BIBLIOGRAPHIC INFORMATION

PB95-203642

Report Nos: BUMINES-IC-9411

Title: Chromium Life Cycle Study.

Date: 1995

Authors: J. F. Papp.

Performing Organization: Bureau of Mines, Washington, DC. Div. of Mineral Commodities.

Type of Report and Period Covered: Information circular/1994.

Supplemental Notes: Library of Congress catalog card no. 94-29994.

NTIS Field/Group Codes: 48A (Mineral Industries), 71N (Nonferrous Metals & Alloys), 68C (Solid Wastes Pollution & Control)

Price: PC A06/MF A02

Availability: Available from the National Technical Information Service, Springfield, VA. 22161

Number of Pages: 102p

Keywords: *Chromium, *Material balance, *Hazardous materials, Waste disposal, Materials recovery, Environmental effects, Industrial wastes, Mineral economics.

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PB95-203642

Information Circular 9411

Chromium Life Cycle Study

By John F. Papp

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES

PB95-203642

Library of Congress Cataloging-in-Publication Data:

Papp, John F.
Chromium life cycle study / by John F. Papp.

p. cm. — (Information circular; 9411)

Includes bibliographical references (p. 91).

1. Chromium industry. I. Title. II. Series: Information circular (United States. Bureau of Mines); 9411.

HD9539.C4P37 1994 338.2'74643—dc20 94-29994 CIP

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Prefixes

G	giga (10^9)	M	mega (10^6)
k	kilo (10^3)	n	nano (10^{-9})
m	milli (10^{-3})	μ	micro (10^{-6})

Suffixes

AC	apparent consumption (measured in contained chromium)	clnkr	clinker production (measured in gross weight)
AlMtl	aluminum metal product (measured in gross weight)	Cu	copper product (measured in gross weight)
Cmnt	cement product (measured in gross weight)	FeCr	ferrochromium (measured in gross weight)
Cr	chromium (indicate contained chromium)	feed	feed material (measured in gross weight)
CrMtl	chromium metal product (measured in gross weight)	gw	gross weight
CrOre	chromite ore (measured in gross weight)	$Na_2Cr_2O_7 \bullet 2H_2O$	sodium bichromate dihydrate (measured in gross weight)
		SS	stainless steel (measured in gross weight)

Units

°C	degree Centigrade	ppb	part per billion
A-hr	ampere-hour	ppm	part per million
g	gram	st	short ton
j	joule	t	ton (metric ton unless otherwise specified)
l	liter	Wh	watt-hour
lb	pound	y	year
m	meter		
pct	percent		

CHROMIUM LIFE CYCLE STUDY

By John F. Papp[1]

ABSTRACT

International and U.S. chromium material flow, losses, and environmental releases and transfers from mining through industrial processing, end use, and recycling are identified and quantified. Average (1983-92) U.S. consumption has been: metallurgical industry, 87 pct; chemical industry, 10 pct; and refractory industry, 3 pct. Average chromium content of aluminum, cobalt, copper, nickel, and titanium alloys and alloy, carbon, and stainless steel alloys was estimated. Anthropogenic chromium consumption was estimated for the cement and copper industries. Non-commodity cycle anthropogenic chromium mobilization resulting from U.S. fuel and fertilizer use was estimated.

Commodity cycle anthropogenic world chromium loss from mining and primary consumer industry was estimated to be equivalent to about 56 pct of chromium contained in chromite ore production and represented a loss rate of 181 kt-Cr/Mt-CrOre. Chromium released to the atmosphere from natural and from anthropogenic sources were comparable in magnitude. Chromium released to soil was mostly from anthropogenic sources, and aquatic releases were all anthropogenic. Domestic product chromium losses exceed process losses by more than a factor of 10 showing the importance and potential environmental impact of post-consumer recycling. The location of historical and current domestic chromium industry processing sites in 23 States were reported. Chromium releases and transfers to the environment were estimated from 1973 through 2002 by primary consumer industry. A decrease in chromium releases and transfers to the environment was anticipated.

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EXECUTIVE SUMMARY

International and U.S. chromium material flow, losses, and environmental releases and transfers from mining through industrial processing, end use, and recycling are identified and quantified for 1989. World chromite ore production was 14.294 Mt-gross weight (4.3 Mt-Cr). That chromite ore was subsequently internationally consumed by the metallurgical (11.292 Mt-CrOre), chemical (1.858 Mt-CrOre), and refractory (1.144 Mt-CrOre) industries.

U.S. chromium material flow in 1989 amounted to 452 kt-Cr contained in chromite ore, chromium ferroalloys and metal, and chromium chemicals and pigments. Average (1983-92) U.S. consumption by primary consumer industry expressed as a percent of 1983-92 average chromium apparent consumption has been: metallurgical industry, 87 pct; chemical industry, 10 pct; and refractory industry, 3 pct. Of the 87 pct consumed by the metallurgical industry, 79 pct went into stainless steel and the remaining 21 pct into other ferrous and nonferrous alloys.

Average chromium content of commercial metal alloys was estimated at: alloy steel, 2.2±0.2 pct; aluminum, 0.04±0.02 pct; carbon steel, 0.01±0.002 pct; cobalt, 20±1 pct; copper, 0.025±0.01 pct; nickel, 14±1 pct; stainless steel, 17±1 pct; and titanium, 0.49±0.01 pct.

Chromium consumption was estimated for the cement and copper industries. Chromium consumption rate was estimated for cement production to have been 30 t-Cr/Mt-cement and for copper production to have been 450 t-Cr/Mt-copper as a result of chromium-containing refractories used by those industries. Non-commodity cycle anthropogenic chromium mobilization resulting from U.S. fuel and fertilizer use was estimated. Chromium mobilization rate resulting from U.S. fuel and fertilizer use was estimated by commodity as follows: coal, 10 t-Cr/Mt-coal; crude oil, 0.1 t-Cr/Mt-crude oil; residual crude oil, 1.3 t-Cr/Mt-residual crude oil; gasoline, 0.017 t-Cr/Mt-gasoline; and potash, 84 t-Cr/Mt-phosphate rock.

Commodity cycle anthropogenic world chromium loss from mining and primary consumer industry in 1989 was estimated based on processing and product losses at 2.5 Mt-Cr, an amount equivalent to about 56 pct of chromium contained in chromite ore production and representing a loss rate of 181 kt-Cr/Mt-CrOre. World chromium released to the environment by major natural sources was 1.1 Mt, an amount equal to about 27 pct of chromium contained in chromite ore production. Chromium released to the atmosphere from natural and from anthropogenic sources was comparable in magnitude. Chromium released to soils was mostly from anthropogenic sources, and aquatic releases were all anthropogenic.

Chromium contained in discarded U.S. commercial and consumer products in 1989 was estimated to have been 13 kt-Cr, chromium in recycled home and prompt scrap was 260 kt-Cr, and chromium in recycled obsolete scrap was 103 kt-Cr. Chromium losses were estimated at 60 kt-Cr from the manufacturing process of which 4.5 kt-Cr was lost during processing and 55 kt-Cr was lost in products. Chromium releases from the domestic manufacturing sector to the environment were 17 kt-Cr while transfers by that sector were reported to have been 16 kt-Cr. As a percent of domestic chromium material flow, chromium released was about 4 pct and transferred was about 3 pct. Domestic product losses exceed process losses by more than a factor of 10 showing the importance and potential environmental impact of post-consumer recycling. Historical and current locations of domestic identified and evaluated chromite resources and chemical, metallurgical, and refractory processors of chromite ore were located in 23 States.

Chromium releases and transfers to the environment were estimated from 1973 through 2002 by primary consumer industry. On average from the 1973-82 time period to the 1983-92 time period, chromium released and transferred to the environment decreased by 3,630 t-Cr (from 28,241 t-Cr to 24,611 t-Cr). A decrease in chromium releases and transfers to the environment on average from the 1982-93 time period to the 1993-2002 time period is projected to be 3,164 t-Cr (from 24,611 t-Cr to 21,447 t-Cr).

INTRODUCTION

LIFE CYCLE ASSESSMENT

The U.S. Bureau of Mines (USBM) has initiated a series of studies on the environmental[2] impacts resulting from the production and use of various minerals. The purpose of this report is to make information about the mining and minerals industry available to environmental analysts. Two kinds of life cycle study are distinguished in this report; the product life cycle study and the mineral life cycle study. The product life cycle study analyzes a consumer, or possibly commercial manufacturing, product. Essentially, the difference between a mineral and a product life cycle study is that the mineral life cycle study focuses on the production requirements, impacts, and diverse uses of minerals whereas a product life cycle study focuses on production requirements, materials demand, and use impact of a product. The mineral life cycle study analyzes a mineral. The purpose of these mineral life cycle studies is: to provide minerals use and material flow information that may be used in product life cycle assessments; to provide USBM and other data that relate to environmental issues, an area currently of great public interest; and to provide a base of background information from which minerals information relating to sustainable development, minerals use, and environmental impact can be culled. Life cycle studies that address the values, impacts, and costs associated with diverse production and consumption options could help in the compromise process used in competing for capital resources to meet national objectives.

The purpose of this chromium life cycle study is to identify and integrate information about chromium use and losses over the chromium life cycle. Here chromium life cycle means from mining through processing, manufacturing, end use, disposal, and reuse of chromium in its various material forms. Environmental concerns about the use of chromium-containing materials lead one to ask: What is the impact on the environment of using chromium? There is not a single, simple answer to this question because there are many chromium-containing materials and even more ways to and reasons for using them. It is one purpose of a product life cycle study to answer this question for a specific product. A complete answer to this question would include an answer to the converse as well: What would be the impact on the environment of not using chromium? This question suggests that not using chromium— even when negative impacts are incurred as a result of its use—may be worse than using chromium. Another way of saying this is that alternatives that exclude chromium use may be more environmentally damaging than those that require chromium use. In other words, chromium use may be the most benign way of addressing some problems. For example, some chromium-containing steels are corrosion resistant and therefore last longer than common grades of steel. The economic advantage of this fact has been demonstrated. However, the environmental benefit has yet to be analyzed.

Product life cycle assessments have been described in general as the assimilation and analysis of information about a product, process, or activity followed by process refinement *(1)*.[3] These life cycle assessments are consumer product oriented. The information collected includes material and energy supplies necessary to produce a product as well as material losses in the production process. Analysis includes an assessment of material and energy losses, the destination of those losses, and the impact of those losses. Process refinement includes changes to the production process that result from the first two parts of the life cycle assessment. Life cycle studies have been used in the past to study a diversity of products *(2)*.

This description of the product life cycle assessment is business and product oriented. Potential uses of such assessments are: the evaluation and modification of the production process to improve economic efficiency or to identify specific environmental impacts, the comparison of products in terms of their material or energy use or environmental impact, or as a public policy tool as when public law is used to change environmental conditions (e.g., reducing air pollution, reducing landfill, volume changing landfill or content profile).

Problems associated with such life cycle assessments include the extent or depth to which a study is carried out and the information basis of the study. For an example of depth, consider the comparison of plastic disposable with cloth reusable diapers. In addition to an energy and material accounting for the cloth diaper main production sequence and subsequent use and disposal, an energy accounting of the cloth reusable

[2]Ecologically, environment is the sum of all external conditions and influences affecting the development and life of an organism. In this report, environment excludes material being used.

[3]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

diaper might include the energy cost of manufacturing stainless steel diaper pins from wire. A deeper analysis might include the energy needed to produce the stainless steel wire from iron. The point is that judgement must be used to decide where to stop when doing a life cycle assessment without distorting the results. Because everything we use is either extracted or harvested, mining and farming[4] appear to be the logical place to start the materials part of a complete life cycle assessment.

As one goes from manufactured product, such as a diaper pin, to the raw material supply, a second problem arises—that of distribution among products. Continuing with the previous example to illustrate this problem, one must estimate what fraction of stainless steel goes into diaper pins and use only that fraction of energy consumption to produce stainless steel as contributing to the diaper pin. Similarly, not all chromium ferroalloys go into stainless steel. That fraction of ferrochromium that goes into stainless steel should be estimated and used to proportion ferrochromium energy consumption used to produce stainless steel. Similarly, to be complete the same procedure should be followed back to ore production for energy and raw material use and waste generation from that use.

A second type of distribution problem arises when a manufacturer produces more than one product. For example, suppose that a plant produces stainless and alloy steel, both of which consume chromium and use chromium materials in the production process. Waste for the plant can be estimated, but the cause of that waste generation among that plant's products may be completely unknown. This same problem exists for industries such as refractories, chemicals, and ferroalloys. As a result of the multiple product problem, the waste associated with chromium as a main stream product based on EPA Toxic Release Inventory data is an overestimate.

As a Federal agency, the USBM seeks to use its expertise in mining and minerals to provide minerals information upon which national policy decisions can be based. Material flow is an integral part of a life cycle assessment. It is the purpose of this report to provide chromium material flow information based on publicly available data. As pointed out above, a complete life cycle assessment should involve material flow starting with mining, at least for the main product sequence. An industry product specialist, one who is knowledgeable about a particular product or process, in carrying out a product life cycle assessment may wish to carry out a complete assessment. Such an assessment requires the collection and analysis of mineral information likely to be outside the product specialist's area of expertise. This mineral-oriented chromium life cycle analysis is intended to be a resource to the product specialist performing a complete life cycle assessment. A product assessment such as the one described here has been proposed by the automobile industry for the purpose of comparing environmental impacts and energy benefits. The proposed study was to start at the mining or extraction of ores and cover production, operation, and recycling of cars *(3)*.

As a mineral life cycle study, this report covers the production and processing of chromium in its various material forms, chromium recycling, and releases and transfers of chromium from other manufacturing processes. Thus, like a product life cycle assessment, this chromium life cycle study treats chromium as the main product. Unlike the product life cycle assessment, this study also addresses chromium associated with the production of other products. This study uses publicly available information and includes energy consumption and material use efficiency (i.e., chromium in product as a percent of chromium in feed materials) information where available. Unlike the product life cycle study that attempts to identify all material inputs and outputs, this mineral life cycle study attempts only to identify and quantify the chromium inputs and outputs. Because the USBM monitors the primary mineral production and use industries and collects data from the domestic minerals industry, domestic mineral production and use are the major focus of this report. Because most chromium processing is done outside the United States (including all mine production, over 98 pct of world ferrochromium production, over 86 pct of world stainless steel production, over 87 pct of world chromium metal production, and over 93 pct of world chromium chemical production), because trade in chromium materials is common, and because world perspective is necessary to creating a sustainable future, it is necessary to adopt an international perspective.

A potential problem with the life cycle assessment is the data upon which the study is based. Confidential information collected by an industry or a representative thereof without benefit of public review inevitably is viewed as suspect by those who disagree with the conclusions of the assessment. Any analysis that is conducted or sponsored by an industry with an economic interest in the report's conclusions will be suspect, especially when that analysis supports the sponsoring industry's position. One can never tell where research ends and advertising begins when data and assumptions are hidden. Thus an assessment

[4]Mining and farming are used here in the most general sense of recovering inorganic or organic resources.

based on confidential data will be perceived as biased. Publicly collected (e.g., Government surveys) and/or reported (e.g., open literature) information is here called public domain data. Public domain data are subject to review by all interested parties. Public domain data are, therefore, more likely to be unbiased and can be the starting point for analysis by any interested party. The analysis can then be criticized based on assumptions and methodology of the analysis. The data provided in this report are public domain data collected by Federal agencies or reported in the open literature wherever possible. Industry representatives provided information in cases where available information did not represent current industry practice or was not available from public domain sources.

CHROMIUM

Chromium is an element that is mined in the form of chromite ore named after its primary mineral constituent, chromite. Chromium was discovered before 1800. Its first use was as a pigment. Subsequently it was used in refractories and as an alloying element, which is its current major use. Chromium forms compounds in a variety of valence states with trivalent and hexavalent chromium compounds predominating. Hexavalent chromium compounds have been classified carcinogenic. Because of the significant environmental impact and health risk difference between trivalent and hexavalent chromium, product life cycle studies should discriminate between these two classes of chromium compounds when accounting for chromium use and losses and when making an environmental impact analysis.

As pointed out above, chromium material flow is an essential part of a mineral life cycle study. Material flow as described in figure 1 consists of material in the use process (e.g., mining, refining, and incorporation in commercial or consumer products), material lost from the use process (e.g., tailings, waste, and scrap generated as part of the processing and use of the material), and material lost to the environment (e.g., landfill, underground injection, air emissions, and effluents). Three kinds of losses associated with chromium material flow will be distinguished in this report; product losses, process losses, and environmental losses. These losses are associated with the way in which the chromium is used, from where it is lost, or to where it is lost. Process and product losses are materials *lost from*, i.e. as a result of, chromium use and refer to materials that exit the use cycle. A product loss is one in which chromium is lost as part of a product that is consumed. An example of a chromium product loss is chromium contained in ink. Once the ink is used, it is dispersed in the environment and no longer recoverable. The loss took place with the ink as part of the product. Such a product could be packaging. A process loss is one in which the chromium lost during a production process. There are two kinds of process loss based on the kind of process. One is associated with the processing of chromium-containing material, the other with the processing of chromium-free materials. An example of each kind of chromium process loss is provided by the manufacturing industry. In particular, a chromium process loss occurs during the production of a chromium-containing material when chromium is lost during electric furnace smelting of chromite ore to produce ferrochromium. Most of the chromium feed into the furnace ends up in the ferrochromium product. However, some chromium escapes the furnace in fumes and some chromium ends up in the slag. A chromium process loss occurs during the production of a non-chromium-containing material when chromium is lost as a result of surface treatment of aluminum alloys with sodium bichromate. When the sodium bichromate bath is consumed, all or part of the chromium contained in the bath is lost and the chromium is not contained in the product—aluminum alloys. Both product and process losses my reenter the chromium material use process cycle through recycling. Environmental loss refers to materials that are *lost to* the environment. Two examples of environmental losses are consumer products sent to landfills and manufacturing industry releases to the environment. In the process loss example given above, when chromium escaping the furnace as fumes is unrecovered, it is an environmental loss as well as a process loss.

U.S. BUREAU OF MINES ROLE

The USBM monitors and assesses domestic and foreign mineral resources and conducts minerals research. Minerals research includes primary and secondary supply processing. Primary chromium supply is that from mining; secondary, from recycling. In order to determine research opportunities for secondary minerals supply, the USBM has studied industrial material processing *(4)*.

The USBM collects information on the domestic production of chromite ore, chromium ferroalloys, and chromium chemicals, and on domestic consumption of primary and secondary supply of chromium by industry survey. The USBM surveys primary and some post-primary consumers of chromium. Primary consumers of chromium include the chemical, metallurgical

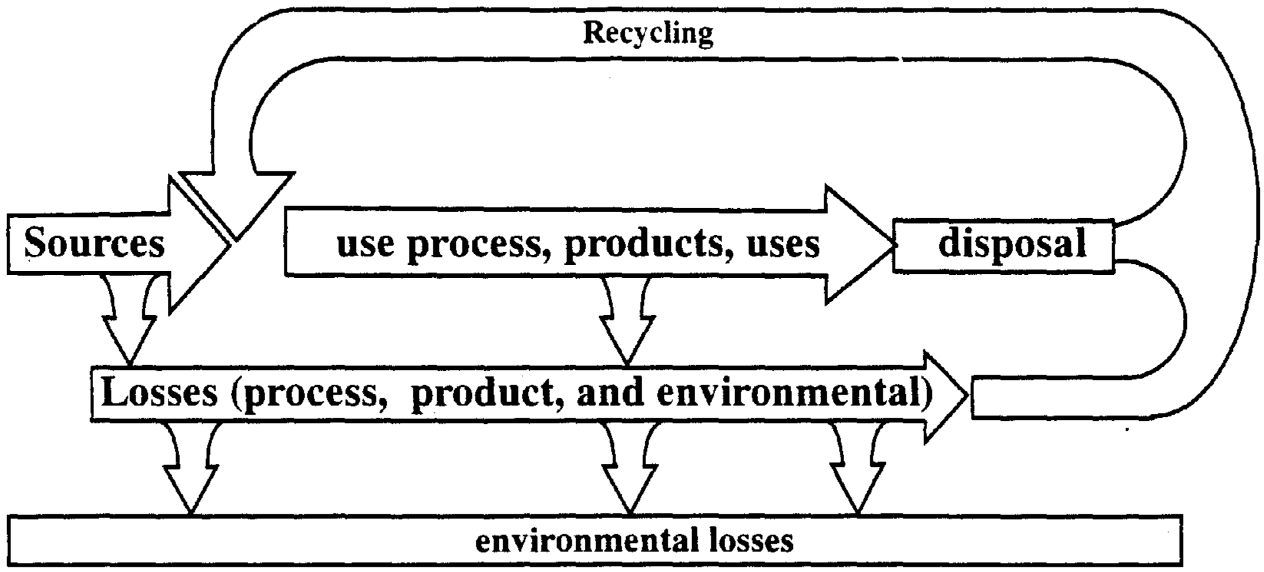


Figure 1. Chromium material flow model.

(chromium ferroalloy or metal producers), and refractory industries. They are the initial consumers of chromium as the material moves through the economy, i.e., those that consume chromite ore to make chromium ferroalloys or chemicals or chromite-containing refractories, or that consume chromium chemicals or ferroalloys to make chromium metal. Post-primary (also called secondary) consumers are those manufacturing industries that consume the primary consumers' products. Bureau-collected data include stocks, shipments, receipts, production, and consumption. In order to assure accurate reporting, the USBM requires mass balance of reported data. This balance in the case of consumption requires ending stocks to equal beginning stocks plus receipts minus shipments minus consumption plus inventory adjustments, for each material reported. All material reported to the USBM is thus accounted for; material losses in the production process are not accounted for in these industry reports. In those cases where both chromium-material consumption and the corresponding chromium-containing product production is surveyed, Bureau data can be used to estimate chromium recovery. In other cases, consumption data reported to the USBM can be compared with production data from non-USBM sources to make similar estimates. It should be noted that industry coverage by these surveys is not complete, as most reporting is voluntary and many companies elect to not report. The USBM also monitors world chromite resources, reserves, and production, consumption, and trade of chromium materials.

Industry endeavors to minimize losses for economic, environmental, and legal reasons. The Environmental Protection Agency (EPA) regulates and monitors industrial impact on the environment. As part of its monitoring activity, EPA collects data on toxic chemicals. For the purpose or data collection, EPA has categorized chromium and chromium compounds as toxic chemicals. That information is made available in the Toxic Release Inventory (TRI). TRI is mandated under Title III of the Superfund Amendments and Reauthorization Act (SARA) of 1986.

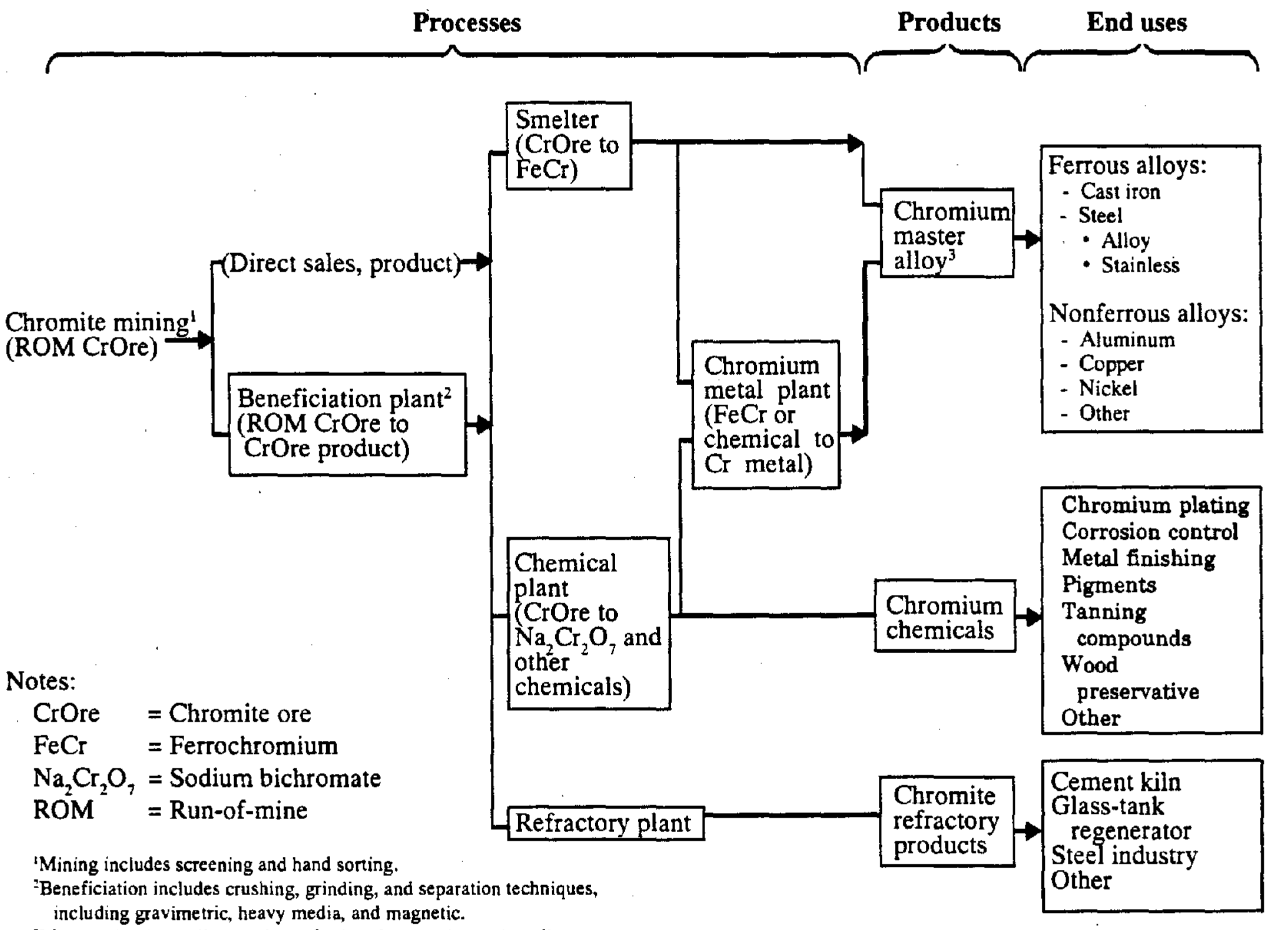
The environmental impact of a chemical depends on the chemical's biological activity, its concentration, and other factors. Chromium environmental impact is complicated by the fact that chromium is an essential element in mammals. However, at high concentrations in the hexavalent form, chromium is toxic. In addition, hexavalent chromium has been identified as a carcinogen. Numerous reviews of the environmental impact of chromium with regard to health have been carried out *(5)*. It is beyond the scope of this report to analyze these studies.

GLOBAL CHROMIUM FLOW

WORLD PRODUCTION AND TRADE IN CHROMIUM MATERIALS

Like other metals, chromium is found at least in small quantities in many types of rock. Chromium is also a constituent of a wide variety of minerals including both oxide and silicate minerals. Chromite, an oxide mineral composed of aluminum, chromium, iron, magnesium, and minor amounts of manganese, nickel, titanium, vanadium, and zinc, is the only chromium mineral of commercial importance. Chromium metal does not occur naturally on earth. Minerals commonly associated with chromite include a group of iron-magnesium silicates. Other minerals associated with chromite include the elements silicon, nickel, calcium, and titanium. Chemical and physical conditions determine which minerals form. At about 185 ppm, chromium is the 13th most common element in the Earth's crust; at about 0.2 ppb, the 26th most common element in seawater *(6)*.

Internationally, chromite ore is consumed in the metallurgical, chemical, and refractory industries. Granville and Statham *(7)* reported that on average about 79 pct of chromium has been consumed by the metallurgical industry, 13 pct by the chemical industry, and 8 pct by the refractory industry worldwide. Boyle and others *(8)* estimated average international distribution of chromite ore products among primary consumer industries in major market economy countries to be: chemical, 14 pct; metallurgical, 77 pct; and refractory (including foundry sand), 9 pct. Gorham *(9)* recently reported that 80 pct of chromium goes into ferrochromium of which 80 pct is used to produce stainless steel. Figure 2 schematically shows the flow of chromium from mine production through end uses.



Notes:

CrOre = Chromite ore
FeCr = Ferrochromium
$Na_2Cr_2O_7$ = Sodium bichromate
ROM = Run-of-mine

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

Figure 2. Industrial chromium material flow.

The industrial chromium material flow figure shows that chromite ore is mined and converted to ferrochromium, chromium chemicals, and incorporated in chromite-containing refractories. By geographically locating mines and manufacturing plants and quantitatively describing chromium production and material movement, one can identify the geographic flow of chromium. Geographic chromium production and material movement data are available in the form of national production and trade statistics. Chromite ore, chromium ferroalloy, and stainless steel production by country data are available from published sources *(10)*. Chromium chemical production data are not available. However, chromium chemical production capacity by country data have been published *(11)*. Domestic industry sources estimated chemical industry chromite ore consumption to have been in the range of from 700 kt-CrOre/y to 800 kt-CrOre/y in 1992, about 6 pct to 7 pct of estimated chromite ore production in that year. Neither production nor production capacity data are available for the chromite-containing refractory industry.

In 1984, the major world chromite ore resource, potential supply, geologic, and production data were reviewed by the U.S. Geological Survey, and availability from market economy countries was analyzed by the USBM *(12)*. Chromite ore producing countries can be divided into three groups based on quantity of production: major, intermediate, and minor producers. Major chromite ore producers are those that consistently produce in excess of 1 Mt-CrOre/y and include South Africa and Kazakhstan. Intermediate chromite ore producers are those that consistently produce between 100 kt-CrOre/y and 1 Mt-CrOre/y and include Albania, Brazil, Finland, India, the Philippines, Turkey, and Zimbabwe. Minor chromite ore producers are those that consistently produce under 100 kt-CrOre/y and include China, Cuba, Egypt, Greece, Indonesia, Iran, Japan, Macedonia, Madagascar, Morocco, Pakistan, Sudan, and Vietnam. Table 1 shows chromite ore production by country. Figure 3 shows the geographic distribution and size of chromite ore producers. Since 1981, at least 2.5 Mt-Cr/y have been mobilized. Mobilization is any process that makes a material mobile (i.e., made available to transportation by natural or human processes). Chromium mobilization is here calculated as the chromium contained in world chromite ore production. Over the 1981 through 1992 time period, the data show an average annual production rate of 3.37 Mt-Cr/y (11.2 Mt-CrOre/y) and an average annual growth rate of 42.9 kt-Cr/y (164 kt-CrOre/y). Chromium reserves in 10 market economy countries were recently estimated at 202.5 Mt-Cr *(13)*.

Ferrochromium production began in technologically developed, industrialized countries that produced steel. In a trend toward vertical integration, chromite-producing countries have been developing ferrochromium production capacity. This trend has worldwide impact. Formerly, ferrochromium was produced mainly by the United States, Europe, and Japan, the major steel-producing areas. Today, South Africa and Kazakhstan are the world's largest ferrochromium producers. As with chromite ore, ferrochromium producing countries can be divided into three major groups based on quantity of production: major, intermediate, and minor. Major ferrochromium producers are those that consistently produce more than 800 kt-FeCr/y and include South Africa and Kazakhstan. Intermediate producers are those that consistently produce from 100 kt-FeCr/y to 300 kt-FeCr/y and include Brazil, Finland, Japan, Russia, Sweden, and Zimbabwe. Minor producers are those that consistently produce less than 100 kt-FeCr/y and include Albania, Chile, China, Croatia, Czechoslovakia, France, Germany, Greece, India, Italy, Macedonia, Norway, Philippines, Poland, Romania, Slovenia, Turkey, and United States. Table 2 shows ferrochromium production by country. Over the 1981 through 1992 time period, the data show an average annual production rate of 1.9 Mt-Cr/y (3.19 Mt-FeCr/y) and an average annual growth rate of 12.7 kt-Cr/y (21.2 kt-FeCr/y). Figure 3 shows the geographic distribution and size of chromium ferroalloy producers.

Stainless steel (SS) was developed around 1900. Production developed in steel producing centers. Today, the use of chromium in stainless steel accounts for the major fraction of world chromium production. The major stainless-steel-producing areas are the Confederation of Independent States (C.I.S.), United States, Europe, and Japan, and these areas are of comparable production volume. As with chromite ore and ferrochromium, stainless-steel-producing countries can be divided into three major groups based on quantity of production: major, intermediate, and minor. Major stainless-steel-producing countries are those that consistently produce in excess of 1 Mt-SS/y and include the C.I.S., United States, Japan, and Germany. Intermediate stainless-steel producers are those that consistently produce between 200 kt-SS/y and 800 kt-SS/y and include Belgium, China, France, Italy, Spain, Sweden, and the United Kingdom. Minor stainless-steel producers are those that consistently produce less than 200 kt-SS/y and include Austria, Brazil, Canada, Finland, India, South Africa, Republic of Korea, Taiwan, and Yugoslavia. (Finland, South Africa, and Republic of Korea have been or are in the process of developing their stainless-steel industries and

Table 1.—World chromite ore production by country

(Thousand metric tons, gross weight)

Country	1981	1982	1983	1984	1985	1986
Albania	710	675	685	720	825	850
Brazil	237	276	161	260	190	353
China	--	--	--	--	--	50
Cuba	21	27	34	38	38	50
Cyprus	10	3	--	--	--	--
Egypt	--	--	--	--	--	--
Finland	412	345	246	446	506	678
Greece	24	29	27	61	59	60
India	335	364	360	423	569	630
Indonesia	--	--	--	--	--	--
Iran	32	41	48	59	56	54
Japan	11	11	8	7	12	11
Kazakhstan	([2])	([2])	([2])	([2])	([2])	([2])
Macedonia	([3])	([3])	([3])	([3])	([3])	([3])
Madagascar	100	44	45	60	127	83
Morocco	--	--	--	--	--	--
New Caledonia	5	50	92	84	79	72
Oman	--	--	24	7	--	5
Pakistan	2	4	6	3	5	8
Philippines	439	322	267	261	272	174
Russia	([2])	([2])	([2])	([2])	([2])	([2])
South Africa	2,870	2,431	2,466	3,407	3,699	3,907
Sudan	25	19	20	20	9	9
Thailand	--	--	--	--	--	--
Turkey	401	453	346	487	589	618
U.S.S.R.	2,903	2,939	2,939	2,940	3,360	3,640
Vietnam	1	1	1	16	4	4
Yugoslavia	NA	--	--	--	10	9
Zimbabwe	561	432	420	477	536	533
Total	9,088	8,480	8,210	9,776	10,945	11,797
Total, Cr content	2,736	2,553	2,473	2,943	3,295	3,551

See footnotes at end of table.

Table 1.—World chromite ore production by country--Continued

(Thousand metric tons, gross weight)

Country	1987	1988	1989	1990	1991	1992
Albania	830	1,109	1,200	910	800	150
Brazil	338	410	476	267	340	340
China	32	26	25	25	25	25
Cuba	52	52	51	50	50	50
Cyprus	--	--	--	--	--	--
Egypt	--	1	2	([1])	1	1
Finland	543	700	498	489	458	480
Greece	64	50	47	22	32	--
India	624	821	1,003	939	995	1,000
Indonesia	--	8	8	8	2	2
Iran	55	60	73	77	90	100
Japan	12	10	12	8	8	8
Kazakhstan	([2])	([2])	([2])	([2])	([2])	3,600
Macedonia	([3])	([3])	([3])	([3])	([3])	9
Madagascar	107	64	63	73	63	63
Morocco	--	1	1	([1])	1	1
New Caledonia	62	70	60	6	--	--
Oman	--	--	13	--	--	--
Pakistan	10	3	27	18	31	30
Philippines	188	129	217	186	184	132
Russia	([2])	([2])	([2])	([2])	([2])	121
South Africa	3,789	4,245	4,951	4,618	5,110	3,361
Sudan	13	8	25	13	10	10
Thailand	--	1	([1])	--	--	--
Turkey	762	851	1,100	800	870	850
U.S.S.R.	3,570	3,700	3,800	3,800	3,800	([4])
Vietnam	4	4	4	4	4	4
Yugoslavia	13	12	12	11	9	([5])
Zimbabwe	570	561	627	643	564	560
Total	11,637	12,896	14,294	12,968	13,445	10,896
Total, Cr content	3,503	3,882	4,303	3,904	4,048	3,208

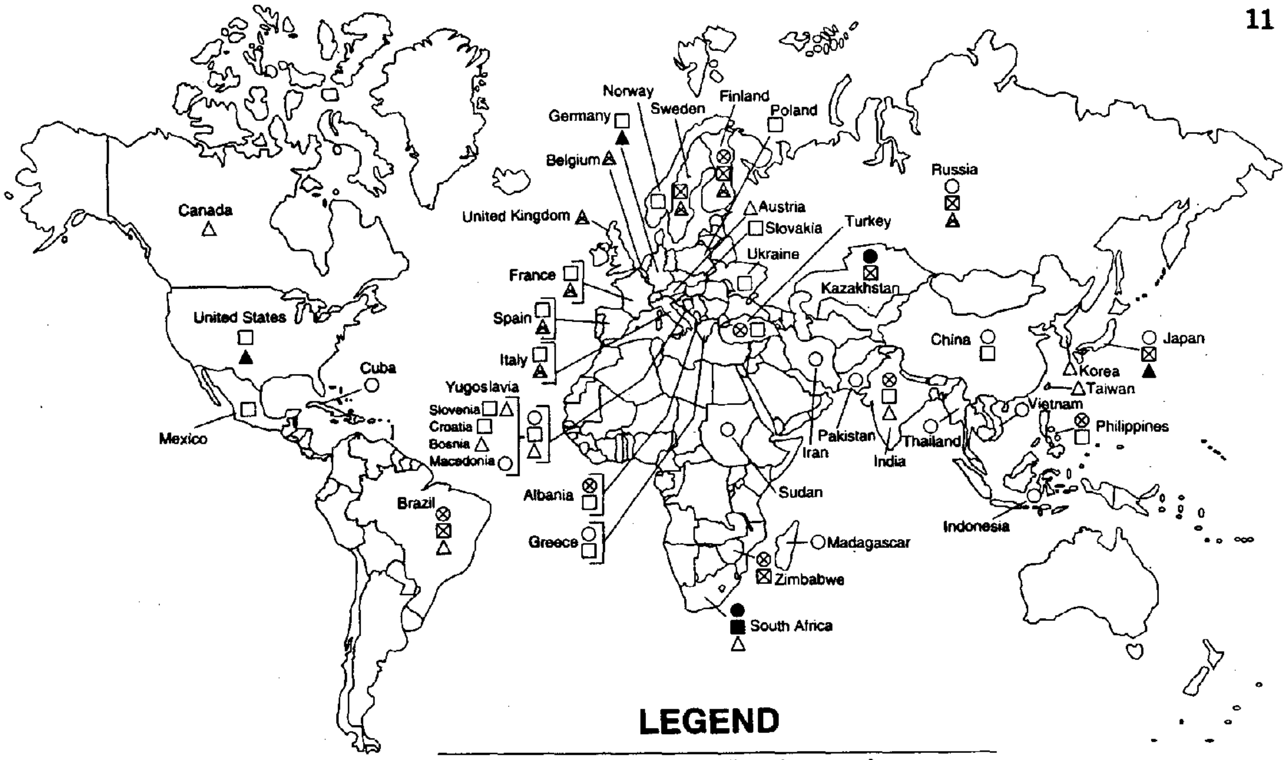
NA Not available. -- No production, production not reported, or production status unknown.
[1]Less than 1/2 unit.
[2]Production reported under U.S.S.R. until 1992.
[3]Production reported under Yugoslavia until 1992.
[4]Dissolved in Dec. 1991.
[5]Dissolved in Apr. 1992.

NOTE. World production converted to chromium content assuming 44 pct Cr_2O_3 average grade of which 68.42 pct is chromium. Chromite ore production is marketable product.
Source: U.S. Bureau of Mines. Chromium. Annu. Rep. various years.

are likely to become intermediate size producers.) Table 3 shows western world stainless steel production by country. Over the 1981 through 1992 time period, the data show an average annual production rate of 1.9 Mt-Cr/y (10.9 Mt-SS/y) and an average annual growth rate of 100 kt-Cr/y (582 kt-SS/y). Figure 3 shows the geographic distribution and size of stainless steel producers.

Based on the production, imports, and exports of chromium-containing materials for a specific geographic area, the chromium consumed in that area can be estimated. National apparent consumption is production plus net trade and represents the average amount of chromium consumed in the national geographic area for the time period and based on the materials used in the calculation. Net trade is imports minus exports. Stock changes impact apparent consumption; however, stock changes are not publicly available information as are imports, exports, and, frequently, production. Using chromite ore production and net trade of that and other chromium materials to calculate chromium apparent consumption, one could map international chromium flow.

The world supply of chromium has been modeled for chromite ore and ferrochromium by Boyle and others *(13)*. Boyle and others evaluated supplier market share (by country) to the major consuming areas (Asia, United States, and Western Europe) for high- and low-carbon ferrochromium. They projected South Africa, Kazakhstan, and Zimbabwe to be the major world chromium (in ore) suppliers under normal market conditions.



LEGEND

	Producer size		
Material	**Major**	**Intermediate**	**Minor**
Chromite ore	●	⊗	○
Ferrochromium	■	⊠	□
Stainless steel	▲	◬	△

Figure 3. World geographic location and size of chromite ore, ferrochromium, and stainless steel producers.

INTERNATIONAL MINING AND BENEFICIATION

In the sense that naturally occurring material is mobilized in the environment, mining is an anthropogenic source of material because the material being mined was fixed in place until it was mined. (Of course, "fixed in place" is based on a human time scale. On a geologic time scale, materials are not fixed in place, they are perpetually circulated.) Part of mine production ultimately becomes manufactured products from which we derive benefit. Another part of mine production, mine waste and tailings, is not used. Mine waste and tailings can represent a substantial amount of low-grade material from which metals may eventually be recovered, as economically warranted. Even municipal waste or dump sites could become the subject of mining; however, probably not for chromium.

