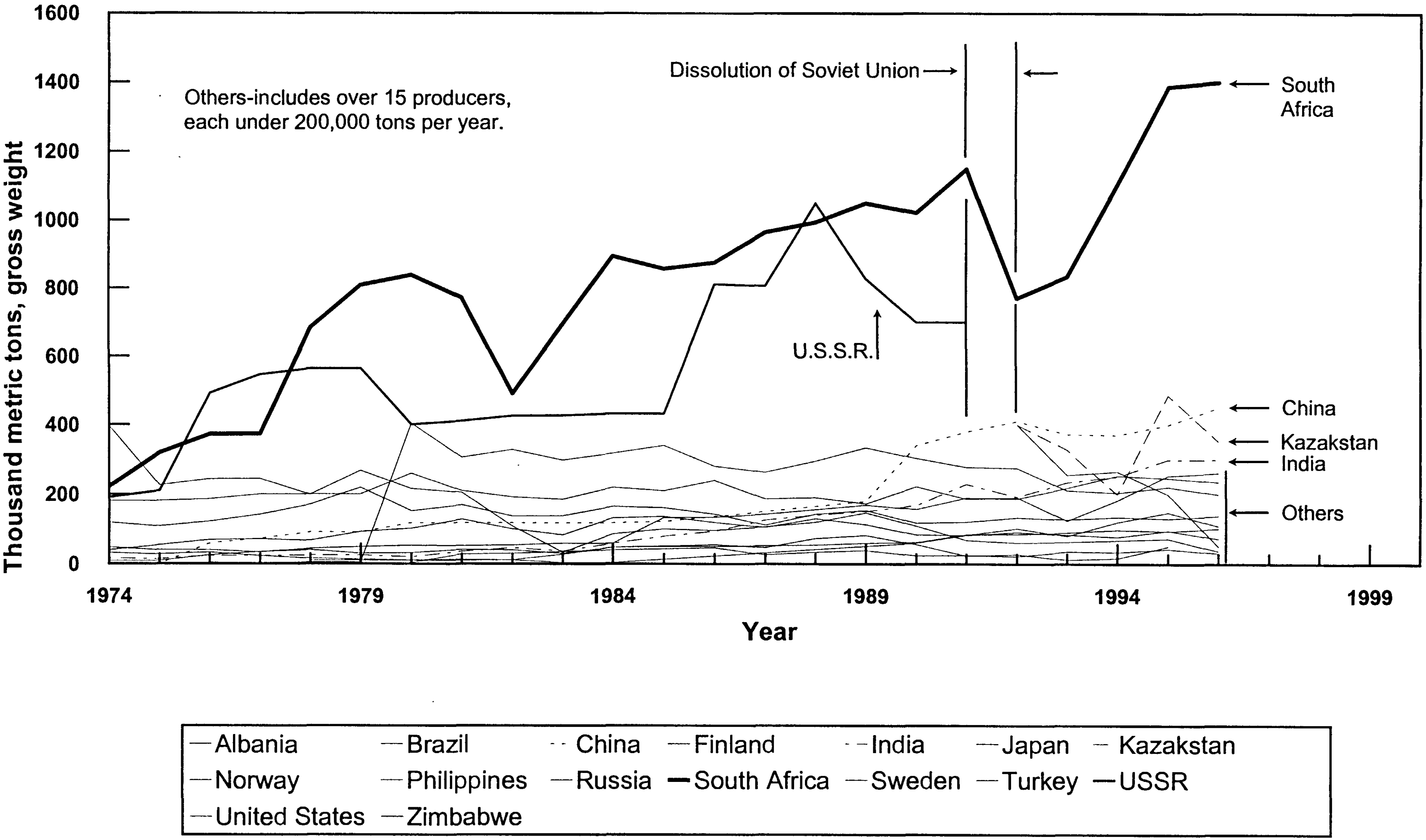


Figure 17 (FB)