The efficiency of domestic and foreign chromite ore mining is dependent on deposit characteristics, mining methods, and commodity value. For example at one extreme, a chromite deposit in which the chromite mineral is massive and clearly visually different from the host rock and that is mined by hand extraction methods may have little waste or losses because only high quality ore is extracted. At the other extreme, a chromite deposit in which the chromite mineral is disseminated (intermixed with host rock) and mining is highly mechanized may require significant amounts of ore beneficiation. As a result of indiscriminate extraction or intermixed minerals, the ore must be beneficiated to produce marketable chromite products. Chromite beneficiation methods such as sorting, screening, and heavy media processing (basically sizing operations) result in 90 pct to 95 pct recovery. (Recovery is process output as a percentage of input. Mine recovery is a term used to identify the amount of material extracted relative to the amount of material in the ground and is not considered in this report. Recovery is here used to identify the amount of chromite products leaving the mining and beneficiation

Table 2.—World ferrochromium production by country

(Thousand metric tons, gross weight)

Country	1981	1982	1983	1984	1985	1986
Albania	28	30	35	40	43	46
Brazil	128	100	83	132	136	119
Chile	--	--	--	--	--	--
China	118	118	118	118	122	NA
Croatia	([1])	([1])	([1])	([1])	([1])	([1])
Czechoslovakia	27	25	25	24	25	28
Finland	52	54	59	59	133	134
France	27	38	20	19	1	1
Germany	70	62	57	64	69	82
Greece	--	--	18	33	34	38
India	36	46	37	59	79	94
Italy	10	36	12	13	58	56
Japan	306	328	298	318	340	281
Kazakhstan	([2])	([2])	([2])	([2])	([2])	([2])
Macedonia	([3])	([3])	([3])	([3])	([3])	([3])
Mexico	3	6	3	7	6	3
Norway	13	11	4	4	--	--
Philippines	10	12	27	48	51	55
Poland	41	35	48	48	49	36
Romania	36	39	42	45	44	44
Russia	([2])	([2])	([2])	([2])	([2])	([2])
Slovenia	([3])	([3])	([3])	([3])	([3])	([3])
South Africa	771	490	693	894	857	875
Spain	17	15	14	14	17	14
Sweden	169	137	138	165	161	143
Turkey	41	40	30	48	50	50
U.S.S.R.	410	425	426	432	432	811
United States	205	108	33	86	100	96
Yugoslavia	74	57	70	73	81	76
Zimbabwe	210	192	185	220	210	240
Total	2,808	2,404	2,475	2,963	3,098	3,322
Total, Cr content	1,685	1,442	1,485	1,778	1,859	1,993

See footnotes at end of table.

Table 2.—World ferrochromium production by country--Continued

(Thousand metric tons, gross weight)

Country	1987	1988	1989	1990	1991	1992
Albania	46	34	39	24	35	15
Brazil	113	130	113	84	82	82
Chile	--	2	3	2	2	2
China	NA	NA	NA	NA	NA	NA
Croatia	([1])	([1])	([1])	([1])	([1])	56
Czechoslovakia	29	29	30	32	34	38
Finland	143	156	169	157	190	187
France	1	13	18	25	23	7
Germany	71	57	55	58	34	27
Greece	42	44	44	30	11	--
India	106	140	135	122	96	100
Italy	59	87	76	53	47	62
Japan	264	295	324	293	271	268
Kazakhstan	([2])	([2])	([2])	([2])	([2])	400
Macedonia	([3])	([3])	([3])	([3])	([3])	6
Mexico	6	9	3	([4])	([4])	([4])
Norway	--	--	--	60	83	102
Philippines	--	73	82	56	24	27
Poland	36	36	24	14	12	10
Romania	42	23	27	21	20	7
Russia	([2])	([2])	([2])	([2])	([2])	500
Slovenia	([3])	([3])	([3])	([3])	([3])	17
South Africa	965	994	1,049	1,022	1,127	665
Spain	16	25	29	15	6	--
Sweden	112	143	154	117	121	130
Turkey	53	54	60	62	85	86
U.S.S.R.	820	1,050	975	975	925	([5])
United States	107	120	147	109	68	61
Yugoslavia	63	93	90	83	60	([6])
Zimbabwe	208	190	210	212	179	186
Total	3,302	3,800	3,856	3,626	3,534	3,041
Total, Cr content	1,981	2,280	2,313	2,176	2,120	1,825

NA Not available. -- No production, production not reported, or production status unknown.

[1]Included with Yugoslavia before 1992.

[2]Production reported under U.S.S.R. until 1992.

[3]Production reported under Yugoslavia until 1992.

[4]Less than 1/2 unit.

[5]Dissolved in Dec. 1991.

[6]Dissolved in Apr. 1992.

NOTE. World ferrochromium production converted to chromium content assuming the average chromium content of ferrochromium to be 60 pct. U.S. 1981-91 ferrochromium imports averaged 58 pct chromium. It is assumed here that world average chromium content of ferrochromium is greater than U.S. average.

Source: U.S. Bureau of Mines. Chromium and Ferroalloys. annu. reports, various years.

process relative to the amount of chromite ore extracted and is measured in contained chromium.) Beneficiation processes (using various forms of gravity separation) result in the recovery of from 65 pct to 85 pct of the chromium contained in the feed material, dependent upon the amount of gravity separation required to produce a marketable chromite ore product. The amount of recovery decreases with increasing number of recovery process stages to which the ore is subjected and increases with declining cutoff grade. (Cutoff grade is the minimum acceptable marketable ore grade.) There are losses at each stage of separation, so recovery declines with the number of sequential stages needed to reach a cutoff grade. As little as 40 pct and as much as 100 pct recovery are achieved. In practice, beneficiation is applied only to material that does not meet marketable product requirements. Material that passes becomes product while material that fails is processed further or becomes waste. Thus, in practice, some material is processed more than others and, on average, a variety of recovery rates is achieved. This wide range of recoveries makes life cycle assessment difficult because one must know from which mine the material came in order to calculate process efficiency and losses. One could estimate average recovery by assuming that most mines use two sequential stages of beneficiation for which each stage yields 85 pct recovery. Average recovery would then be about 72 pct. A world weighted average chromite ore mining industry recovery number would be useful. However, none is

Table 3.—Western world stainless steel production by country

(Thousand metric tons, gross weight)

Country	1981	1982	1983	1984	1985	1986
Australia	38	24	28	39	38	41
Austria	71	74	68	78	68	48
Argentina	--	--	--	10	10	10
Belgium	114	113	133	149	151	165
Brazil	105	94	102	120	140	160
Canada	--	--	30	30	20	70
China	--	--	205	210	215	215
C.I.S.[1]	--	1,710	1,760	1,852	1,922	1,980
Eastern Europe	--	130	120	130	140	160
Finland	87	109	123	158	176	173
France	509	529	544	646	560	611
Germany	753	680	747	878	808	888
India	--	--	70	65	105	137
Italy	393	438	438	520	509	540
Japan	1,862	2,121	2,230	2,595	2,638	2,570
Mexico	--	--	--	5	5	10
South Africa	--	--	--	70	99	102
South Korea	10	10	10	15	20	20
Spain	160	192	197	292	271	273
Sweden	330	329	372	441	435	436
Taiwan	--	--	--	26	32	100
United Kingdom	243	219	229	256	283	294
United States	1,583	1,119	1,591	1,608	1,527	1,529
Yugoslavia	20	20	20	20	20	30
Total	6,374	8,008	9,057	10,213	10,192	10,563
Total, Cr content	1,100	1,381	1,562	1,762	1,758	1,822

See footnotes at end of table.

Table 3.—Western world stainless steel production by country—Continued

(Thousand metric tons, gross weight)

Country	1987	1988	1989	1990	1991	1992
Australia	45	34	--	--	--	--
Austria	54	67	65	49	36	30
Argentina	10	--	--	--	--	--
Belgium	182	264	337	372	360	445
Brazil	192	188	196	186	190	185
Canada	85	127	154	145	150	162
China	220	240	250	240	260	250
C.I.S.[1]	2,000	2,270	2,140	1,790	1,600	1,260
Eastern Europe	185	200	210	140	140	100
Finland	189	206	192	226	258	322
France	700	781	727	797	772	814
Germany	957	1,187	1,169	1,146	1,154	1,163
India	162	176	188	220	265	245
Italy	547	629	619	574	606	645
Japan	2,722	3,160	3,134	3,130	3,357	3,148
Mexico	10	--	--	--	--	--
South Africa	120	122	112	118	120	150
South Korea	40	80	180	360	430	495
Spain	320	426	367	461	454	483
Sweden	455	482	457	471	429	483
Taiwan	131	139	140	150	157	162
United Kingdom	393	428	380	388	374	388
United States	1,836	1,996	1,748	1,851	1,708	1,820
Yugoslavia	35	35	30	31	20	10
Total	11,590	13,237	12,792	12,845	12,840	12,760
Total, Cr content	1,999	2,283	2,207	2,216	2,215	2,201

-- No production, production not reported, or production status unknown.

[1]C.I.S. Confederation of Independent States.

NOTE. World stainless steel production converted to chromium content assuming the average chromium content of stainless steel to be 17.25 pct. (USBM IC 9275.)

Source: World Bureau of Metal Statistics and Inco Europe Limited. World Stainless Steel Statistics, 1991, 1992, and 1993 editions.

available. Fortunately, a recent study *(14)* analyzed average recovery from major market economy country chromite ore producers. That study found average chromite ore mining industry recovery based on Cr_2O_3 recovery to have been 84.3 pct, ranging from 65.9 pct to 90.1 pct. Based on 1989 production reported in table 1, the countries analyzed by production accounted for about 65 pct of the chromite mining industry.

An 84.3 pct recovery suggests that 15.7 pct is unrecovered. However, a second factor in recovery is time. For chromite ore, the average marketable grade has declined. This means that what was mined but not recovered in 1900, or even 1960, may now be marketable grade. Material unrecovered from the mining and beneficiation process yesterday and today (i.e., mine tailings) may be ore at some future time. Indeed, the processing of mine tailings to recover remaining mineral values is practiced for some minerals such as copper, zinc, gold, and silver. To date, the processing of chromite ore tailings for chromite or another mineral, has not been practiced for economic reasons. For the purpose of estimating long-term environmental impact, however, one should at least recognize the possibility of reprocessing tailings. Mine tailings offer a significant economic advantage to the consumer because their mining and milling cost has already been paid. The distinction has here been made between recovered and unrecovered mined material. The term unrecovered was deliberately chosen because there are different points of view about how that material should be classified. In the mining industry, unrecovered material is tailings, i.e., what is left after ore for further processing is separated from mined material (run-of-mine production). As pointed out above, today's unrecovered material may be tomorrow's ore. The tailings may be used to backfill or may be stockpiled. In the short term, chromium contained in tailings is lost and is described as such from a mining and material processing point of view. If one views the beneficiation process as a starting point, tailings may be viewed as losses and material releases to the environment. However, in another sense, chromium contained in tailings is returned to the earth. The tailings are chemically and mineralogically in the same form in which they were taken but physically altered.

Material that has been mined or otherwise exposed to natural forces is generally called mobilized. Tailings that are returned to an underground mine site are not mobile.

The terms losses, releases, and transfers are intended to have a neutral connotation. In other words, one should not consider these materials as automatically ecologically deleterious, an environmental contaminant, or a threat to health. Losses always occur during material processing and use. The quantity of loss that is acceptable is, socially, a moral question and, to industry, an economic question. Practically speaking, zero losses is an unreasonable expectation except when there is zero processing and consumption. Some of mining tailings and waste are releases to the environment. That there is mine waste does not imply that mining is wasteful. Wasteful suggests the generation of waste without regard for the consequences of that waste generation. Waste always occurs in association with processing. As pointed out above, releases from mining can be as simple as returning unaltered material to the earth from which it was taken. For chromium, hexavalent chromium compounds are generally recognized as toxic and, therefore, hazardous. Chromium compounds in which the chromium compounds are in other valance states are generally recognized as not hazardous.

When mining is mechanized, energy in the form of electricity and/or diesel fuel is required. When beneficiation is required, energy is required to operate the screening, classification, crushing and grinding equipment, and/or heavy media separation processes.

Chromite beneficiation may include a variety of crushing or grinding and gravity separation methods which require water to carry the chromite ore through the process. Water is particularly required when ore is reduced to fine sizes. Chemicals are typically not used in the beneficiation processes applied to chromite ore. When gravity separation is required to beneficiate chromite ore from run-of-mine ore to marketable grade products, electrical energy consumption ranges from 10 to 25 kWh/t of run-of-mine ore feed to the treatment process as reported in table 4. Estimated water consumption for beneficiating chromite ore from run-of-mine ore to marketable grade products is about 8 kl/t of ore feed to the treatment process. When grinding is required, grinding balls, rods, and liners are consumed. Estimated grinding components for beneficiating chromite ore from run-of-mine to marketable grade range from 0.25 kg/t-feed to 0.5 kg/t-feed of components *(15)*. When heavy media separation is carried out, ferrosilicon is used for the heavy media. Ferrosilicon is manufactured via an energy-intensive process. (See table 4.)

Table 4.—Chromium processing energy and water losses

Process	Consumption: Electric energy (kWh/t)	Water (kl/t)
Beneficiation[1]	10 to 25	8
Chemical production[2]	12	57
Ferrochromium production[2]	3,954	NA
Chromium metal production[2]	17,000	NA

NA Not available.
[1]Per ton of run-of-mine chromite ore feed processed by gravimetric methods.
[2]Per ton of product.

Sources:
Boyle, E. H., Jr. Minerals Availability Field Office, USBM. Private communication.
Reference 23.
Reference 33.

A potential problem with estimating the material and environmental cost of mining a mineral occurs where the mining/beneficiation operation produces multiple products. The problem is that of allocating cost among byproducts or coproducts. Relative to the principal product, coproducts are those that are of similar economic value; byproducts are of lesser economic value. For chromite mining, there is currently no coproduct or byproduct, and chromite is not currently a coproduct or byproduct of some other mineral mining. This situation may not last because fairly high-grade chromite-containing tailings are associated with platinum group metal production from the UG2 seam in the Republic of South Africa. Eventually, chromite products may be extracted from these platinum-mining tailings and that chromite will be considered a byproduct.

NATURAL AND ANTHROPOGENIC SOURCES OF CHROMIUM

Chromium is ubiquitous in small quantities in the environment. Chromium concentrations associated with various types of rocks and materials are shown in table 5. The largest range and average concentration of chromium is found in the rock types in which chromite ore is found, ultramafic and serpentine rocks. Chromite ore typically ranges from 35 pct to 50 pct Cr_2O_3 content which, in the units of table 5, is equivalent to 2,400 to 3,400 g/t. The presence, distribution, and mobility of chromium within the physical environment (i.e., soil and rock, air, and water) and within the biological environment has been studied.

Commercially used metals are, with only rare exceptions, alloys. Alloys are metallic substances composed of more than one, usually metallic, element. In this context, the metallic constituent of an alloy present in the highest proportion is called the base metal, and the remaining elements are called alloying elements. The major use of some metals is as a base metal, for example aluminum, copper, iron, and lead. The major use of other metals is as an alloying element, for example chromium, columbium, molybdenum, nickel, tantalum, and vanadium. Chromium is an alloying element used primarily to make stainless steel. In the process of being used to make stainless steel, chromite ore is first smelted to produce ferrochromium, an iron-chromium master alloy. The term master alloy is used because ferrochromium is an intermediate industrial commodity used as a source for chromium units to make commercial alloys from which parts, components, and products are manufactured. Ferrochromium is added to molten iron along with other materials and processed to make steel. In addition to alloying with iron to make stainless or alloy steel, chromium is also alloyed with aluminum, cobalt, copper, nickel, and titanium. Ferrochromium or some other master alloy is the source of chromium for alloying with these metals. Chromium is lost to the environment at each stage of the commercial metal production process: mining, beneficiating, transporting, smelting, alloy production, and processing into parts and products.

World natural and anthropogenic sources of chromium air emissions have been studied and quantified *(16)*. Table 6 shows world emissions of chromium to the atmosphere from natural and anthropogenic sources. The table shows that natural and anthropogenic sources are comparable in magnitude and that, together, they are about 2 pct of chromium contained in 1989 world chromite ore production. The largest natural source is windblown soil particles, and the largest anthropogenic source is from iron and steel manufacturing.

World anthropogenic chromium input to aquatic ecosystems has been studied and quantified *(17)*. Table 7 shows anthropogenic chromium input to aquatic ecosystems. The table shows that metals manufacturing is the major anthropogenic source of chromium to aquatic ecosystems. World anthropogenic chromium input to aquatic ecosystems is about 3 pct of chromium contained in 1989 world chromite production.

World sources of chromium to soil have been studied and quantified (7). Table 8 shows chromium inputs to soil by source category. The table shows that discarded manufactured products are the major source of chromium input to soil. Chromium input to soils is about 21 pct of chromium contained in 1989 world chromite production. The authors of table 8 data appear to have erred in their estimate of "Discarded manufactured products." See Estimation of Chromium Release to Soils section under Discussion.

Two major inputs to soils are absent, mine tailings and smelter slags and wastes. Both of these sources are substantial but of local impact and are of ambiguous status. As pointed out previously in this report, tailings may be returned (and thereby immobilized) to their place of origin as backfill or may, at some later time, become ore. Ferrochromium slag too can be exploited for the recovery of metal content. Ferrochromium slag is currently being studied and exploited for its chromium content *(18)*.

In table 8, process losses appear to be included in "Solid wastes from metal fabrication" and product losses in "Discarded manufactured products." Losses from manufacturing process other than metals fabrication do not appear to be accounted for.

World estimates of chromium released to the environment (i.e., air, water, and soil) by major sources amounted to about 26 pct of chromium contained in 1989 world chromite mine production, based on world production from table 1, emissions from table 6, aquatic inputs from table 7, and soil inputs from table 8. Chromium released to the atmosphere from natural and anthropogenic sources (as reported in table 6) were comparable in magnitude. Chromium released to soils (as reported in table 8) were mostly from anthropogenic sources, and aquatic releases (as reported in table 7) were all anthropogenic.

Table 5.—Chromium in the environment

(Grams per metric ton)

Type of material	Chromium content[1] Range	Chromium content[1] Average	Chromium content[2]
Continental crust	--	--	88
Oceanic crust	--	--	317
Ultramafic and serpentine	1,100 - 3,400	1,800	--
Basaltic and gabbroic rocks	60 - 420	200	168
Andesitic, dioritic rocks	10 - 200	50	--
Granitic rocks	2 - 60	5	12
Granulitic rocks	--	--	88
Gneisses, mica schists	--	--	76
Limestones	--	--	11
Limestones and dolomites	--	11	--
Sandstones	--	35	--
Shales	--	--	90
Greywackes	--	--	50

See footnotes at end of table.

Table 5.—Chromium in the environment--Continued

(Grams per metric ton)

Type of material	Chromium content[1] Range	Chromium content[1] Average	Chromium content[2]
Clays and shales	1 - 200	90	--
Soils	10 - 150	40	--
Phosphorites	30 - 3,000	300	--
Coal	--	10	--
Brown	--	--	9
Hard	--	--	13
Crude oil	--	--	0.12
Water:			
River	--	--	0.001
Sea	--	--	0.0002

-- Not reported.
[1]Environmental Protection Agency. Reviews of the Environmental Effects of Pollutants: III. Chromium. EPA-600/1-78-023, May 1978, p. 200.
[2] Wedepohl, K. H. The Composition of the Upper Earth's Crust and the Natural Cycles of Selected Metals. Metals in Natural Raw Materials. Natural Resources. A paper in Metals and Their Compounds in the Environment. Occurrence, Analysis and Biological Relevance. Ed. by E. Merian. VCH, New York, 1991, pp. 3-17.

Table 6.—World emissions of chromium to the atmosphere by source category

(Thousand metric tons per year)

Source category	Range	Median
NATURAL[1]		
Wind-borne soil particles	3.6 - 50	27
Seasalt spray	0.03 - 1.4	0.07
Volcanoes	0.81 - 29	15
Wild forest fires	0 - 0.18	0.09
Biogenic (total):	(0.1 - 2.22)	(1.11)
Continental particulates	0.1 - 2.0	1.0
Continental volatiles	0 - 0.10	0.05
Marine	0 - 0.12	0.06
Total	4.5 - 83	44
ANTHROPOGENIC[2]		
Energy production (total):	(3.365 - 22)	12.7
Coal combustion:		
Electric utilities	1.24 - 7.75	--
Industry and domestic	1.68 - 11.88	--
Oil combustion:		
Electric utilities	0.087 - 0.58	--
Industry and domestic	0.358 - 1.79	--
Mining	NS	--
Smelting and refining:		
Copper-nickel production	NS	--
Zinc-cadmium production	NS	--

See footnotes at end of table.

Table 6.—World emissions of chromium to the atmosphere by source category--Continued

(Thousand metric tons per year)

Source category	Range	Median
ANTHROPOGENIC[2]		
Lead production	NS	--
Secondary nonferrous production	NS	--
Manufacturing processes:		
Steel and iron manufacturing	2.84 - 28.4	17
Refuse incineration (total):	(0.248 - 1.43)	0.84
Municipal	0.098 - 0.98	--
Sewage sludge	0.15 - 0.45	--
Phosphate fertilizer	NS	--
Cement production	0.89 - 1.78	--
Wood combustion	NS	--
Mobile sources	NS	--
Miscellaneous	NS	--
Total	7.34 - 53.61	30.48

NS Not significant. -- Not reported.
[1]Reference 16.
[2]Reference 17.

Table 7.—World anthropogenic chromium input to aquatic ecosystems by source

(Thousand metric tons per year)

Source category	Range[1]	Median[2]
Domestic wastewater (total):	(14.1 - 78)	46
Central	8.1 - 36	--
Non-central	6.0 - 42	--
Electric powerplants	4.8 - 18	5.7
Base metal mining and smelting (total):	(3 - 20.7)	12
Base metal mining and dressing	0 - 0.7	--
Iron and steel	NS	--
Nonferrous metals	3 - 20	--
Manufacturing processes (total):	(17.51 - 83.71)	51
Metals	15 - 58	--
Chemicals	2.5 - 24	--
Pulp and paper	0.01 - 1.5	--
Petroleum products	0 - 0.21	--
Atmospheric fallout	2.2 - 16	9.1
Sewage discharges	5.8 - 32	19
Total	45 - 239	143

NS Not significant. -- Not reported.
[1]First work cited in reference 17.
[2]Second work cited in reference 17.

Table 8.—World chromium inputs to soils by source category in 1983

(Thousand metric tons per year)

Source category	Range[1]	Median[2]
Agricultural and animal wastes (total):	(14.5 - 150)	82
Agricultural and food wastes	4.5 - 90	--
Animal wastes, manure	10 - 60	--
Logging and wood wastes	2.2 - 18	10
Urban refuse	6.6 - 33	20
Municipal sewage and organic waste (total):	(1.5 - 11.48)	6.5
Municipal sewage sludge	1.4 - 11	--
Miscellaneous organic, including excreta	0.1 - 0.48	--
Solid wastes from metal fabrication	0.65 - 2.4	1.5
Coal ashes	149 - 446	298
Fertilizers and peat (total):	(0.07 - 0.57)	0.32
Fertilizer	0.03 - 0.38	--
Peat (agricultural and fuel uses)	0.04 - 0.19	--
Discarded manufactured products (see note)	305 - 610	458
Atmospheric fallout	5.1 - 38	22
Total	484 -1,309	898
Mine tailings	--	--
Smelter slags and wastes	--	--
Total discharge on land	--	--

-- Not reported.
[1]First work cited in reference 17.
[2]Second work cited in reference 17.

NOTE. The source identifies "Discarded manufactured products" as material that ended up in soil as a result of commercial use (for example, in chemical, pigments, or fertilizers) or lost to soil during or after commercial use (for example, discarded, applied, or washed off due to corrosion). Source authors reported assuming "Discarded manufactured products" to have been 5% to 10% of world mine production of 8.9 million tons. These estimates are too large by a factor of more than two. See discussion section of this report.

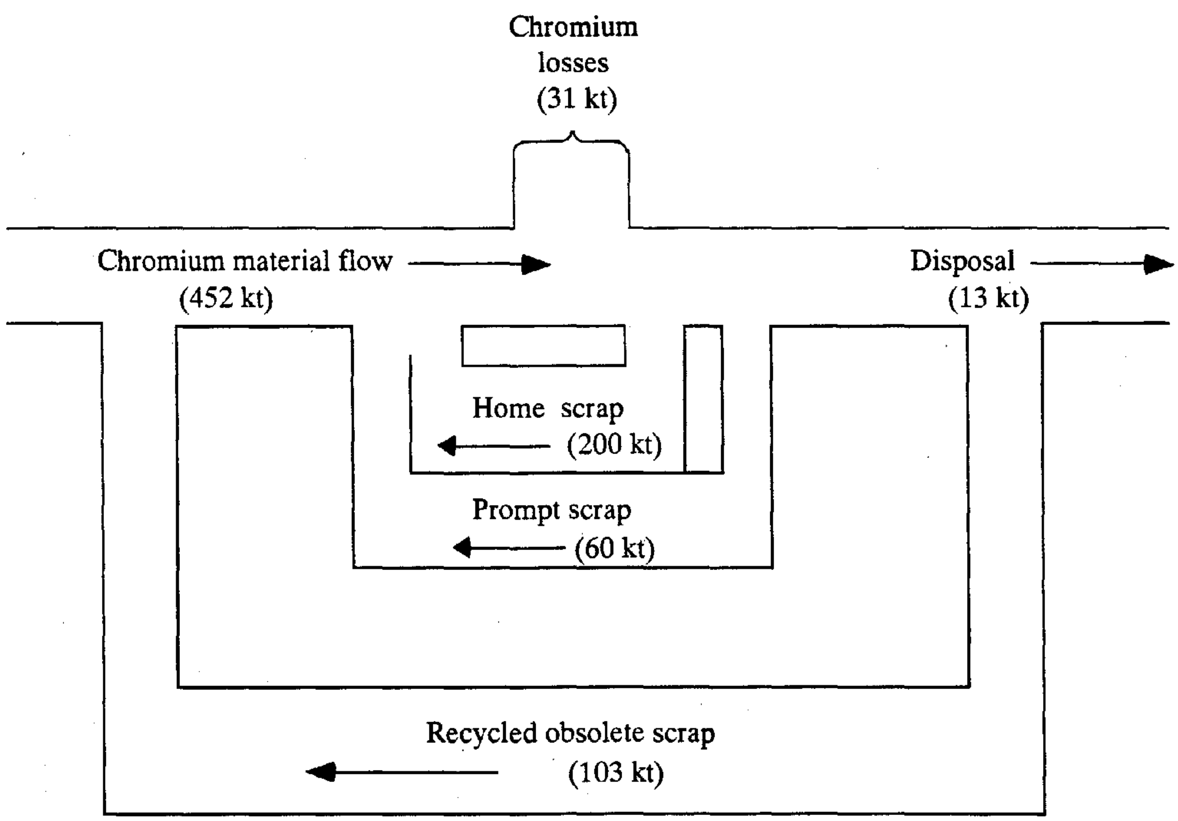
U.S. CHROMIUM FLOW

Chromite ore is not currently mined in the United States. Imported chromite and other chromium-containing materials are processed by domestic primary consumers (chemical, metallurgical, and refractory industries). These industries supply post-primary domestic industry and export their chromium-containing products. Post-primary domestic industry uses both domestically produced and imported chromium-containing materials.

On average, from 1983 through 1992, U.S. chromium apparent consumption was about 87 pct by the metallurgical industry, 10 pct by the chemical industry, and 3 pct by the refractory industry. During the same time period, average chromium apparent consumption was 400 kt-Cr/yr. Apparent consumption is production plus net trade plus stock changes. For the purpose of this calculation, production included only recycled stainless steel scrap reported as stainless steel scrap receipts to the USBM. Net trade is imports minus exports and included chromite ore, chromium ferroalloys and metal, and selected chromium chemicals—mostly sodium and potassium bichromate but including other chemicals where trade data and chromium content factors were available. Stock changes were limited to those reported by consumers and producers. This method differs slightly from that typically used by the USBM to calculate chromium apparent consumption in that for this report, National Defense Stockpile stock changes were ignored. To calculate the metallurgical, chemical, and refractory components of U.S. apparent consumption: production, net trade, and stock changes need to be divided among these industries. Stocks clearly distribute among these industries by which company is reporting them. Production clearly distributes among these industries because only stainless steel receipts used to make steel alloy products contributed—all of which belongs in the metallurgical industry. The problem comes in distributing the trade data (especially chromite ore) among these industries. Chromium ferroalloys and metal trade was allocated to the metallurgical industry. Chromium chemical trade was allocated to the chemical industry. No refractory trade data were used in the chromium apparent consumption calculation. Chromite ore consumption is reported to the USBM by all three industries. Reported chromite consumption data were used to distribute chromite ore trade (imports and exports) among the primary consumer industries in proportion to their fraction of reported consumption. U.S. chromium apparent consumption was thus calculated by primary consumer industry.

U.S. MINING AND BENEFICIATION

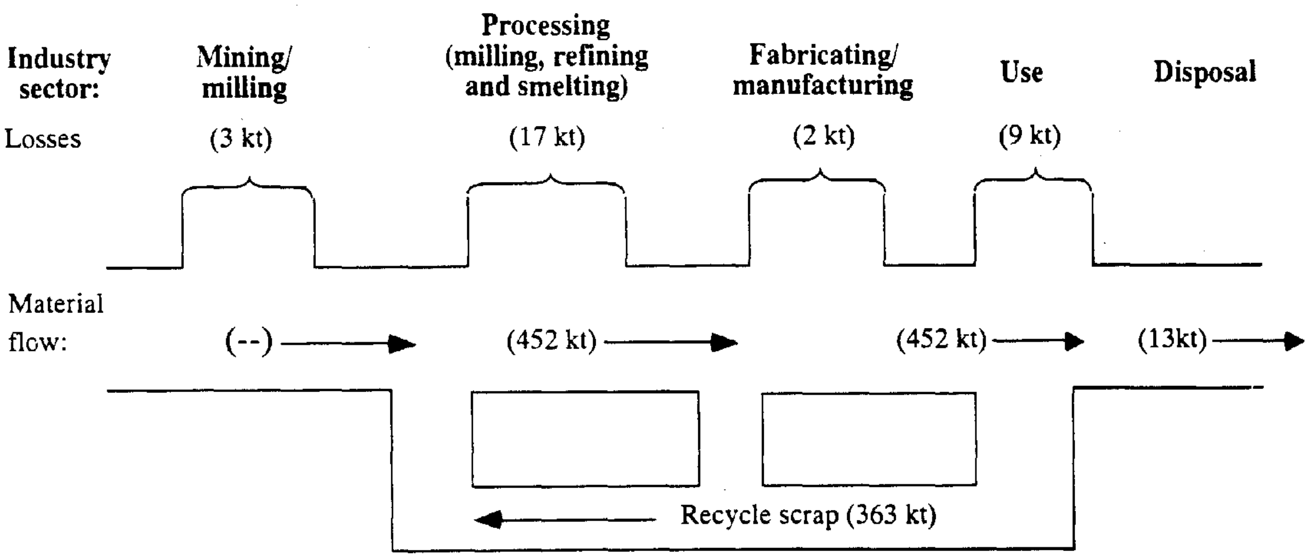
No chromite ore has been mined in the United States since 1976 (production data were withheld company proprietary information). No significant time period of continuous chromite ore mining has occurred in the United States since the Defense Production Act (DPA) of 1950 encouraged domestic chromite ore mining during the Korean war. Chromite ore mining ended shortly after the DPA expired in 1959. Thus, domestic chromite ore material flow in the mining industry is zero. (See Historical Trends in U.S. Chromium Flow section of this report for more



Sources: Gabler, R. U. S. Bureau of Mines.
Environmental Protection Agency, Toxic Release Inventory (TRI).

NOTES: Chromium losses include manufacturing releases as reported in TRI, releases for coal and oil combustion, and release from phosphate mining.
Chromium material flow is apparent consumption which is primary plus secondary production plus imports minus exports plus adjustment for stock changes. Secondary production is purchased stainless steel scrap.
Disposal is transfers as reported in TRI.
Home scrap is home scrap as reported by Gabler, U. S. Bureau of Mines.
Prompt scrap is prompt scrap as reported by Gabler, U. S. Bureau of Mines.
Obsolete scrap is obsolete scrap as reported by Gabler, U. S. Bureau of Mines, also includes obsolete stainless steel, superalloys, and foundry sand.

Figure 4. U.S. chromium material flow, recycling, and losses in 1989. (Thousand metric tons, contained chromium)



Sources: U. S. Bureau of Mines:
Gabler, R.
Mineral Commodity Summaries 1992.
Environmental Protection Agency. Toxic Release Inventory (TRI).

NOTES: Losses are chromium contained in chromium and chromium compound releases reported in TRI database plus releases from coal and oil combustion, and processing and use of phosphate rock.
Material flow is: null for mining; chromium apparent consumption as reported in Mineral Commodity Summaries for processing and fabrication/manufacturing; and is transfers as reported in TRI database.
Recycled is chromium contained in home, prompt, and obsolete scrap as reported by Gabler.
Disposal is chromium contained in chromium and chromium compound transfers reported in TRI database.

Figure 5. U.S. chromium material flow, losses, disposal, and recycling in 1989 by industry. (Thousand metric tons, contained chromium)

historical information about chromite ore mining in the United States.)

CHROMITE ORE USE

Chromite consumption in the United States by primary consumer industry is monitored by the USBM; statistics provided voluntarily by domestic industry on the consumption of chromite and chromium-containing materials are collected. Most recently available statistics show that chromite ore is consumed by the chemical and metallurgical, and refractory industries and that chromium ferroalloys and metal are consumed by the metallurgical industry (including steel, cast iron, superalloy, and welding material producers). Table 9 identifies the chromite ore and chromium ferroalloy and metal by primary consumer industry and shows the quantity (both gross weight and contained weight) of material consumed in 1990. The table shows that the chemical and metallurgical industry is the major domestic consumer of chromite ore and that the steel industry is the major user of chromium ferroalloys and metal.

Chromite ore use by the chemical or metallurgical industry is not publicly available. Chemical industry chromite ore use in the United States has been combined with metallurgical industry chromite ore use to protect company proprietary data collected by the Bureau since Allied Chemicals closed its Baltimore, MD, chromium chemicals plant in 1985 leaving only two U.S. primary chromium chemical producers. At about the same time, the number of metallurgical industry chromite ore consumers dropped to only two companies. Industry sources estimate that U.S. chemical industry chromite ore consumption is in the range of 140 kt-CrOre/y to 160 kt-CrOre/y.

By comparing reported consumption of chromite ore and reported production of chromium materials from that ore, overall industry chromium recovery efficiency can be estimated. The chemical, metallurgical, and refractory industries voluntarily provide the USBM with chromite ore consumption data; the chemical and metallurgical industries voluntarily provide the Bureau with chromium material production data. The refractory industry has the option to provide chromium-containing material shipments data.

Table 9.—Quantity and percent of chromium reported consumption in the United States by primary consumer industry in 1990

Primary consumer industry	Quantity consumed: Gross weight (metric tons)	Quantity consumed: Chromium content (metric tons)	Percent of total chromium consumed
Chromite ore:			
Chemical and metallurgical	361,176	108,237	90.0
Refractory	44,237	12,046	10.0
Total	405,413	120,107	100.0
Chromium ferroalloys and metal:			
Steel	362,099	207,609	91.7
Cast irons	9,890	5,910	2.6
Superalloys	12,199	9,318	4.1
Welding materials	1,413	963	0.4
Other materials	3,273	2,015	0.9
Misc. and unspec[1]	805	540	0.2
Total	389,680	226,355	99.9

[1]Miscellaneous and unspecified.

Source: Papp, J.F. Chromium. USBM Annu. Rep., 1993, 51 pp.

However, no refractory producers elect to provide shipment data. Because of differing accounting practices and design of USBM survey forms, it is not possible to precisely account for all chromium material flow. However, it is possible to estimate industry chromium recovery based on reported chromite ore consumption and chromium material production or shipments. Because USBM surveys do not try to account for all material flow, our recovery estimate is likely to be low. For example, because information on material sent off-site for reclamation or stockpiled for later processing is not collected, such material would not be accounted for in the USBM's data collection process and would simply disappear from the accounting system, resulting in lower recovery estimates.

Recovery is the percent chromium contained in products with respect to that in feed material, i.e., chromium contained in products divided by chromium contained in feed stock times 100. By this definition, 100 pct recovery indicates that all of the chromium contained in the input material ended up in the product and that there are no chromium losses. Table 10 shows recovery by industry averaged over a time period based on USBM data, on published sources, and on estimates.

The chemical and metallurgical industries are substantially different in chromite ore processing and the magnitudes and destination of losses. It would be desirable, therefore, to analyze consumption by these industries independently. Because there are few domestic producers in these industries (two ferrochromium and two chemical producers), the USBM withholds consumption data to protect company proprietary information.

Chemical Industry

In the chemical industry, chromite ore is converted to sodium bichromate, the common name for sodium dichromate dihydrate. Chromite ore is typically kiln roasted with soda ash to produce sodium bichromate. Although chemical manufacture is a mature industry, process changes continue to take place.

In 1956, Copson *(19)* reported that sodium chromate was produced from chromite ore, soda ash, lime, and recycled residue by roasting in a kiln. The kiln product was then converted to sodium bichromate. Quantity of feed materials used depends on the composition of the chromite ore among other factors. However, to produce 1 ton of sodium bichromate from a 44 pct Cr_2O_3 South African ore, it took a range of from 1.35 t-CrOre to 1.55 t-CrOre, 0.8 t to 1.2 t of soda ash (Na_2CO_3), zero to 0.9 t of lime (CaO), 0.425 t to 0.75 t of sulfuric acid, 30 MBtu to 50 MBtu of fuel, 0.4 MWh to 0.6 MWh of electrical energy, and 15 to 25 workerhours. In addition to the sodium bichromate product, the process yielded 0.6 t to 0.9 t of sodium sulfate (Na_2SO_4). Alumina and vanadium byproducts may also be recovered. Incomplete oxidation in the roasting process and incomplete leaching result in chromium losses in the range of from 10 pct to 20 pct of that contained in the chromite ore. Recycling of the residue, a common practice, increases recovery. However, losses of 10 pct

Table 10.—Chromium recovery[1] by end-use industry

(Percent)

Industry	U.S. Bureau of Mines: Chromium recovery	U.S. Bureau of Mines: Standard deviation or range	Open literature: Chromium recovery	Open literature: Standard deviation	Estimated: Chromium recovery
Beneficiation[2]	[3] 84.3	[3] 65.9-90.1	[4] 13 - 92	NA	NA
Chemical[5]	81	5.4	[6] 80 - 90	NA	NA
Metallurgical[7]	80	7.4	80 - 95	NA	NA
Refractory	NA	NA	NA	NA	70

NA Not available.
[1]Chromium recovery is chromium contained in product divided by chromium contained in feed material(s) times 100.
[2]International chromite mining industry, selected producers. (See reference 13.)
[3]Reference 14.
[4]Indian Bur. of Mines. Mineral Facts and Problems No. 6. Chromite. Mar. 1982, pp. 301-316.
[5]U.S. Chemical industry included three plants that converted chromite ore into sodium bichromate.
[6]Reference 19.
[7]U.S. metallurgical industry included two plants that converted chromite ore into ferrochromium.

NOTE. Chromium recovery is calculated as an industry average from 1983 to 1992. Efficiency based on consumption and production and may not include material recovered from process waste streams.

to 20 pct were reported, indicating 80 pct to 90 pct recovery.

In 1979, Hartford *(20)* reported that chromite ore, soda ash, and (optionally) lime and leachate residue are kiln roasted to produce sodium chromate, which is subsequently dissolved and precipitated as sodium bichromate. Depending on the production technology, up to 0.57 t of lime and up to 3 t of leachate residue may be used per ton of ore feed. A typical mix for the first stage of a two-stage roasting process was 0.625 t of soda ash, 0.5 t of lime, and 0.490 t of leachate residue per ton of chromite ore feed. In 1981, Foley *(21)* reported raw material feed stock use per ton of sodium bichromate product at 1.3 t-CrOre, 0.98 t of soda ash, and 2.0 t of residue. In 1984, Thompson *(22)* found recoveries to vary from 45.6 pct to 81.3 pct depending on the chemical composition of the chromite ore being processed. In this laboratory scale study, the objective was to determine the effect of mineral structure on recovery, so a wide variety of chromite ores were used including many not considered to be chemical grade. Interestingly, in that study chromite ore from the Republic of South Africa had the highest recovery. Republic of South African ore is the preferred chromite ore for chemical industry processing. In 1989, Hersch *(23)* estimated material and energy requirements to produce 1 ton of sodium bichromate at 1.1 t-CrOre to 1.3 t-CrOre, 1.7 t of limestone, 0.8 t of lime, 0.5 t of sulfuric acid, 57 kl of water, and 12 MWh. In 1993, industry sources characterized U.S. sodium bichromate production as requiring in the range of 1.2 t-CrOre to 1.5 t-CrOre, 0.4 t to 1.0 t of soda ash, zero to 0.6 t of sulfuric acid, 20 MBtu to 30 MBtu of fuel, 0.3 MWh to 0.5 MWh of electrical energy per ton of sodium bichromate product.

The USBM chemical industry survey data on chromite consumption and chromium chemical production from 1983 to 1992 for the three chromium chemical producers active during that time period yielded an average recovery of 81 pct with a standard deviation of 5 pct. (See table 10.)

The USBM has developed a process to recover chromium in the form of sodium chromate from low-grade domestic ores *(24)*. The Bureau process includes the roasting of chromite ore with sodium hydroxide. In laboratory scale trials, the best chromium extraction achieved ranged from 69.5 pct to 98.9 pct, depending on ore characteristics. Best recoveries were achieved at higher reaction temperatures, longer reaction times, and larger sodium hydroxide to chromite ore weight ratios. Four units of sodium hydroxide to one unit of chromite ore was identified as the minimum useful weight ratio with tests carried out at weight ratios up to 6 to 1.

Refractory Industry

Chromite ore is consumed in the refractory industry to make refractory products. The major product is refractory bricks, which are a combination of chromite and magnesia. The process by which refractory bricks are produced includes crushing, grinding, and sizing of chromite ore. Refractory industry processes that lead to chromium emissions include ore handling; crushing, grinding, and sizing; casting; fusing; and milling *(25)*. The desired combination of chromite and magnesite is blended, compressed, and sometimes baked. Other chromite refractory products include shapes (other than bricks), plastics, and mortars. Chromite refractories are consumed in the steel, copper, glass, and cement producing industries. Cr_2O_3, a chemical industry product, is also used to make chromium-containing refractories for the glass manufacturing industry.

Because particle sizing and the correct mixture of particle sizes is important in refractory manufacturing, for the purpose of estimating recovery, it was assumed that chromite beneficiation in the refractory industry is a sequential two-stage process and that each stage has 85 pct recovery. Thus, refractory industry recovery is estimated at about 70 pct. (See table 10.)

Metallurgical Industry

Chromium Ferroalloy Industry

Chromite ore is fed into an electric arc furnace where it is heated to a high temperature (at least 1,100 °C to 1,200 °C) and reacted with carbon. Under these conditions, the chromite (a compound of chromium, iron, and oxygen) reacts with carbon, leaving an iron and chromium compound that solidifies into ferrochromium. Other materials are added, which form slag. Chromium ferroalloys are an industrial product used by the metallurgical industry to add chromium to metal alloys. Chromium ferroalloy production is an electrical-energy-intensive process.

There are three major grades of chromium ferroalloy: high-carbon ferrochromium, low-carbon ferrochromium, and ferrochromium-silicon. High-carbon ferrochromium has two major subdivisions, high-chromium and low-chromium, which is also called charge-grade or charge chrome. Different processes, resulting in different material and energy consumption, have been and are currently used to produce low- and high-carbon ferrochromium and ferrochromium-silicon. Robiette *(26)* identifies several methods associated with the production of low-carbon ferrochromium and ferrochromium-silicon. The various methods are shown in table 11. Each chromium ferroalloy is produced in a somewhat different manner and therefore requires different amounts of energy, raw materials, and water. Since the oil energy crisis of the 1970's, high-carbon ferrochromium processes have been designed to be energy conservative (by minimizing waste heat). Others have been designed to substitute other sources of energy for electrical energy, yet others have been designed to substitute other reductants for metallurgical-grade coke.

Historically, direct produced stainless steel (low-carbon steel smelted with chromite ore) was replaced by aluminothermically produced low-carbon ferrochromium added to iron to make stainless steel, which was replaced by high-carbon ferrochromium added to iron and refined to reduce carbon to make stainless steel. Since about 1960, when carbon-reducing refining processes were introduced, high-carbon ferrochromium has replaced low-carbon ferrochromium as the major source of chromium units for the production of stainless steel. In the United States today, low-carbon ferrochromium consumption is only about 10 pct of that of high-carbon ferrochromium, and ferrochromium-silicon consumption is even less than that of low-carbon ferrochromium.

Based on USBM survey data, on average from 1983 through 1992, stainless steel production accounted for 79 pct of reported consumption and high-carbon ferrochromium accounted for 95 pct of reported material consumption by the stainless steel industry. Based on the overwhelming fraction of chromium use in stainless steel and the overwhelming use of high-carbon ferrochromium in the production of stainless steel, it is recommended that material and energy consumption for high-carbon ferrochromium be used in life cycle studies unless specific product information suggests otherwise.

Udy *(27)* reported electrical energy required for high-carbon ferrochromium production to have been in the range of 5.5 MWh/t-FeCr to 10.5 MWh/t-FeCr; low-carbon ferrochromium and ferrochromium-silicon, in the range of 13.5 MWh/t-FeCr to 14.5 MWh/t-FeCr.

Robiette *(26)* reported chromium recovery efficiency to have been 85 pct to 90 pct (85 pct without chromium recovery from slag, 90 pct with chromium from slag recycled) and iron recovery efficiency to have been 95 pct for high-carbon ferrochromium production. Robiette reported conventional electric arc furnace smelting energy consumption to have been in the range of 3.94 MWh/t-FeCr to 4.35 MWh/t-FeCr with the higher value associated with charge-grade material. Robiette reported material consumption, per ton of high-carbon ferrochromium product, to have been: ore, 2.236 t; gravel (silica source), 0.214 t; coke and wood chips (carbon source), 0.473 tons; concentrates from slag and scrap, 0.115 t; alumina-containing material, 0.179 t; and electrodes, 0.022 t. Material consumption was reported to have been, per ton of charge grade high-carbon ferrochromium product: ore, 2.43 t; quartz

Table 11.—Processes by which chromium ferroalloys are produced

Chromium ferroalloy	Process
Ferrochromium-silicon[1] . .	Single stage.
	Two stage.
	[2]Indian.
Ferrochromium:	
Low-carbon[1]	[2]Aluminothermic.
	Duplex (variation of Perrin).
	Perrin.
	Simplex.
	Swedish (Triplex).
High-carbon	[2]Open furnace.
	Semiclosed furnace.
	Preheated and/or prereduced charge.
	Outokumpu.
	Showa Denko.
	Japan Metals and Chemicals.
	[2]Chromite Direct Reduction (Krupp/MS&A).
	DC electric arc plasma furnace.

[1]Reference 26.
[2]Not practiced in 1993.

NOTE. All processes require the use of an electric arc furnace at some point in the processing of chromite ore into chromium ferroalloy.

(silica source), 0.14 t; fluorspar, 0.03 t; coal and coke (carbon source), 0.62 t; and electrodes, 0.015 t.

Elyutin and others *(28)* reported a process that consumed 1.85 t of chromite ore (50 pct Cr_2O_3—an uncommonly high grade) and 0.45 t of coke dust product to produce 1 t of ferrochromium at an energy cost of from 3.4 MWh to 3.5 MWh. In this process, chromium recovery was 90 pct to 94 pct. Lowering the carbon content of the product increased the energy consumption to 3.7 MWh/t-FeCr. An Office of Technology Assessment *(29)* study of potential chromium recovery in the United States based on 1974 data identified the efficiency of the domestic ferrochromium industry at that time to have been about 85 pct to 90 pct, i.e., about 15 pct to 10 pct of chromium contained in feed material was not recovered in useful products.

Subramanian and others *(30)* reported that a recently constructed ferrochromium plant designed to take advantage of less expensive fine ore required fine ore agglomeration followed by smelting of a blend of briquetted fine and lumpy ore, conventional with the briquetting process. Smelting required about 3.9 MWh/t-FeCr with cold feed stock. It was found that recovery of waste heat in the form of hot gases resulting from smelting could reduce the smelting energy requirement by 0.08 MWh for every 100 °C that the feed material temperature could be raised. Energy and materials are required for agglomeration when such a process is used. Subramanian and others reported chromium recovery from the beneficiation process to have been from 63.70 pct to 74.56 pct, and material use per ton of ferrochromium product to have been about as follows: chromite ore (lump plus briquettes), 2.6 t; coke, 0.5 t; coal, 0.15 t; fixed carbon, 0.5 t; quartz, 0.03 t to 0.06 t; bauxite, 0.03 t to 0.15 t; electrode paste, 0.014 t to 0.029 t. Slag production per ton of product was about 1.2 t to 1.3 t. Chromium recovery in salable product was about 88 pct of chromium contained in feed material with 6 pct of chromium reporting to slag, unrecovered at the time of the report.

Today more energy-efficient processes are available and used. Neuschütz *(31)* reviewed the chromium direct reduction process in 1992 and estimated energy consumption per unit of high-carbon ferrochromium product for several currently used industrial processes. Neuschütz estimated energy consumption by process, all of which end in submerged-arc furnace smelting, as follows: traditional process (using lumpy ore), 4 MWh/t-FeCr; Outokumpu process (using agglomerated and preheated fine ore), 3 MWh/t-FeCr; Showa Denko (using pelletized and partially prereduced fine ore), 2 MWh/t-FeCr; and Direct Reduction (using kiln roasted prereduced fine ore), 1.2 MWh/t-FeCr.

Papp *(32)* reported that current efficient industry practice for the production of high-carbon ferrochromium requires from 2 MWh/t-FeCr to 3.8 MWh/t-FeCr of electrical energy. These higher efficiencies result from the recovery of heat from exhaust gases to preheat feed material (preheating process) and the reduction of chromite ore before it is fed into the electric arc furnace (prereduction process). Prereduction processes permit the substitution of other forms of energy (e.g., coal, oil, gas) for electrical energy.

Because of the large variety of processes, ores, other materials, and practices used to make high-carbon ferrochromium and the absence of information about how much ferrochromium is produced by which process, material and energy use can only be estimated based on typical values reported when conducting a life cycle analysis. A recent cost structure study *(33)* of the high-carbon ferrochromium industry from 1988 to 1990 reported average energy consumption in 1990 to have been 3.954 MWh/t-FeCr and ranged from 2 MWh/t-FeCr to 5 MWh/t-FeCr; chromite ore consumption averaged about 2.5 t-CrOre/t-FeCr and ranged from 1.75 t-CrOre/t-FeCr to 3.0 t-CrOre/t-FeCr; chromium recovery in salable product averaged 78 pct and ranged from 67 pct to 92 pct; reductant consumption averaged

158 kg/t-FeCr of coal, 10 kt/t-FeCr of charcoal, and 425 kg/t-FeCr of metallurgical grade coke; labor was about 10 workerhours/t-FeCr.

Boyle and others (*13*) reported ferrochromium energy consumption for a wide range of industrial processes or proposed processes. Boyle reported a range of electrical energy consumption values by process as follows: conventional and conventional with briquetting, 3.8 MWh/t-FeCr to 4.2 MWh/t-FeCr; Krupp-CODIR, 1.4 MWh/t-FeCr to 1.5 MWh/t-FeCr; Outokumpu, 3.1 MWh/t-FeCr to 3.2 MWh/t-FeCr; plasma arc, 4.0 MWh/t-FeCr to 4.5 MWh/t-FeCr; and solid-state reduction of chromite, 2.1 MWh/t-FeCr to 2.2 MWh/t-FeCr. These energy consumptions were based on data collected and compiled around 1985-88 in the course of preparing a minerals availability study for the chromium industry.

A wide variety of ferrochromium production operational parameters are quoted here. In part, the variation results from the wide range in time covered by the collected data (1956-93), the wide range of production processes and practices, and the range of perspective (e.g., commercial perspective of energy consumed by the plant to physical chemist or metallurgists perspective of energy required to carry out a reaction). Table 12 is a summary of material and energy consumption and other attributes of a variety of production methods or processes.

Energy consumption for ferrochromium production depends on production process equipment (including energy-recovery equipment) and on ore used. The three types of furnaces used include open, semiclosed, and closed. In an open furnace, gases resulting from the smelting process are at too low a temperature for efficient energy recovery and the gases must be cleaned. In semiclosed and closed furnaces, combustion of gases resulting from the smelting process are controlled to permit energy recovery. Recovered energy may be used to dry and preheat furnace feed materials thereby making the smelting process more energy efficient. Energy consumption depends on ore characteristics. Ferrochromium production results in production of slag in about the same volume as the ferrochromium product. Slag is formed in the furnace at about the same temperature as the ferrochromium product. Thus a large fraction of the energy required to heat feed materials ends up in the slag. Chromite ore characteristics affect the slag to product ratio which, in turn, affects energy consumption.

Chromium Metal Industry

Chromium metal production can also be an electrical energy intensive process. However, chromium metal is not produced from chromite ore. There are two industrial processes by which most chromium metal is produced, electrolytic and aluminothermic. In the electrolytic chromium metal production process, chromic acid, chromite ore, or ferrochromium is dissolved and chromium is electroplated out of solution. There are two ways of doing this; electroplate from a chromic acid bath or from a chromium-alum bath. The chromic acid bath method results in chromium metal at an electrical energy cost of about 30 kWh/lb-CrMtl (*34*). The chromic acid bath method is the same process used for electroplating. From among these variations on the electrolytic process, chromium metal deposition from a chromium alum solution generated from the dissolution of ferrochromium is the one that is commercially practiced.

In 1956, Lloyd (*35*) reported electrowinning chromium metal from a chromium-alum solution. The solution was made by dissolving ferrochromium (chromite ore dissolution is possible but not practiced) then removing iron. Chromium metal was then electrodeposited at an electrical energy cost of about 5 kWh/lb-CrMtl (typical cell energy consumption). In 1993, according to industry sources, commercial chromium recovery from ferrochromium-to-chromium-metal process is in the range of 85 pct to 90 pct and electrical energy cost is about 8.5 kWh/lb-CrMtl. Chromium losses are to solution and in filtration. A complete accounting would require adding the cost of ferrochromium production to that of chromium metal production by this process.

In aluminothermic chromium metal production process, chromic oxide is combined with aluminum metal powder. Aluminum metal is produced by electrowinning aluminum from alumina at an energy cost of from 215.3 GJ/t-AlMtl to 256.6 GJ/t-AlMtl of aluminum produced (including mining, smelting, and milling) (*36*). Chromic oxide is a chemical industry product derivative of sodium bichromate, which is produced at an energy cost of 22 GJ/t-$Na_2Cr_2O_7 \bullet 2H_2O$ to 34 GJ/t-$Na_2Cr_2O_7 \bullet 2H_2O$ (fuel plus electrical energy to produce sodium bichromate from chromite ore).

Manufacturing Industry

In 1976 Dressel and others (*37*) identified numerous industrial losses by manufacturing industry and type of loss. They also identified which losses were being recycled, not being recycled, and which could be recycled. The authors found annual chromium loss by industry or end use to have been: ferrochromium, 4.5 kst-Cr; stainless steel, 11.2 kst-Cr; foundry and refractory, 40 kst-Cr; primary chemical, 4 kst-Cr; etching and plating wastes, 6 kst-Cr; and other uses,

Table 12.—Attributes of high-carbon ferrochromium production by method/process of production

Attribute[1]	Conventional	Outokumpu Oy	SRC process	Plasma	CDR process	1990 plant average[2]
			INPUTS			
Materials:						
Chromite (t)	2.50 - 2.85	2.3	1.8 - 1.9	1.75 - 2.10	1.75 - 2.10	2.5
SiO_2 (kg)	28 - 465	170 - 204	150	210	152 - 228	NA
Limestone or dolomite (kg)	60 - 231	59	300	175	228 - 342	NA
Coal (kg)	60 - 370	None	200 - 300	201	2,100 - 2,500	158
Coke (kg)	190 - 530	472 - 511	600	788	None	425
Charcoal (kg)	NA	NA	NA	NA	NA	10
Bentonite (kg)	None	36	60	None	None	NA
Electrodes (kg)	14 - 29	9	20	NA	8	NA
Bauxite or corundum (kg)	6 - 430	None	None	None	None	NA
Heavy Oil (l)	20 - 30	28 - 154	208	NA	NA	NA
H_2O	NA	NA	NA	NA	NA	NA
Labor (man-hours)	NA	NA	NA	NA	NA	10
Energy:						
Electric furnace (MWh)	3.8 - 4.2	2.8 - 2.9	1.7 - 2.2	4.0 - 4.5	1.1	3.954
Total (MWh)	3.8 - 4.2	3.1 - 3.2	2.1 - 2.7	4.0 - 4.5	1.4 - 1.5	NA
			OUTPUTS			
Production volume of:						
Slag (t)	1.2 - 1.35	1.11 - 1.21	1.10 - 1.30	0.80	1.68	NA
Dust (t)	NA	NA	NA	0.16	0.59	NA
			PROCESS CHARACTERISTICS			
Prereduction (pct[4])	None	40	55 - 75	None	90	NA
Recovery in:[5]						
Product (pct)	73 - 85	84 - 86	91 - 93	92 - 93	92 - 93	[6]78
Slag (pct)	5 - 24.5	9 - 10	4 - 5	3 - 4	3 - 4	NA
Dust (pct)	2.5 - 12	5 - 6	3 - 4	3 - 4	3 - 4	NA

NA Not available.
[1]Quantity is per metric ton of ferrochromium product.
[2]Reference 33.
[3]Values range from 2 MWh/t-FeCr to 5 MWh/t-FeCr.
[4]Pct of chromium in ore feed reduced before electric furnace smelting.
[5]Pct of chromium in ore feed recovered.
[6]Values range from 67 pct to 92 pct.

NOTE. Chromite ore consumption based on the following. Conventional: 84 pct recovery of 47 pct Cr_2O_3 lumpy ore for 67 pct chromium in ferrochromium (lower limit); 70 pct recovery of 39 pct Cr_2O_3 fine ore for 53 pct chromium in ferrochromium (upper limit). Outokumpu: 20 pct lump ore, 80 pct pellets. SRC: 100 pct hot charged pellets. Plasma: based on Swedish plant operated from 1987 to 1990. CDR: Estimated.

Source: Edward H. Boyle Jr., Minerals Availability Program, Denver Center, Private Communication unless otherwise noted.

1.1 kst-Cr. Neumeier and Adam *(38)* found that in 1985 very little in-plant recycling of chromium-containing furnace dusts, mill scale, and swarfs was being done. However, a process which could recycle 90 pct of that material within the plant was developed by the USBM.

In order to elucidate material flow losses of chromium, Gabler *(4)* has developed a model and estimated the flows and losses for many industrial processes. Gabler divided 1989 domestic apparent consumption among end-use industries as follows: 84 pct metallurgical, 13 pct chemical, and 3 pct refractory. He found that in 1989 about 420 kt-Cr, about 99 kt-Cr of which was from recycling, was processed by the domestic economy. Gabler identified and quantified various forms of scrap including (1989 quantity in parenthesis): home, (196.2 kt-Cr), prompt (59.6 kt-Cr), and obsolete (315 kt-Cr of which 102.9 kt-Cr was recycled). Gabler estimated losses from processing at 38.8 kt-Cr, which included such things as fume, dust, slag, sludge, mill scale, etc.; losses from manufacturing at 18.1 kt-Cr, which included such things as trimmings, cuttings, punching scrap; losses from recovery at 155.5 kt-Cr including uncollected material; and recycling losses at 13.1 kt-Cr, which included downgraded materials. Thus most losses identified by Gabler were chromium contained in materials that left the processing stream. The chromium contained in the downgraded materials is lost to the chromium use cycle but is not lost to the environment because it is still in use.

Chromium in Selected Alloys

A product specialist may know which alloys are used in a product or may only know which class of alloys is used. A variety of alloys contain chromium including aluminum, cobalt, copper, iron, nickel, and titanium alloys. By knowing which alloys are used in a product, the amount of chromium contained in the product may be estimated. There are, of course, also losses associated with the introduction of chromium into an alloy and with the shaping or forming of a specific part. However, at the alloy production stage of manufacturing and after, recoveries are high and recycling is frequently practiced. The chromium content of these alloys will be estimated here. However, the detailed values for energy and material consumption and losses are left to the commodity life cycle study for the specific base metal or products.

If one does not know which alloys are used in a specific product, a statistical approach to estimating the amount of chromium use may be used. For example, one may only know that 1 kg of stainless steel is used in the specific product and not know which grade or grades are used and in what proportion to make up that 1 kg. In such a case, the average chromium content of stainless steel may be used to estimate the chromium content of the specific product.

Using USBM and industry data, there are three methods by which to calculate an average chromium content of a class of alloy such as stainless steel or aluminum alloys. The methods are:

Method 1. Average the chromium chemical specification of the grades that constitute the alloy class.

The advantage of this method is that chemical specifications by alloy grade are readily available and averaging is a straightforward process. The disadvantage of this method is that it does not account for production distribution among alloy grades.

Method 2. Divide alloy class production by chromium consumed to produce that class of alloy.

The advantage of this method is that the computation is simple and production and consumption data are both available. The disadvantage of this method is that reported consumption and production data are incomplete and generated by different groups. For example, the USBM reports ferroalloy consumption by ferroalloy grade and end use; the American Iron and Steel Institute reports stainless steel production by alloy grade.

Method 3. Calculate a production weighted average chromium content based on production by alloy grade and chromium chemical specification by alloy grade.

The advantage of this method is that it is accurate. The disadvantage is that production by alloy grade data are available only for stainless steel alloys.

Stainless steel is the most common alloy using chromium and there is information upon which average chromium contents can be based. However, the chromium content of other chromium-containing alloys can not be so confidently estimated because production by grade information is not available. We can, however, estimate chromium content of other alloys based on alloy grades (see method 1 above) or based on reported or estimated industry chromium consumption relative to alloy production (see method 2 above). Using the alloy grade approach, we can estimate the chromium content of aluminum, cobalt, copper, nickel, and titanium alloys. In analyzing the chromium chemical specifications of these alloys, nominal contents were treated as if they were both a minimum specification and a maximum specification; maximum only contents were averaged with maximum contents that have a corresponding minimum. Using the consumption relative to production approach, we can estimate the chromium content of aluminum alloys and of iron alloys by grade including carbon, alloy, and stainless steel.

These methods are applied to the alloy classes to estimate average chromium content so that (1) an average chromium content is available to those who do have specific alloy quantity and grade information and (2) as a cross check to see if several estimation methods yield about the same average value.

Alloy Steel

Application of method 1 to alloy steel yields an average chromium content for alloy steels of 0.68±0.11 pct. For alloy steel, table 13 shows the 307 alloy steel grades that have a chromium chemical specification. These alloys represent about 65 pct of active alloy steels listed in the source of that data *(39)*. The average chromium content 1.05±0.17 pct for those alloy steels which specify chromium and was 0.68±0.11 pct when averaged over all active alloy steel grades. Application of method 2 to alloy steel using alloy steel production reported by American Iron and Steel Institute (AISI) and consumption of chromium-containing materials reported by the USBM and averaged over the 1987 through 1990 time period yields an average chromium content for alloy steel of 0.22±0.02 pct.

Carbon Steel

Application of method 1 to carbon steel yields an average chromium content for carbon steels of 0.007±0.0005 pct. For carbon steel, table 14 shows the seven carbon steel grades that have a chromium chemical specification. These alloys represent about 3 pct of active carbon steels listed in the source of that data *(39)*. The average chromium content 0.29±0.02 pct for those carbon steels which specify chromium and was 0.007(5)±0.0005 pct when averaged over all active carbon steel grades. Application of method 2 to carbon steel using carbon steel production reported by AISI and consumption of chromium-containing materials reported by the USBM and averaged over the 1987 through 1990 time period yields an average chromium content for carbon steel of 0.01±0.002 pct.

Stainless Steel

By far the greatest use of chromium is in stainless steel. Application of method 1, see table 15, yields an average chromium content for stainless and heat-resisting steel of 17.86±1.04 pct. For stainless and heat-resisting steels, all grades require chromium. Application of method 2 using stainless and heat-resisting steel production data from the AISI and reported consumption of chromium materials by the USBM yields an average chromium content of stainless and heat resisting steel of 9.0±0.8 pct averaged over 1987 through 1990. A historical study, using method 3 described above, of chromium use in stainless steel found that the average chromium content of U.S.-produced stainless and heat resisting steel is 17.25±1.02 pct based on production by grade from 1962 through 1983 *(40)*. This is a chromium content averaged over all grades and weighted by AISI reported production by grade. Stainless and heat-resisting steel is the only alloy class for which all three methods can be applied.

Because all grades of stainless steel contain chromium, a stainless steel user should estimate some content. The average fraction calculated by methods 1 and 3 should serve as an estimate whenever grade specific information is lacking, even when volume of use is small or limited to only a few grades.

Aluminum

Application of method 1 to aluminum alloys yields an average chromium content for aluminum alloys of 0.04±0.02 pct. For aluminum, table 16 shows the 147 aluminum alloys that have a chromium chemical specification. These alloys represent about 34 pct of active aluminum alloys listed in the source of that data *(39)*. The average chromium content was 0.17±0.04 pct for those aluminum alloys which specify chromium and was 0.04±0.02 pct when averaged over all active aluminum alloy grades. Application of method 2 to aluminum using chromium-aluminum master alloy shipments data from The Aluminum Association and aluminum alloy shipments data from Aluminum Statistical Review for 1991 yields an average chromium content for aluminum alloys of 0.008 pct averaged over 1987 through 1990.

Cobalt

Application of method 1 to cobalt alloys yields an average chromium content for cobalt alloys of 20.1±0.9 pct. For cobalt, table 17 shows the 28 cobalt alloys that have a chemical specification for chromium. These alloys represent 93 pct of the active cobalt alloys listed in the source of that data *(39)*. The average chromium content was 21.5±0.9 pct for those grades that specify chromium and was 20.1±0.9 pct when averaged over all active cobalt alloy grades.

Copper

Application of method 1 to copper alloys yields an average chromium content for copper alloys of 0.025±0.010 pct. For copper, table 17 shows the 31 copper alloys that have a chemical specification for chromium. These alloys represent 6 pct of the active copper alloys listed in the source of that data *(39)*. The average chromium content was 0.44±0.18 pct for those grades that specify chromium and was 0.025±0.010 pct when averaged over all active copper alloy grades.

Nickel

The application of method 1 to nickel alloys yields an average chromium content for nickel alloys of 14±1 pct. For nickel, table 18 shows the 142 nickel alloys that have a chemical specification for chromium. These alloys represent 82 pct of the active nickel alloys listed in the source of that data *(39)*. The average chromium content was 17.2±1.4 pct for those grades that specify chromium and was 14.2±1.1 pct when averaged over all active nickel alloy grades.

Titanium

The application of method 1 to titanium alloys yields an average chromium content for titanium alloy of 0.49±0.01 pct. For titanium, table 17 shows the four titanium alloys that have a chemical specification for chromium. These alloys represent 10 pct of the active titanium alloys listed in the source of that data *(39)*. The average chromium content was 5.3±0.2 pct for those grades that specify chromium and was 0.49±0.01 pct when averaged over all titanium alloy active grades.

Chromium Alloy Summary

Table 19 shows some information on chromium consumption and alloy production for carbon, alloy, and stainless steel and aluminum used for method 2. The results of the various methods and recommended chromium contents for the various alloy classes are summarized in table 20. With the exception of carbon steel, method 2 (ratio of reported chromium master alloy to chromium-containing alloy production, table 19) yields lower chromium content estimates than the other methods employed. Only for stainless steel was there sufficient information to apply all three methods, the most reliable method being method 3. For stainless steel, method 3 and method 1 yielded the same result within the uncertainty of the estimates. The similarity between method 3 and method 1 results along with the disparity between method 3 and method 2 results leads one to conclude that method 1 results may be more reliable than method 2 results. Method 1 results were, therefore, preferred over those of method 2.

Refractories

Chromium-containing refractories are used in a variety of industries as process materials as opposed to feed stock materials. In other words, chromium-containing refractories are consumed in the manufacturing process. However, no chromium ends up in the manufactured product. Chromium-containing refractories are used to produce copper, nickel, cement, and glass.

Weibel *(41)* reported that in Germany chromite refractories displaced low alumina magnesia-alumina refractories in the mid-1930's based on improved price/performance ratio and that current production practice results in basic brick consumption of 0.565 kg/t-clinker for preheater and precalciner kilns and 0.765 kg/t-clinker for wet kilns. Typical Cr_2O_3 content of chromite-containing refractories was 5.5 pct to 15 pct. In the United States, from 1973 to 1992 dry kilns have increased from 44 pct to 64 pct of total number of kilns *(42)*. Griffin and others *(43)* estimated U.S. basic refractory (i.e., doloma, magnesia, and chromite refractories) by the U.S. cement industry to have been 60 kst in 1982 and 50 kst in 1993 of which magnesia-chromite brick accounted for 60 pct in 1982 and 15 pct in 1993. According to industry sources, the grade of magnesia-chromite brick has also changed over the time period from about 16 pct Cr_2O_3 in the 1980 time period to about 8 pct in the 1990 time period. Refractories advertised for the cement industry by U.S. manufacturers range in Cr_2O_3 content from about 8 pct to about 25 pct. The USBM reported clinker production in 1982 to have been 59,326 kst and estimated 1993 production at 69,183 kst *(44)*. By comparing these data, the U.S. cement industry basic refractory consumption ratio in 1982 was 1 t of basic refractory per kt-clinker production and in 1993 was 0.7 t of basic brick per kt-clinker production. Thus it appears that not only has basic refractory unit consumption been decreasing, but that the magnesia-chromite fraction of that basic refractory has been decreasing and the chromic oxide content of the magnesia-chromite brick also has been decreasing. The problems associated with magnesia-chromite refractories in the cement industry and alternatives to its use have been described by Moore and others *(45)*. Using 0.7 t of basic refractory per kt-clinker production, 40 pct of basic refractory to be magnesia-chromite, 10 pct of magnesia-chromite refractory to be Cr_2O_3, and

Table 13.—Chromium specification for chromium-containing alloy steel by Unified Number System (UNS) number

UNS number	Chromium specification	UNS number	Chromium specification	UNS number	Chromium specification
		ALLOY STEEL			
G31400	.55 - .75	G86451	.4 - .6	K11797	1 - 1.5
G33106	1.4 - 1.75	G86500	.4 - .6	K11800	.15 maximum
G41180	.4 - .6	G86550	.4 - .6	K11801	.15 maximum
G41200	.4 - .6	G86600	.4 - .6	K11802	.15 maximum
G41210	.45 - .65	G87200	.4 - .6	K11831	.25 maximum
G41300	.8 - 1.1	G87350	.4 - .6	K11835	.33 maximum
G41350	.8 - 1.1	G87400	.4 - .6	K11846	.25 maximum
G41370	.8 - 1.1	G87420	.4 - .6	K11847	.5 - .8
G41400	.8 - 1.1	G88220	.4 - .6	K11852	.25 maximum
G41420	.8 - 1.1	G92540	.6 - .8	K11856	.5 - .8
G41450	.8 - 1.1	G92620	.25 - .4	K11872	.5 - .9
G41470	.8 - 1.1	G93106	1 - 1.4	K11914	.5 - .75
G41500	.8 - 1.1	G94151	.3 - .5	K11940	.7 - .9
G41610	.7 - .9	G94171	.3 - .5	K11948	.4 - .6
G43200	.4 - .6	G94301	.3 - .5	K12031	.25 maximum
G43370	.7 - .9	G94401	.3 - .5	K12032	.1 - .25
G43376	.7 - .9	G98400	.7 - .9	K12033	.27 - .53
G43400	.7 - .9	G98500	.7 - .9	K12037	.25 maximum
G43406	.7 - .9	K10882	.3 maximum	K12040	.5 - 1
G41750	.45 - .65	K10940	.15 maximum	K12042	.25 maximum
G41780	.35 - .55	K10943	.4 - .75	K12043	.4 - .7
G47200	.35 - .55	K10982	.3 maximum	K12047	.8 - 1.25
G50150	.3 - .5	K11040	.15 maximum	K12048	.4 - .6
G50460	.2 - .35	K11043	.4 - .75	K12049	.45 - 1.05
G50600	.4 - .6	K11072	1 - 1.75	K12062	.8 - 1.25
G50986	.4 - .6	K11172	1 - 1.75	K12087	.45 - .65
G51150	.7 - .9	K11245	.5 - .8	K12103	.3 - .4
G51170	.7 - .9	K11250	.3 maximum	K12122	.5 - .81
G51200	.7 - .9	K11260	.15 maximum	K12125	.4 - .6
G51300	.8 - 1.1	K11267	.44 - 1.01	K12143	.46 - .85
G51320	.75 - 1	K11356	.74 - 1.26	K12147	.4 - .6
G51350	.8 - 1.05	K11365	.5 - .75	K12187	.45 - .65
G51400	.7 - .9	K11430	.37 - .68	K12220	.25 maximum
G51450	.7 - .9	K11526	.24 - 1.31	K12238	.42 - .68
G51470	.85 - 1.15	K11535	.24 - 1.31	K12244	.37 - .73
G51500	.7 - .9	K11538	.3 - .5	K12254	.55 - .95
G51550	.7 - .9	K11541	.3 maximum	K12437	.25 maximum
G51600	.7 - .9	K11542	.8 - 1.1	K12447	.25 maximum
G51601	.7 - .9	K11546	.8 - 1.1	K12542	.31 - .64
G51986	.9 - 1.15	K11547	.5 - .81	K12765	.25 - .45
G52986	1.3 - 1.6	K11552	.5 - .9	K12766	.25 - .45
G61180	.5 - .7	K11562	.8 - 1.25	K13020	.25 maximum
G61200	.7 - .9	K11564	.8 - 1.1	K13047	.8 - 1.15
G61500	.8 - 1.1	K11572	1 - 1.5	K13048	.4 - .6
G81150	.3 - .5	K11576	.4 - .65	K13049	.4 - .65
G81451	.35 - .55	K11591	.8 - 1.25	K13051	.8 - 1.1
G86150	.4 - .6	K11597	1 - 1.5	K13147	.8 - 1.1
G86170	.4 - .6	K11598	1 - 1.5	K13148	.8 - 1.1
G86200	.4 - .6	K11630	.4 - .65	K13149	.8 - 1.1
G86220	.4 - .6	K11640	.55• - .75	K13247	.8 - 1.1
G86250	.4 - .6	K11646	.4 - .65	K13262	.4 minimum
G86270	.4 - .6	K11662	.85 - 1.2	K13502	.25 maximum
G86300	.4 - .6	K11682	1.15 - 1.65	K13521	.22 - .43
G86370	.4 - .6	K11695	1.34 - 2.06	K13547	.4 - .65
G86400	.4 - .6	K11742	.31 - .64	K13548	.8 - 1.15
G86420	.4 - .6	K11757	.74 - 1.21	K13550	.4 - .6
G86450	.4 - .6	K11789	.94 - 1.56	K13586	.7 maximum

See Source at end of table.

Table 13.—Chromium specification for chromium-containing alloy steel by Unified Number System (UNS) number--Continued

UNS number	Chromium specification	UNS number	Chromium specification	UNS number	Chromium specification
		ALLOY STEEL--CONTINUED			
K13643	.42 - .68	K22375	1.5 - 2	K32045	1 - 1.8
K13650	.45 minimum	K22440	.2 maximum	K32550	.2 - .4
K14044	.75 - 1.15	K22573	.5 maximum	K32723	.5 maximum
K14047	.8 - 1.1	K22578	.75 maximum	K32800	.75 - 2
K14048	.8 - 1.15	K22720	.8 - 1.2	K33020	1 - 1.35
K14072	.8 - 1.15	K22770	1 - 1.5	K33125	.5 maximum
K14073	.8 - 1.15	K22773	.5 maximum	K33370	.65 - .9
K14185	.95 - 1.35	K22878	.75 maximum	K33517	.65 - .9
K14245	.75 - 1.5	K22925	.9 - 1.2	K33585	3 - 3.6
K14247	.8 - 1.15	K22950	.7 - .9	K34035	.8 - 2
K14248	.8 - 1.15	K23010	.9 - 1.5	K34378	1.9 - 2.25
K14358	.47 - .83	K23015	1 - 1.5	K41245	4 - 6
K14507	1.25 maximum	K23016	1 - 1.5	K41370	.25 - .5
K14542	.7 - 1.25	K23028	.75 maximum	K41545	4 - 6
K14557	1.5 maximum	K23080	.75 - 1	K42247	1.44 - 2.06
K14675	.8 - 1.1	K23116	1 - 1.5	K42338	1.44 - 2.06
K15047	.8 - 1.1	K23205	.85 - 1.25	K42339	1.44 - 2.06
K15048	.8 - 1.1	K23477	.65 - .9	K42343	1.25 - 2
K15590	.6 - .8	K23550	.8 - 2	K42348	1.25 - 2
K15747	.8 - 1.15	K23577	.65 - .9	K42365	1.5 - 2
K18597	.85 - 1.15	K23578	.75 maximum	K42544	4 - 6
K19195	1.4 - 1.8	K23579	1.25 maximum	K42570	1.25 - 1.75
K19667	.9 - 1.2	K23705	.85 - 1.25	K42598	1.4 - 1.65
K19964	1.3 - 1.6	K23725	.9 - 1.2	K42885	1.25 - 2
K19965	1.1 - 1.5	K24040	.65 - .95	K44045	.8 - 2
K19990	1.1 - 1.5	K24045	.6 - .9	K44220	.7 - .95
K20500	1.2 - 1.5	K24055	.7 - .9	K44414	1 - 1.4
K20900	1.2 - 1.5	K24064	.7 - .95	K44910	1.25 - 1.75
K20915	.55 maximum	K24070	.7 - .9	K51210	1.35 - 1.75
K20930	.6 maximum	K24245	.6 minimum	K51255	.4 - .7
K20934	.56 - .94	K24336	.8 - 1.05	K51545	4 - 6
K21015	.55 maximum	K24535	.5 - 1.25	K52355	1 - 1.25
K21028	.4 - .6	K24562	.7 - 1.25	K90941	8 - 10
K21030	.6 maximum	K24728	.9 - 1.2	K91094	.2 - .35
K21135	.2 - .55	K30560	2.3 - 2.7	K91122	.35 - .6
K21205	.9 - 1.2	K30960	2.3 - 2.7	K91283	.9 - 1.1
K21390	2 - 2.5	K31015	2.25 - 3	K91352	11 - 12.5
K21509	1.65 - 2.35	K31115	2.25 - 3	K91401	.61 - .89
K21590	2 - 2.5	K31210	.15 maximum	K91472	.65 - .85
K21604	1.4 - 2	K31310	.15 maximum	K91555	3.5 - 6
K21650	.85 - 1.2	K31509	2.15 - 2.85	K91890	4.5 - 5.5
K21940	1.25 - 1.65	K31545	2.65 - 3.35	K91930	4.75 - 5.25
K22033	.55 - .75	K31820	1 - 1.8	K91940	4.75 - 5.25
K22094	1 - 1.5	K31830	2.75 - 3.25	K91955	3.5 - 6
K22097	.9 - 1.15	K32026	.2 maximum	K91970	1.8 - 2.2
				K92571	1.8 - 2.2

Number of alloy steel grades reported: 475.
Number of active alloys
that have a chromium specification: 307,
reported: 473.
Average chromium content
over all active alloys that specify chromium: 1.05±0.17 pct,
over all active alloys: 0.68±0.11 pct.

Source: Reference 39.

Table 14.—Chromium specification for chromium-containing carbon steel by Unified Number System (UNS) number

UNS number	Chromium specification	UNS number	Chromium specification	UNS number	Chromium specification
K02400	.25 maximum	K03046	.4 maximum	K03810	.3 .55
K02741	.25 maximum	K03047	.4 maximum	K05500	.25 .25
				K08700	.04 maximum

Number of carbon steels reported: 268.
Number of active alloys
 that have a chromium specification: 7,
 reported: 268.
Average chromium content
 over all active alloys that specify chromium: 0.29±0.02 pct,
 over all active alloys: 0.0075±0.0005 pct.

Source: Reference 39.

Table 15.—Chromium specification for stainless steel alloys by Unified Number System (UNS) number

UNS number	Chromium specification	UNS number	Chromium specification	UNS number	Chromium specification
S13800	12.25 - 13.25	S28200	17 - 19	S30900	22 - 24
S13889	12.25 - 13.25	S30100	16 - 18	S30908	22 - 24
S14800	13.75 - 45	S30115	16.5 - 17.5	S30909	22 - 24
S15500	14 - 15.5	S30200	17 - 19	S30940	22 - 24
S15700	14 - 16	S30210	17 - 19	S30941	22 - 24
S15780	14 - 15.25	S30215	17 - 19	S30980	23 - 25
S15789	14 - 15.25	S30260	16 - 18	S30981	23 - 25
S16600	15 - 16	S30300	17 - 19	S30983	23 - 25
S16800	14.5 - 16.5	S30310	17 - 19	S31000	24 - 26
S16880	14.5 - 16.5	S30323	17 - 19	S31008	24 - 26
S17400	15.5 - 17.5	S30330	17 - 19	S31009	24 - 26
S17480	16 - 16.75	S30345	17 - 19	S31040	24 - 26
S17600	15 - 17.5	S30360	17 - 19	S31041	24 - 26
S17700	16 - 18	S30400	18 - 20	S31050	24 - 26
S17780	16 - 17.5	S30403	18 - 20	S31080	25 - 28
S18200	17.5 - 19.5	S30409	18 - 20	S31100	25 - 27
S20100	16 - 18	S30415	18 - 19	S31200	24 - 26
S20161	15 - 18	S30430	17 - 19	S31254	19.5 - 20.5
S20200	17 - 19	S30431	16 - 19	S31260	24 - 26
S20300	16 - 18	S30451	18 - 20	S31380	28 - 32
S20500	16 - 18	S30452	18 - 20	S31400	23 - 26
S20910	20.5 - 23.5	S30453	18 - 20	S31500	18 - 19
S20980	20.5 - 24	S30454	18 - 20	S31600	16 - 18
S21000	18 - 23	S30483	18 minimum	S31603	16 - 18
S21300	16 - 21	S30500	17 - 19	S31609	16 - 18
S21400	17 - 18.5	S30560	17 minimum	S31620	17 - 19
S21460	17 - 19	S30600	17 - 18.5	S31635	16 - 18
S21500	14 - 16	S30615	17 - 19.5	S31640	16 - 18
S21600	17.5 - 22	S30780	19.5 - 22	S31651	16 - 18
S21603	17.5 - 22	S30800	19 - 21	S31653	16 - 18
S21800	16 - 18	S30815	20 - 22	S31654	16 - 18
S21880	16 - 18	S30880	19.5 - 22	S31680	18 - 20
S21900	19 - 21.5	S30881	19.5 - 22	S31681	18 - 20
S21904	19 - 21.5	S30882	18 - 21	S31683	18 - 22
S21980	19 - 21.5	S30883	19.5 - 22	S31688	18 - 20
S23980	17 - 19	S30884	18 - 20	S31700	18 - 20
S24000	17 - 19	S30886	18 - 21	S31703	18 - 20
S24100	16.5 - 19.5	S30888	19.5 - 22	S31725	18 - 20

See Source at end of table.