U.S. chromite ore consumption end use by industry

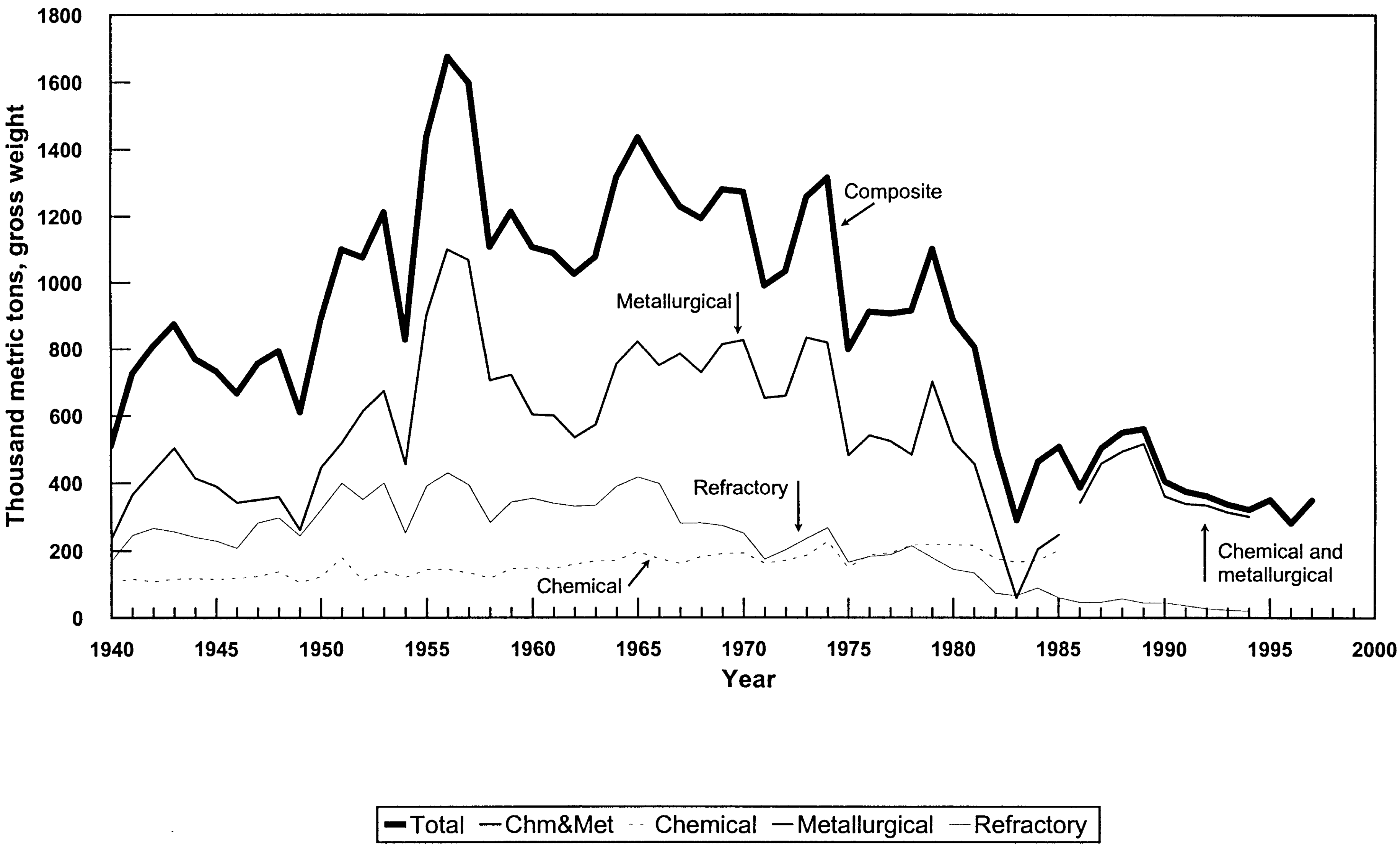
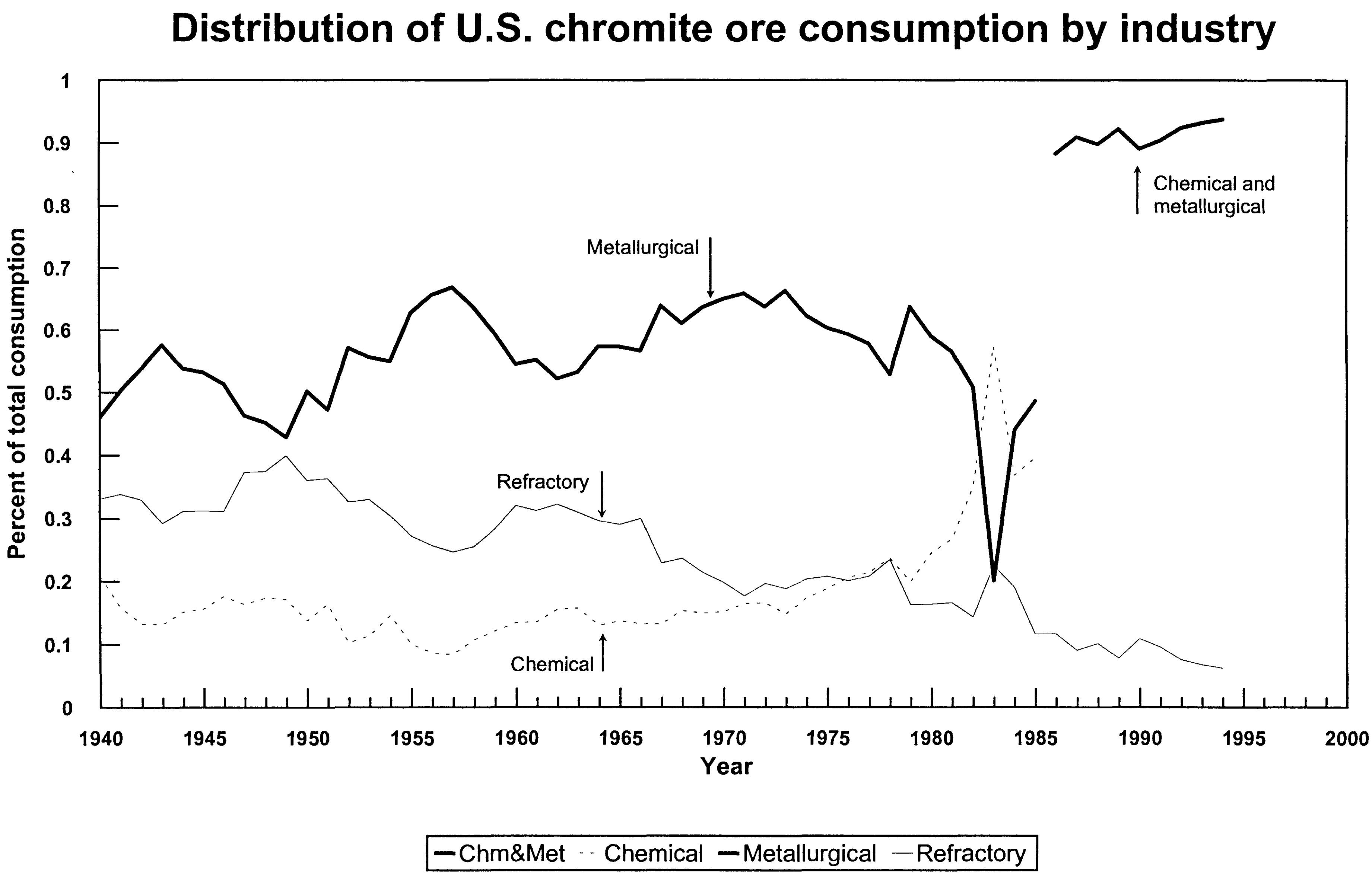


Figure 18 (FC)



Distribution of U.S. chromite ore consumption by industry
Percent of total consumption
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
Metallurgical
Refractory
Chemical
Chemical and metallurgical
Chm&Met
Chemical
Metallurgical
Refractory

Figure 19 (FD)

U.S. production of chromium ferroalloys and metal

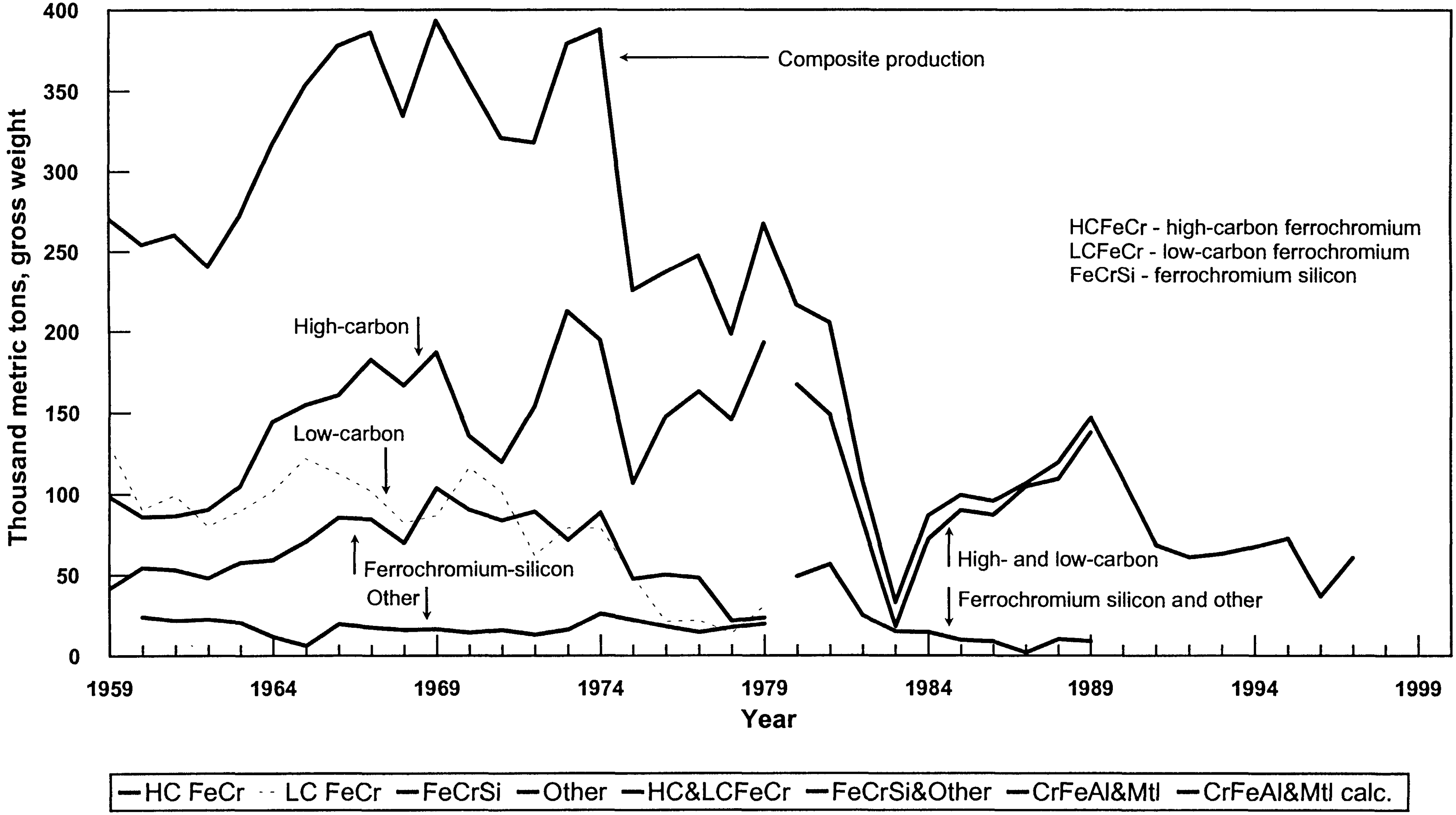


Figure 20 (FE)

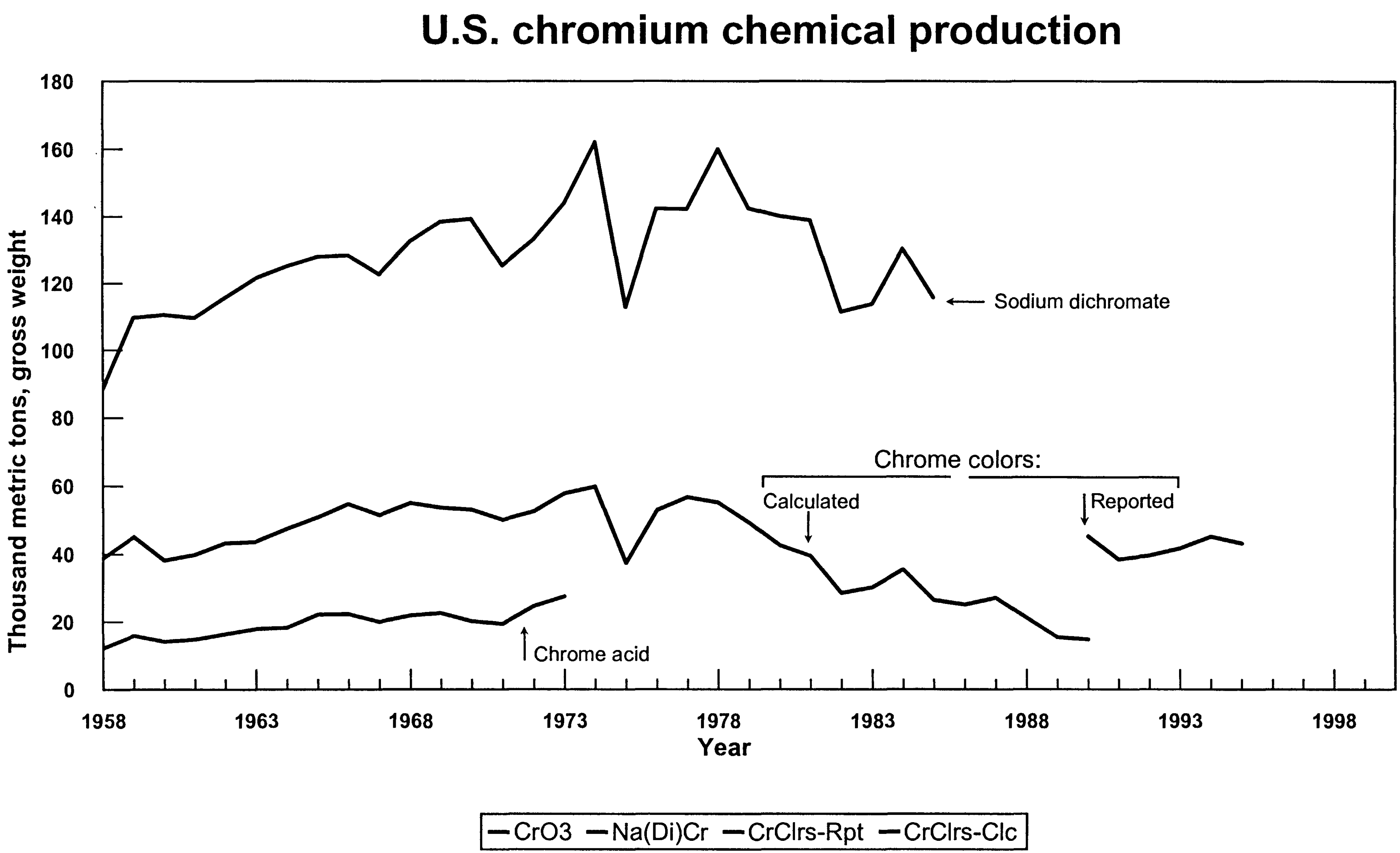

U.S. chromium chemical production
Thousand metric tons, gross weight
0
20
40
60
80
100
120
140
160
180
1958
1963
1968
1973
1978
1983
1988
1993
1998
Year
Sodium dichromate
Chrome colors:
Calculated
Reported
Chrome acid
CrO3
Na(Di)Cr
CrClrs-Rpt
CrClrs-Clc

Figure 21 (FF)

U.S. chromium pigment production

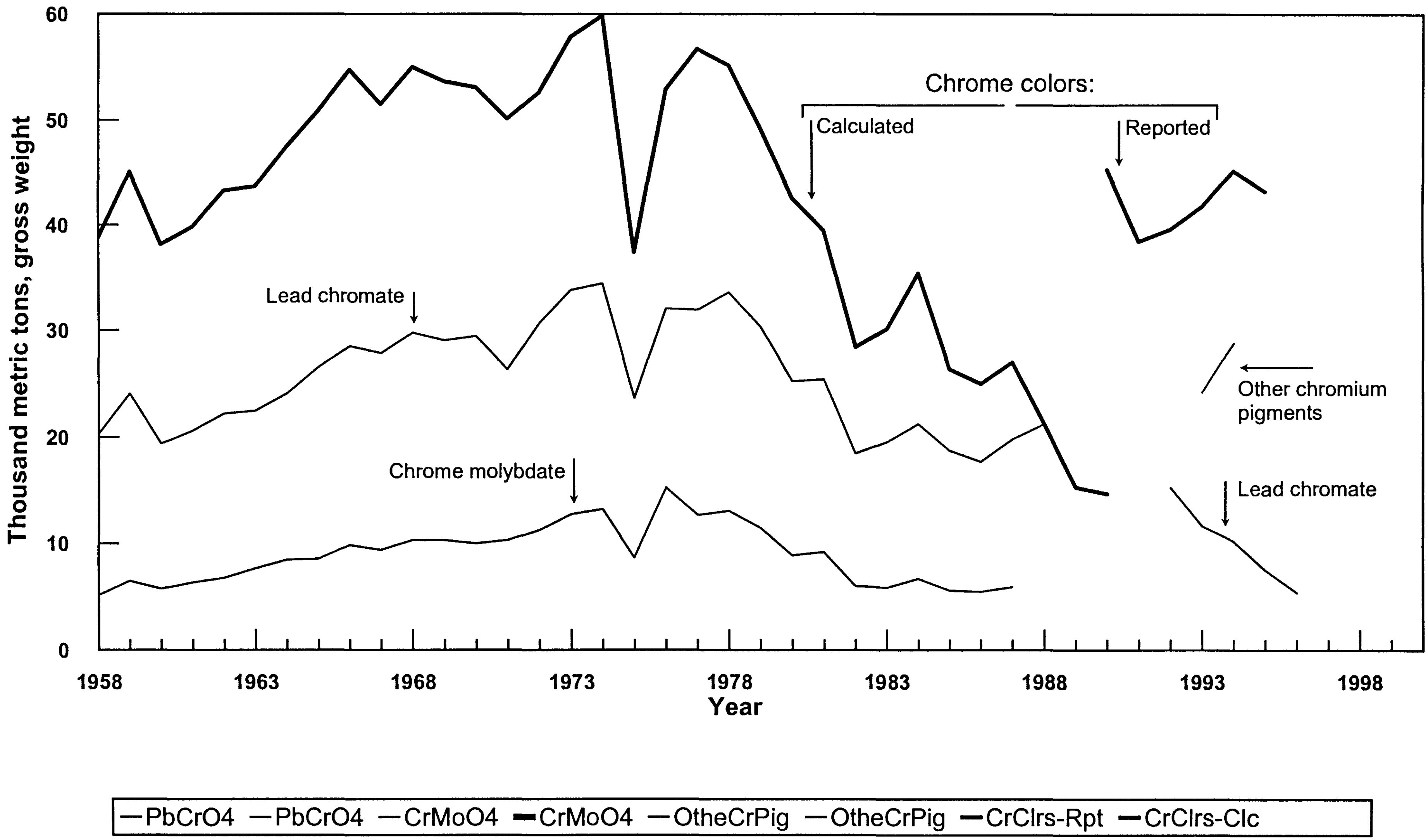


Figure 22 (FG)