Table 15.—Chromium specification for stainless steel alloys by Unified Number System (UNS) number--Continued

UNS number	Chromium specification	UNS number	Chromium specification	UNS number	Chromium specification
S31726	17 - 20	S41026	11.5 - 13.5	S44626	25 - 27
S31700	18 - 20	S41040	11.5 - 13.5	S44627	25 - 27
S31753	18 - 20	S41041	11.5 - 13	S44635	24.5 - 26
S31780	18.5 - 20.5	S41050	10.5 - 12.5	S44660	25 - 27
S31783	18.5 - 20.5	S41080	11.5 - 13.5	S44687	25 - 27.5
S31803	21 - 23	S41081	11.5 - 12.5	S44700	28 - 30
S31980	18 - 20	S41086	11 - 12.5	S44735	28 - 30
S32100	17 - 19	S41400	11.5 - 13.5	S44736	28 - 30
S32109	17 - 20	S41500	11.5 - 14	S44800	28 - 30
S32180	18.5 - 20.5	S41600	12 - 14	S45000	16 - 18
S32304	21.5 - 24.5	S41610	12 - 14	S45500	16 - 18
S32404	20.5 - 22.5	S41623	12 - 14	S50100	4 - 6
S32550	24 - 27	S41780	11 - 12.5	S50180	4.8 - 6
S32615	16 - 21	S41800	12 - 14	S50181	4.8 - 6
S32750	24 - 26	S41880	12 - 14	S50200	4 - 6
S32760	24 - 26	S42000	12 - 14	S50280	4 - 6
S32900	23 - 28	S42010	13.5 - 15	S50281	4.5 - 6
S32950	26 - 29	S42020	12 - 14	S50300	6 - 8
S33100	7 - 9	S42023	12 - 14	S50400	8 - 10
S34700	17 - 19	S42080	12 - 14	S50480	8 - 10.5
S34709	17 - 20	S42100	11 - 12.5	S50481	8 - 10.5
S34720	17 - 19	S42200	11.5 - 13.5	S63005	12 - 13.5
S34723	17 - 19	S42201	11 - 13.5	S63007	20 - 22
S34740	17 - 19	S42300	11 - 12	S63008	20 - 22
S34741	17 - 19	S42400	12 - 14	S63011	20.5 - 22
S34780	19 - 21.5	S42700	14 - 15	S63012	19.25 - 21.5
S34781	17 - 19	S42800	13.7 - 14.8	S63013	20 - 22
S34788	19 - 21.5	S42900	14 - 16	S63014	18 - 20
S34800	17 - 19	S43000	16 - 18	S63015	18 - 20
S34809	17 - 20	S43020	16 - 18	S63016	20.5 - 22
S35000	16 - 17	S43023	16 - 18	S63017	20 - 22
S35080	16 - 17	S43035	17 - 19	S63018	22 - 24
S35500	15 - 16	S43036	16 - 19.5	S63019	20 - 22
S35580	15 - 16	S43080	15.5 - 17	S63197	19 - 21.5
S36200	14 - 15	S43100	15 - 17	S63198	18 - 21
S37000	12.5 - 14.5	S43400	16 - 18	S63199	18 - 21
S38100	17 - 19	S43600	16 - 18	S64005	7.5 - 8.5
S38400	15 - 17	S44002	16 - 18	S64006	1.5 - 2.5
S38500	11.5 - 13.5	S44003	16 - 18	S64152	11 - 12.5
S38660	12.5 - 14.5	S44004	16 - 18	S64299	27 - 31
S40300	11.5 - 13	S44020	16 - 18	S64299	27 - 31
S40500	11.5 - 14.5	S44023	16 - 18	S65006	19 - 21
S40800	11.5 - 13	S44025	16 - 18	S65007	8 - 9
S40900	10.5 - 11.75	S44100	17.5 - 19.5	S65150	19 - 21
S40940	10.5 - 11.75	S44200	18 - 23	S65770	13.5 - 14.5
S41000	11.5 - 13.5	S44300	18 - 23	S66009	12 - 15
S41001	11.5 - 13.5	S44400	17.5 - 19.5	S66220	12 - 15
S41008	11.5 - 13.5	S44600	23 - 27	S66286	13.5 - 16
S41025	11.5 - 13.5	S44625	25 - 27.5	S66545	12 - 15

Number of stainless steel alloys reported: 261.
Number of active alloys
that have a chromium specification: 257,
reported: 257.
Average chromium content
over all active alloys that specify chromium: 17.86±1.04 pct,
over all active alloys: 17.86±1.04 pct.

Source: Reference 39.

Table 16.—Chromium specification for chromium-containing aluminum alloys by Unified Number System (UNS) number

UNS number	Chromium specification	UNS number	Chromium specification	UNS number	Chromium specification
A02420	0.25 maximum	A92037	0.10 maximum	A96003	0.35 maximum
A02421	0.25 maximum	A92038	0.20	A96005	0.10 maximum
A02430	0.20 - 0.40	A92090	0.05 maximum	A96006	0.10 maximum
A02431	0.20 - 0.40	A92091	0.10	A96007	0.05 - 0.25
A03050	0.25 maximum	A92117	0.10 maximum	A96009	0.10 maximum
A03280	0.35 maximum	A92124	0.10 maximum	A96010	0.10 maximum
A03281	0.35 maximum	A92214	0.10 maximum	A96011	0.30 maximum
A03430	0.10 maximum	A92218	0.10 maximum	A96013	0.10 maximum
A03431	0.10 maximum	A92224	0.10 maximum	A96017	0.10 maximum
A03550	0.25 maximum	A92324	0.10 maximum	A96053	0.15 - 0.35
A03551	0.25 maximum	A93005	0.10 maximum	A96060	0.05 maximum
A03580	0.20 maximum	A93006	0.20 maximum	A96061	0.04 - 0.35
A03582	0.05 maximum	A93007	0.20 maximum	A96063	0.10 maximum
A03610	0.20 - 0.30	A93009	0.05 maximum	A96066	0.40 maximum
A03611	0.20 - 0.30	A93010	0.05 - 0.40	A96070	0.10 maximum
A03640	0.25 - 0.50	A93011	0.10 - 0.40	A96101	0.03 maximum
A03642	0.25 - 0.50	A93105	0.20 maximum	A96105	0.10 maximum
A03690	0.30 - 0.40	A94032	0.10 maximum	A96110	0.04 - 0.25
A03691	0.30 - 0.40	A94145	0.15 maximum	A96111	0.10
A04430	0.25 maximum	A94543	0.05 maximum	A96151	0.15 - 0.35
A04431	0.25 maximum	A95005	0.10 maximum	A96162	0.10 maximum
A07050	0.20 - 0.40	A95006	0.10 maximum	A96201	0.03 maximum
A07051	0.20 - 0.40	A95010	0.15 maximum	A96205	0.05 - 0.15
A07070	0.20 - 0.40	A95016	0.10 maximum	A96253	0.15 - 0.35
A07071	0.20 - 0.40	A95040	0.10 - 0.30	A96262	0.04 - 0.14
A07120	0.40 - 0.6	A95042	0.10 maximum	A96301	0.10 maximum
A07122	0.40 - 0.6	A95043	0.05 maximum	A97001	0.18 - 0.35
A07130	0.35 maximum	A95051	0.10 maximum	A97004	0.05 maximum
A07131	0.35 maximum	A95052	0.15 - 0.35	A97005	0.06 - 0.20
A07710	0.06 - 0.20	A95056	0.05 - 0.20	A97008	0.12 - 0.25
A07712	0.06 - 0.20	A95082	0.15 maximum	A97010	0.05 maximum
A07720	0.06 - 0.20	A95083	0.05 - 0.25	A97021	0.05 maximum
A07722	0.06 - 0.20	A95086	0.05 - 0.25	A97039	0.15 - 0.25
A12420	0.15 - 0.25	A95150	0.04 maximum	A97049	0.10 - 0.22
A12421	0.15 - 0.25	A95151	0.10 maximum	A97050	0.04 maximum
A12422	0.15 - 0.25	A95154	0.15 - 0.35	A97075	0.18 - 0.28
A14430	0.25 maximum	A95182	0.10 maximum	A97079	0.10 - 0.25
A14431	0.25 maximum	A95183	0.05 - 0.25	A97129	0.10 maximum
A33551	0.25 maximum	A95205	0.10 maximum	A97146	0.10 - 0.22
A91170	0.03 maximum	A95254	0.15 - 0.35	A97149	0.10 - 0.22
A91350	0.01 maximum	A95352	0.10 maximum	A97150	0.04 maximum
A92008	0.10 maximum	A95356	0.05 - 0.20	A97175	0.18 - 0.28
A92014	0.10 maximum	A95451	0.15 - 0.35	A97178	0.18 - 0.35
A92017	0.10 maximum	A95454	0.05 - 0.20	A97179	0.10 - 0.25
A92018	0.10 maximum	A95456	0.05 - 0.20	A97277	0.18 - 0.35
A92024	0.10 maximum	A95554	0.05 - 0.20	A97475	0.18 - 0.25
A92025	0.10 maximum	A95556	0.05 - 0.20	A98010	0.20 maximum
A92034	0.05	A95652	0.15 - 0.35	A98111	0.05
A92036	0.10 maximum	A95654	0.15 - 0.35	A98112	0.20 maximum

Number of aluminum alloys reported: 472.
Number of active alloys
that have a chromium specification: 147,
reported: 447.
Average chromium content
over all active alloys that specify chromium: 0.17±0.04 pct,
over all active alloys: 0.04±0.02 pct.

Source: Reference 39.

Table 17.—Chromium specification for chromium-containing cobalt, copper, and titanium alloys by Unified Number System (UNS) number

COBALT

UNS number	Chromium specification	UNS number	Chromium specification	UNS number	Chromium specification
R30001	30.0 nominal	R30027	26 nominal	R30477	17.7 - 18.
R30002	26.0 - 32.0	R30031	24.50 - 26.50	R30556	21.0 - 23.0
R30003	19.0 - 21.0	R30035	19.00 - 21.00	R30590	19.00 - 22.00
R30004	19.0 - 21.0	R30036	17.50 - 19.50	R30600	11.7 - 12.3
R30006	27.0 - 31.0	R30040	18.0 - 20.0	R30605	19.0 - 21.0
R30007	19.0 - 21.0	R30100	20.0 - 22.50	R30700	11.7 - 12.3
R30012	30.0 nominal	R30155	20.00 - 22.50	R30816	19.00 - 21.00
R30021	25.00 - 29.00	R30159	18.0 - 20.0	R39001	18.0 - 20.0
R30023	24 nominal	R30188	20.00 - 24.00		
R30027	25 nominal	R30260	11.7 - 12.3		

Number of cobalt alloys reported: 30.
Number of active alloys
that have a chromium specification: 28,
reported: 30.
Average chromium content
over all active alloys that specify chromium: 21.5±0.9 pct,
over all active alloys: 20.1±0.9 pct.

COPPER

UNS number	Chromium specification	UNS number	Chromium specification	UNS number	Chromium specification
C18000	0.10 - 0.6	C18500	0.40 - 1.0	C81540	0.10 - 0.6
C18030	0.10 - 0.20	C18550	0.60 - 1.0	C82000	0.10 maximum
C18040	0.25 - 0.35	C18990	0.10 - 0.20	C82400	0.10 maximum
C18050	0.05 - 0.15	C63020	0.05 maximum	C82500	0.10 maximum
C18070	0.15 - 0.40	C65400	0.01 - 0.12	C82510	0.10 maximum
C18090	0.30 - 1.0	C70320	0.18 - 0.50	C82600	0.10 maximum
C18100	0.40 - 1.0	C71900	2.2 - 3.0	C82700	0.10 maximum
C18135	0.20 - 0.6	C72200	0.30 - 0.7	C82800	0.10 maximum
C18150	0.50 - 1.5	C72420	0.50 maximum	C95520	0.05 maximum
C18200	0.6 - 1.2	C81400	0.6 - 1		
C18400	0.4 - 1.2	C81500	0.40 - 1.5		

Number of copper alloys reported: 563.
Number of active alloys
that have a chromium specification: 31,
reported: 536.
Average chromium content
over all active alloys that specify chromium: 0.44±0.18 pct,
over all active alloys: 0.025±0.010 pct.
NOTE. One brass brazing rod alloy (C26380) that was erroneously reported by UNS to contain chromium has been ignored.

TITANIUM

UNS number	Chromium specification	UNS number	Chromium specification	UNS number	Chromium specification
R54621	0.25 maximum	R58640	6	R58650	3.50 - 4.50
R58010	11				

Number of titanium alloys reported: 44
Number of active alloys
that have a chromium specification: 4,
reported: 43.
Average chromium content
over all active alloys that specify chromium: 5.3±0.2 pct,
over all active alloys: 0.49±0.01 pct.

Source: Reference 39.

Table 18.—Chromium specification for chromium-containing nickel alloys by Unified Number System (UNS) number

UNS number	Chromium specification	UNS number	Chromium specification	UNS number	Chromium specification
N02270	0.001 maximum	N07263	19.0 - 21.0	N08705	24.0 - 28.0
N02290	0.001 maximum	N07500	15.00 - 20.00	N08800	19.0 - 23.0
N03260	0.05 maximum	N07626	20.0 - 23.0	N08801	19.0 - 22.0
N06001	21.0 - 23.0	N07702	14.0 - 17.0	N08802	19.0 - 23.0
N06002	20.5 - 23.0	N07713	12.00 - 14.00	N08810	19.0 - 23.0
N06003	19 -21	N07716	19.0 - 22.0	N08811	19.0 - 23.0
N06004	14 -18	N07718	17.0 - 21.0	N08825	19.5 - 23.5
N06005	29.00 nominal	N07721	15.0 - 17.0	N08904	19.0 - 23.0
N06006	15.0 - 19.0	N07722	14.0 - 17.0	N08925	19.0 - 21.0
N06007	21.0 - 23.5	N07725	19.0 - 22.5	N08932	24.0 - 26.0
N06008	29.0 - 31.0	N07750	14.0 - 17.0	N09027	12.50 - 14.00
N06009	19.0 - 21.0	N07751	14.0 - 17.0	N09706	14.5 - 17.5
N06010	9.0 - 11.0	N07754	19.0 - 23.0	N09901	11.00 - 14.00
N06022	20.0 - 22.5	N08001	10.0 - 14.0	N09902	4.90 - 5.75
N06030	28.0 - 31.5	N08002	13.0 - 17.0	N09911	11.0 - 14.0
N06040	14.0 - 17.0	N08004	17.0 - 21.0	N09925	19.5 - 23.5
N06050	15.0 - 19.0	N08005	17.0 - 21.0	N09926	14.0 - 18.0
N06062	14.00 - 17.00	N08006	10.0 - 14.0	N09979	14.0 - 16.0
N06075	18.0 - 21.0	N08007	19.0 - 22.0	N10001	1.0 maximum
N06082	18.0 - 22.0	N08008	13.0 - 17.0	N10002	14.5 - 16.5
N06102	14.0 - 16.0	N08020	19.0 - 21.0	N10003	6.0 - 8.0
N06110	27.0 - 33.0	N08021	19.0 - 21.0	N10004	4.00 - 6.00
N06230	20.0 - 24.0	N08022	19.0 - 21.0	N10276	14.5 - 16.5
N06333	24.00 - 27.00	N08024	22.5 - 25.0	N10665	1.0 maximum
N06455	14.0 - 18.0	N08026	22.00 - 26.00	N13009	8.00 - 10.00
N06600	14.00 - 17.00	N08028	26.0 - 28.0	N13010	7.50 - 8.50
N06601	21.0 - 25.0	N08030	13.0 - 17.0	N13017	14.0 - 16.0
N06602	14.0 - 17.0	N08032	22.0	N13020	14.0 - 16.0
N06617	20.0 - 24.0	N08050	15.0 - 19.0	N13021	14.0 - 15.7
N06621	18.0 - 21.0	N08065	19.5 - 23.5	N13100	8.0 - 11.0
N06625	20.0 - 23.0	N08151	19.0 - 21.0	N13246	8.0 - 10.0
N06635	14.5 - 17.0	N08221	20.0 - 22.0	N14052	0.25 maximum
N06690	27.0 - 31.0	N08310	24.0 - 26.0	N19903	1.00 maximum
N06782	26.0 nominal	N08320	21.0 - 23.0	N19907	1.00 maximum
N06804	28.0 - 31.0	N08321	19.0 - 21.0	N19909	1.00 maximum
N06975	23.0 - 26.0	N08330	17.0 - 20.0	N99600	13.0 - 15.0
N06985	21.0 - 23.5	N08331	15.0 - 17.0	N99610	13.0 - 15.0
N07001	18.00 - 21.00	N08332	17.0 - 20.0	N99612	13.5 - 16.5
N07002	16.00 nominal	N08334	17.0 - 20.0	N99620	6.0 - 8.0
N07012	11.5 - 12.5	N08366	20.0 - 22.0	N99622	10.0 - 13.0
N07013	12.2 - 13.0	N08367	20.0 - 22.0	N99624	9.0 - 11.75
N07031	22.0 - 23.0	N08421	20.0 - 22.0	N99644	8.0 - 14.0
N07041	18.00 - 20.00	N08603	13.0 - 17.0	N99645	10.0 - 16.0
N07069	14.0 - 17.0	N08604	28.0 - 32.0	N99646	12.0 - 18.0
N07080	18.0 - 21.0	N08605	15.0 - 19.0	N99650	18.5 - 19.5
N07090	18.0 - 21.0	N08613	28.0 - 32.0	N99710	13.0 - 15.0
N07092	14.00 - 17.00	N08614	28.0 - 32.0		
N07252	18.00 - 20.00	N08700	19.0 - 23.0		

Number of nickel alloys reported: 174
Number of active alloys
that have a chromium specification: 142,
reported: 173.
Average chromium content
over all active alloys that specify chromium: 17.2±1.4 pct,
over all active alloys: 14.2±1.1 pct.

Source: Reference 39.

Table 19.—Chromium consumption in the aluminum and alloy, carbon, and stainless steel industries in 1987-90

(Metric tons, except where noted)

	1987	1988	1989	1990
Aluminum[1]				
Master alloy consumption (gross)	1,433	1,727	1,680	2,064
Master alloy consumption (content)	627	515	495	677
Aluminum alloy production	7,436,195	7,637,137	7,820,842	7,727,855
Average chromium content (pct)	0.008	0.007	0.006	0.009
Alloy steel[2]				
Master alloy consumption (gross)	33,667	32,320	32,704	34,947
Master alloy consumption (content)	19,551	18,862	19,665	20,248
Alloy steel alloy production	8,298,021	9,890,131	8,877,712	9,324,955
Average chromium content (pct)	2.4	1.9	2.2	2.2
Carbon steel[3]				
Master alloy consumption (gross)	9,667	12,306	18,008	11,275
Master alloy consumption (content)	5,938	7,551	9,419	6,880
Carbon steel alloy production	70,730,493	78,764,523	78,226,563	78,553,149
Average chromium content (pct)	0.008	0.010	0.012	0.009
Stainless steel[4]				
Master alloy consumption (gross)	329,901	305,355	254,585	274,736
Master alloy consumption (content)	188,193	176,303	150,411	156,686
Stainless steel alloy production	1,839,771	1,994,900	1,747,238	1,847,936
Average chromium content (pct)	10.2	8.8	8.6	8.5

[1] Data from The Aluminum Association reports. Master alloy gross and content quantity from Aluminum Master Alloys Consumer Shipments, Fourth Quarter, various years. Aluminum alloy production estimated as total product net shipments from the 1991 Aluminum Statistical Review, page 13.

[2] Master alloy data from USBM reported consumption of chromium ferroalloys and metal in full-alloy and tool steel in the Chromium chapter of the Minerals Yearbook, various years. Production data from the 1991 Annual Statistical Report of the AISI, page 71.

[3] Master alloy data from USBM reported consumption of chromium ferroalloys and metal in carbon and low-alloy and electric steel in the Chromium chapter of the Minerals Yearbook, various years. Production data from the 1991 Annual Statistical Report of the AISI, page 71.

[4] Master alloy data from USBM reported consumption of chromium ferroalloys and metal in stainless steel in the Chromium chapter of the Minerals Yearbook, various years. Production data from the 1991 Annual Statistical Report of the AISI, page 71. A more detailed study showed chromium contained in stainless steel was 17±1 pct (USBM IC 9275).

Table 20.—Summary of results and recommended average chromium contents of various alloys

(Percent)

Alloy	Method 1	Method 2	Method 3	Best available chromium content
Aluminum	0.04 ± 0.02	0.008 ± 0.001	--	0.04 ± 0.02
Cobalt	20.1 ± 0.9	--	--	20 ± 1
Copper	0.025 ± 0.010	--	--	0.025 ± 0.010
Nickel	14 ± 1	--	--	14 ± 1
Steel:				
Alloy	.68 ± 0.11	0.22 ± 0.02	--	0.68 ± 0.11
Carbon	.007 ± 0.0005	0.01 ± 0.002	--	0.007 ± 0.0005
Stainless	17.86 ± 1.04	9.0 ± 0.8	17.25 ± 1.02	17 ± 1
Titanium	0.49 ± 0.01	--	--	0.49 ± 0.01

-- Not calculated.

NOTE.

Method 1 estimation based on chemical specification by alloy grade averaged over all grades.

Method 2 estimation based on ratio of chromium consumption to alloy production.

Method 3 estimation based on production weighted average of chemical specification by alloy grades.

68.42 pct of Cr_2O_3 to be chromium, one estimates that there is about 0.02 t-Cr/kt-clinker.

Using USBM reported domestic and international production data *(46)*, chromium consumed by the cement industry in 1989 can be estimated. In 1989, annual domestic clinker production of about 70 Mst suggests that about 1.3 kt-Cr are currently being consumed annually by the cement industry. All of this material is lost to the chromium use cycle. At world cement production of about 1,249 Mt in 1989, world chromium release due to cement production is about 23 kt-Cr/y or about 0.5 pct of chromium contained in world chromite ore production.

It is estimated that from 2 kt to 4 kt of Cr_2O_3 (a chemical industry product) is consumed annually for predominantly greater than 60 pct Cr_2O_3 refractories for the glass manufacturing industry. Because these refractories offer three to four times the life of alternatives, EPA regulations are expected to have minimal effect on their use.

Air emission estimates put chromium release to air resulting from cement manufacture at between 2 nt-Cr/t-Cmnt for controlled emission and 10 μt-Cr/t-Cmnt for uncontrolled emission *(47)*. It was estimated that about 16 tons was released in 1984 *(48)*.

Chromite-magnesia and magnesia-chromite[5] refractories are used throughout copper converters. In 1979, average refractory consumption was reported to range from 0.002 t to 0.0045 t of chromite refractories per ton of copper produced, with the United States reporting 0.0036 t of refractory per ton of copper produced. Refractory bricks for use in the copper industry range in Cr_2O_3 content from about 15 pct to more than 20 pct. For the purpose of this study, assume an average Cr_2O_3 of 20 pct. Then about 300 μt-Cr/t-Cu to 600 μt-Cr/t-Cu *(49)*. At 1989 U.S. copper smelter production rates of about 1 Mt-Cu/y, U.S. chromium consumed in refractories in converter furnaces is about 300 t to 600 t annually. At 1989 world copper smelter production rates of about 9 Mt-Cr/y, world chromium consumed in refractories in converter furnaces is about 2.7 kt-Cr to 5.4 kt-Cr or about 0.1 pct of chromium contained in 1989 world chromite production.

Insufficient information was available to estimate chromium consumption in refractories used to produce nickel metal or glass, especially fiberglass.

The USBM has developed methods for recycling chromite-bearing refractory materials *(50)*.

[5]Chromite-magnesia refractories are composed predominantly of chromite; magnesia-chromite, predominantly of magnesia.

ANTHROPOGENIC SOURCES OF CHROMIUM

Some sources of chromium to the environment in the United States have been studied and documented. The environment is usually subdivided into soil, aquatic, and atmospheric. Sources are subdivided into natural and anthropogenic. Anthropogenic sources of chromium are those associated with human activity mostly the chromium production industry or the industrial end use of chromium (i.e., process losses) or when chromium-containing consumer products become obsolete (i.e., product losses). In some cases chromium releases to the environment are completely incidental. Chromium may be associated with a material of commercial interest. When the commercial material is consumed, the associated chromium is released. Chromium as a trace metal associated with coal or oil is an example of such a case. Many sources of chromium are associated with the end use of chromium materials.

Several industrial sources of chromium emission to air have been identified and the quantity of their air emissions has been estimated *(47, 48, 51)*. These sources include chromite ore beneficiation, ferrochromium production, refractory manufacture, chromium chemical manufacture, chromium plating, chromium anodizing, steel production, and leather tanning. Other sources of chromium emission to the air include coal and oil combustion, cement production, municipal refuse and sewage sludge incineration, cooling towers, asbestos mining and milling, and coke production. Table 21 shows atmospheric emissions of chromium in and emission factors for the United States. The table shows that steel production is the single largest source of chromium emissions in the United States and that refractory and ferrochromium production have the largest chromium emission factors (release per unit of production).

Chromium plating operations and water cooling towers are two sources of chromium emissions singled out for regulation because they were found to have been significant sources of chromium emissions. Those industries were studied in detail *(51)*.

Plating

It was estimated that there were about 1,540 hard chromium plating shops operating in the United States in 1989. Hard chromium plating is the application of a relatively thick layer of chromium (typically between 1.3 μm and 762 μm to a steel substrate) to provide surface wear resistance; a low coefficient of friction, hardness, and corrosion resistance; or to rebuild surfaces that have been eroded. Uses of hard

Table 21.—Atmospheric chromium emissions and emission factor estimates by source category in the United States

Source category	Chromium emissions[1] (Metric tons/year)	Chromium emission factor[2] (g-Cr/t-product)[3]
Chromite ore production	--	--
Chromite ore refining	3	4-58
Ferrochromium production[4]	43	5,791
Chromium chemical production[5]	450-900	150
Refractory production	90	53,000
Sewage sludge incineration	25	0.03-4.6
Steel production[6]	2,870	1,230-3,020
Chromium plating and anodizing:[7]		
Hexavalent plating:		
Hard	145	--
Decorative	10	--
Trivalent plating	0	--
Anodizing	3.6	--
Cooling towers:[7]		
Industrial	85	--
Comfort cooling	33	--
Cement production	16	1.7-5
Combustion of coal and oil:		
Boilers	737	--
Process heaters	556	--
Total	5,066.6 - 5,516.6	

[1]Reference 48, except as noted.
[2]Reference 47.
[3]Units are grams of chromium released per ton of product produced.
[4]Melting plus handling.
[5]Sodium bichromate.
[6]Stainless steel.
[7]Reference 51.

chromium plating include hydraulic cylinders and rods, industrial rolls, zinc die castings, plastic molds, engine components, and marine hardware. Chromic acid is the source of chromium units for hard chromium plating. The source of chromium emissions from these plating baths is the entrainment of chromic acid solution in hydrogen bubbles generated by chemical reactions in and evolving from the bath. This process results in a chromic-acid-containing mist. It was found that hexavalent chromium emission from hard chromium plating averaged 9.8 mg/A-hr. Hexavalent chromium emission ranged from 3.2 mg/A-hr to 22.5 mg/A-hr. Emission control devices were found to eliminate 90 pct to 98 pct of emissions. Nationwide emission was estimated at 145 t of hexavalent chromium per year from hard chromium plating operations.

It was estimated that there were about 2,800 decorative chromium plating shops operating in the United States in 1989. Decorative chromium plating is the application of a relatively thin layer of chromium (typically between 0.0001 μm to 2.5 μm over a nickel layer to an aluminum, brass, steel, or plastic substrate) to provide a bright surface with wear and tarnish resistance. Uses of decorative chromium plating include automotive trim, metal furniture, bicycles, hand tools, and plumbing fixtures. Chromic acid is the source of chromium units for decorative chromium plating and is also used in etching, a preplating process applied to plastics. As with hard chromium plating, the source of chromium emissions from these plating baths is the entrainment of chromic acid solution in hydrogen bubbles generated by chemical reactions in and evolving from the bath. This process also results in a chromic-acid-containing mist. It was found that hexavalent chromium emission from decorative (hexavalent) chromium plating averaged 1.6 mg/A-hr. Uncontrolled hexavalent chromium emission ranged from 1.6 mg/A-hr to 2.0 mg/A-hr. Emission control devices were found to remove up to 99 pct of emissions. Nationwide emission from hexavalent-chromium plating operations was estimated at 10 t of hexavalent chromium per year from decorative chromium platers.

Trivalent chromium chemical baths can also be used for decorative chromium plating. Trivalent chromium chemical baths do not mist.

It was estimated that there were about 680 chromic acid anodizing shops operating in the United States in

1989. Chromic acid anodizing is a surface treatment process applied to aluminum to provide corrosion protection, electrical insulation, ease of coloring, and improved dielectric strength. Uses of acid anodizing include aircraft parts and architectural structures that are subject to high stress and corrosion. Uncontrolled hexavalent chromium emission from acid anodizing baths was estimated at 0.6 grams per hour per square meter of tank surface area. Nationwide emission was estimated at 3.6 t of hexavalent chromium per year.

Cooling Towers

Cooling towers are devices used to cool warm water by exchange of heat with ambient air. Recirculating water chemical treatments are used to prevent corrosion and may contain chromium. Industrial process cooling towers are those used to cool water used in manufacturing processes. Comfort cooling towers are those used to cool water for heating, ventilation, and air conditioning and for refrigeration. Chromium is emitted to the air when water circulated in the cooling tower is entrained by air in the cooling tower and escapes with that air.

It was estimated that 2,855 chromium-chemical-using industrial process cooling towers were used by 476 petroleum refineries, 2,039 at chemical plants, 224 at primary metals plants, 110 at miscellaneous plants, and 6 at utilities. This represents about 31 pct of industrial process cooling towers. Nationwide emission from these operations was estimated at 85 tons of hexavalent chromium per year for which the distribution was: 51 pct from chemical manufacturers, 38 pct from petroleum refining, 10 pct from primary metals, 0.3 pct from tobacco products, 0.2 pct from tire and rubber, 0.1 pct from textile manufacturing, 0.01 pct from glass manufacturing, and 1 pct from utilities.

It was estimated that 37,500 chromium-chemical-using comfort cooling towers were used by hospitals, hotels, educational facilities, office buildings, and shopping malls for heating, ventilation, and air conditioning and by ice-skating rinks, cold-storage warehouses and other commercial operations for refrigeration. This represents about 15 pct of comfort cooling towers operated. Nationwide emission from comfort cooling towers was estimated at 33 t of hexavalent chromium per year.

In 1990, EPA prohibited the use of hexavalent chromium chemicals in comfort cooling towers *(52)*. In 1993, EPA proposed the elimination of chromium based chemicals in new and existing industrial process cooling towers. EPA planned to make a final ruling by November 1994.

HISTORICAL TRENDS IN U.S. CHROMIUM FLOW

MINING AND MANUFACTURING

Chromium material flow is temporally dynamic due to changes in the consuming industries and changes in the attitude of consuming nations. As shown by table 9, chromium consumption is closely tied to the metallurgical industry and in particular to the steel industry. Major impacts on the chromium industry were made by the invention of stainless steel, the evolution of steelmaking from the open hearth furnace to electric furnaces, and the invention of the argon-oxygen decarburization and other ladle refining processes.

Chromite ore deposits in the United States were reviewed by the U.S. Geological Survey (USGS) in 1962 *(53)* and domestic chromium availability was analyzed by the USBM in 1982 *(54)*.

Chromite ore was once mined in the United States and continues to be processed here. Primary processing locations have been identified in the chromium chapter of the USBM annual Minerals Yearbook since 1967. All chromium and chromium compound processing locations that meet EPA's minimum reporting requirements are identified in TRI database. Figure 6 shows historical chromite production in the United States. The United States has been dependent on imports for a long time. In recent years, the United States has consumed about 10 to 15 pct of world chromite production. In 1989, U.S. apparent consumption was 11 pct of chromium contained in world chromite ore production. Figure 7 shows domestic chromite consumption and world chromite production. Before World War II, the United States was the world's major consumer of chromite; and before World War I, the United States was a major chromite producer. Commercially significant quantities of chromite ore have not been mined in the United States since before about 1900. The Federal Government encouraged chromite ore production during the World War I and II and Korean war time periods.

The major stopping points of chromium as it moves from extraction through the manufacturing industry, consumer and commercial products, to disposal and reuse include chromite deposit sites, primary consumer plants, manufacturing plants, scrap yards and recycling

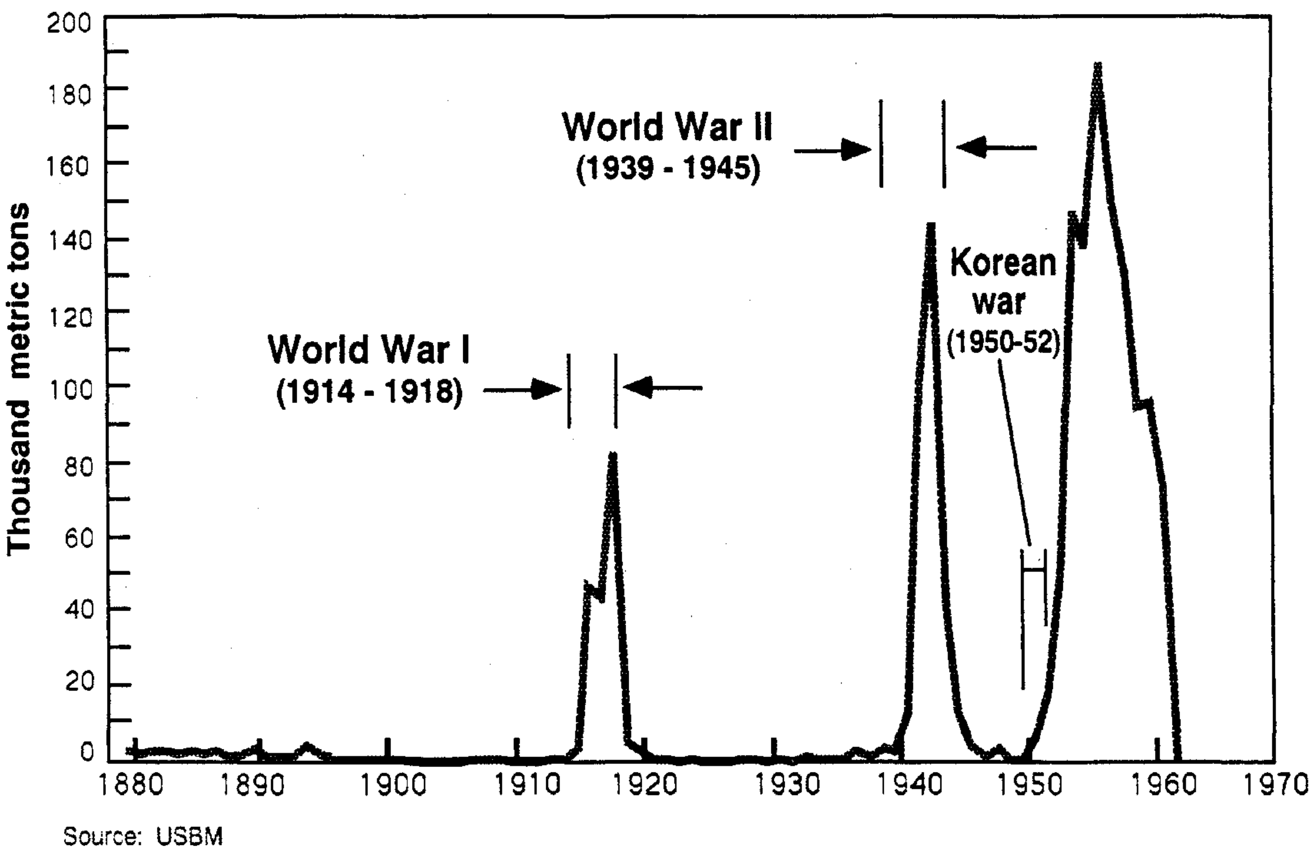
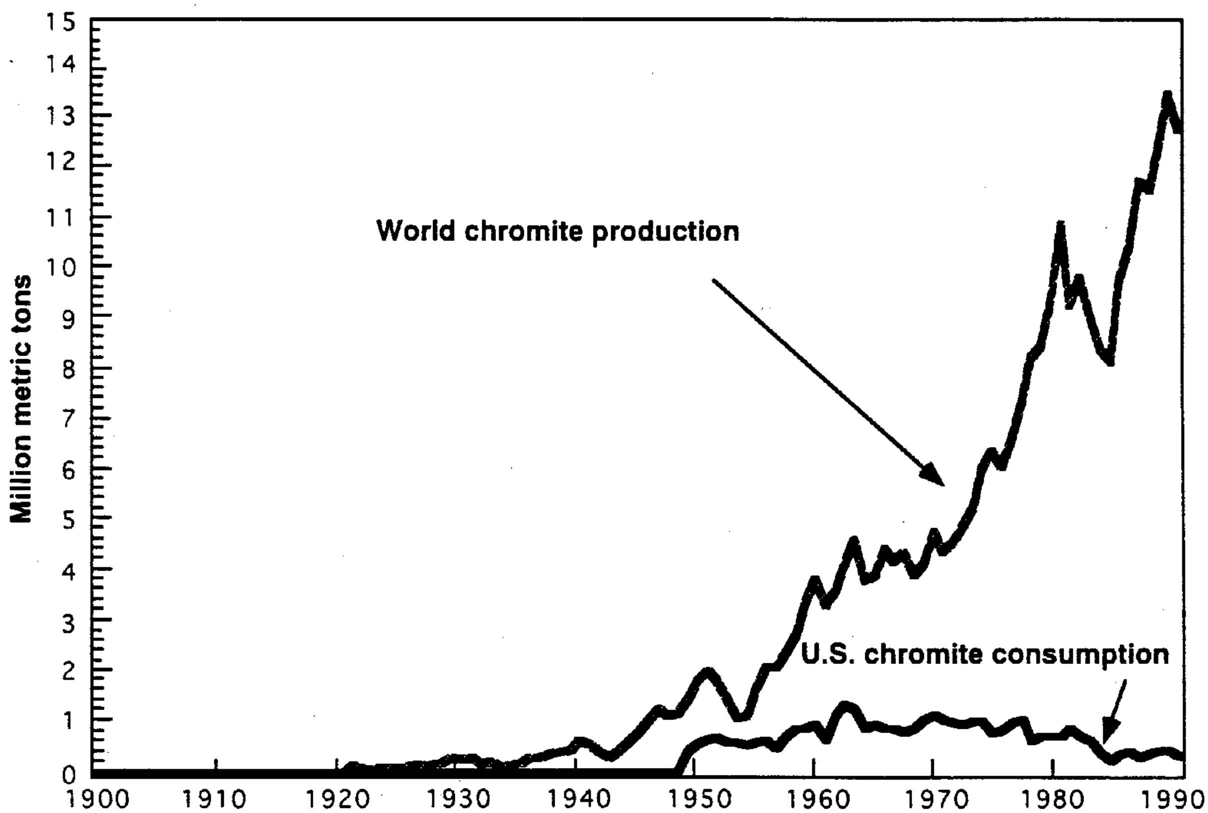


Figure 6. Chromite ore production in the United States from 1880 to 1960.



Source: USBM.

Figure 7. World production and U.S. consumption of chromite ore from 1900 to 1990.

centers. Other chromium materials remain geographically dispersed or are stored at waste disposal sites.

The USGS identifies chromium resources in the United States. The USBM evaluates some of those resources. The EPA monitors releases and transfers of chromium and chromium compounds by location within the manufacturing industry. Each of these Federal agencies has data about chromium stopping points. The USGS reported the location of domestic chromium deposits *(53)*. USGS reported the location information for more than 70 domestic deposits along with references for other information about those deposits. The USBM reported evaluation of several domestic deposits *(54)* and the location of domestic primary chromium process plants *(55)*. The location information about domestic chromium deposits, evaluated chromium resources, and primary consumer industry is shown in table 22 and in figure 8 for the entire United States. The following figures show the same information for each State (figure 9 through figure 29).

U.S. chromium apparent consumption, on average from 1973 through 1983, was about 516 kst-Cr and was distributed among primary consumer industries as follows; 70 pct metallurgical, 18 pct chemical, 12 pct refractory *(56)*. Since that result was published, industry practice has changed. Chromite ore consumption by the refractory industry has declined and the trend of obtaining chromium units through ferrochromium imports as opposed to chromite ore imports has continued. U.S. chromium apparent consumption was here recalculated, including reported domestic industry but ignoring National Defense Stockpile annual stock changes, for the years from 1971-92 and 10-year averages were calculated for the 1973-82 and the 1983-92 time periods. Ten-year time periods were chosen to minimize the effect of annual variations (mostly resulting from changes in stainless steel demand) while showing the trend changes. Table 23 shows the results of those calculations. Over the two time periods, U.S. chromium consumption has declined from a 1973-82 average of 459 kt-Cr to a 1983-92 average of 400 kt-Cr, a 13 pct decline. Not only has chromium apparent consumption and apparent consumption attributed to each primary consumer industry declined (figure 30), but the distribution among those industries has changed dramatically. The metallurgical industry share of consumption has increased from 79 pct in the 1973-82 time period to 87 pct in the 1983-92 time period while that of the refractory industry has dropped from 9 pct to 3 pct over the same period. Chemical industry consumption declined from 12 pct to 10 pct over the same period. Reported consumption by end use shows changes over the same time period (figure 31). High-carbon ferrochromium consumption by the stainless steel industry increased from 76 pct of materials used in the 1973-82 time period to 95 pct in the 1983-92 time period (table 23).

HISTORICAL ENVIRONMENTAL CHROMIUM RELEASES AND TRANSFERS

International industry changes and changing trade patterns starting around 1970 resulted in declining use of chromite ore and increasing use of ferrochromium as a source of chromium in the United States. The release of chromium to the environment in 1980 was estimated to have been about 12,000 metric tons based on consumption of chromium materials *(57)*. Any domestic historical analysis of environmental chromium releases should take into account the changing use patterns of chromium materials in the United States.

Chromium has been classified as a toxic material by Congress in Section 313 of the Emergency Planning and Community Right to Know Act of 1986. Companies that release or transfer materials classified as toxic are required by that Act to report those releases and transfers to EPA *(58)*. In turn, EPA collates the reported information and makes it publicly available in the form of the Toxic Release Inventory database.

EPA has been collecting environmental release information since 1987 from facilities that employ 10 or more persons and use a threshold amount of chromium contained in chromium compounds. EPA data collection is limited to manufacturing and fabricating facilities, i.e., companies that are included in Standard Industrial Classification (SIC) Codes 20 through 39. The threshold amount decreased from 1987 to 1989, after which it remained constant. The threshold limit for a facility that manufactured or processed chromium compounds was 75,000 pounds of contained chromium in 1987, 50,000 pounds in 1988, and 25,000 pounds in 1989 and subsequent years. The threshold limit for facilities that otherwise used chromium compounds has been and remains 10,000 pounds.[6] When reporting chromium releases, a facility must add up the chromium released from all sources that exceed a de

[6]Note that EPA has definitions for manufacture, process, and otherwise use for the purpose of reporting releases. For the purpose of EPA reporting: manufacture means to produce, prepare, compound, or import a listed toxic chemical; process means the preparation of a listed toxic chemical, after its manufacture, for distribution in commerce; and otherwise use encompasses any activity involving a listed toxic chemical at a facility that does not fall under the definitions of manufacture or process.

Table 22.—Location of U.S. identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore

Name	Location			
			Coordinates	
	State	City or county	Lat.[1]	Long.[2]
CHEMICAL INDUSTRY				
Allied Chemical Corp.	MD	Baltimore	39°17.3′	76°37.0′
American Chrome & Chemicals Inc[3]	TX	Corpus Christi	27°46.8′	97°23.9′
Diamond Shamrock Corp.	NJ	Kearny	40°45.8′	74°09.1′
Diamond Shamrock Corp.	OH	Painsville	41°43.4′	81°15.0′
Hercules, Inc.	NY	Glenn Falls	42°15.3′	74°01.7′
Occidental Chemicals Corp.[4]	NC	Castle Hayne	34°21.2′	77°54.0′
METALLURGICAL INDUSTRY				
Chromium Mining and Smelting Corp.	TN	Woodstock	35°16.4′	89°58.9′
Elkem Metals Co.[5]	OH	Marietta	39°24.9′	81°27.0′
Elkem Metals Co.[5]	WV	Alloy	38°08.3′	81°16.5′
Globe Metallurgical Inc.[6]	OH	Beverly	39°32.9′	81°38.4′
Foote Mineral Co.	IA	Keokuk	40°23.9′	91°23.8′
Foote Mineral Co.	OH	Vancoram	40°01.5′	81°35.2′
Foote Mineral Co.	WV	Graham	39°01.2′	82°02.0′
Macalloy Inc.[7]	SC	Charleston	32°45.8′	79°55.8′
Ohio Ferro-Alloys Corp.	OH	Brilliant	40°53.9′	80°37.6′
Ohio Ferro-Alloys Corp.	WA	Tacoma	47°14.2′	122°26.0′
Prairie Metals and Chemicals, Inc.	MS	Prairie	33°47.7′	88°40.0′
Satralloy Corp.	OH	Steubenville	40°21.6′	80°37.1′
SKW Alloys Inc.	KY	Calvert City	37°01.9′	88°20.9′
SKW Alloys Inc.	NY	Niagara Falls	43°05.8′	79°03.4′
Union Carbide Corp.	NY	Niagara Falls	43°05.8′	79°03.4′
REFRACTORY INDUSTRY				
A. P. Green Refractory Co.	MO	Mexico	39°10.2′	91°53.0′
Babcock & Wilcox Co.	GA	Augusta	33°28.2′	81°58.0′
Basic Inc.	OH	Maple Grove	41°09.5′	83°24.8′
Corhart Refractories Co. Inc.	KY	Louisville	38°14.2′	85°45.7′
Corhart Refractories Co. Inc.	MS	Pascagoula	30°21.2′	88°32.8′
Corhart Refractories Co. Inc.	WV	Buckhannon	38°59.5′	80°13.8′
Davis Refractories Inc.	OH	Jackson	39°03.1′	82°38.6′
D. J. Lavino & Co.	CA	Newark	37°31.8′	122°02.2′
General Refractories Co.	UT	Lehi	40°23.6′	111°51.0′
General Refractories Co.	IN	Gary	41°36.0′	87°20.0′
General Refractories Co.	MD	Baltimore	39°17.3′	76°37.0′
H. K. Porter Co., Inc.	MS	Pascagoula	30°21.2′	88°32.8′
Harbison-Walker Refractories	CA	Warm Springs	37°29.2′	121°55.7′
Harbison-Walker Refractories	IN	Hammond	41°37.8′	87°30.3′
Harbison-Walker Refractories	MD	Baltimore	39°17.3′	76°37.0′
Kaiser Aluminum & Chemical Corp.[8]	PA	Plymouth Meeting	40°06.0′	75°16.6′
National Refractories & Minerals Corp.[9]	CA	Moss Landing	36°48.1′	121°47.2′
National Refractories & Minerals Corp.[9]	OH	Columbiana	40°53.3′	80°41.8′
North American Refractories Co. Ltd	PA	Womelsdorf	40°21.7′	76°11.1′
Ohio Fire Brick Co.	OH	Jackson	39°03.1′	82°38.6′
CHROMITE ORE RESOURCES EVALUATED				
Claim Point	AK	Seldovia	59°12.4′	151°49.2′
Red Bluff Bay	AK	Port Alexander	56°51.2′	134°42.7′
Red Mountain	AK	Seldovia	59°22.5′	151°28.5′
Bar Rick Mine	CA	Del Norte	41°39.7′	123°56.6′
McGuffy Creek	CA	Siskiyou	41°43.0′	123°02.5′
North Elder Creek	CA	Tehama	40°01.6′	122°39.2′
Pilliken Mine	CA	El Dorado	38°46.9′	121°05.5′

See footnotes at end of table.

Table 22.—Location of U.S. identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore—Continued

Name	Location			
			Coordinates	
	State	City or county	Lat.[1]	Long.[2]
CHROMITE ORE RESOURCES EVALUATED--CONTINUED				
Siead Creek/Emma Bell Mines	CA	Siskiyou	41°54.7′	123°08.6′
Louise Chromite	GA	Troup	33°04.9′	84°54.4′
West Placer Area	MD	Cecil	39°44.1′	76°10.6′
Mouat Mine[10]	MT	Stillwater	45°23.1′	109°54.2′
Benbow Mine[10]	MT	Stillwater	45°21.3′	109°48.1′
Gish Mine[10]	MT	Sweetgrass	45°28.7′	110°12.1′
North Carolina Area:				
Morgan Hill	NC	Buncombe	35°46.3′	82°30.4′
Holcombe Branch	NC	Madison	35°48.0′	82°29.0′
Leichester	NC	Buncombe	35°39.0′	82°42.0′
Southwest Oregon Beach Sands	OR	Coos	43°14.6′	124°35.6′
Renshaw Placer	PA	Chester	39°44.4′	76°03.0′
Casper Mountain	WY	Natrona	42°44.2′	106°19.4′
Pine Flat Area:				
Gasquet Laterite	CA	Del Norte	41°50.6′	124°00.9′
Little Rattlesnake	CA	Del Norte	41°41.8′	123°58.3′
Lower Elk Camp	CA	Del Norte	41°51.2′	123°56.1′
Pine Flat Mountain	CA	Sonoma	38°44.1′	122°45.1′
Red Mountain	CA	Trinity	40°05.6′	123°13.8′
Eight Dollar Mountain	OR	Josephine	42°14.9′	123°39.1′
Red Flat	OR	Curry	42°21.1′	124°17.9′
Rough and Ready	OR	Josephine	42°05.0′	123°44.6′
Woodcock	OR	Josephine	42°07.2′	123°40.7′
CHROMITE DEPOSITS IDENTIFIED				
Cressent City Beach Sands	CA	NA	41°44′	124°10′
Cressent City Beach Sands	CA	NA	41°42′	124°10′
High Plateau and Bonanza Mines	CA	NA	41°56′	123°56′
High Dome (4 deposits)	CA	NA	41°57′	123°52′
French Hill Mine (2 deposits)	CA	NA	41°49′	123°59′
Soldiers Well (8 deposits)	CA	NA	41°42′	123°57′
Old Doe (4 deposits)	CA	NA	41°41′	123°56′
Cyclone Gap	CA	NA	41°52′	123°37′
Seiad Creek (Mountain View)	CA	NA	41°54′	123°08′
Fairview	CA	NA	41°48′	123°06′
McGuffy Creek group (8 deposits)	CA	NA	41°43′	123°03′
Gazelle Mountain (2 deposits)	CA	NA	41°25′	122°36′
Coggins	CA	NA	41°11′	122°17′
Railroad Lease (5 deposits)	CA	NA	41°09′	122°31′
Forest Queen group (7 deposits)	CA	NA	41°03′	122°24′
Little Castle Creek	CA	NA	41°11′	122°18′
Grau Mine (3 deposits)	CA	NA	40°02′	122°40′
Nobel Electric Steel group (10 deposits)	CA	NA	40°02′	122°39′
Blace diamond group (23 deposits)	CA	NA	39°44′	122°35′
Lambert	CA	NA	39°47′	121°37′
Boiler Pit (30 deposits)	CA	NA	39°08′	120°45′
Dobbas (2 deposits)	CA	NA	38°48′	121°06′
Pillikan (6 deposits)	CA	NA	38°47′	121°06′
Murphy (2 deposits)	CA	NA	38°32′	120°57′
Peoria Flat area (12 deposits)	CA	NA	37°55′	120°30′
McCormick (6 deposits)	CA	NA	37°52′	120°30′
Marshs Flat group (7 deposits)	CA	NA	37°48′	120°22′
Number 5 and Adobe Canyon groups (30 deposits)	CA	NA	37°25′	120°24′
Butler Estate (Mistake)	CA	NA	36°19′	120°33′

See footnotes at end of table.

Table 22.—Location of U.S. identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore--Continued

Name	Location: State	City or county	Coordinates: Lat.[1]	Long.[2]
CHROMITE DEPOSITS IDENTIFIED--CONTINUED				
Clara H., Lacey (13 deposits)	CA	NA	36°57′	119°25′
Jack Spratt (9 deposits)	CA	NA	36°54′	119°19′
Holston	CA	NA	36°02′	118°56′
Sweetwater-Norcross group (15 deposits)	CA	NA	35°25′	120°45′
Castro group (10 deposits)	CA	NA	35°23′	120°42′
Trinidad-Pick and Shovel group (6 mines)	CA	NA	35°22′	120°41′
Sousa Ranch	CA	NA	35°15′	120°42′
Reed (Wilkins) mine	MD	NA	39°37′	76°27′
Gallon Jug claims	MT	NA	45°02′	109°28′
Drill, North Star, Pick, and Shovel claims	MT	NA	45°03′	109°27′
Highline claim	MT	NA	45°02′	109°25′
Benbow mine	MT	NA	45°22′	109°48′
Mouat mine	MT	NA	45°23′	109°54′
Central Stillwater deposits	MT	NA	45°25′	110°05′
Gish deposit	MT	NA	45°29′	110°12′
Dry Camp (and 5 others)	OR	NA	44°22′	118°47′
Chambers mine (5 deposits)	OR	NA	44°21′	118°50′
Haggard and New (and 4 deposits)	OR	NA	44°21′	118°53′
Iron King Mine (and 3 deposits)	OR	NA	44°21′	118°56′
Chollard (Golconda)	OR	NA	42°05′	123°33′
Sordy mine	OR	NA	42°26′	123°44′
Oregon mine	OR	NA	42°21′	123°46′
Chrome King (and 2 others)	OR	NA	42°19′	123°49′
McCaleb group	OR	NA	42°16′	123°51′
Sour Dough mine	OR	NA	42°02′	123°57′
South Slough area	OR	NA	43°19′	124°18′
South Slough area (8 deposits)	OR	NA	43°16′	124°18′
Seven Devils Terrace (12 deposits)	OR	NA	43°15′	124°22′
Pioneer Terrace and Lagoons (6 deposits)	OR	NA	43°12′	124°22′
Unexplored deposits (2)	OR	NA	43°04′	124°33′
Present beach	OR	NA	43°05′	124°26′
Butler mine (3 deposits)	OR	NA	42°51′	124°28′
Present beach	OR	NA	42°49′	124°32′
Ophir beach	OR	NA	42°34′	124°23′
Present beach	OR	NA	42°28′	124°25′
Rogue River beaches	OR	NA	42°25′	124°25′
Line, Red, and Jenkins pits (6 deposits)	PA	NA	39°43′	76°10′
Wood mine (3 deposits)	PA	NA	39°43′	76°10′
Lambert	WA	NA	48°41′	121°59′
Three Lakes (3 deposits)	WA	NA	48°38′	121°54′
Cle Elum River deposits	WA	NA	47°26′	121°04′
Blewett deposits	WA	NA	47°25′	120°40′
Casper Mountain	WY	NA	42°45′	106°18′

NA Not available.
[1]North latitude.
[2]West longitude.
[3]Formerly PPG Industries, Inc.
[4]Formerly Diamond Shamrock Corp.
[5]Formerly Union Carbide Corp.
[6]Formerly Interlake Inc.
[7]Formerly Airco Alloys.
[8]Formerly E. J. Lavino & Co.
[9]Formerly Kaiser Aluminum & Chemical Corp.
[10]Part of the Stillwater Complex.

Sources:
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Reference 53.
Reference 54.
Reference 55.

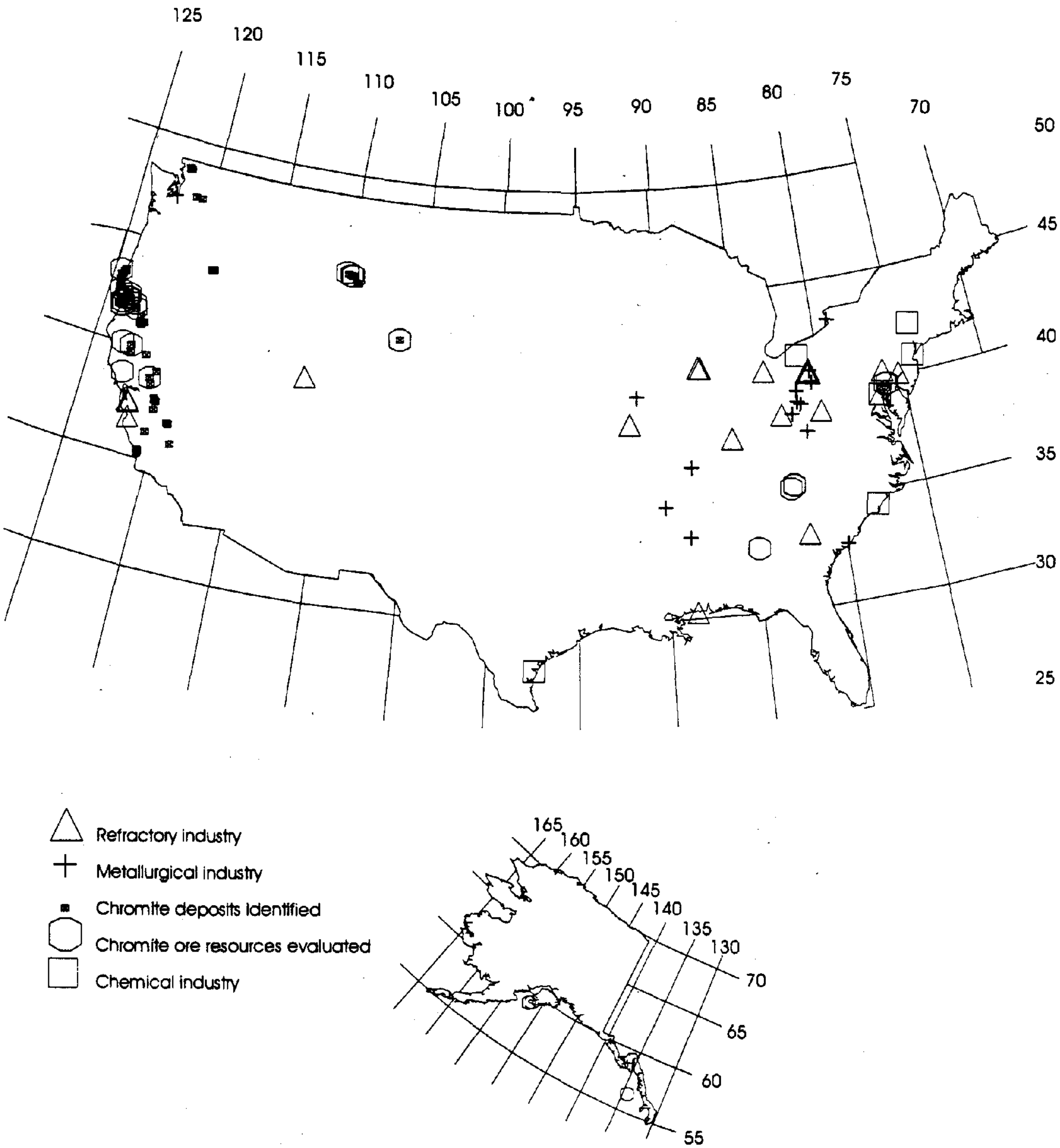


Figure 8. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in the United States.

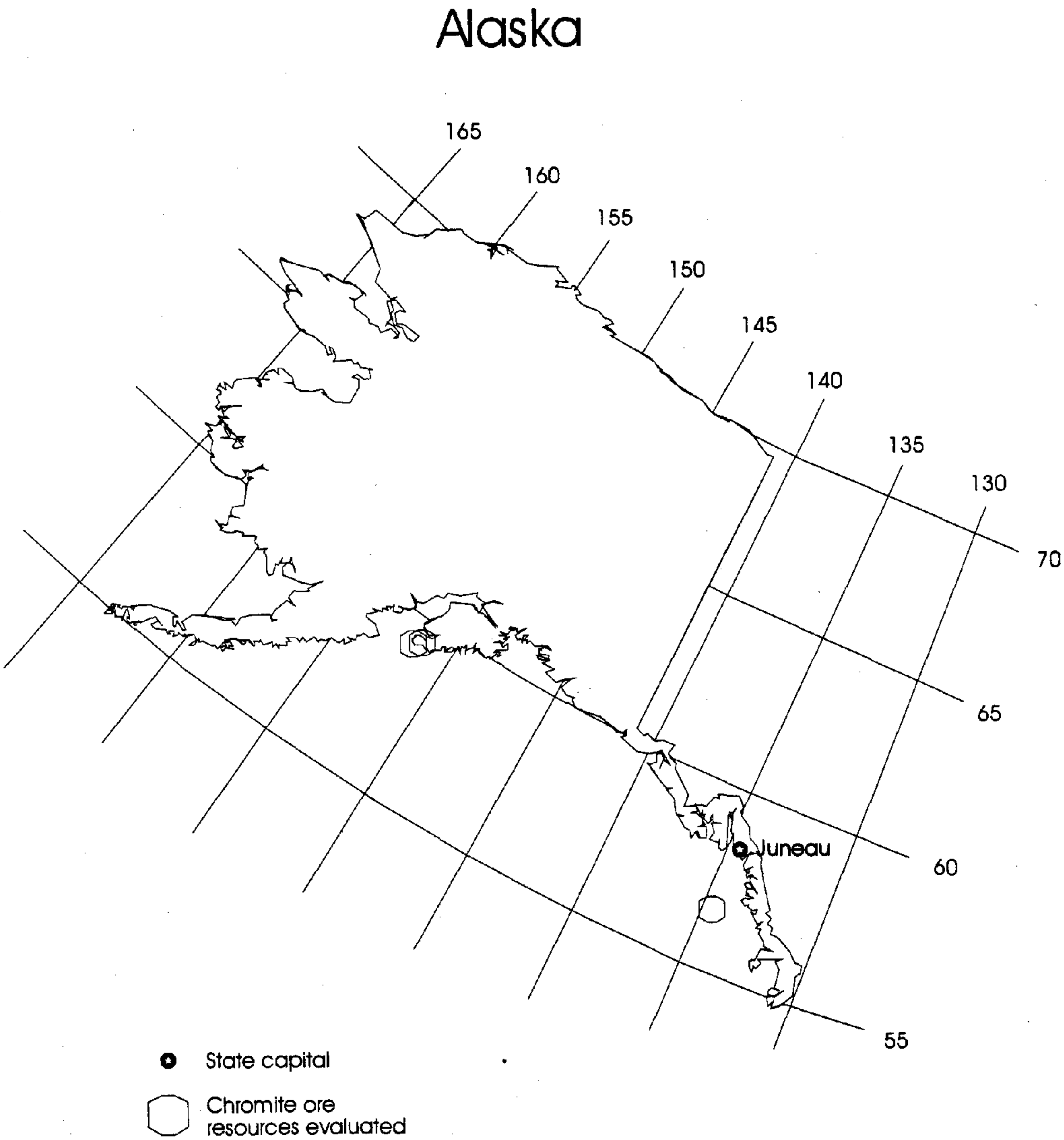


Figure 9. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Alaska.

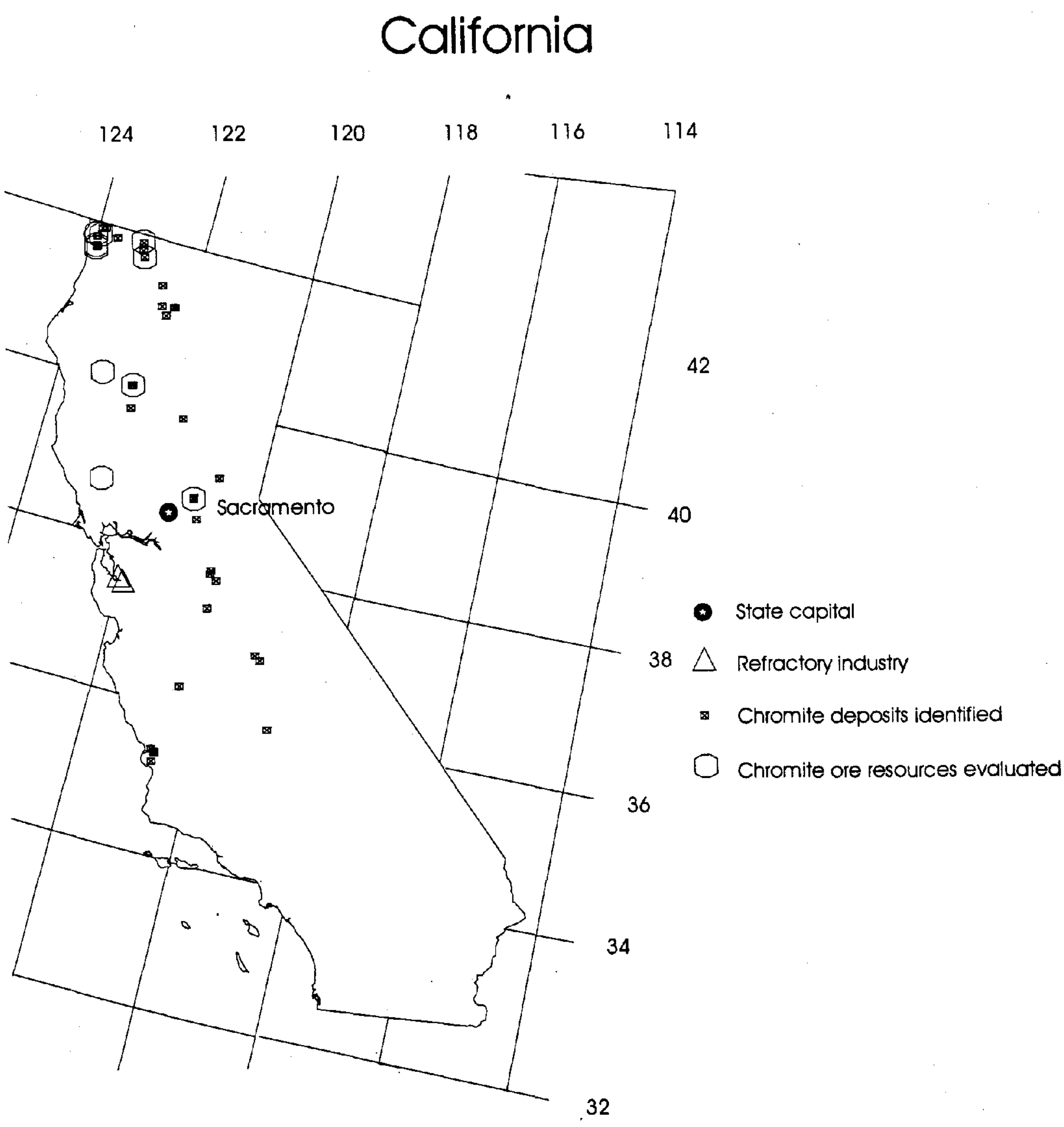


Figure 10. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in California.

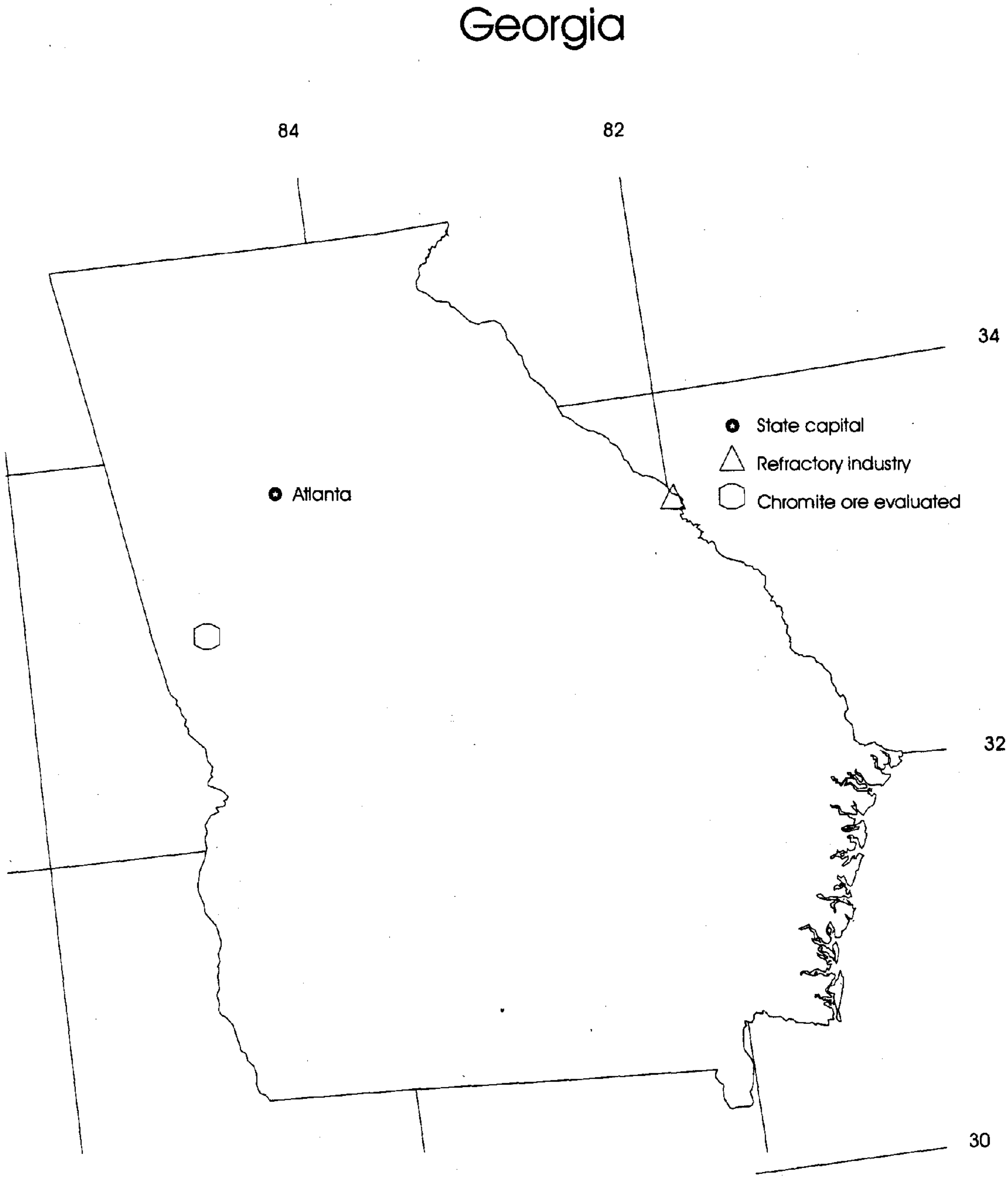


Figure 11. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Georgia.

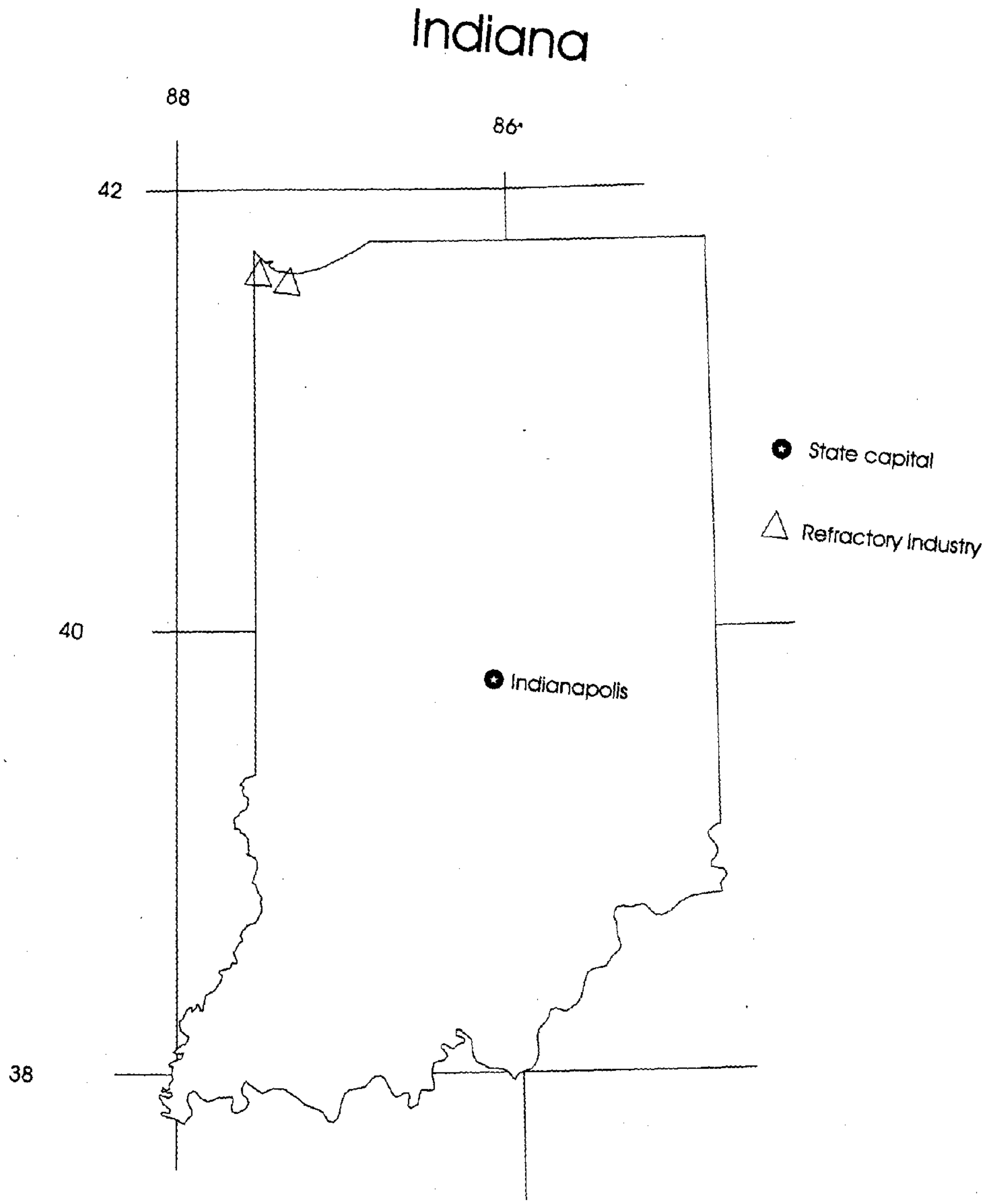


Figure 12. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Indiana.

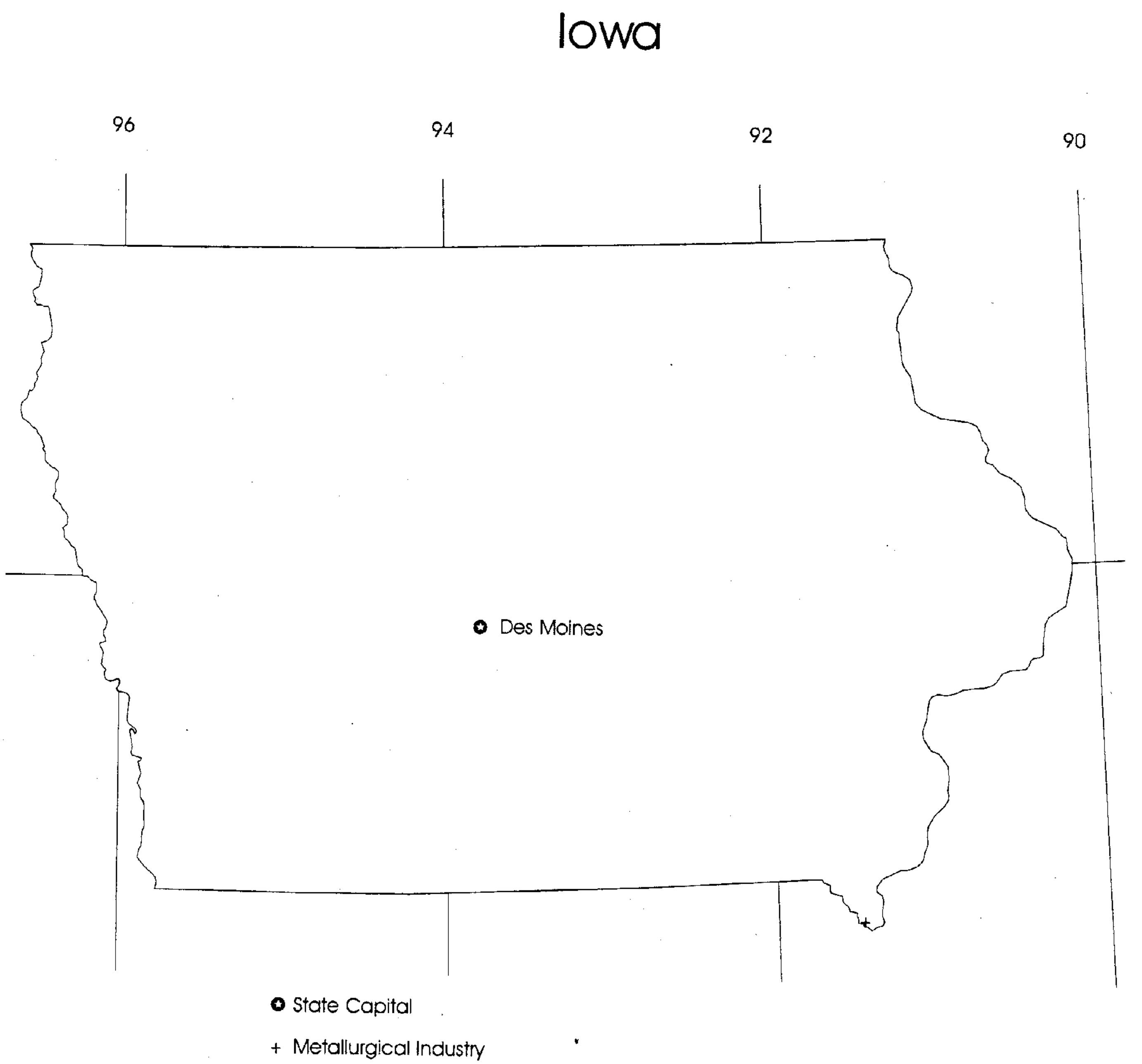


Figure 13. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Iowa.

Figure 14. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Kentucky.

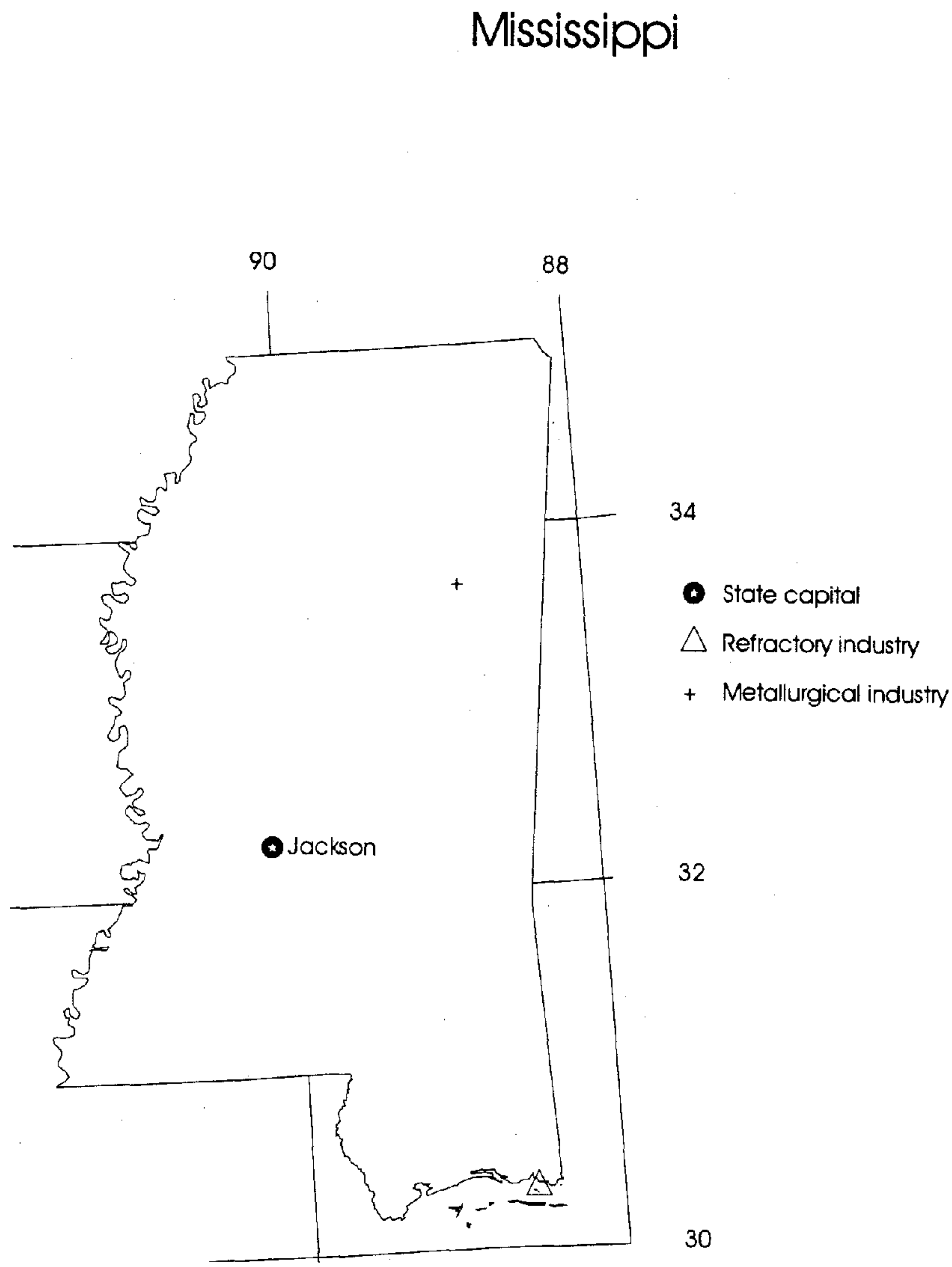


Figure 15. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Mississippi.

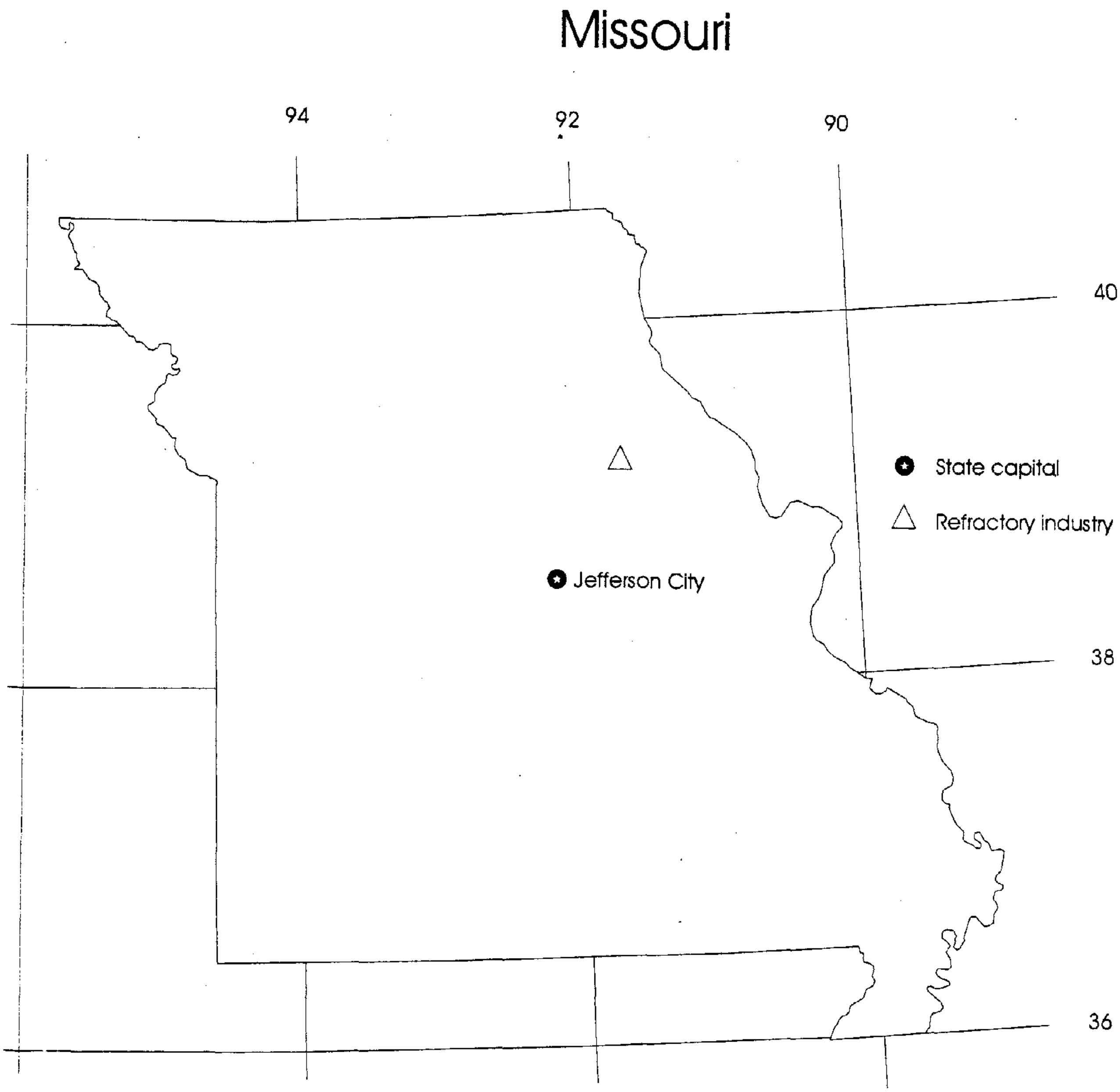


Figure 16. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Missouri.