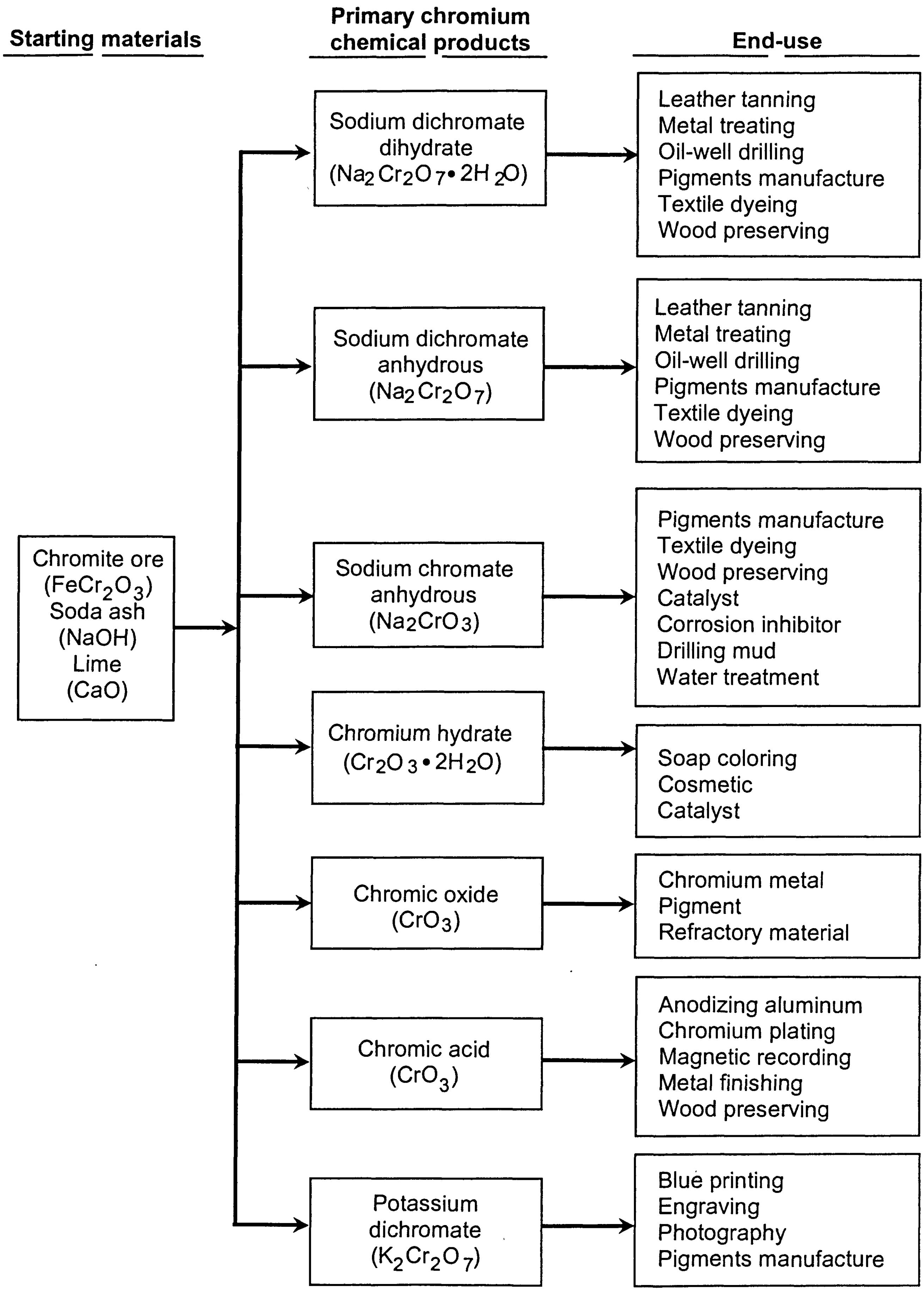
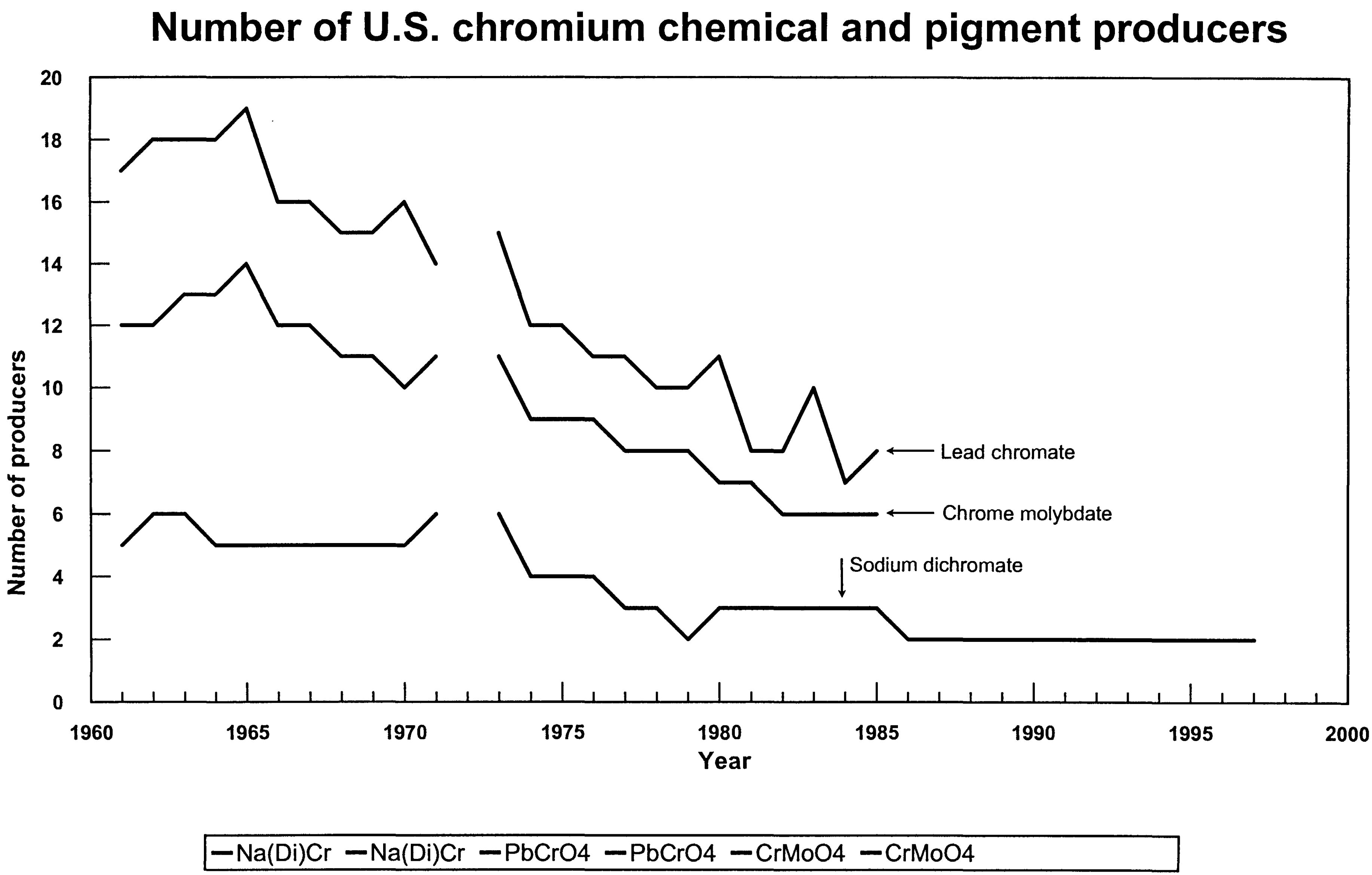