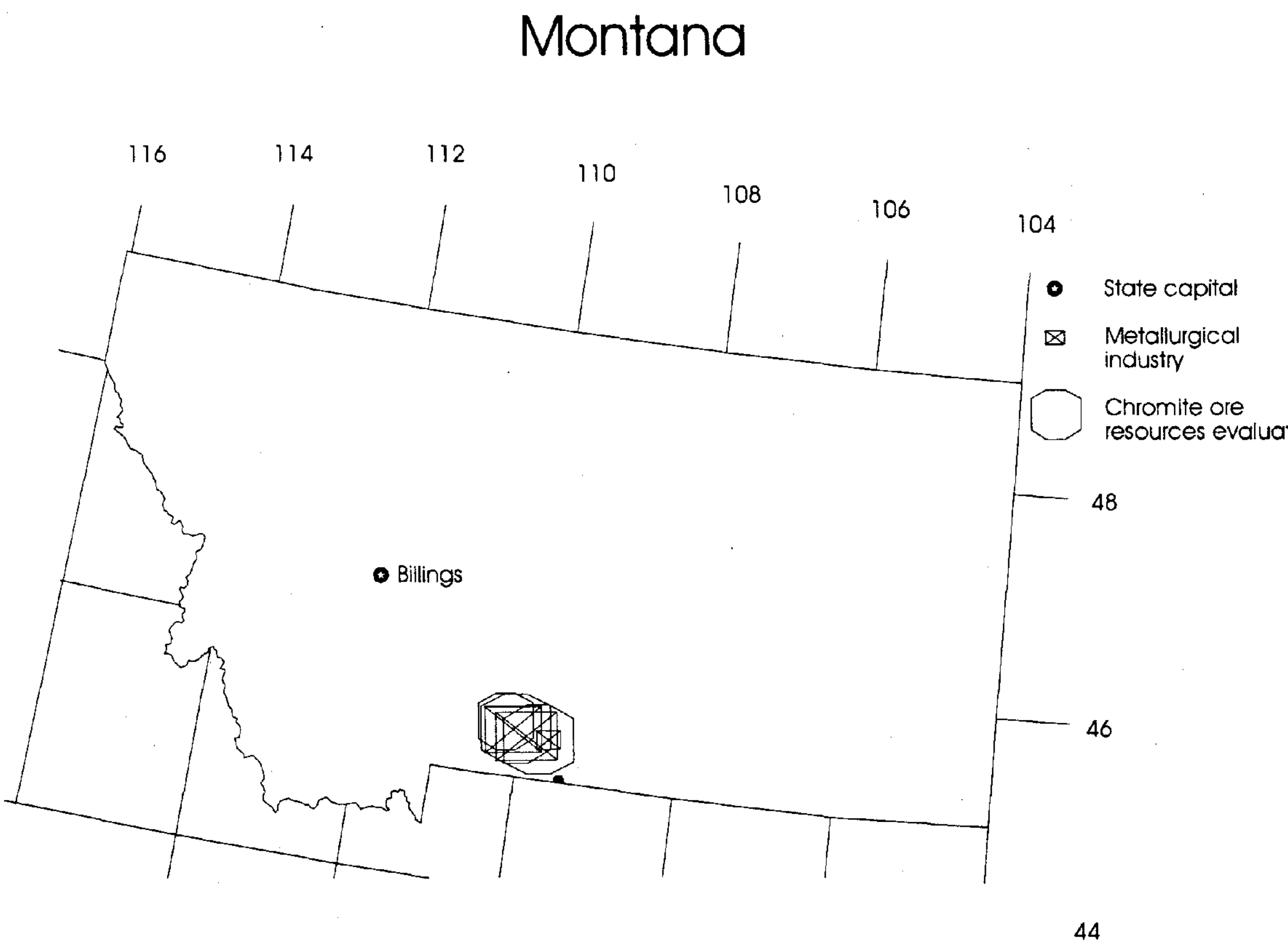
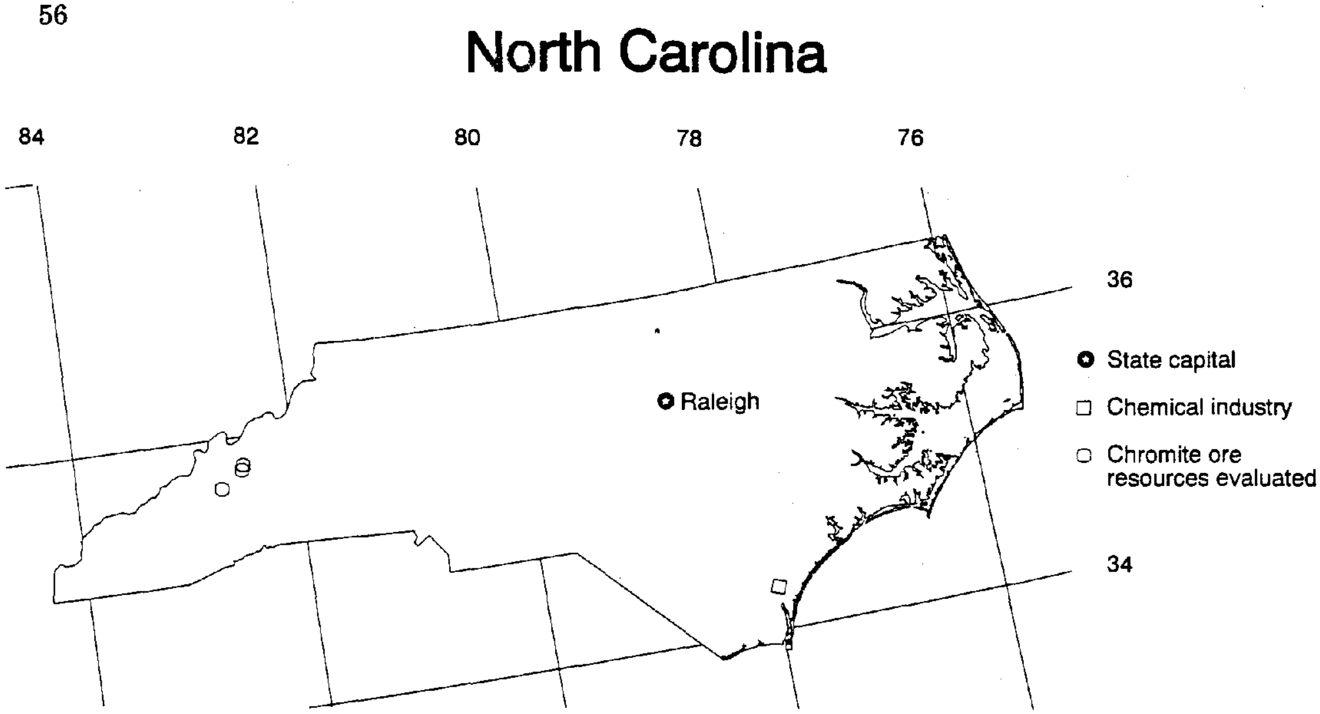


Figure 17. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Montana.



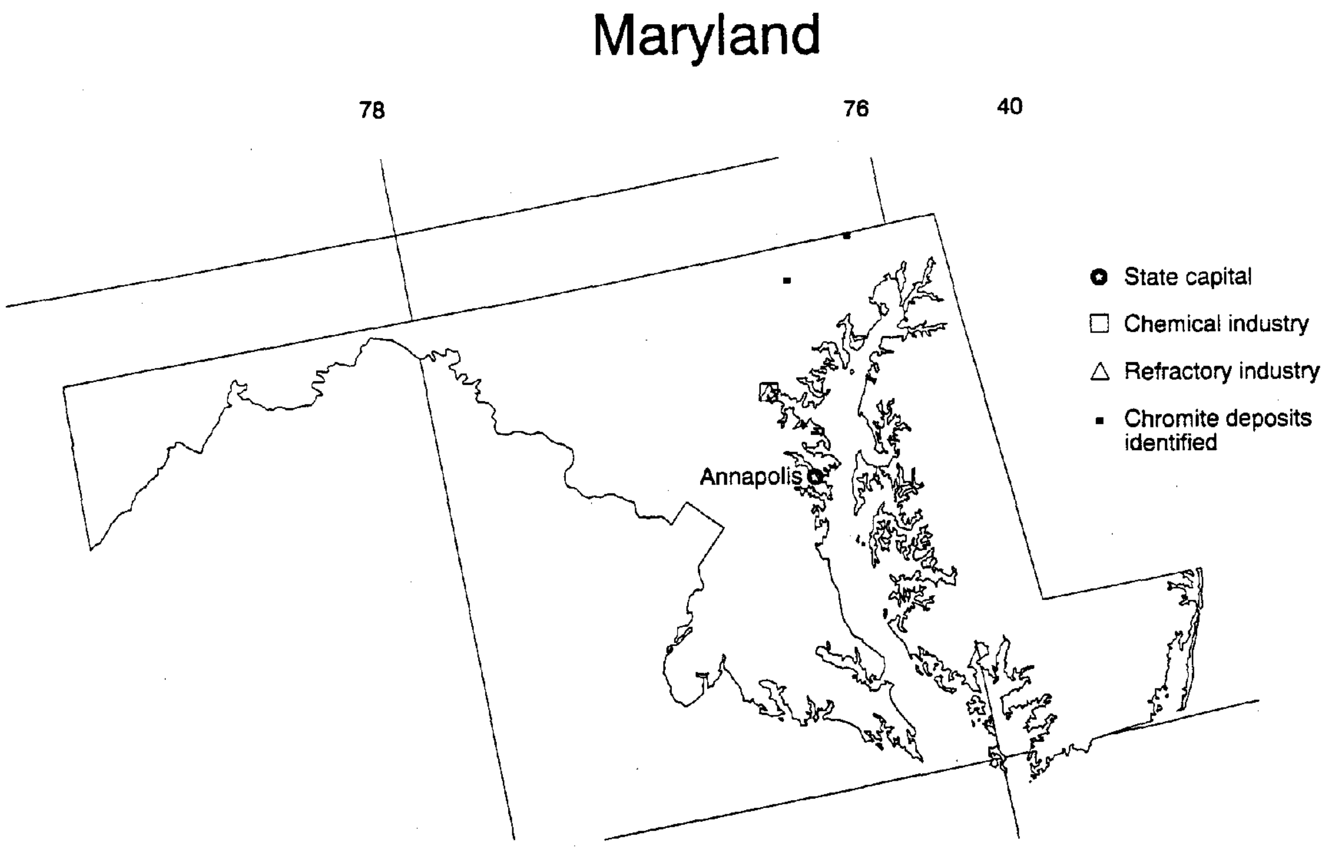


Figure 18. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in North Carolina and Maryland.

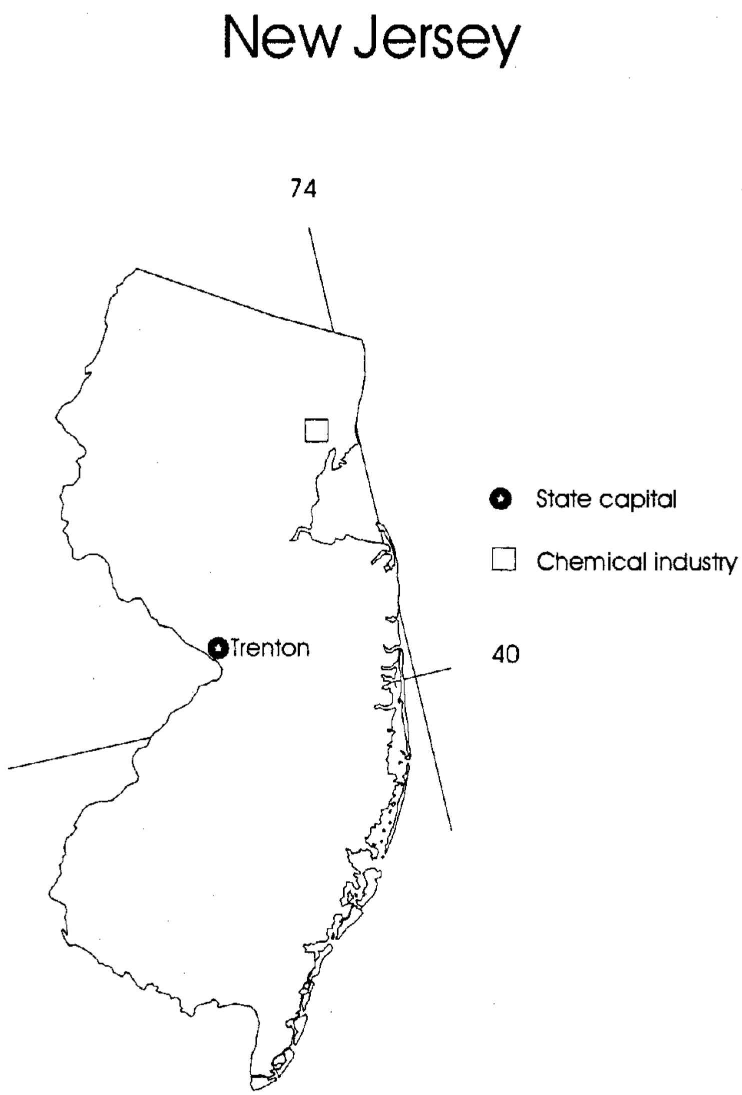


Figure 19. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in New Jersey.

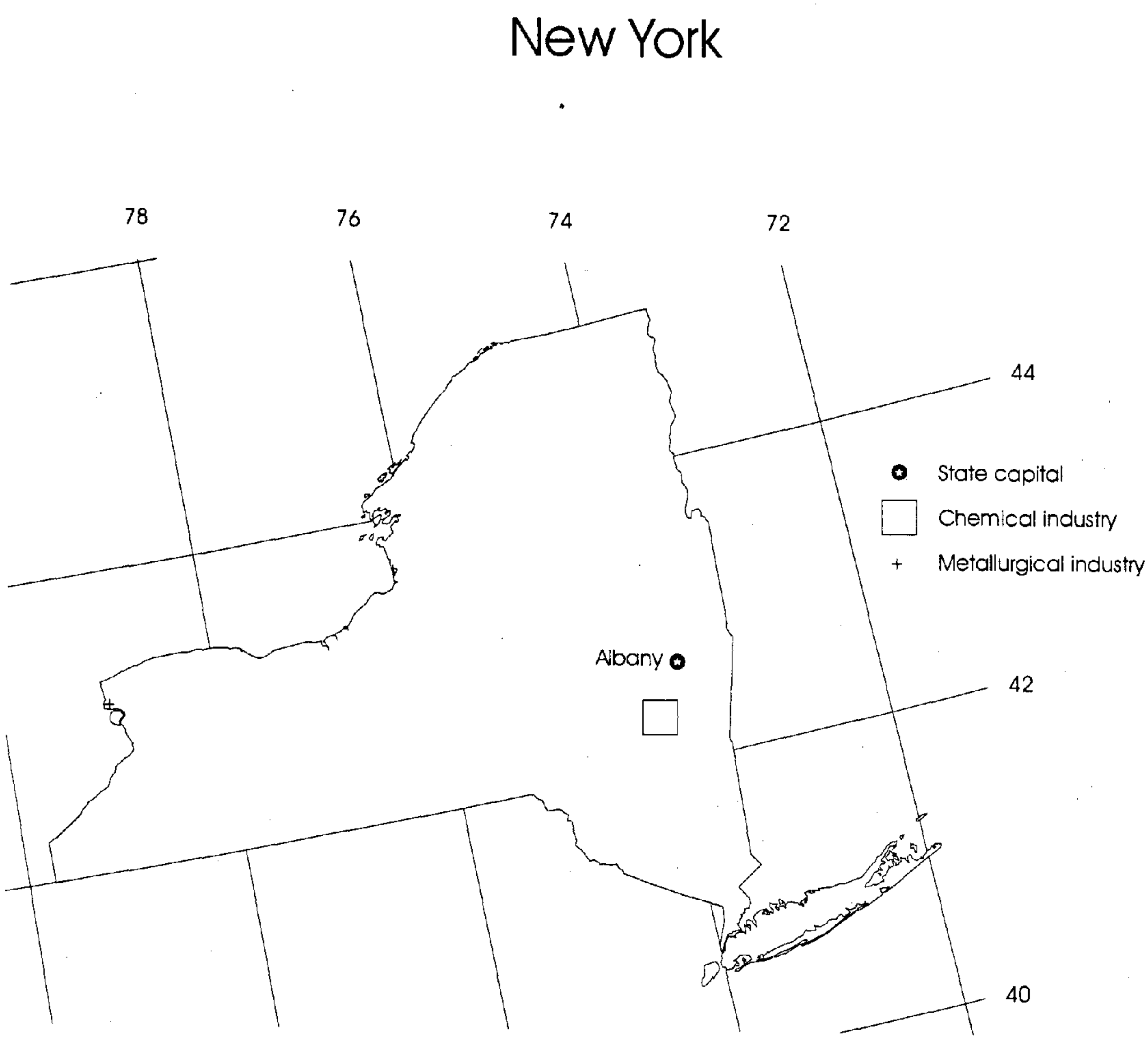
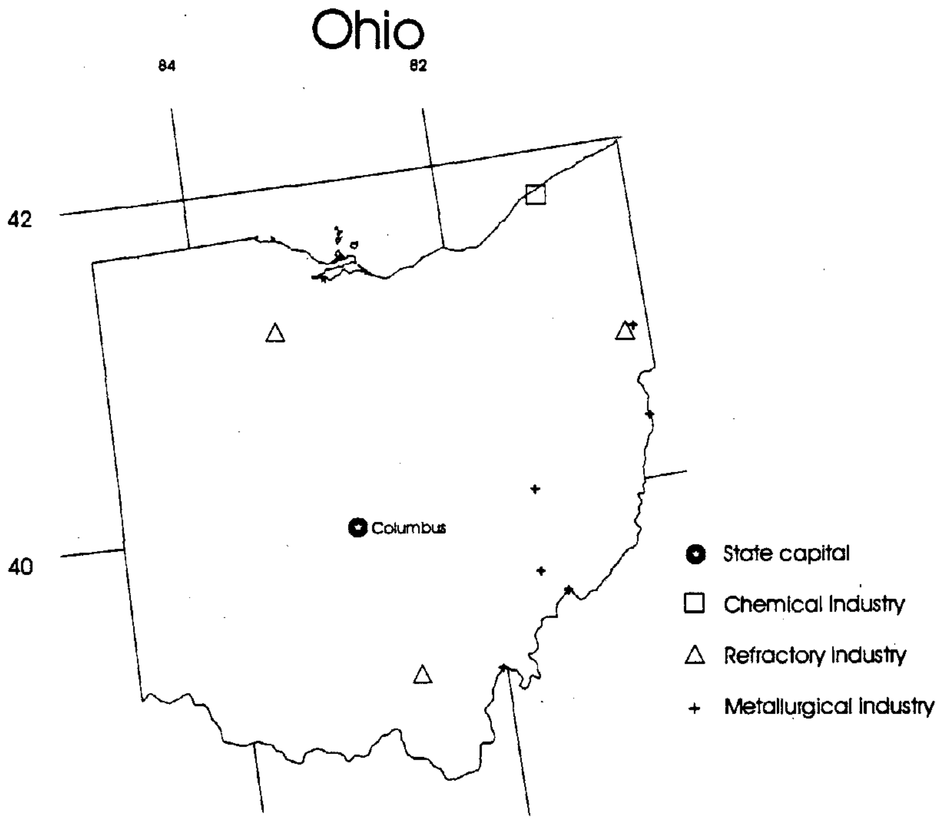


Figure 20. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in New York.



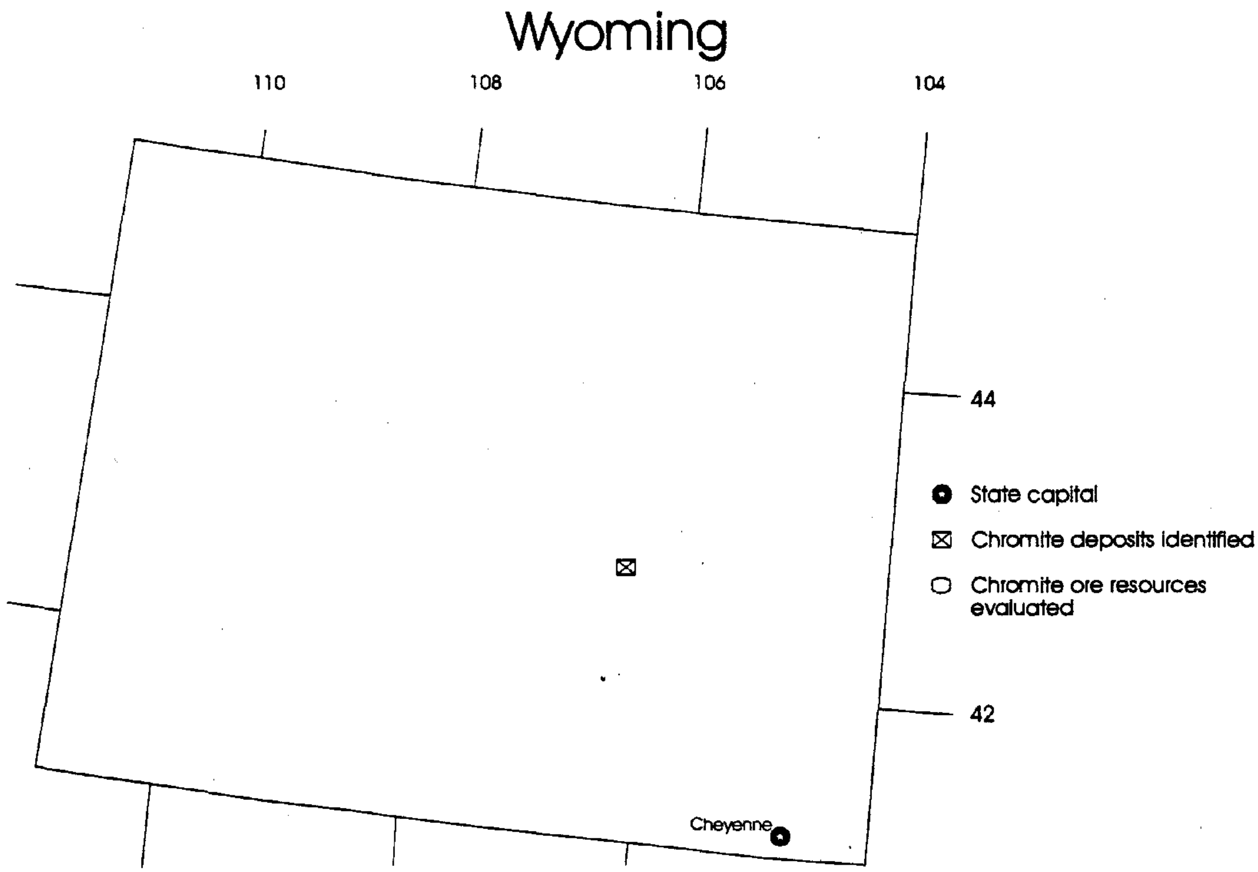


Figure 21. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Ohio and Wyoming.

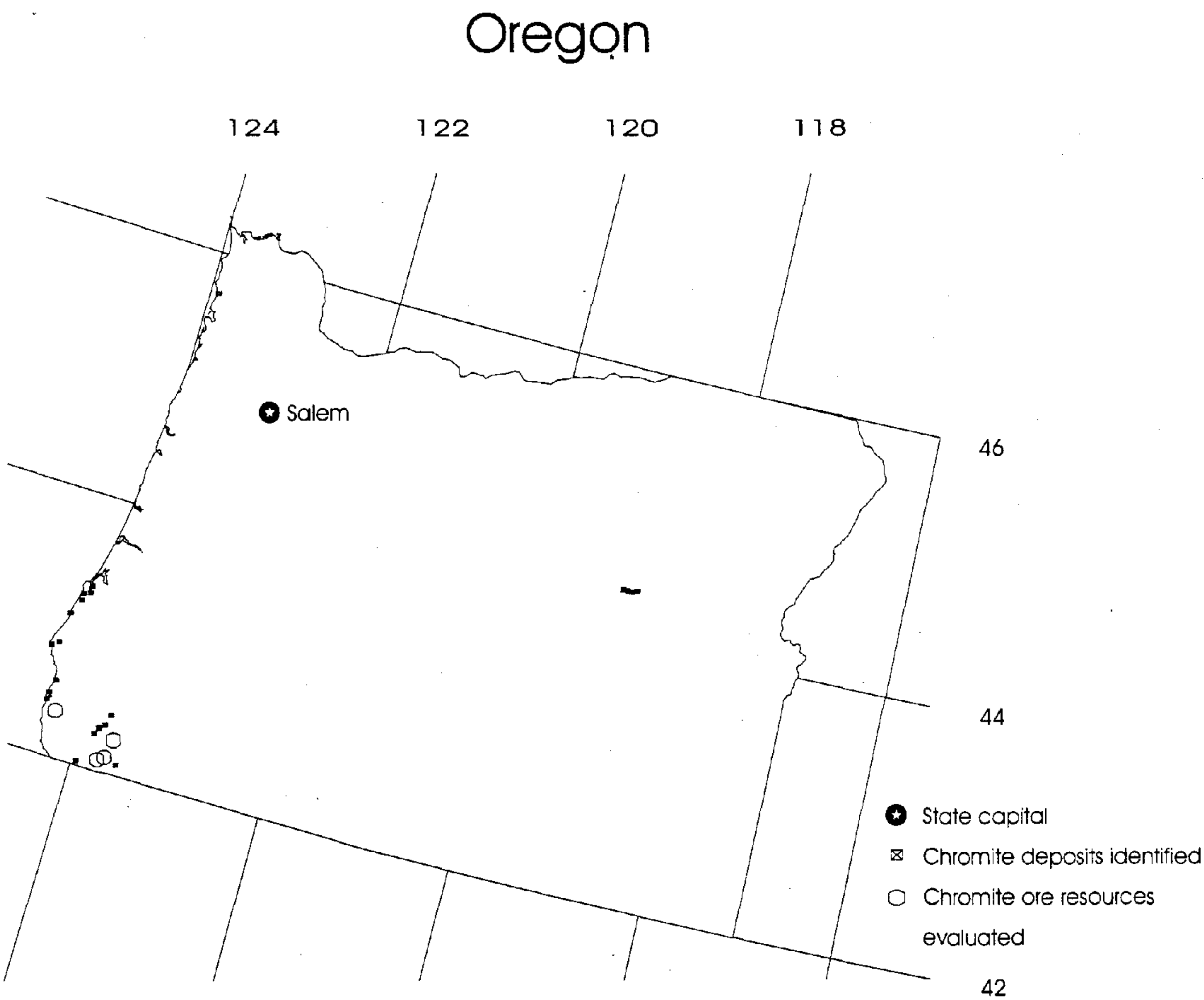


Figure 22. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Oregon.

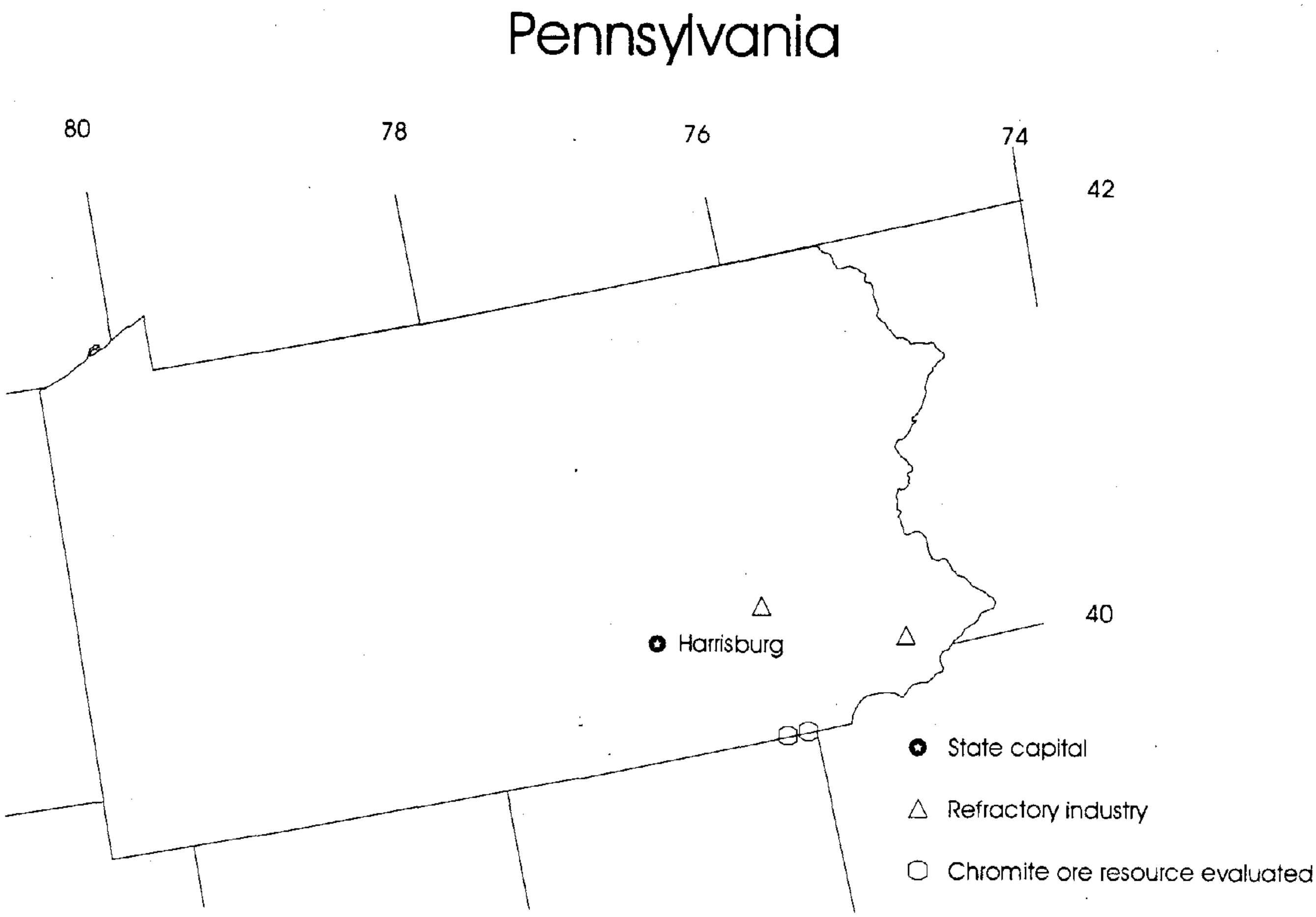


Figure 23. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Pennsylvania.

Figure 24. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Sourth Carolina.

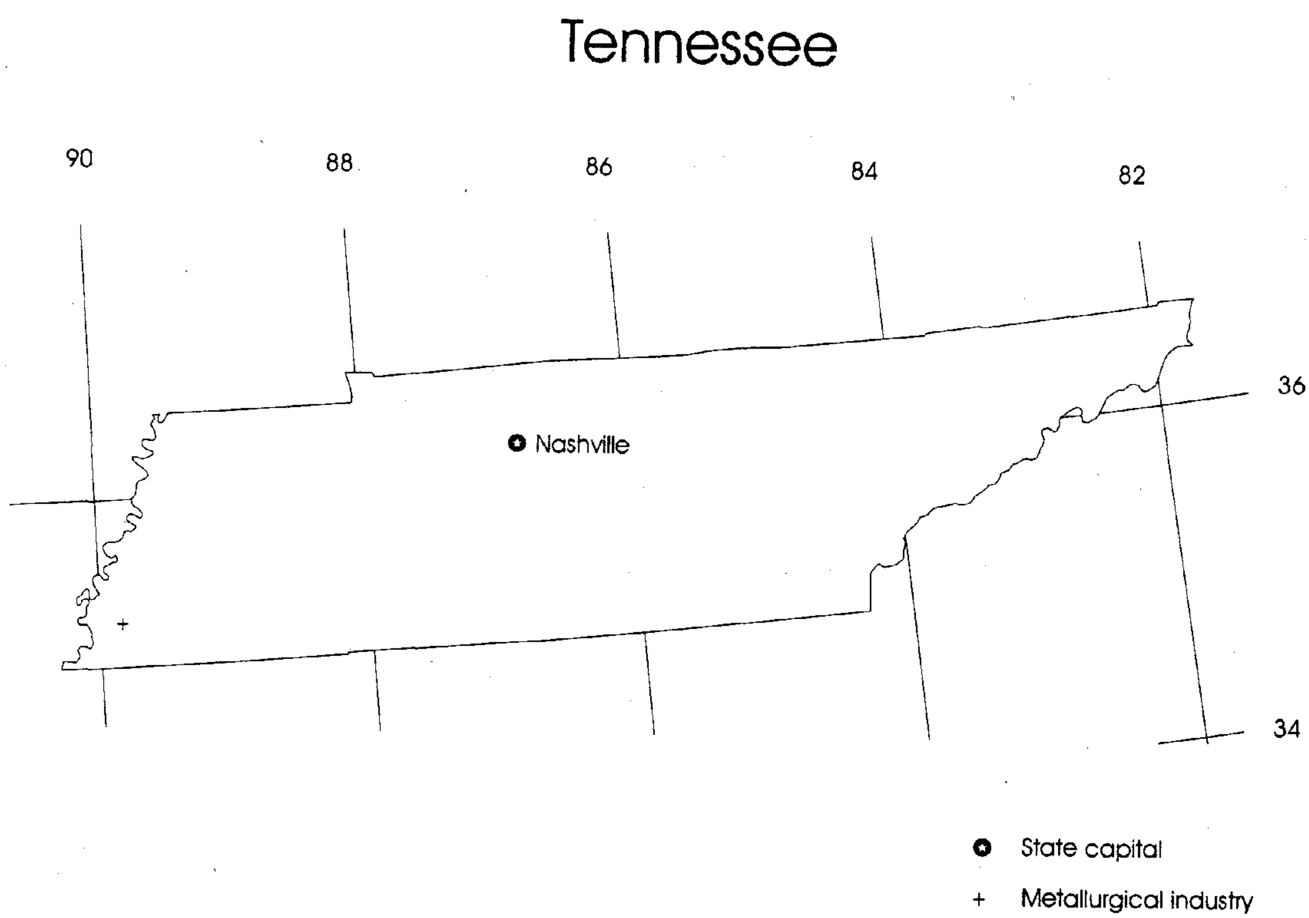


Figure 25. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Tennessee.

Texas

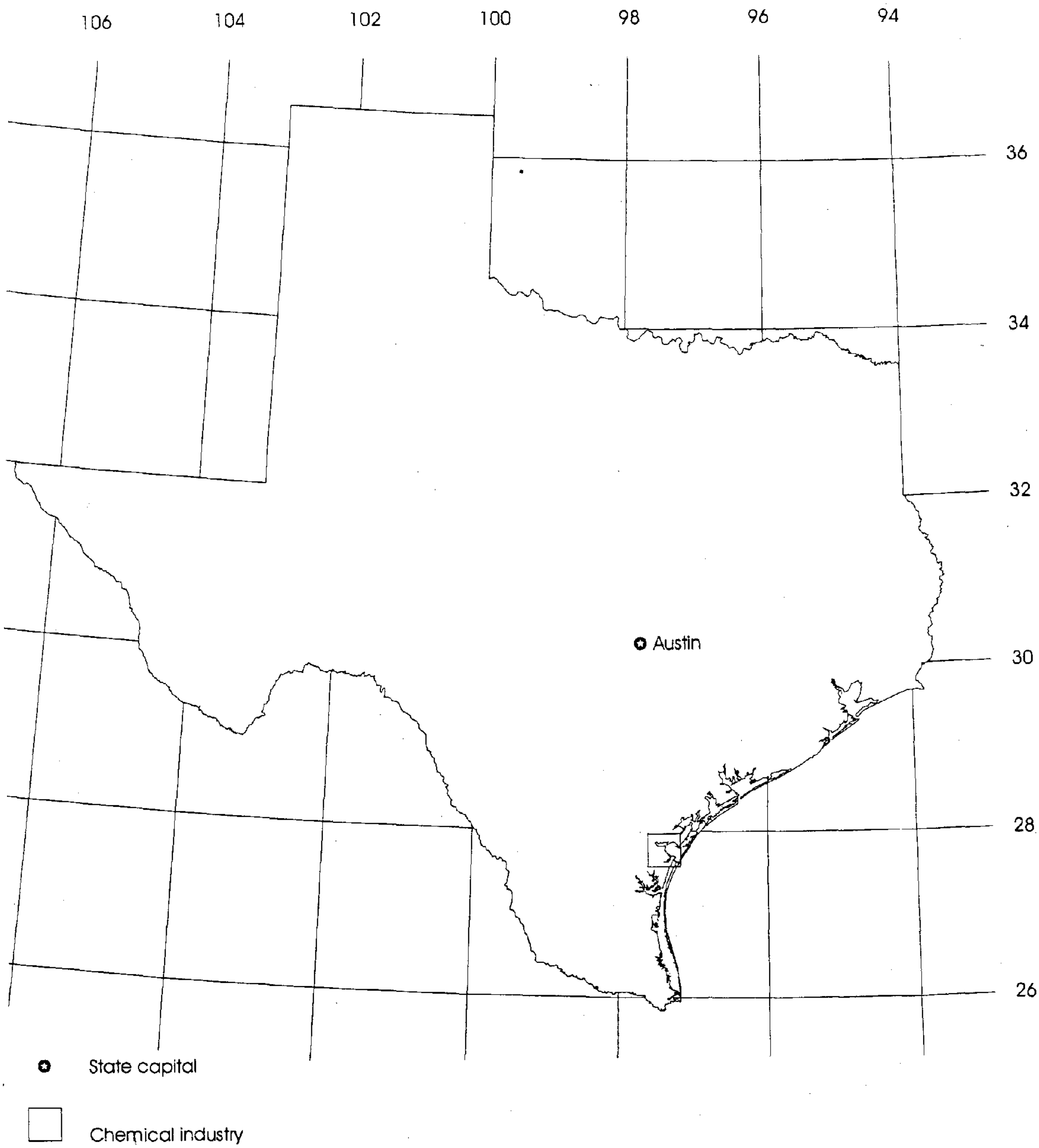


Figure 26. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Texas.

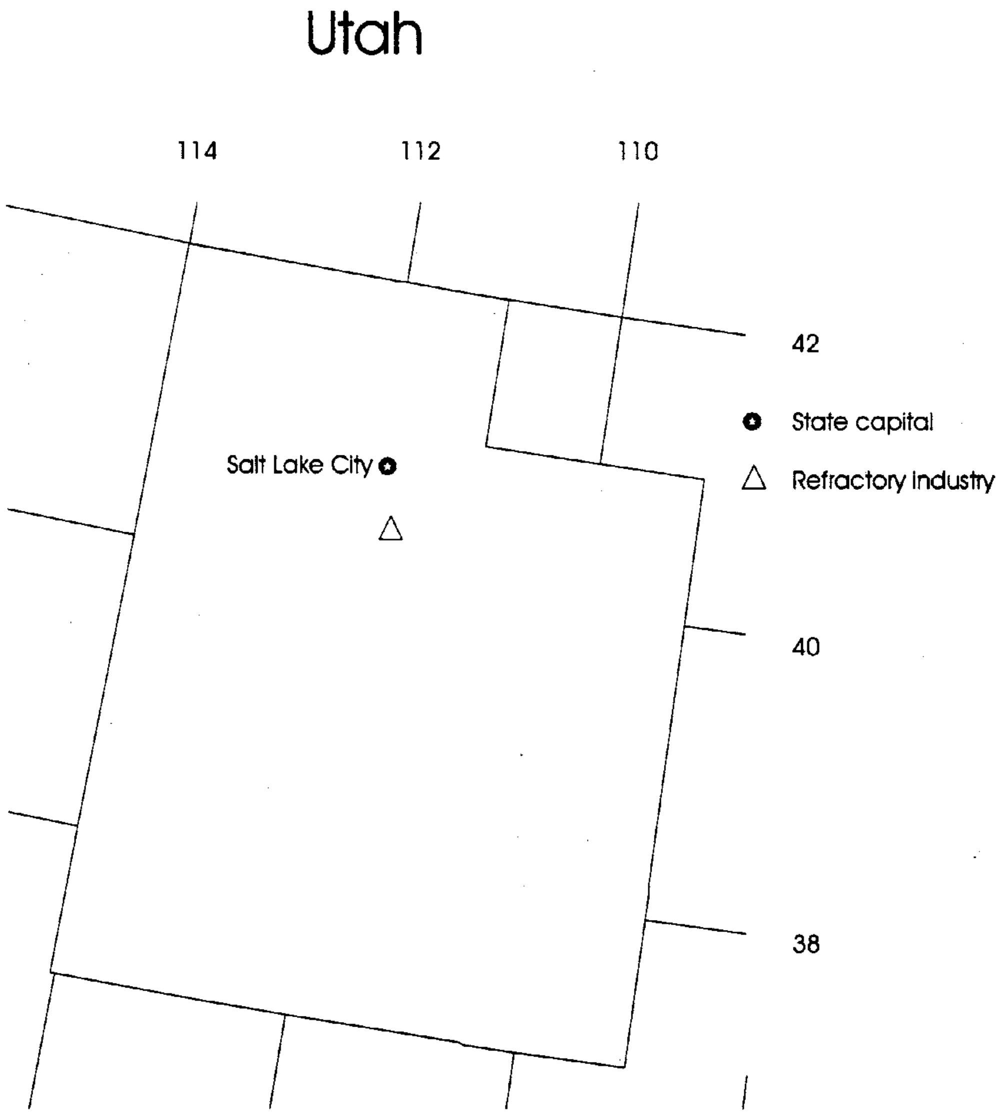


Figure 27. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Utah.