Starting materials
Primary chromium chemical products
End-use
Chromite ore ($FeCr_2O_3$) Soda ash (NaOH) Lime (CaO)
Sodium dichromate dihydrate ($Na_2Cr_2O_7 \cdot 2H_2O$)
Leather tanning
Metal treating
Oil-well drilling
Pigments manufacture
Textile dyeing
Wood preserving
Sodium dichromate anhydrous ($Na_2Cr_2O_7$)
Leather tanning
Metal treating
Oil-well drilling
Pigments manufacture
Textile dyeing
Wood preserving
Sodium chromate anhydrous (Na_2CrO_3)
Pigments manufacture
Textile dyeing
Wood preserving
Catalyst
Corrosion inhibitor
Drilling mud
Water treatment
Chromium hydrate ($Cr_2O_3 \cdot 2H_2O$)
Soap coloring
Cosmetic
Catalyst
Chromic oxide (CrO_3)
Chromium metal
Pigment
Refractory material
Chromic acid (CrO_3)
Anodizing aluminum
Chromium plating
Magnetic recording
Metal finishing
Wood preserving
Potassium dichromate ($K_2Cr_2O_7$)
Blue printing
Engraving
Photography
Pigments manufacture

Figure 23 (FH)



Number of U.S. chromium chemical and pigment producers
Number of producers
20
18
16
14
12
10
8
6
4
2
0
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
Lead chromate
Chrome molybdate
Sodium dichromate
—Na(Di)Cr —Na(Di)Cr —PbCrO4 —PbCrO4 —CrMoO4 —CrMoO4

Figure 24 (FI)

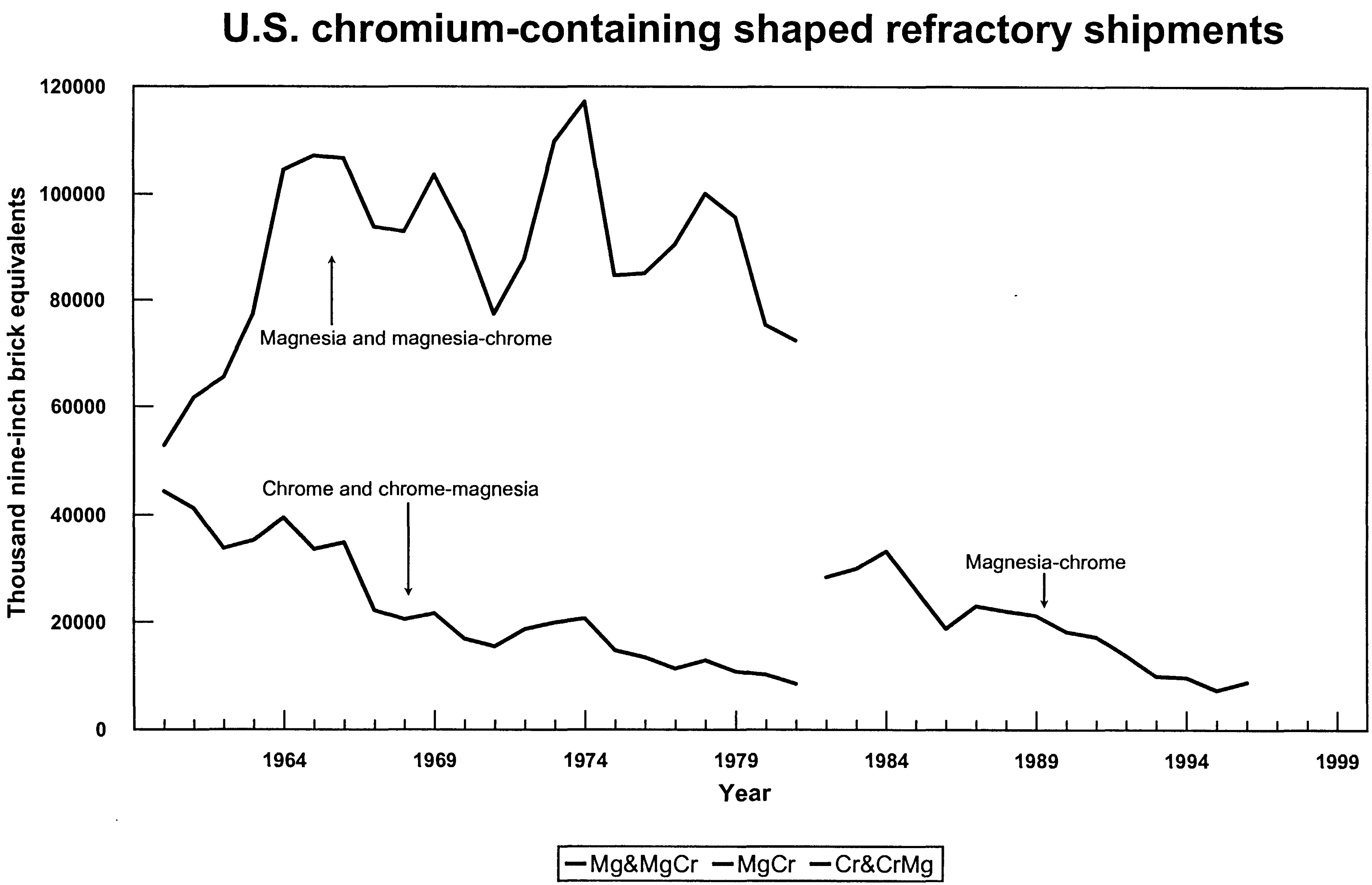

U.S. chromium-containing shaped refractory shipments
Thousand nine-inch brick equivalents
120000
100000
80000
60000
40000
20000
0
Magnesia and magnesia-chrome
Chrome and chrome-magnesia
Magnesia-chrome
1964
1969
1974
1979
1984
1989
1994
1999
Year
Mg&MgCr
MgCr
Cr&CrMg

Figure 25 (FJ)