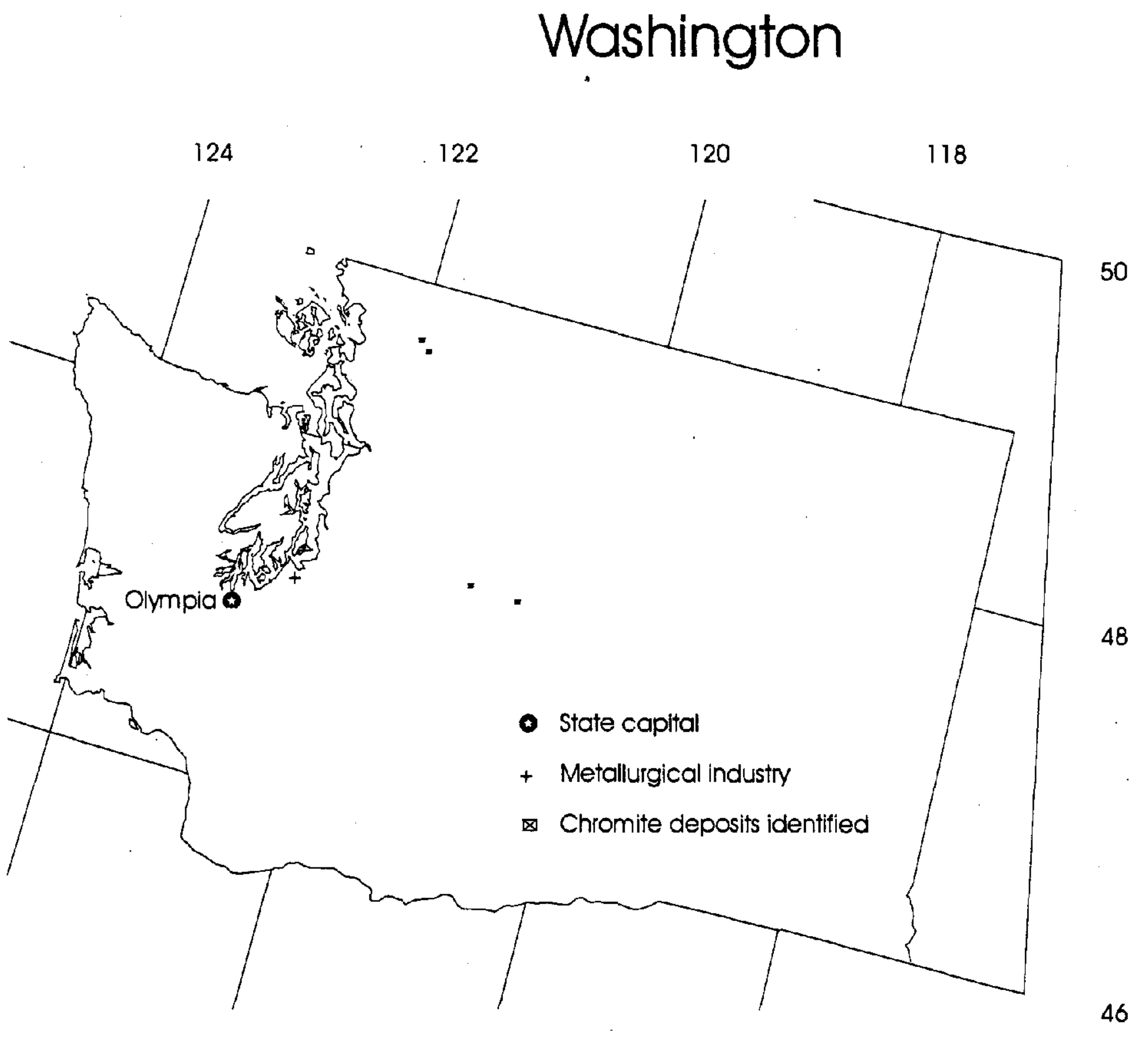


Figure 28. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in Washington.

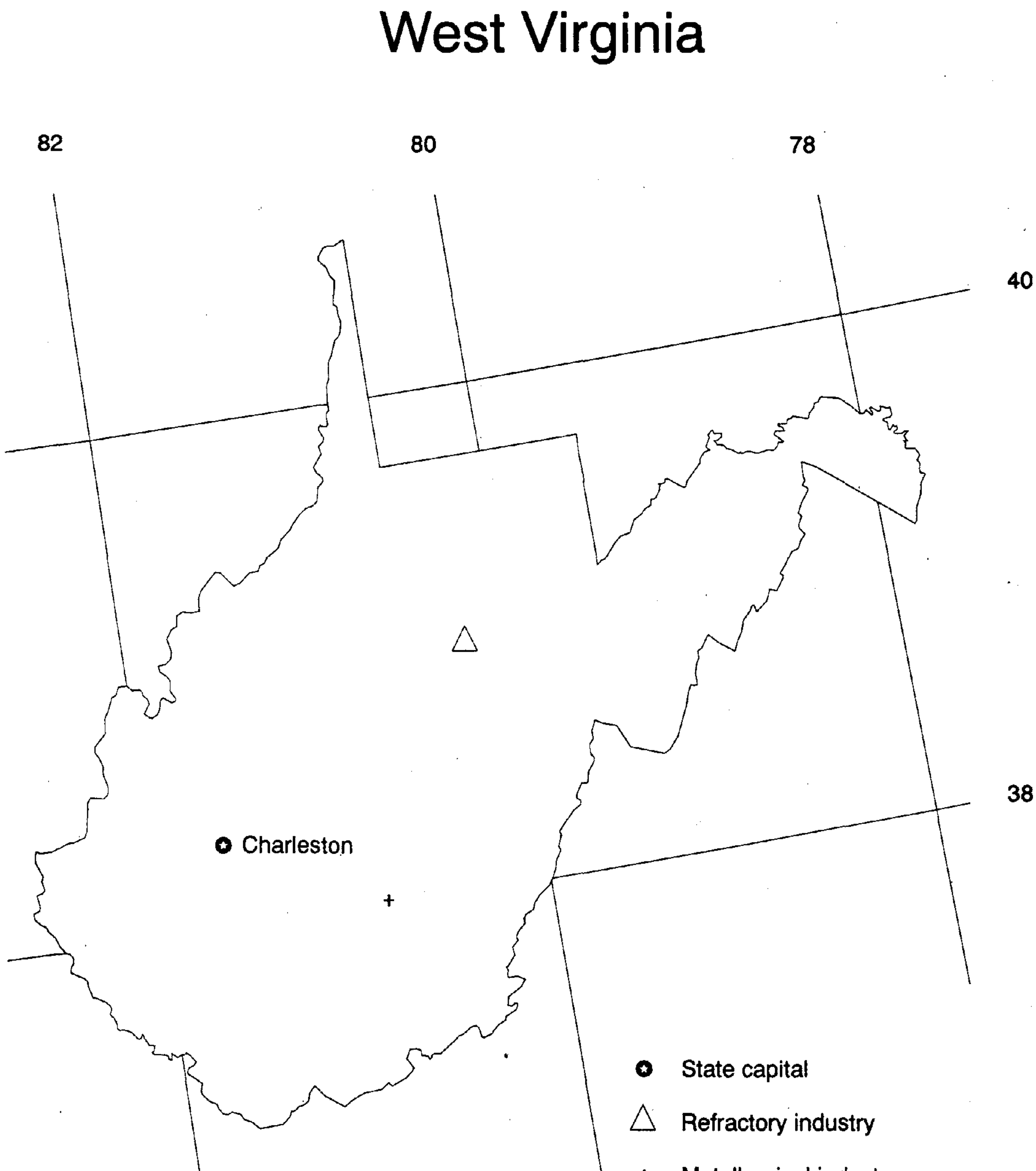


Figure 29. Geographic location of identified and evaluated chromite resources and chemical, metallurgical, and refractory industry processors of chromite ore in West Virginia.

Table 23.—U.S. chromium apparent consumption, reported consumption, and distribution thereof during the 1973 through 1982 and the 1983 through 1992 time periods

(Thousand metric tons, contained chromium)

	1973-82		1983-92	
	(kt-Cr)	Percent	(kt-Cr)	Percent
AVERAGE U.S. CHROMIUM APPARENT CONSUMPTION				
Industry:				
Chemical	51	12	41	10
Metallurgical	365	79	347	87
Refractory	43	9	12	3
Total	459	100	400	100
REPORTED U.S. CHROMIUM CONSUMPTION				
Industry:				
Steel:				
Alloy	36,185	16.7	16,817	7.6
Carbon	3,708	1.5	6,788	3.1
Stainless	154,843	68.9	174,429	78.9
HSLA	6,768	3.2	4,994	2.3
Tool	2,616	1.2	2,274	1.0
Cast iron	5,878	2.7	3,720	1.7
Superalloy	6,830	3.1	6,906	3.1
Welding	1,143	.5	572	.3
Other	2,677	1.2	1,698	.8
Misc. & Unspec	1,923	.9	2,837	1.3
Total	222,544	100.0	221,035	100.0
STAINLESS STEEL INDUSTRY REPORTED MATERIAL CONSUMPTION				
Material:				
Ferrochromium:				
Low-carbon	28,051	16.6	6,063	3.6
High-carbon	117,993	75.9	159,414	94.7
Ferrochromium-silicon	12,463	7.3	2,552	4.5
Other	245	.2	274	.2
Total	158,752	100.0	168,303	100.0

HSLA High strength low alloy. Misc. & Unspec. Miscellaneous and unspecified.

NOTE. Percent is percentage of time period average total.

minimis concentration. The de minimis concentration for chromium is 0.1 pct. Facilities report the amount of chromium released, transferred, and recovered. Released chromium means chromium released to the environment and is accounted for by its destination. Release destinations include air, water, and earth environment. Transferred chromium means chromium transferred to another facility and is accounted for by its destination. Transfer destinations include publicly owned treatment works and off-site locations. Recovered chromium means chromium recovered on-site. The collected data are called the Toxic Release Inventory (TRI).

One would expect industry to operate at a steady rate, even when demand and prices are fluctuating, because industrial processes are design to operate efficiently at certain rates. Operation of a plant outside of design production rates incurs a cost penalty owing to inefficient operation. Some inefficiency may be tolerated during periods of high demand and high prices because higher than average prices provide above average profits that can be used to offset higher cost of production because of inefficient operation. There are also limits above and below which production is not possible without modification of the physical plant. Often, production is considered an indication of economic activity within an economic sector while shipments and stocks are used as a broader indicator of the economic strength of a sector. Production reflects what that sector is doing; shipments reflects how that sector is interacting. Based on these factors and the fact that releases and transfers are proportional to production, one would expect industrial releases and transfers to be steady, as steady as production modified

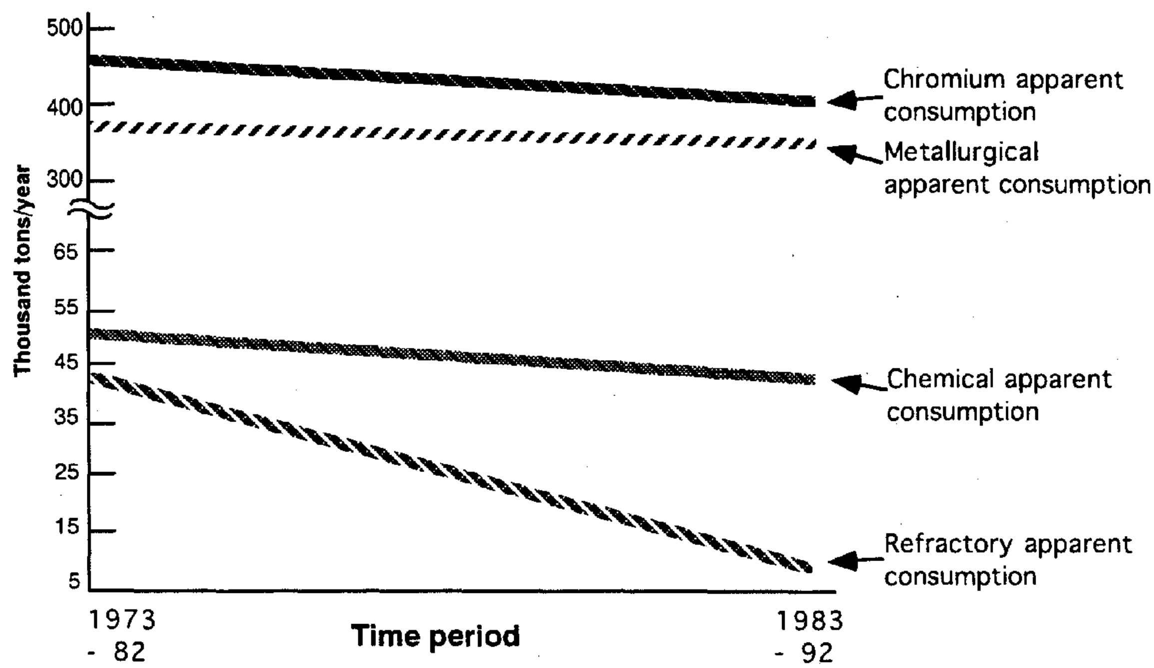


Figure 30. Trend of average U.S. Chromium apparent consumption from the 1973-82 time period to the 1983-92 time period.

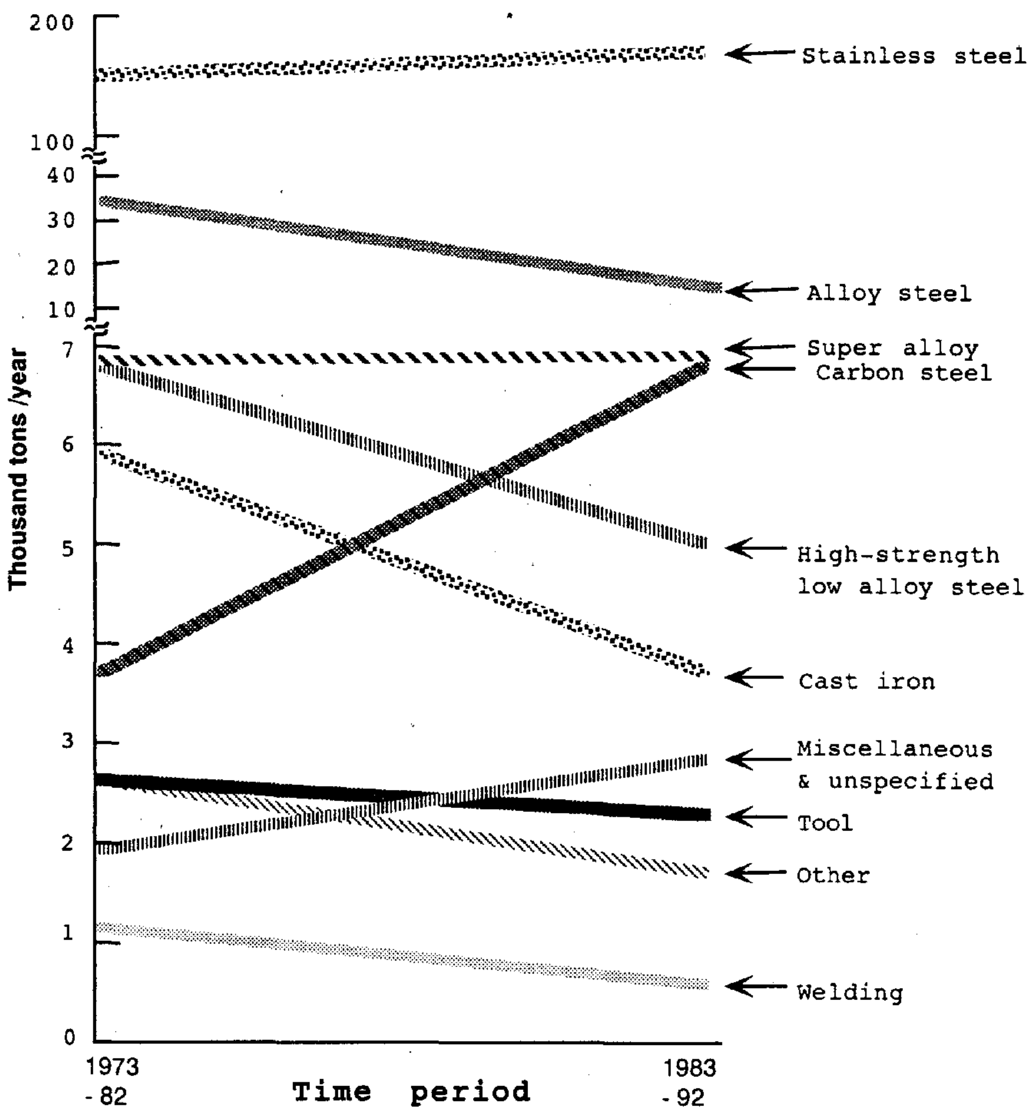


Figure 31. Trend of average U.S. reported chromium consumption from the 1973-82 time period to the 1983-92 time period.

by changes in industrial practices that impact releases and transfers. However, the TRI data show significant variations. (See table 24.) From 1987, the start of the program, until 1991, total releases nearly doubled then halved. These are large changes that prompt one to seek their cause.

All other factors remaining unchanged and based on the decreasing threshold limit per facility, we would expect the historical series of chromium releases to be initially increasing. Decreasing the threshold limit for reporting means that more facilities, and therefore more releases, would have been added to the database. Confusion and misunderstanding may have resulted in over- or under-estimating chromium releases, so no specific direction of influence on release and transfer trends would be expected. Collectively these errors may compensate for one another. Releases and transfers are proportional to the amount of material industry processes and to the amount of recycling, reuse, or recovery that takes place. Assuming that the generation rate (i.e., the amount of chromium released or transferred per unit of material processed) and recovery rate (i.e., the amount of chromium recovered instead of released or transferred per unit of material processed) remain constant, releases and transfers are likely to be greater when more material is processed, that is, when manufacturing is strongest.

Table 24 shows the quantity of chromium (contained in EPA categories chromium and chromium compounds) released by the manufacturing industries to the environment from 1987 through 1991 by release and transfer categories and the pct of release or transfer by mode. Table 24 shows that the major release of chromium and chromium compounds is to land and that transfers to other off-site locations far exceed those to publicly owned treatment works. EPA reported data covers Standard Industrial Classification (SIC) Codes in Division D, Manufacturing, Groups 20 through 39. EPA does not cover Division B, Mining, Groups 10 through 14. Table 25 further delineates the release of chromium contained in chromium and chromium compounds showing the total release and transfer from 1987 through 1991 by manufacturing industry. Table 25 shows that the largest releases of chromium and chromium compounds have been by the chemical and primary metals industries. Tables 26 through 30 show the quantity of chromium released and transfer by mode for each major manufacturing industry in 1987 through 1991.

As part of its 33/50 Program (Industrial Toxics Project), EPA is interested in monitoring chromium releases to the environment and voluntary reductions thereof. EPA sought to achieve 33 pct reduction of chromium emission by 1992 and to achieve 50 pct reduction by 1995 based on 1988 TRI data.

TRI data identify the quantity of chromium released and transferred by destination. Releases and transfers can be traced in the database to specific companies. A question which comes immediately to mind is "What is the unit release of chromium?" Here, "unit" implies per unit of chromium consumed. So, "unit chromium release and transfer" means the amount of chromium released and transferred per amount of chromium consumed. A decrease in unit release indicates increased industry efficiency or less waste. Unfortunately, the amount of chromium material consumed annually by U.S. industry can vary substantially. In a USBM analysis of data from 1987 to 1991, the chromium contained in domestically consumed chromium materials varied from a low of 382 kt in 1987 to a high of 537 kt in 1988 *(59)*. Ideally, one could combine TRI data on releases and transfers with USBM data on chromium consumption to get unit release values. Unfortunately, owing to the concealment of company proprietary data, neither the Department of Commerce nor the USBM publishes chromium material production or consumption data in sufficient detail to be useful for the purpose of calculating unit release values by industry.

There are two problems with the TRI database and the life cycle study: (1) unit release information is not available and (2) product specific information is not available. Unit releases for some material production has been estimated in this report and many EPA reports detail unit release estimates. Product specific information means chromium released as a result of the manufacture of a specific product. In conducting a life cycle study, one has a product and the quantity of materials that go into that product. In order to calculate releases associated with a product one must associate the quantity of releases with the amount of material used to make the product, i.e., the unit release by product. Many manufacturers produce more than one product. As a result, one can not be sure when using TRI data what fraction of the reported releases should be associated with which products.

Metallic contents of combustibles are mobilized during mining and concentrated or released during combustion. Chromium is found in coal, oil, and gasoline. An estimated chromium content of various combustibles is shown in table 31 along with reported consumption of these materials in the United States from 1987 through 1990. The data show that about 8 Kt-Cr/yr is introduced into the environment from the combustion of coal. An additional approximately 155

Table 24.—Manufacturing industry chromium[1] release to the environment and transfer by mode and by year from 1987 through 1991

Mode	1987	1988	1989	1990	1991
	(Metric tons, contained chromium)				
Releases to:					
Air	532	603	1,072	535	502
Water	272	182	248	203	160
Underground	29	25	27	38	16
Land	10,109	18,247	15,639	12,817	11,753
Total releases	10,943	19,057	16,986	13,593	12,431
Transfers to:					
POTW	1,119	962	603	505	422
Treatment:					
Off-site	2,447	1,745	1,934	1,679	1,801
On-site	809	2,866	2,427	4,606	142
Disposal	11,993	9,752	10,574	9,879	7,229
R&ER	NA	NA	NA	NA	30,936
Total transfers[2]	16,367	15,326	15,537	16,669	40,530
Grand total	27,311	34,383	32,523	30,262	52,961
	(Percent)				
Releases to:[3]					
Air	5	3	6	4	4
Water	2	1	1	1	1
Underground	([4])	([4])	([4])	([4])	([4])
Land	92	96	92	94	95
Transfers to:[5]					
POTW	7	6	4	3	1
Treatment:					
Off-site	15	11	12	10	4
On-site	5	19	16	28	([4])
Disposal	73	64	68	59	18
R&ER	NA	NA	NA	NA	76
Totals:[6]					
Releases	40	55	52	45	23
Transfers	60	45	48	55	77

NA Not applicable. POTW Publicly owned treatment works. R&ER Recycle and energy recovery.
[1]Chromium contained in EPA categories chromium and chromium compounds.
[2]Data may not add to total shown because of to independent rounding.
[3]Releases as pct of total releases.
[4]Less than 1/2 unit.
[5]Transfers as pct of total transfers.
[6]Total releases and total transfers as pct of grand total.

NOTE. Air includes point and nonpoint (i.e., stack and fugitive) sources.

Source: Environmental Protection Agency, Toxic Release Inventory (Nov. 1993).

t-Cr/yr is introduced to the environment through the use of crude oil, residual crude oil, and gasoline.

Chromium releases resulting from the combustion of coal, oil, and gasoline may be estimated from the data in table 31. All of the chromium mobilized by combustion of coal, oil, and gasoline is lost. This amounted to about 8,240 tons of chromium in 1989.

Industrial Economics, Inc. (IEI) estimated chromium releases from phosphate fertilizer for EPA *(60)*. IEI estimated chromium released to water and land from phosphate rock processing and use at about 3.4 kt in 1988. That release is based on a phosphate rock chromium content of 84 ppm and phosphate rock production of 90,456 Mlb. It is here assumed that this same release approximates that of 1989.

USBM and EPA data can be compared at the national level to estimated chromium use efficiency or national unit release. Table 32 shows chromium processed by the domestic industry (i.e., apparent consumption) and chromium released and transferred by year. The release percent and release plus transferred percent were calculated as a percent of chromium processed. Table 24 shows that the distribution of releases among modes over time is

Table 25.—Chromium[1] released to the environment and transferred by industry from 1987 through 1991

(Metric tons, contained chromium)

SIC[2]	Industry	1987	1988	1989	1990	1991
20	Food products	14	1	26	72	85
21	Tobacco products	--	--	--	--	([3])
22	Textile mill products	6	13	18	29	36
23	Apparel	16	--	68	--	29
24	Lumber and wood products	603	95	31	133	87
25	Furniture	15	15	1	9	70
26	Paper and allied products	78	81	165	171	149
27	Printing and publishing	9	2	19	5	4
28	Chemical and allied products	5,543	10,137	10,602	8,306	9,946
29	Petroleum and coal	888	501	463	409	294
30	Rubber and plastic	130	65	178	106	182
31	Leather and leather products	741	835	884	758	824
32	Stone, clay, glass, and concrete	1,080	831	1,072	793	761
33	Primary metals	12,284	15,894	13,647	11,893	20,266
34	Fabricated metals	1,948	2,526	2,049	1,866	6,297
35	Machinery and computer equipment	1,680	1,520	1,449	3,895	7,217
36	Electrical and electronic equipment	212	228	304	184	1,040
37	Transportation equipment	1,936	1,442	963	1,604	5,145
38	Instruments	66	48	56	17	212
39	Miscellaneous manufacturing	54	106	74	7	58
NA	SIC code not available	8	43	454	4	259
	Total	27,311	34,383	32,523	30,262	52,961

-- None reported. NA Not available.
[1]Chromium contained in EPA categories chromium and chromium compounds.
[2]Standard industrial classification code.
[3]Less than 1/2 unit.
Source: Environmental Protection Agency, Toxic Release Inventory (Nov. 1993).

Table 26.—Chromium and chromium compound releases and transfers in 1987 by industry and destination

(Metric tons, contained chromium)

	RELEASES								
	Air emissions								
SIC	Fugitive	Point	Water	Underground injection	Landfill	Land treatment	Surface impoundment	Other	Total[1]
20	([2])	--	13	([2])	--	1	--	--	14
21	--	--	--	--	--	--	--	--	--
22	--	([2])	([2])	--	--	--	--	([2])	([2])
23	--	--	--	--	--	--	--	--	--
24	1	20	1	--	([2])	--	1	--	23
25	1	([2])	--	--	([2])	--	--	--	1
26	([2])	6	43	--	15	--	([2])	([2])	64
27	([2])	([2])	--	--	--	--	--	--	1
28	37	74	50	28	681	5	3,558	8	4,442
29	54	61	29	([2])	8	276	173	3	604
30	1	1	([2])	--	([2])	--	--	--	3
31	1	1	1	--	1	5	([2])	([2])	9
32	8	22	1	--	284	--	10	15	341
33	71	75	123	([2])	2,653	36	1,301	880	5,140
34	23	10	4	--	36	1	([2])	13	88
35	10	12	([2])	--	87	--	1	3	113
36	2	2	([2])	--	5	--	--	([2])	9

See footnotes at end of table.

Table 26.—Chromium and chromium compound releases and transfers in 1987 by industry and destination--Continued

(Metric tons, contained chromium)

RELEASES--CONTINUED

SIC	Air emissions: Fugitive	Air emissions: Point	Water	Underground injection	Landfill	Land treatment	Surface impoundment	Other	Total[1]
37	20	13	4	(2)	33	--	(2)	1	70
38	(2)	(2)	2	--	(2)	--	--	--	4
39	(2)	(2)	(2)	--	--	--	--	15	15
NA	1	1	(2)	--	(2)	--	--	(2)	2
Total[1]	232	30	272	29	3,804	324	5,044	938	10,943

TRANSFERS

SIC	POTW	Treatment: Off-site	Treatment: On-site	Disposal	Total	Total[1] (releases + transfers)
20	--	--	--	--	--	14
21	--	--	--	--	--	--
22	4	1	(2)	(2)	5	6
23	2	--	--	14	16	16
24	(2)	(2)	1	577	579	603
25	1	--	--	12	14	15
26	7	1	(2)	6	14	78
27	(2)	1	1	7	9	9
28	172	226	38	665	1,102	5,543
29	54	45	10	176	284	888
30	7	3	--	117	127	130
31	378	10	37	306	731	741
32	(2)	--	37	703	740	1,080
33	19	408	441	6,276	7,144	12,284
34	352	338	156	1,014	1,861	1,948
35	26	464	11	1,067	1,567	1,680
36	8	24	48	122	203	212
37	84	860	14	907	1,866	1,936
38	3	47	1	11	62	66
39	(2)	19	13	6	39	54
NA	(2)	(2)	(2)	5	6	8
Total[1]	1,119	2,447	809	11,993	16,367	27,311

-- None reported. NA Not available. POTW Privately owned treatment works.
[1]Data may not add to total shown because of independent rounding.
[2]Less than 1/2 unit.

Source: Environmental Protection Agency, Toxic Release Inventory (Nov. 1993).

steady. Thus, a decrease in release percent indicates reduced environmental releases and, therefore, reduced environmental impact. A decrease in release plus transfer percent indicates improved processing efficiency.

From 1987 to 1988, percent released increased from 3 pct to 4 pct. At the same time, chromium processed by domestic industry increased from 382 kt to 537 kt tons. The increase in percent release may have resulted from operating production facilities above optimum levels. Percent released then declined from 4 pct to 3 pct from 1989 to 1990 while processing decreased by only a small amount. The 1989 to 1990 percent released decline suggests that domestic industry improved its chromium material processing efficiency during that time period or returned to more efficient operating rates. Released plus transferred percent decreased from 1987 to 1990 suggesting that industry improved recovery efficiency over that time period. However, released plus transferred material increased dramatically (doubled) from 1990 to 1991 while change in material processed by industry over that same time period actually declined.

Let us now consider whether or not what we know about chromium industry efficiency-inferred losses is consistent with what has been reported to EPA. The

Table 27.—Chromium and chromium compound releases and transfers in 1988 by industry and destination

(Metric tons, contained chromium)

RELEASES

SIC	Air emissions: Fugitive	Air emissions: Point	Water	Underground injection	Landfill	Land treatment	Surface impoundment	Other	Total[1]
20	–	–	([2])	–	–	([2])	–	–	([2])
21	–	–	–	–	–	–	–	–	–
22	–	([2])	1	–	–	–	–	1	1
23	–	–	–	–	–	–	–	–	–
24	1	([2])	7	–	2	–	–	–	32
25	([2])	–	–	–	–	–	–	–	1
26	([2])	21	36	–	16	–	4	–	61
27	–	([2])	–	–	–	–	–	–	([2])
28	29	4	37	20	34	9	8,663	21	8,877
29	23	([2])	19	1	52	90	38	1	295
30	2	64	([2])	–	–	–	–	([2])	4
31	1	70	1	–	8	–	77	–	87
32	9	2	1	–	292	–	4	22	347
33	79	1	70	3	6,915	13	867	477	8,507
34	79	19	3	([2])	41	2	455	6	606
35	12	10	1	–	([2])	–	([2])	([2])	25
36	27	1	([2])	–	([2])	–	–	([2])	29
37	14	23	3	([2])	9	–	([2])	22	71
38	([2])	2	2	–	2	1	20	([2])	27
39	1	1	–	–	–	–	52	–	53
NA	1	1	([2])	–	33	–	–	–	35
Total[1]	279	324	182	25	7,402	115	10,180	550	19,057

TRANSFERS

SIC	POTW	Treatment: Off-site	Treatment: On-site	Disposal	Total	Total[1] (releases + transfers)
20	–	1	([2])	–	1	1
21	–	–	–	–	–	–
22	1	–	10	1	12	13
23	–	–	–	–	–	–
24	([2])	([2])	4	60	64	95
25	([2])	3	–	11	14	15
26	9	3	–	8	21	81
27	([2])	([2])	–	1	2	2
28	417	141	78	624	1,260	10,137
29	43	36	8	121	207	501
30	8	14	7	33	61	65
31	281	([2])	2	464	748	835
32	3	8	([2])	472	483	831
33	37	437	2,742	4,171	7,387	15,894
34	73	359	7	1,482	1,920	2,526
35	31	195	3	1,267	1,495	1,520
36	3	13	–	184	199	228
37	53	524	6	789	1,371	1,442
38	2	9	([2])	9	20	48
39	([2])	–	–	52	53	106
NA	1	2	–	5	8	43
Total[1]	962	1,745	2,866	9,752	15,326	34,383

– None reported. NA Not available. POTW Privately owned treatment works.
[1]Data may not add to total shown because of independent rounding.
[2]Less than 1/2 unit.

Source: Environmental Protection Agency, Toxic Release Inventory (Nov. 1993).

Table 28.—Chromium and chromium compound releases and transfers in 1989 by industry and destination

(Metric tons, contained chromium)

RELEASES

SIC	Air emissions: Fugitive	Air emissions: Point	Water	Underground injection	Landfill	Land treatment	Surface impoundment	Other	Total[1]
20	([2])	([2])	1	–	([2])	7	–	–	9
21	–	–	–	–	–	–	–	–	–
22	([2])	([2])	1	–	–	–	–	–	1
23	–	–	–	–	–	–	–	–	–
24	([2])	10	12	–	([2])	–	–	([2])	23
25	1	([2])	–	–	–	–	–	–	1
26	1	13	104	–	16	–	4	–	137
27	([2])	([2])	–	–	–	–	–	–	([2])
28	32	45	31	25	33	([2])	9,526	15	9,706
29	36	59	17	([2])	6	141	28	1	288
30	5	4	([2])	–	1	–	–	–	10
31	2	2	1	–	1	–	80	([2])	86
32	8	17	1	–	229	([2])	20	2	277
33	299	107	69	2	3,472	18	1,860	111	5,937
34	238	26	5	–	22	3	([2])	1	296
35	20	14	2	–	9	–	([2])	24	69
36	71	10	1	–	–	–	–	([2])	82
37	21	26	2	([2])	4	–	([2])	–	54
38	1	1	2	–	1	([2])	([2])	–	5
39	1	1	([2])	–	–	–	–	–	2
NA	1	([2])	–	–	–	–	([2])	–	1
Total[1]	737	335	248	27	3,795	170	11,519	155	16,986

TRANSFERS

SIC	POTW	Treatment: Off-site	Treatment: On-site	Disposal	Total	Total[1] (releases + transfers)
20	([2])	2	–	15	17	26
21	–	–	–	–	–	–
22	6	1	–	3	16	18
23	([2])	1	–	67	68	68
24	([2])	([2])	8	7	8	31
25	([2])	([2])	1	([2])	1	1
26	11	6	–	11	28	165
27	([2])	1	–	17	19	19
28	159	127	([2])	571	896	10,602
29	35	6	([2])	128	175	463
30	4	27	39	137	168	178
31	239	1	5	509	797	884
32	1	([2])	3	790	795	1,072
33	19	588	2,299	4,848	7,709	13,647
34	49	567	9	1,088	1,753	2,049
35	30	187	5	1,162	1,380	1,449
36	7	33	41	179	221	304
37	40	376	–	480	909	963
38	1	10	2	40	51	56
39	([2])	([2])	13	72	73	74
NA	([2])	([2])	1	451	453	454
Total[1]	603	1,934	2,427	10,574	15,537	32,523

– None reported. NA Not available. POTW Privately owned treatment works.
[1]Data may not add to total shown because of independent rounding.
[2]Less than 1/2 unit.

Source: Environmental Protection Agency, Toxic Release Inventory (Nov. 1993).

Table 29.—Chromium and chromium compound releases and transfers in 1990 by industry and destination

(Metric tons, contained chromium)

RELEASES

SIC	Air emissions: Fugitive	Air emissions: Point	Water	Underground injection	Landfill	Land treatment	Surface impoundment	Other	Total[1]
20	([2])	([2])	1	([2])	([2])	6	–	–	7
21	–	–	–	–	–	–	–	–	–
22	([2])	1	1	–	–	–	–	–	2
23	–	–	–	–	–	–	–	–	–
24	([2])	13	13	([2])	([2])	([2])	([2])	([2])	27
25	([2])	([2])	([2])	–	–	–	–	–	([2])
26	([2])	4	93	([2])	20	–	5	–	123
27	–	([2])	–	–	–	–	–	–	([2])
28	23	39	19	35	2,283	1	5,106	12	7,517
29	17	68	12	([2])	10	134	9	([2])	250
30	4	2	([2])	–	1	–	–	–	8
31	1	1	1	–	2	–	2	–	6
32	26	14	1	([2])	111	([2])	3	([2])	156
33	73	81	57	3	3,623	1	1,147	302	5,287
34	70	21	2	([2])	16	6	7	2	125
35	14	9	1	–	5	–	([2])	1	29
36	7	1	([2])	–	([2])	–	–	([2])	8
37	24	15	2	–	([2])	–	–	([2])	41
38	([2])	1	([2])	([2])	([2])	([2])	([2])	([2])	2
39	1	1	([2])	–	–	–	–	([2])	2
NA	1	([2])	–	–	–	–	([2])	–	1
Total[1]	264	271	203	38	6,071	148	6,279	319	13,593

TRANSFERS

SIC	POTW	Treatment: Off-site	Treatment: On-site	Disposal	Total	Total[1] (releases + transfers)
20	–	2	–	62	65	72
21	–	–	–	–	–	–
22	6	1	([2])	21	27	29
23	–	–	–	–	–	–
24	([2])	10	([2])	96	106	133
25	([2])	3	5	([2])	9	9
26	14	8	–	27	48	171
27	1	([2])	–	4	5	5
28	166	99	17	507	789	8,306
29	11	13	([2])	135	159	409
30	2	14	–	83	99	106
31	219	1	41	490	752	758
32	1	1	–	636	637	793
33	12	555	1,792	4,247	6,606	11,893
34	37	513	53	1,138	1,741	1,866
35	5	122	2,684	1,055	3,866	3,895
36	2	29	2	142	176	184
37	29	301	10	1,222	1,562	1,604
38	1	5	([2])	9	15	17
39	([2])	1	–	3	5	7
NA	([2])	1	–	2	3	4
Total[1]	505	1,679	4,606	9,879	16,669	30,262

– None reported. NA Not available. POTW Privately owned treatment works.
[1]Data may not add to total shown because of independent rounding.
[2]Less than 1/2 unit.

Source: Environmental Protection Agency, Toxic Release Inventory (Nov. 1993).

Table 30.—Chromium and chromium compound releases and transfers in 1991 by industry and destination

(Metric tons, contained chromium)

RELEASES

SIC	Air emissions: Fugitive	Air emissions: Point	Water	Underground injection	Landfill	Land treatment	Surface impoundment	Other	Total[1]
20	([2])	([2])	([2])	([2])	–	2	–	–	3
21	–	–	–	–	–	–	–	–	–
22	([2])	([2])	2	–	([2])	([2])	1	–	3
23	([2])	–	–	–	–	–	–	–	([2])
24	([2])	23	([2])	–	–	–	–	([2])	24
25	([2])	([2])	([2])	–	–	–	–	–	1
26	([2])	3	94	–	16	–	5	–	118
27	–	([2])	–	–	–	–	–	–	1
28	13	30	19	15	64	3	8,791	1	8,935
29	15	34	11	([2])	3	20	2	1	85
30	4	29	([2])	–	([2])	–	–	–	33
31	1	1	1	–	15	–	1	3	23
32	83	10	([2])	–	58	([2])	11	1	164
33	50	63	27	1	1,837	([2])	683	125	2,785
34	69	22	1	–	36	15	9	8	160
35	11	9	1	–	2	([2])	–	5	29
36	3	([2])	([2])	–	33	–	–	([2])	37
37	9	16	2	([2])	([2])	–	–	([2])	28
38	([2])	([2])	1	–	([2])	([2])	([2])	–	3
39	1	1	([2])	–	([2])	–	–	–	2
NA	([2])	([2])	([2])	–	–	–	–	([2])	1
Total[1]	260	242	160	16	2,065	41	9,504	143	12,431

TRANSFERS

SIC	POTW	Treatment: Off-site	Treatment: On-site	Disposal	Recycling	Recovery	Total	Total[1] (releases + transfers)
20	–	2	3	12	64	–	82	85
21	–	–	–	([2])	–	–	([2])	([2])
22	19	([2])	([2])	12	–	1	33	36
23	–	–	–	([2])	29	–	29	29
24	([2])	5	([2])	58	([2])	([2])	64	87
25	([2])	8	([2])	7	54	–	70	70
26	14	1	–	16	–	–	31	149
27	1	([2])	–	3	–	–	4	4
28	95	132	([2])	413	359	12	1,011	9,946
29	17	12	4	118	51	7	209	294
30	1	38	([2])	88	22	([2])	149	182
31	212	([2])	39	445	105	–	801	824
32	5	4	([2])	330	258	–	597	761
33	6	508	5	3,227	13,731	4	17,481	20,266
34	29	403	35	752	4,919	([2])	6,138	6,297
35	3	59	18	828	6,280	1	7,188	7,217
36	1	137	10	369	480	6	1,003	1,040
37	17	489	1	412	4,197	1	5,117	5,145
38	([2])	1	–	10	198	–	209	212
39	([2])	([2])	–	12	44	–	56	58
NA	2	([2])	16	117	113	–	258	259
Total[1]	422	1,801	142	7,229	30,904	32	40,530	52,961

– None reported. NA Not available. POTW Privately owned treatment works.
[1]Data may not add to total shown because of independent rounding.
[2]Less than 1/2 unit.

Source: Environmental Protection Agency, Toxic Release Inventory (Nov. 1993).

Table 31.—Chromium contained in coal, crude oil, residual fuel oil, and gasoline; reported combustion of coal and oil in the United States from 1987 through 1990; and calculated chromium mobilization resulting from coal, oil, and gasoline consumption

	Combustible material and chromium content[1] (Tons of chromium/million tons of product)			
	Coal (10 t/Mt)	Crude Oil (0.1 t/Mt)	Residual crude oil (1.3 t/Mt)	Gasoline (0.017 t/Mt)
CONSUMPTION:[2] (MILLION METRIC TONS)				
1987	759	645	63	356
1988	802	650	68	364
1989	808	665	67	360
1990	813	651	62	360
CHROMIUM MOBILIZED: (METRIC TONS)				
1987	7,592	64.5	82	6.1
1988	8,017	65.0	88	6.2
1989	8,079	66.5	88	6.1
1990	8,132	65.1	81	6.1

[1] Vouk, V. B., and W. T. Piver. Metallic Elements in Fossil Fuel Combustion Products: Amounts and Form of Emissions and Evaluation of Carcinogenicity and Mutagenicity. Environmental Health Perspectives, v. 47, 1983, pp. 201-225.

[2] Coal: The U.S. Coal Industry, 1970-1990: Two Decades of Change, Nov. 1992, Energy Information Agency.

Crude and residual crude oil and gasoline: Monthly Energy Review, Jan. 1993, Energy Information Agency, pp. 57, 61, and 42-43.

NOTE. The following factors were used: 0.136 t per barrel of oil, 10 ppm of chromium in coal, 0.1 ppm of chromium in crude oil, 1.3 ppm of chromium in residual crude oil, and 0.017 ppm of chromium in gasoline.