U.S. chromium-containing unshaped refractory shipments

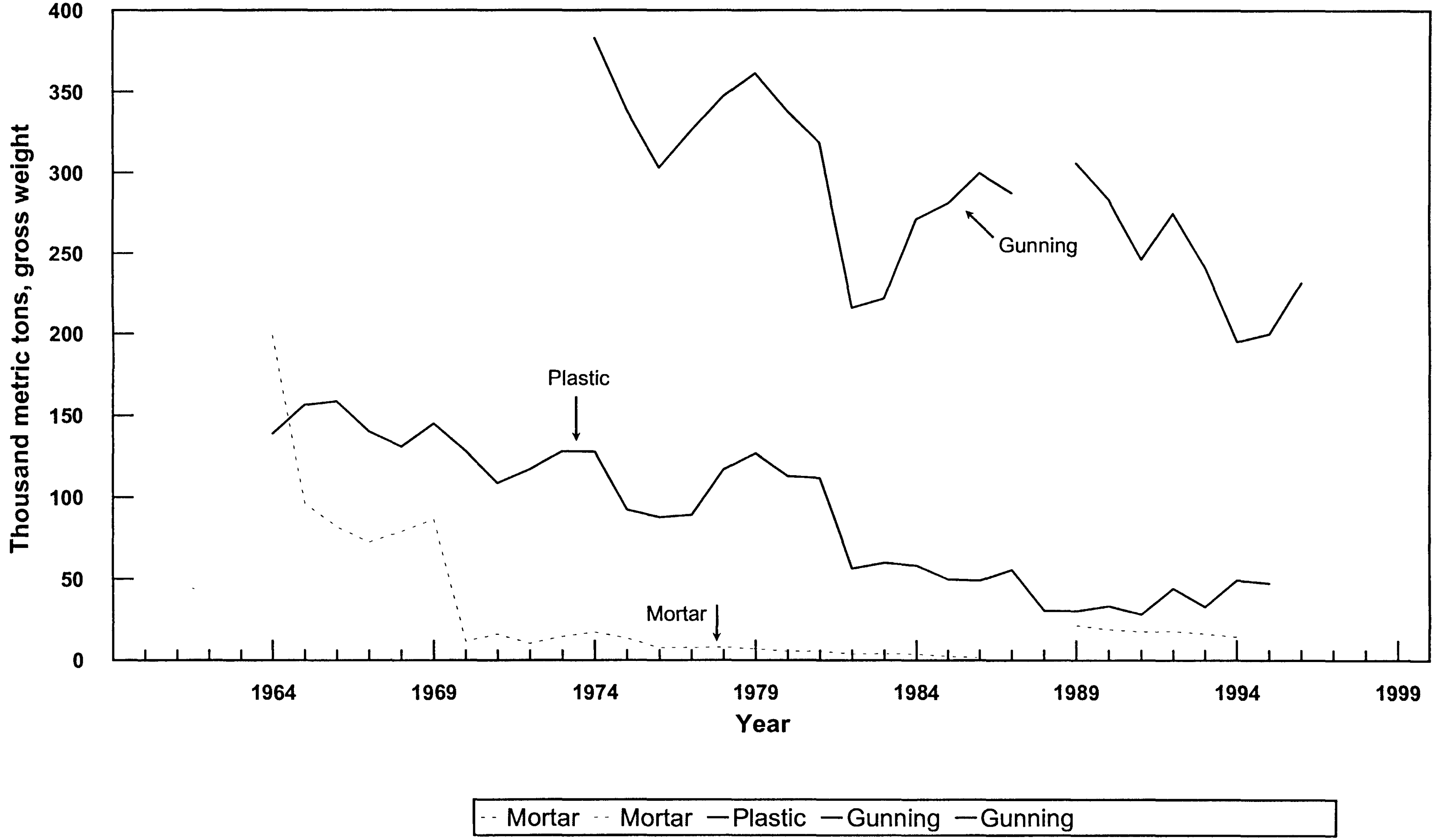
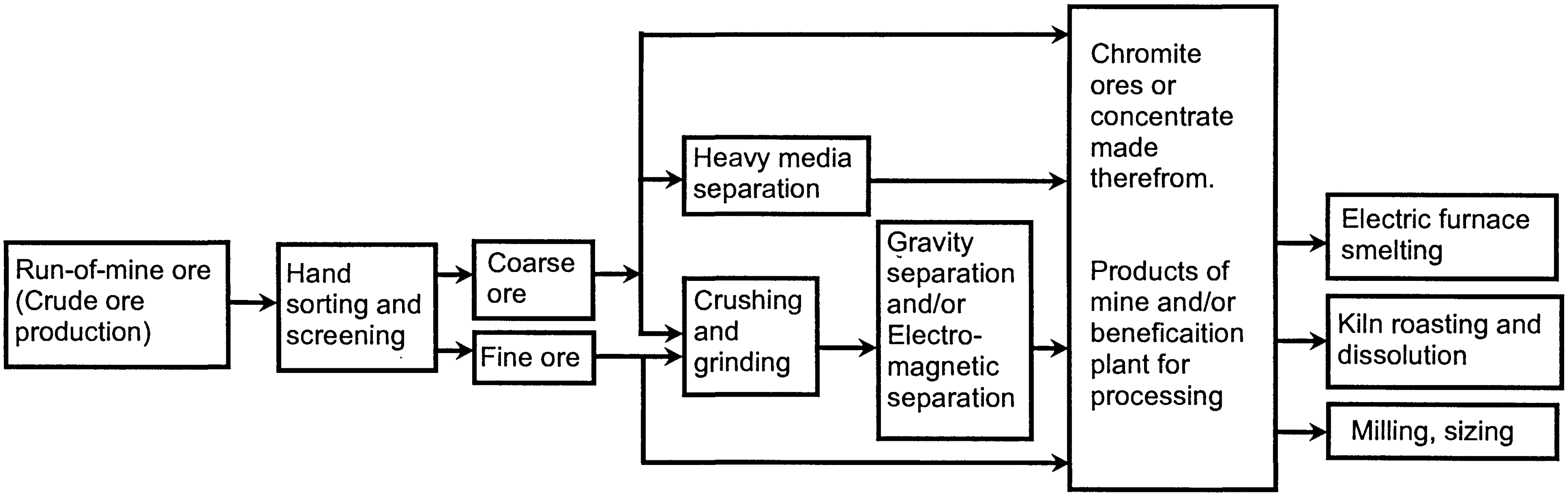


Figure 26 (FK)

Chromite material flow process



Note:
Not shown above are reject and recycle fraction that are associated with most processes as shown to the right.

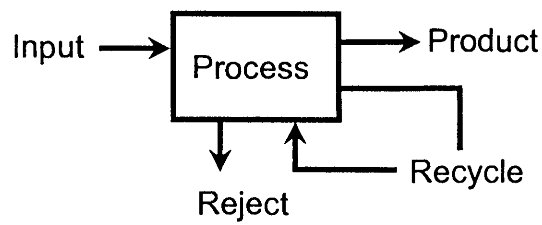
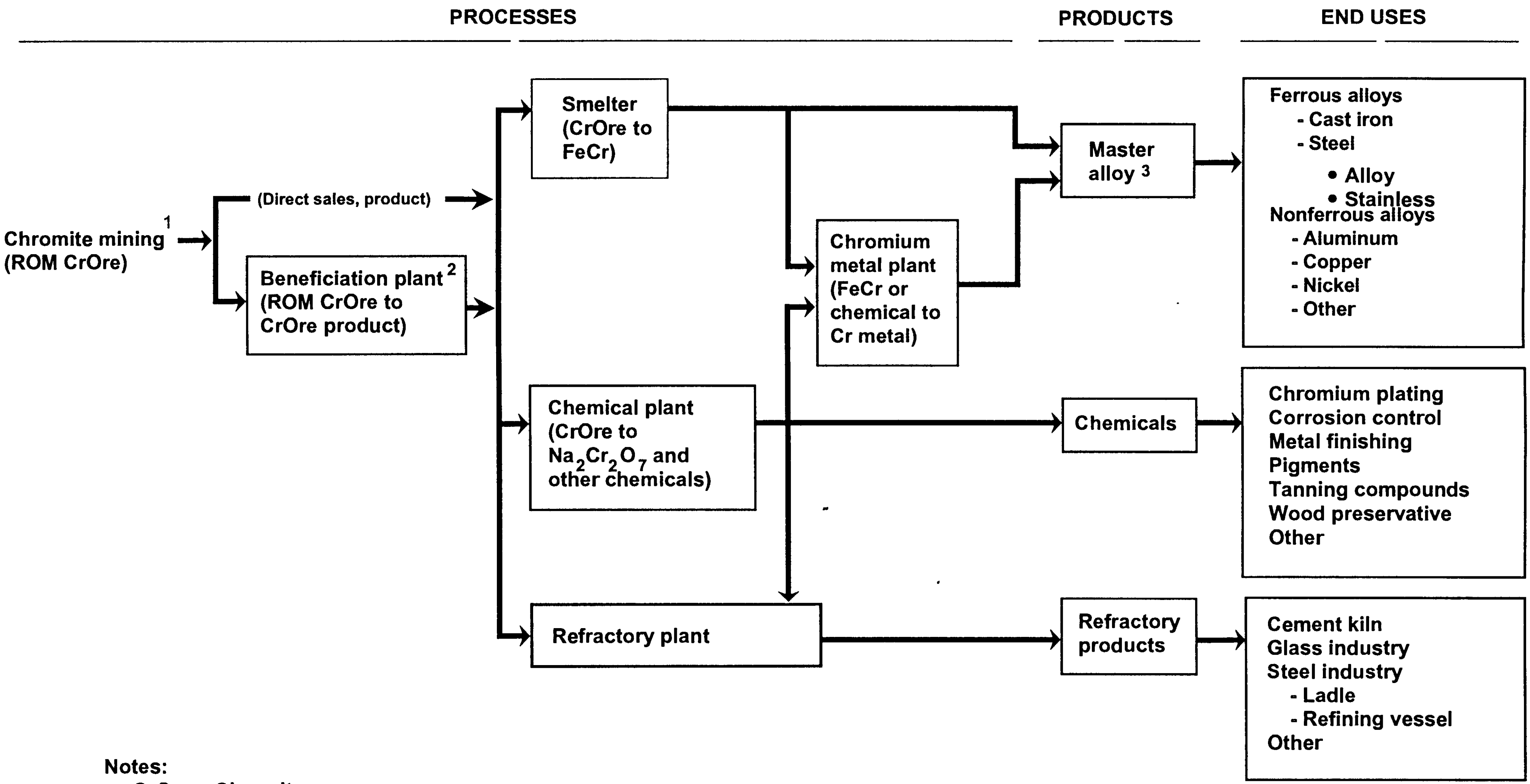


Figure 27 (GA)

Chromium material flow process



Notes:
CrOre = Chromite ore
FeCr = Ferrochromium
$Na_2Cr_2O_7$ = Sodium dichromate
ROM = Run-of-Mine

[1] Mining includes screening and hand sorting.
[2] Benefication includes crushing, grinding, and separation techniques including gravimetric, heavy media, magnetic, and spiral.
[3] Master alloy is an alloy used as a feed stock to produce other alloys.

Figure 28 (GB)

U.S. chromium apparent consumption, and stainless steel production, scrap receipts and consumption

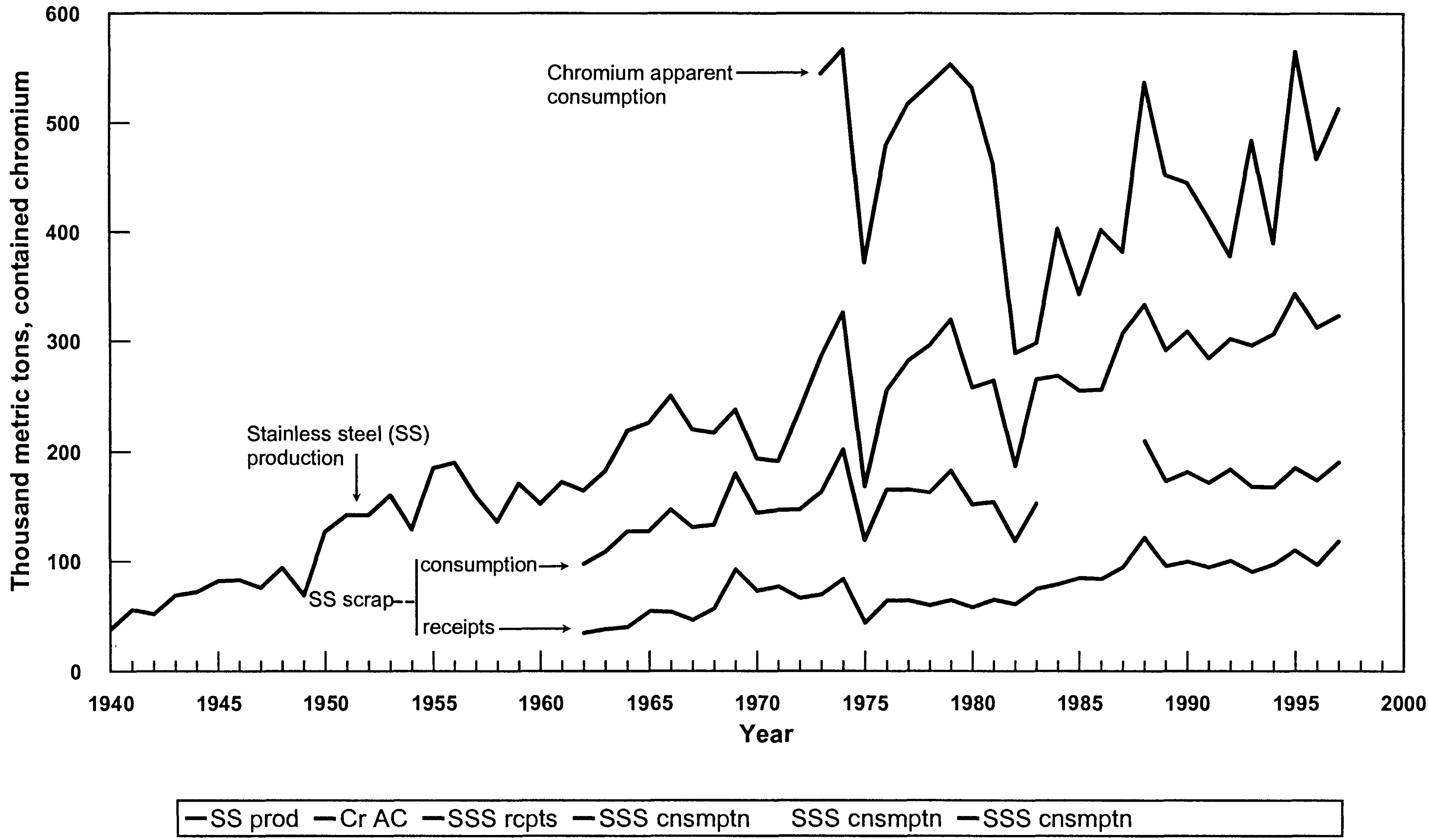


Figure 29 (LA)

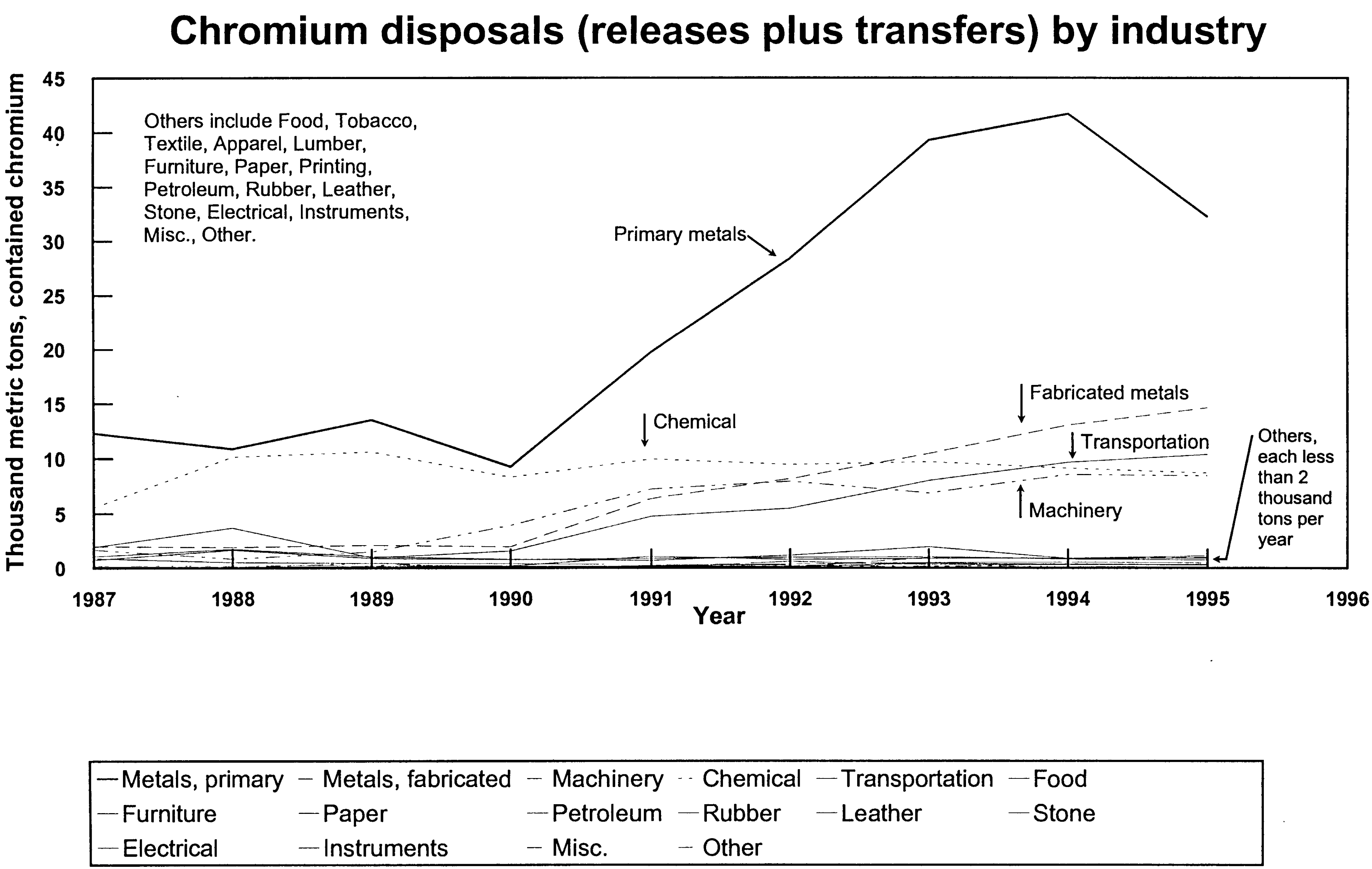

Chromium disposals (releases plus transfers) by industry
Thousand metric tons, contained chromium
45
40
35
30
25
20
15
10
5
0
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
Year
Others include Food, Tobacco, Textile, Apparel, Lumber, Furniture, Paper, Printing, Petroleum, Rubber, Leather, Stone, Electrical, Instruments, Misc., Other.
Primary metals
Chemical
Fabricated metals
Transportation
Machinery
Others, each less than 2 thousand tons per year
Metals, primary
Metals, fabricated
Machinery
Chemical
Transportation
Food
Furniture
Paper
Petroleum
Rubber
Leather
Stone
Electrical
Instruments
Misc.
Other

Figure 30 (LB)

U.S. chromium release and transfers by mode

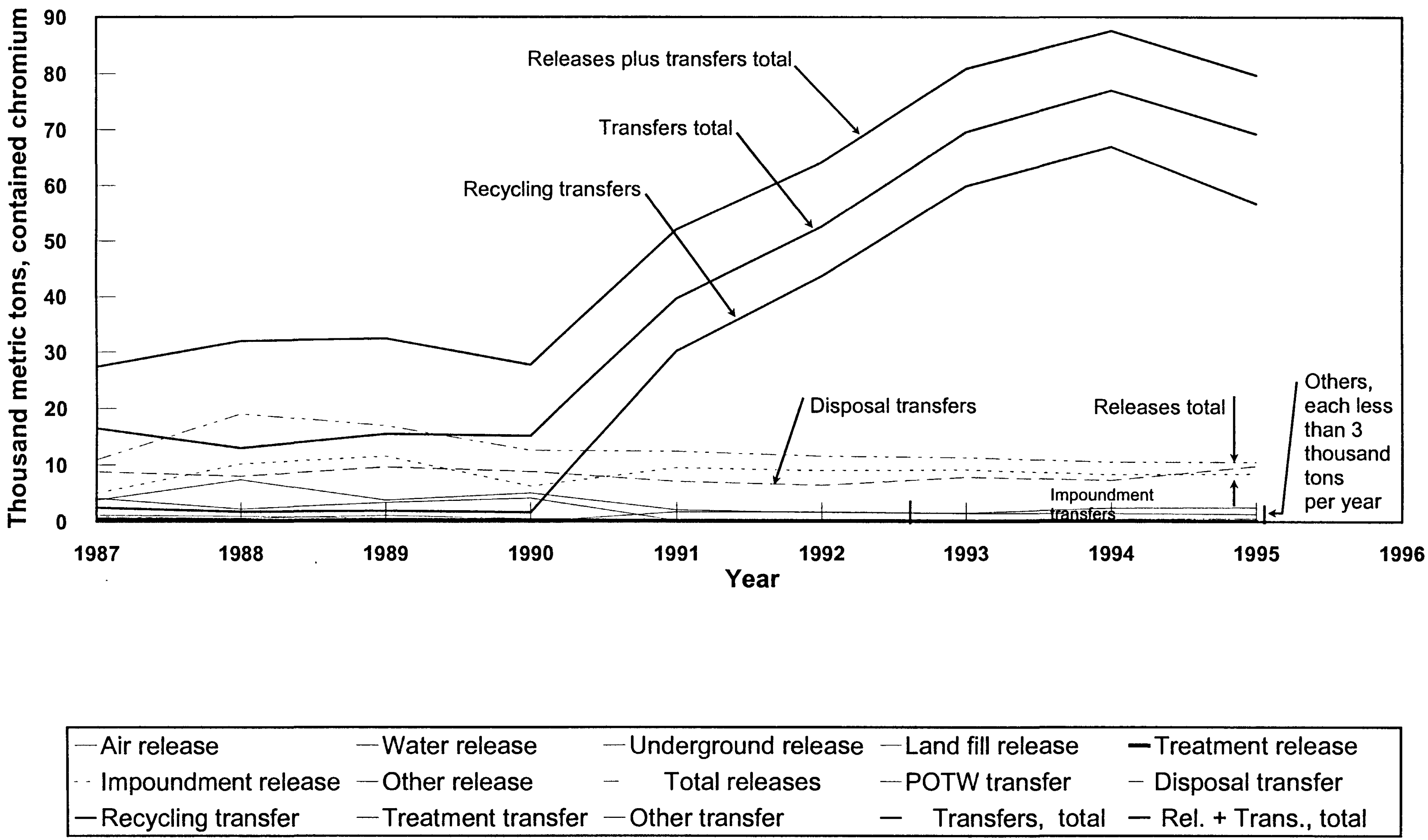


Figure 31 (LC)