TRI data quantify chromium lost to the environment (environmental losses). TRI reported releases can be viewed as a lower bound on chromium lost to the environment because it is reported data and all companies that lose material are not accounted for. Not included are, for example, material released from nonmanufacturing sources, manufacturing sources releasing below the minimum level required for reporting, and reporting manufacturers releasing material in below de minimis amounts. The losses estimated previously in this report may be viewed as an upper bound on chromium loss to the environment because not all process losses and product losses go unrecovered.

It has been estimated previously in this report based on reported consumption and production of the primary chromium consumer industry that chromium recovery has been about 85 pct suggesting a 15 pct loss. EPA surveys the chromium industry including the primary chromium industry. Table 32 shows that chromium releases and transfers are 5 pct to 8 pct of chromium processed. Comparing the 15 pct process loss and 5 pct to 8 pct environmental loss suggests that industry recycles from one-third to one-half of its losses.

The USBM covers early, less efficient, stages of production, such as beneficiation and primary industrial consumption. However, TRI covers later, more efficient, stages of manufacturing in addition to some of the early stages of use covered by the Bureau. Thus, the TRI data are weighted to the higher recovery efficiencies and cover a broader segment of U.S. industry. A part of releases and transfers reported in table 32 may be double counted. That is, what is transferred from one company may end up being released by another. Because table 32 data on releases and transfers comes only from major users, some material is not counted.

Data from USBM and EPA sources have been combined to estimate chromium flow in the United States. Figure 4 shows U.S. chromium flow, recycling, and releases in 1989. Figure 5 further breaks down U.S. chromium flow by mining, processing, fabrication and manufacture, and use industry sectors. No chromite ore was mined in the United States so chromium material flow was zero. Releases, however, may come from any mining source. Chromium release from phosphate mining was discussed previously in this report. The mining industry is not covered by EPA. Milling can take place at or off of the mine site. When milling is done at the mine site, it is part of the mining industry. When milling is done off of the mine site, it is part of the manufacturing industry (Division D, SIC 20-39). In figure 5, milling, smelting, and refining are part of the processing industry. Chromium material flow in the processing industry was calculated as the chromium apparent consumption. In these figures, losses from the processing industry were estimated as TRI releases from the chemical and allied products and the primary metals industries (i.e., SIC 28 plus 33). Material flow in the fabricating and manufacturing industry was estimated to be the same as that of the processing industry. Losses from the fabricating and manufacturing industry were calculated as releases from the following industries: stone, clay, glass, and concrete (SIC 32); fabricated metals (SIC 34); machinery and computer equipment (SIC 35); electrical and electronic equipment (SIC 36); transportation equipment (SIC 37); instruments (SIC 38); and miscellaneous manufacturing (SIC 39). Chromium material flow through the use industry was estimated to have been the same as that of the fabricating and manufacturing industry. Losses from the use industry were calculated as releases from the following industries: food products (SIC 20); tobacco products (SIC 21); textile mill products (SIC 22); apparel (SIC 23); lumber and wood products (SIC 24); furniture (SIC

25); paper and allied products (SIC 26); printing and publishing (SIC 27); petroleum and coal (SIC 29); rubber and plastic (SIC 30); and leather and leather products (SIC 31), and mobilization from the combustion of coal and oil. Disposal was estimated as TRI reported transfers from all manufacturing industries (SIC 20-39).

Table 32.—Chromium processed, released, and transferred in the United States by year from 1987 through 1991

	1987	1988	1989	1990	1991
Processed (kt-Cr)[1]	382	537	452	439	377
Released (kt-Cr)	11	19	17	14	12
Transferred (kt-Cr)	16	15	16	17	41
Released (pct)[2]	3	4	4	3	3
Released + transferred (pct)[3]	7	6	7	7	14

[1]U.S. chromium apparent consumption, thousand metric tons of contained chromium.
[2]Pct released is released as a pct of processed.
[3]Pct released plus transferred is released plus transferred as a pct of processed.

Sources: U.S. Bureau of Mines. Mineral Commodity Summaries.
Environmental Protection Agency. Toxic Release Inventory database.

DISCUSSION

The year 1989 was taken as an example year because that was the most recent year for which data were available when this study was started. One problem with studies that include release of industrial or consumer products into the environment or recycling is to identify when those products are disposed of or become available for recycling. Different products have different lifetimes. Some analysts assume a lifetime for industrial products then estimate the generation of scrap in the current year based on production from a lifetime ago. They then compare secondary consumption in the current year with estimated generation of scrap and describe difference (secondary consumption always being the lesser) as lost. In this report, it was assumed that all materials moved through the use cycle in 1 year. In other words, there was no attempt to adjust for the useful life of a product. In addition to product performance, product lifetime and the extension of product lifetime are important factors for chromium use.

ESTIMATION OF CHROMIUM RELEASE TO SOILS

The authors of table 8 data appear to have erred in their estimate of "Discarded manufactured products." They reported that they estimated "Discarded manufactured products" as 5 pct to 10 pct of world mine production which they reported as 8.9 "million tons." In 1983, the USBM estimated 1983 world chromite ore mine production at 8.9 Mst-CrOre (equivalent to 8.1 Mt-CrOre). The Bureau subsequently (in 1987) revised 1983 world chromite ore production to have been 9.05 Mst-CrOre (equivalent to 8.2 Mt-CrOre). Chromite ore is characterized by its chromic oxide content. Typical commercial chromite ores vary in chromic oxide content from as low as about 35 pct Cr_2O_3 to as high as about 55 pct Cr_2O_3 with the common grade, chromite from the Republic of South Africa, at about 44 pct Cr_2O_3 content. Cr_2O_3 is about 68.5 pct chromium by weight. The authors of table 8 reported bounds for chromium lost to soil from "Discarded manufactured products" to have been from 305 kt-Cr/yr to 610 kt-Cr/yr, the magnitude of which is equivalent to from 5 pct to 10 pct of 68.5 pct of 8.9 million tons, respectively. Thus the source of table 8 appears to have reported the Cr_2O_3 content of world chromite ore production measured in short tons as the Cr content of that production measured in metric tons. As a result, the authors of table 8 overestimated chromium lost to soil via "Discarded manufactured products" by a factor of over 2. Using the assumptions of the source of table 8 (i.e., chromium lost to soil from "Discarded manufactured products" is from 5 pct to 10 pct of chromium contained in world chromite ore production), the loss rate was here calculated using 1983 chromite ore production of 8.2 Mt-CrOre, 0.44 t-Cr_2O_3/t-CrOre, and 0.685 t-Cr/t-Cr_2O_3, the loss to soil was from 124 kt-Cr to 247 kt-Cr. As a result of this change, the range total reported in table 8 is reduced to 301 kt-Cr to 943 kt-Cr and the median is reduced to 527 kt-Cr.

INTERNATIONAL CHROMIUM LOSSES AND RELEASES

India, Kazakhstan, and South Africa hold the highest chromite ore production rates. (See table 1 and figure 3.) Most chromium is processed outside the United States. Ferrochromium production, stainless steel production, and manufactured commercial and consumer products are the major sources of chromium demand internationally. International chromium loss is here defined as processing plus product loss and is estimated for the year 1989.

It is probably most useful to describe international chromium loss in terms of world chromite ore production because world chromite ore production is the only readily available measure of international chromium industry activity. So, in this section, chromium losses will be expressed in kilotons of chromium lost per megaton world chromite ore production measured as gross weight of chromite ore products (kt-Cr/Mt-CrOre). Chromium losses internationally will be estimated by industry (metallurgical, chemical, and refractory) and by type of loss (process or product). These classifications have been chosen because they represent all of the chromite ore end uses and sufficient information is available or reasonable assumptions can be made about them. Chromium analysts have estimated world chromium use by major industry (*7*, *13*). This breakdown is important to the chromite mining industry because end-use industry determines what quantities and grades of chromite ore are marketable. For the purpose of estimating international chromium losses, process losses are those that occur as a result of chromium industry conversion of feed materials into products. This usage of the term process loss is somewhat different from that used earlier in this report. Product losses are those that occur as a result of product disposal. For example, any chromium that was mined and did not end up in a product is a process loss. Process losses include (but are not limited to) tailings from beneficiation, dust and slag from the smelting of chromite ore to ferrochromium, and dust and slag from the manufacture of stainless steel from ferrochromium and stainless steel scrap. Product losses, for example, would include (but are not limited to) chromium contained in metals, refractories, or chemical industry products (e.g., pigments, chromic acid, sodium bichromate) that are not recycled. Refractories have been disposed of in landfills after use as have chemical products like paint. Sufficient information is available to estimate process and product losses from the mining and metallurgical industries. For the chemical and refractory industries, essentially all chromium entering those industries is lost and not recovered. There is, of course, some recycling of material as part of the manufacturing process. However, the products of those industries are not recycled. Except for chromium metal and special refractories produced from chromic oxide, chemical industry products are dissipative uses of chromium. In-plant recycling of chromite foundry sand is practiced. However, recovery and recycling of chromite-containing refractories is not practiced. So, for the purpose of estimating losses, not only is insufficient information available to distinguish between process and product losses in the chemical and refractory industries, but it is unnecessary to do so. As a result of these industry characteristics, for the purpose of estimating international chromium losses, a process loss factor will be estimated for the mining and metallurgical industries. A product loss factor will be estimated for the metallurgical industry. A process plus product loss factor will be estimated for the chemical and refractory industries. The combination of all these loss factors, then, is international chromium loss.

International Chromium Process Losses

International chromium process loss is mining plus metallurgical plus chemical plus refractory industry process loss. Mining plus metallurgical losses include those from chromite ore, ferrochromium, and stainless steel production. That is, mining and primary metal production industries. For the other major end-use industries, chemicals and refractories, insufficient information is available to distinguish product and process losses. Chemicals and refractory losses are considered under product losses in a following section. Because essentially all chromium entering the chemical and refractory industries is eventually lost, it is not essential to discriminate between process and product loss for the purpose of estimating international chromium loss from those industries.

Mining and Metallurgical Industry Process Losses

Chromite ore production in 1989 of about 14.3 Mt-CrOre containing about 4.3 Mt-Cr (see table 1) and a processing chromium loss rate of 47 kt-Cr/Mt-CrOre for the mining industry (based on 84.3 pct recovery—see table 10, beneficiation) resulted in a loss of about 676 kt-Cr from the beneficiation of mined chromite ore alone. Further processing of chromite ore into ferrochromium at 1989 production of about 3.9 Mt-FeCr containing about 2.3 Mt-Cr (see table 2) and a processing chromium loss rate of 132 kt-Cr/Mt-FeCr (equivalent to 36 kt-Cr/Mt-CrOre) (based on 78 pct recovery—see table 12) resulted in a loss of about 509 kt-Cr. Further processing of ferrochromium into stainless steel at 1989 production of about 12.8 Mt-SS containing about 2.2 Mt-Cr (see table 3) and at a processing chromium loss rate of 17 kt-Cr/Mt-SS (equivalent to 15 kt-Cr/Mt-CrOre) (assuming 90 pct chromium recovery from chromium-containing feed material to produce stainless steel containing average 17 pct chromium—see table 20) resulted in a loss of about 221 kt-Cr. Thus chromium processing loss in 1989 was about 1.4 Mt-Cr indicating a chromium loss rate of 98 kt-Cr/Mt-CrOre.

International Chromium Product Losses

The destination of chromium contained in products can be estimated by considering the production in each industry. World chromium use roughly breaks down by end use as follows: 79 pct to the metallurgical industry, 13 pct to the chemical industry, and 8 pct to the refractory industry (7). Because chromite ore, ferrochromium, and stainless steel production are reported worldwide, metallurgical industry losses estimated above do not require an estimation of distribution of ore among end-use industries. However, neither chromite ore consumption by the chemical or refractory industries, nor production by those industries are available, so estimates of chromium material flow to those industrial sectors are required.

Refractory

Foundry sand, a small part of the refractory industry, is the only part of the chromite-refractory industry that practices recycling. Virtually all of the chromium contained in chromite refractories has been released to the environment at the end of the refractories' life cycle. So, for the purpose of estimating product plus process loss of chromium in the refractory industry, 100 pct of chromium contained in the 8 pct of chromite ore production consumed by the refractory industry is ultimately lost. Thus refractory chromium process plus product loss in 1989 was 344 kt-Cr, an amount equivalent to 24 kt-Cr/Mt-CrOre. In the United States, EPA is in the process of regulating chromium-containing waste from the refractory industry. Implementation of EPA regulations is expected to reduce U.S. chromite consumption in the refractory industry and increase recycling of chromium-containing refractories.

Chemical

Chromium contained in chemicals is virtually all dispersed or disposed of. Some chromium chemical production is converted to chromium metal which ends up in high-value alloys that are recycled, and some ends up in high-value refractories that are recycled. However, many chromium-containing chemical uses result in chromium dissemination in the end product, such as pigments, leather tanning, wood preservatives, and plating, or end up being disposed of, such as spent plating solution, tanning baths, and surface-treatment baths. However, all of the chromium entering the chemical industry still ends up as a product or process loss because virtually all products are lost. Reduced waste and greater efficiency reduces process losses but not product losses. Given these conditions, one could estimate chromium losses from chemicals at, say, 90 pct of market share noting the likelihood that either that fraction will decline or chemical industry market share will decline as product replacement takes place. So, for the purpose of estimating process plus product loss of chromium in the chemical industry, 90 pct of the 13 pct of chromium contained in ore production consumed by the chemical industry is lost. Thus chemical process plus product chromium loss in 1989 was 503 kt-Cr, an amount equivalent to 35 kt-Cr/Mt-CrOre. In the United States, EPA has regulated chromite-containing waste from the chemical industry and from the metal finishing industry, a major source of chromium release to the environment and an end use that accounts for a substantial fraction of chromium chemical end use. These regulations are expected to result in more efficient U.S. industry use of chromium materials, more in-plant recycling and less waste.

Metallurgical

Of the 79 pct of chromium used by the metallurgical industry, about 70 pct is used as an alloying element in stainless steel and the remainder is used in other alloys, mostly alloy steel. Noting that stainless steel does not rust, that the steel industry and subsequent metal-consuming manufacturing industries are material efficient for cost reasons, that the metallurgical industry has been practicing recycling for a long time, and that stainless steel is a high value steel alloy, it is likely that only stainless steel made into small parts contained in larger systems is lost to the chromium use cycle. Considering these factors and the results of the two studies described below, it is estimated that 10 pct of chromium entering the metallurgical industry production process becomes a product loss. Other material may be viewed as temporarily stockpiled in waste collection centers awaiting recycling.

An Office of Technology Assessment (OTA) report found that 40 pct of obsolete scrap could not be accounted for in 1974 *(61)*. In that year, about 100 kt-Cr contained in obsolete products was unrecovered or unaccounted for. OTA did not discriminate among obsolete scrap alloys. Chromium was used primarily in stainless and alloy steel in the amount of about 55 kt in alloy steel and 245 kt in stainless steel. Assuming that all of the chromium used in alloy steel was unrecovered or unaccounted for, the remaining 45 kt-Cr unrecovered or unaccounted for was contained in stainless steel. Assuming all of this chromium to have been contained in stainless steel that had an average chromium content of 17.25 pct, about 255 kt-SS were lost. Stainless steel production in 1974 was about 1.950 Mt. So unrecovered obsolete scrap amounted to about 13 pct of stainless steel production.

Kusic and others *(62)* identified the amount of chromium in scrap generated that was lost in 1977. In that year, unrecovered stainless steel scrap was estimated to have been 206 kt containing about 40 kt-Cr. Stainless steel production in 1977 was about 1.687 Mt. So unrecovered stainless steel scrap was about 12.2 pct of stainless steel production in 1977. All of unrecovered scrap was obsolete scrap.

The scrap industry is generally regarded as a volatile industry which is highly price sensitive. Chromium in scrap substitutes for that in ferrochromium as a feed material to the stainless or alloy steel production process. Chromium consumers switch, within limits permitted by production processes, between ferrochromium and stainless steel scrap based on price. Thus, recovery can vary substantially with price, which in turn varies with time. The price to which stainless steel scrap is sensitive is nickel price because the value of nickel in stainless steel scrap is usually substantially higher than that of chromium. Part of the estimated unrecovered stainless steel scrap in 1974 and 1977 may well have been recovered in subsequent years when nickel prices were higher or when ferrochromium demand resulted in shortages of ferrochromium supply.

Considering these two estimates of stainless steel loss, 13 pct in 1974 and 12 pct in 1977, a product loss of 10 pct was estimated. It is further assumed for the purpose of estimating losses in this study that the same loss factor (i.e., 10 pct) applies to alloys other than stainless steel. Then 10 pct of chromium used in the metallurgical industry becomes a product loss.

What happens to this "lost chromium"? Where is it? There are three possible destinations for this lost chromium: (1) the environment, (2) in an alloy that does not require chromium, and (3) in an alloy that requires chromium. Some of lost chromium ends up in the environment. That is, it ends up in a landfill or some other environmental destination. Some of the lost chromium is downgraded to metallic scrap not graded for its chromium content. This scrap material is lost to the chromium use cycle in the sense that it ends up in alloys that do not require chromium. Some of the scrap material may incidentally end up in chromium requiring alloys. This material remains in the chromium use cycle. However, it is lost in the sense that is not accounted for as a secondary supply material.

For the purpose of estimating chromium product loss, chromium contained in 10 pct of the 79 pct of chromium contained in ore consumed by the metallurgical industry is product loss. Thus metallurgical industry chromium product loss in 1989 was 240 kt-Cr, an amount equivalent to 24 kt-Cr/Mt-CrOre.

International Chromium Losses

International chromium loss has here been estimated as chromium lost in processing and chromium lost in products. Applying the chromium loss rates arrived at above, international chromium losses in 1989 were calculated. In 1989, international chromium loss was about 2,593 kt-Cr, which represents a loss rate of 181 kt-Cr/Mt-CrOre. In other words about 60 pct of chromium contained in chromite ore mined in 1989 was lost to the chromium use cycle. The breakdown by losses by industry and by type of loss are shown in table 33.

INTERNATIONAL ANTHROPOGENIC AND NATURAL CHROMIUM RELEASES

World estimates of anthropogenic and natural chromium releases from a variety of sources and to various sectors of the environment have been made. Major sources of chromium have been identified and releases from those sources estimated. Major sources vary among environmental sectors to which chromium is released. The environmental sectors are air, soil, and water.

World anthropogenic air emissions were comparable in magnitude to natural air emissions and together were estimated to have amounted to about 74 kt-Cr in 1989. (See table 6.) These emissions amount to about

Table 33.—Summary of international chromium losses in 1989 and chromium loss rates by industry and type of loss

	1989 loss (kt-Cr)			1989 loss rate (kt-Cr/Mt-CrOre)		
	Process	Product	Total	Process	Product	Total
Mining	676	NA	676	47	NA	47
Chemical	NE	NE	503	NE	NE	35
Refractory	NE	NE	344	NE	NE	24
Metallurgical industry:						
Ferrochromium	509	NA	NE	36	NA	36
Stainless steel	221	NE	NE	15	NE	15
Subtotal (Met. ind.)	730	340	1,070	51	24	75
Total	--	--	2,593	--	--	181

NA Not applicable. NE Not estimated.

0.5 pct of 1989 world chromite ore production. World anthropogenic chromium effluents to aquatic ecosystems were estimated at about 142 kt-Cr in 1989. (See table 7.) These effluents amount to about 1.0 pct of 1989 world chromite ore production. World anthropogenic sources of chromium inputs to soil were estimated at about 527 kt-Cr in 1989. (See table 8.) These inputs amount to about 3.7 pct of 1989 world chromite ore production. Combining these estimates, world anthropogenic and natural releases as estimated by source amount to about 743 Mt-Cr as estimated in 1989. This release amounts to about 5.2 pct of 1989 world chromite ore production.

COMPARISON OF INTERNATIONAL CHROMIUM LOSSES AND RELEASES

The combined anthropogenic and natural chromium releases (estimated in the open literature at 1,113 kt-Cr) are substantially different from the amount of chromium estimated lost from the use cycle in this report (estimated at 2,593 kt-Cr). A major difference between these estimates is that the anthropogenic and natural chromium release estimates exclude processing losses at the mining and smelting stages of production. Processing loss was here estimated at 676 kt-Cr at the mining stage of production and at 509 kt-Cr at the smelter stage of production.

It would be reasonable to except mining releases from the anthropogenic and natural releases because that chromium is contained in mine tailings that may be processed sometime in the future.

Another major difference between the anthropogenic and natural releases is in the amount of chromium in discarded manufactured products. The release based on sources sets the amount at about 500 kt. Other estimates used in this report found losses to have been about 40 kt in stainless steel in 1977 and 100 kt in all alloys in 1974. These values are 5 to 10 times smaller than the anthropogenic and natural release estimate. Chromium consumption increased from the 1970's to the 1980's, but not enough to account for such a large difference in estimated losses.

A problem in estimating chromium product loss is that of identifying and quantifying sources. Chromium apparent consumption reported here accounts for trade in chromite ore, chromium ferroalloys and metal, and chromium chemicals. It does not include trade in stainless steel or other alloys, scrap, or commercial or consumer products. Trade categories are not structured in a way that permit one to simply analyze for chromium contained in these categories. In addition to not knowing how much chromium is domestically lost from those categories, one does not know what fraction of those losses are releases to the environment.

Anthropogenic chromium release estimated from reported releases and transfers may be low. Assuming that all identified sources reported accurately, the estimate is low by the amount released from nonreporting sources. The releases cited were reported based on measurements and estimates of identified release sources. Such a procedure is likely to underestimate because not all sources are accounted for. On the other hand, anthropogenic chromium release estimated by applying loss factors to material processed may be high. Assuming that all processes are accounted for and accurate loss factors were applied, the estimate is high by the amount of apparent loss that is actually recovered and recycled.

A problem with the international chromium loss estimates made here is that they account only for losses from primary producer and consumer industries. These are undoubtedly the major sources and the estimates made for product loss probably cover downstream losses from downstream consumers. However, there may still be metallurgical industry downstream losses. Such losses are suggested by the inability of analysts to account for the destination of historical production. For want of information on that material, we must simply assume that it ended up as downgraded scrap.

DOMESTIC LOSSES

Chromium is not mined in the United States. Thus U.S. supply is imported or derived from recycled materials, and chromium is not "lost" in the mining economic sector as a result of chromite ore mining and mine-site beneficiating (i.e., processing). Chromium may, however, be incidentally associated with the mining of other minerals or rocks and, therefore, be released or mobilized as a result of the mining of those rocks or minerals.

Chromium is used by U.S. industry in a wide variety of forms for a wide variety of purposes. The major primary consumer industries are the metallurgical, chemical, and refractory industries. Chromium-containing products of these industries include ferrochromium, which is subsequently used in the production of stainless steel, alloy steel, and nickel-base alloys from the metallurgical industry; chromium chemicals for plating and surface finishing and pigments for paints and dyes; and refractory materials for use in the steel-, cement-, copper-, and glass-producing industries. The chromium-containing metal alloys and chemicals are incorporated in a wide variety of commercial and consumer products and are used in manufacturing processes to produce non-chromium-containing products. The major end use for chromium is in stainless steel, which, in turn, is used in a wide variety of products. In addition to the United States, Germany and Japan are major stainless steel producers.

It is probably most useful to describe domestic chromium loss in terms of U.S. apparent consumption because U.S. apparent consumption is the only readily available measure of domestic chromium industry activity. So, in this section, chromium losses will be expressed in kilotons of chromium lost per kiloton of U.S. apparent chromium consumption (kt-Cr/kt-AC). Apparent consumption is production plus net trade plus stock changes. Production is primary production (i.e., from domestic mines) plus secondary production (i.e., recycled material). Net trade is imports minus exports. Chromium apparent consumption is calculated in units of contained chromium. Reporting losses per unit of production, as was done in the international section, is not a useful concept for reporting domestic losses because chemical, refractory, and, to a lesser degree, metallurgical industry production is unknown. Inputs to those industries are, however, quantifiable.

For the purpose of estimating chromium losses, essentially the same assumptions about the domestic chromium industry will be made as were made about the international chromium industry. The major differences between the U.S. and the international chromium industries is that there is no chromite ore mining in the United States and there are major stainless steel and chromium chemical manufacturers in the United States. Thus there is no chromium loss associated with chromite ore mining. Three historical studies of domestic chromium losses will be reviewed. Current national chromium losses will then be calculated based on estimated major industry performance.

Product life cycle studies require estimates of material consumption and losses with which to estimate environmental impact of the product life cycle. Average material use efficiency, environmental losses, and energy and water consumption factors associated with primary chromium material production processes have been identified. Average chromium contents of common industrial metal alloys were estimated as follows: alloy steel, 0.68 pct; aluminum alloys, 0.04 pct; cobalt alloys, 20 pct; copper alloys, 0.025 pct; nickel alloys, 14 pct; stainless steel, 17 pct; and titanium alloys, 0.49 pct. Coincidental chromium releases associated with the use of chromium materials to produce non-chromium-containing products such as cement and coal were also estimated.

A chromium material flow study was part of an Office of Technology Assessment (OTA) study on the technical options for the conservation of chromium in 1978 (*61*). That report was prepared by Battelle Columbus Laboratories for the Office of Technology Assessment and was based on USBM collected and reported data *(63)* and on industry interviews. The OTA study reported data from 1974 for which year the USBM reported chromium apparent consumption of 567 kt-Cr. That OTA study tracked only processed material and identified opportunities for recycling. The OTA study identified chromium industry losses. OTA reported that in 1974 the refractory industry accounted for 64 kt-Cr use (equivalent to 0.11 kt-Cr/kt-AC) and that those refractories were used predominantly for metallurgical furnaces and were not recovered. OTA reported that the chemical industry accounted for 70 kt-Cr use (equivalent to 0.12 kt-Cr/kt-AC) and that, while the chemical industry was efficient, the end uses were predominantly dissipative. The remaining 433 kt-Cr then would have been metallurgical industry consumption (equivalent to 0.76 kt-Cr/kt-AC). (OTA reported 263 kt-Cr contained in chromite ore into the ferrochromium industry, 105 kt-Cr from ferrochromium imports, and 65 kt-Cr from scrap.) OTA reported chromium recovery during ferrochromium production at 86 pct and that, based on reported consumption, the stainless steel industry accounted for 80 pct of metallurgical consumption. Losses from these industries mostly reported to slag and dust. OTA reported chromium losses from various industry sectors in quantity and reported here also as a percent of apparent consumption as follows; material processing and manufacturing, 75 kt-Cr (equivalent to 0.13 kt-Cr/kt-AC); product manufacturing, 5 kt-Cr (equivalent to 0.009 kt-Cr/kt-AC), dissipative uses, 103 kt (equivalent to 0.18 kt-Cr/kt-AC), and unrecovered and unknown, 100 kt (equivalent to 0.18 kt-Cr/kt-AC).

Chromium utilization was reported in 1978 by the National Materials Advisory Board (NMAB) *(64)*. NMAB showed that domestic chromium use by primary consumer industry, as a percent of U.S. chromium apparent consumption from 1950 to 1976, was as follows: the metallurgical industry accounted for a range of 55 pct to 70 pct, refractories accounted for a range of about 15 pct to 30 pct and declined from 30 pct to 15 pct over the time period, chemicals accounted for a range of from 10 pct to more than 20 pct and increased from about 10 pct to more than 20 pct over the time period. Potentially recoverable losses were reported, in magnitude for 1977 and as percent of industry sector chromium consumption in 1977, to have been for the metallurgical industry, 13.3 kt-Cr or 4.5 pct of metallurgical industry chromium consumption; for the refractory industry, 36 kt-Cr or 65 pct of refractory industry chromium consumption; and for the chemical industry, 3.8 kt-Cr or 6.0 pct of chemical industry chromium industry consumption. If these were the technologically recoverable amounts, the losses in excess of these amounts were unrecoverable, part of which would likely end up in the environment. Based on chromium loss to stainless steel slags, NMAB reported chromium recovery for stainless steel production to have been 85 pct with the technological potential of moving that recovery to 93 pct.

The USBM studied chromium industry losses for the purpose of identifying potential recycling opportunities (*4*). The Bureau analyzed data from 1989 for which year chromium apparent consumption was about 452 kt-Cr. Based on distribution of chromium to various end-use industries and an analysis of those industries, chromium losses were estimated at about 226 kt-Cr, about 0.5 kt-Cr/kt-AC.

On average, from 1983 through 1992 and based on industry data reported to the USBM, U.S. chromium apparent consumption was about 400 kt-Cr use of which by major consuming industry was 87 pct by the metallurgical industry, 10 pct by the chemical industry, and 3 pct by the refractory industry. As with international chromium use, assume chromium process plus product losses (as a percent of apparent consumption) by primary consumer industry to have been as follows: 20 pct for metallurgical (10 pct process plus 10 pct product); 90 pct for chemical; and 100 pct for refractory. Then average domestic chromium loss by primary consumer industry was 36 kt-Cr (an amount equivalent to 9 pct of apparent consumption) for the chemical industry, 70 kt-Cr (an amount equivalent to 17 pct of apparent consumption), and 12 kt-Cr (an amount equivalent to 3 pct of apparent consumption). Thus, U.S. average loss was 118 kt-Cr (an amount equivalent to 29 pct of apparent consumption). This is substantially better (i.e., less lost) than the 31.8 pct of apparent consumption reported in the OTA study (i.e., material processing, 13 pct; manufacturing, 0.8 pct; and dissipative, 18 pct).

Thus, we see that a wide variety of studies have been conducted to elucidate chromium losses. The studies were carried out by Government (Congress and the executive branch), academic, and industrial authors. They include both a national and an industrial perspective.

Let us now consider environmental chromium losses. In the United States, chromium releases and transfers from the manufacturing and fabricating industries are monitored by the EPA. Chromium releases and transfers are a subset of process losses and exclude product losses. Chromium recycling from obsolete products and from processing byproducts is partly monitored by the USBM. Sources of recycled chromium have been studied and quantified by the Bureau. Analysis of the EPA TRI reported data showed that releases to the environment were comparable in magnitude to transfers. The largest quantity of releases was to land; the largest quantity of transfers, to off-site locations. The manufacturing industries accounting for the largest quantity of releases and transfers were chemical and allied products and primary metals. Relative to the releases and transfers from other manufacturing industries, substantial quantities have been released and transferred by the petroleum and coal; stone, clay, glass, and concrete; fabricated metals; machinery and computer equipment; and transportation equipment industries. TRI reported releases and transfers in 1989 were 32.523 kt-Cr. (See table 28). TRI reported releases and transfers are included in what has here been called processing losses. TRI data would not include what has here been called product losses because TRI does not monitor the production of products or of scrap.

Let us now estimate environmental losses in 1989 based on reported loss factors and production, and compare these estimates with reported EPA data. Domestic process losses are first estimated, then total losses are estimated by adding product to process losses. Domestic chromite ore consumption in 1989 was 560.711 kt-CrOre (43.78 kt-CrOre, refractory at 39.5 pct Cr_2O_3; 516.931 kt-CrOre, chemical plus metallurgical at 42.8 pct Cr_2O_3). For the refractory component, assuming a process loss factor of 0.053 t-Cr/t-CrOre consumed and a product loss factor of remaining contained chromium, the refractory industry accounted for a process loss of about 0.627 kt-Cr and a product loss of 11.2 kt-Cr in 1989. (Refractory process loss factor is based on chromium emission factor from table 21.) Using the 87 pct of chromite ore to the metallurgical industry and 10 pct to the chemical industry division referred to above to partition the remaining 516.931 kt-CrOre, about 53.292 kt-CrOre was consumed in the chemical industry and 463.639 kt-CrOre in the metallurgical industry. For the chemical component, use chromium process loss factor of 1.4×10^{-4} t-Cr/t-CrOre processed and a chromium product loss factor of 90 pct of the remaining chromium contained in chromite ore processed to get a process loss of 2 t-Cr and a product loss of 14 kt-Cr in 1989. (The chemical industry process loss factor used here was deduced as follows. Table 21 reports an emission factor of 1.5×10^{-4} t-Cr/t-$Na_2Cr_2O_7$ production. Sodium bichromate production is not available. However, estimates of chromite ore consumption by the chemical industry and the chromite ore to sodium bichromate conversion ratio are available. The chromite ore to sodium bichromate conversion ratio is estimated to be 1.1 t-CrOre/t-$Na_2Cr_2O_7$ based on a chromium recovery factor of 81 pct as reported in table 10, 44 pct Cr_2O_3 content of ore, 68.42 pct Cr in Cr_2O_3, and 22.034 pct Cr in $Na_2Cr_2O_7 \bullet H_2O$. Thus, the loss rate of 1.5×10^{-4} t-Cr/t-$Na_2Cr_2O_7$ is equivalent to 1.4×10^{-4} t-Cr/t-CrOre feed material.) For the metallurgical industry, assume that all 463.639 kt-CrOre was converted to ferrochromium then to stainless steel. Ferrochromium production is not available so estimate process loss (due to ferrochromium production) as a function of chromite ore feed. For the ferrochromium production process, use a chromium process loss factor of 2.3×10^{-3} t-Cr/t-CrOre feed consumed. One then gets a process loss of 0.314 kt-Cr in 1989. (The ferrochromium industry process loss factor used here was deduced as follows. Table 21 reports an emission factor of 5.791×10^{-3} t-Cr/t-FeCr. Table 12 reports 2.5 t-CrOre/t-FeCr. Thus the loss rate of 5.791×10^{-3} t-Cr/t-FeCr is equivalent to a loss rate of 2.32×10^{-3} t-Cr/t-CrOre feed material.) For stainless steel, production data are available. Stainless steel domestic production was 1,753.629 kt-SS in 1989. Stainless steel process loss factor is 2×10^{-3} t-Cr/t-SS, which amounts to 3.507 kt-Cr in 1989. Stainless steel loss factor is emission factor from table 21.) So domestic metallurgical chromium processing losses in 1989 were about 3.822 kt-Cr. Domestic chromium processing losses were 4.451 kt-Cr; product losses, 55.06 kt-Cr; and total losses, 59.511 kt-Cr. Because process losses were estimated based only on air emissions and accounted only for losses from the primary consumer industries, we would expect process losses here estimated to be less than EPA reported TRI releases. Total losses to the environment (i.e., process plus product losses) may exceed TRI releases and transfers because TRI does not account for product losses, and product losses are substantially greater than process losses. (See table 34.)

EPA reported TRI releases and transfers were 32.523 kt-Cr in 1989 of which 16.986 kt-Cr was releases. As expected TRI releases were substantially greater than primary industry process losses of 6.768 kt-Cr estimated above. Total losses to the environment in 1989 estimated above at 46.555 kt-Cr is of comparable magnitude to releases and transfers reported by EPA. Domestic product losses exceed process losses by more than a factor of 5 showing the importance and potential impact of recycling environmental protection.

EPA estimated chromium air emissions by source were about 5.2 kt-Cr in 1983 (see table 21) and were about four times greater than air emissions reported in the TRI at a high value of 1.344 kt-Cr in 1989 (see table 24). The difference between EPA 1983 reported air emissions and those reported by TRI is substantial. TRI reported air emissions from 1987 through 1991. TRI reported emission showed a range of from 0.621 kt-Cr to 1.344 kt-Cr, a factor of 2. In fact, the 1983 EPA report has steel industry chromium emission alone exceeding TRI reported emissions. This suggests that emission factors in that report may be outdated relative to current domestic industry practice and that the domestic industry has substantially reduced air emissions since those factors were estimated. Indeed, since the 1983 EPA air emissions data were reported, major changes have taken place in the refractories industry. A Baltimore, MD, based refractory plant included in that study has been closed and emission from the remaining plants has been reduced by about 90 pct *(65)*. Chromite ore processed by the refractory industry has declined from about 100,000 tons per year in the pre-1983 time period to about 30,000 tons in 1992 *(66)*.

Table 34.—Estimated U.S. chromium losses in 1989

Industry	Fraction of chromite ore consumed[1]	Loss rate (t-Cr/t-CrOre) Process	Loss rate (t-Cr/t-CrOre) Product	Loss amount (kt-Cr) Process	Loss amount (kt-Cr) Product
Chemical	0.10	0.001[2]	0.9	0.002	14
Refractory	0.03	0.053[3]	1	0.62	11
Metallurgical:					
Ferrochromium	0.87	0.002[4]	NA	0.31	NA
		(t-Cr/t-SS)			
Stainless steel	NA	0.002[5]	0.1	3.5	30
Total				4.5	55

NA Not applicable.

[1]Domestic chromite ore distribution in 1989 estimated as average over 1983 through 1992. Domestic chromite ore consumption in 1989 was 561 kt-CrOre.

[2]Chemical industry process loss rate estimate is based on an air emission rate of 1.5×10^{-4} t-Cr/t-$Na_2Cr_2O_7$ (from EPA-450/4-84-007g) converted to units of t-Cr/t-CrOre assuming an industry Cr recovery of 0.81 t-Cr(in $Na_2Cr_2O_7$)/t-Cr(in CrOre), 0.44 Cr_2O_3 chromite ore grade, 0.6842 Cr/Cr_2O_3, and 0.22034 Cr/$Na_2Cr_2O_7 \cdot 2H_2O$ product grade. For the purpose of calculating loss amount, 0.428 Cr_2O_3 ore grade reported by industry was used.

[3]Refractory industry process loss rate estimate is based on air emission rate of 5.3×10^{-2} t-Cr/t-CrOre (from EPA-450/4-84-007g). For the purpose of calculating loss amount, 0.395 Cr_2O_3 ore grade reported by industry was used.

[4]Ferrochromium industry process loss rate estimate is based on ferrochromium smelter air emission rate of 5.791×10^{-3} t-Cr/t-FeCr (from EPA-450/4-84-007g) converted to units of t-Cr/t-FeCr assuming a 2.5 t-CrOre/t-FeCr conversion rate.

[5]Stainless steel industry process loss rate estimate is based on an air emission rate of 2.13×10^{-3} t-Cr/t-SS (from EPA-450/4-84-007g). U.S. stainless steel production in 1989 was 1,754 kt-SS.

CHROMIUM INDUSTRY TREND ENVIRONMENTAL IMPACT

Changes in the domestic chromium industry will impact chromium releases and transfers. Changes occur both in quantity and distribution of chromium use among primary consumer industries and in how the primary consumer industry handles the chromium materials that it consumes. Quantity and distribution of chromium by primary consumer industry was presented previously in this report (see table 23, figure 30, and figure 31.) How domestic industry handles the chromium materials that it consumes was presented in the form of domestic releases and transfers previously in this report (see table 26 through table 30). The primary consumer industry is part of the manufacturing industry. For expediency, primary consumer industry releases and transfers are here assumed to be the same as their component of manufacturing industry releases and transfers. In particular, chemical primary consumer industry releases and transfers are assumed to be the same as those of that part of the manufacturing industry identified as Chemical and Allied Products industry (SIC 28), metallurgical primary consumer industry releases and transfers are assumed to be the same as those of Primary Metals industry (SIC 33), and refractory primary consumer industry releases and transfers are assumed to be the same as those of Stone, Clay, Glass, and Concrete industry (SIC 32). We shall assume the current release and transfer rates apply to past and future time periods in order to identify industry trends.

The decline in chromium average apparent consumption from the 1973-82 time period (459 kt-Cr) to the 1983-92 time period (400 kt-Cr) by 59 kt-Cr (equivalent to 13 pct of 1973-82 annual average apparent consumption) implies that releases and transfers too have declined. The chromium industry (i.e., manufacturing industries SIC 28, 32, and 33) reported 1987-91 annual average releases plus transfers of 24,611 t-Cr. Assuming that these releases and transfers are typical, the chemical primary consumer industry average release plus transfer rate was 62 t-Cr/kt-AC. Thus the 13 pct decline in chromium industry average apparent consumption from the 1973-82 time period to the 1983-92 time period is estimated to have accounted for a release plus transfer reduction of 3,658 t-Cr. Assuming similar performance for the next 10 years (i.e., a 13 pct reduction of chromium apparent consumption between the 1983-92 time period and the 1993-2002 time period with unit release plus transfer unchanged), a reduction of domestic releases plus transfers of 3,199 t-Cr is anticipated. (See table 35.)

The largest fractional decline (i.e., decrease in use as a percent of 1973-82 time period use) took place in reverse order of industry size. The smaller the consumer industry, the larger the fractional decline. The refractory industry, accounting for only 9 pct of

1973-82 annual average apparent consumption (43 kt-Cr) decreased market share to 3 pct of 1983-92 annual average consumption (12 kt-Cr), a decline of 31 kt-Cr representing 72 pct of the refractory industry share of 1973-82 annual average apparent consumption. The Stone, Clay, Glass, and Concrete industry reported 1987-91 annual average releases plus transfers of 907 t-Cr. Assuming that these releases and transfers are typical, the refractory primary consumer industry average release plus transfer rate was 76 t-Cr/kt-Refr-AC. Thus the 72 pct decline in refractory chromium average apparent consumption from the 1973-82 time period to the 1983-92 time period is estimated to have accounted for a release plus transfer reduction of 2,344 t-Cr. Assuming similar performance for the next 10 years (i.e., a 72 pct reduction of refractory average chromium apparent consumption between the 1983-92 time period and the 1993-2002 with unit release and transfer rate unchanged), a reduction of domestic releases plus transfers of 654 t-Cr is anticipated. (See table 35.)

The chemical industry, accounting for 12 pct of 1973-82 annual average apparent consumption (51 kt-Cr) decreased market share to 10 pct of 1983-92 annual average consumption (41 kt-Cr), a decline of 10 kt-Cr representing 20 pct of the chemical industry share of 1973-82 annual average apparent consumption. The Chemical and Allied Products industry reported 1987-91 annual average releases plus transfers of 8,907 t-Cr. Assuming that these releases and transfers are typical, the chemical primary consumer industry average release plus transfer rate was 217 t-Cr/kt-Chem-AC. Thus the 20 pct decline in chemical industry chromium average apparent consumption from the 1973-82 time period to the 1983-92 time period is estimated to have accounted for a release plus transfer reduction of 2,172 t-Cr. Assuming similar performance for the next 10 years (i.e., a 20 pct reduction of chemical average chromium apparent consumption between the 1983-92 time period and the 1993-2002 with unit release unchanged), a reduction of domestic releases plus transfers of 1,746 t-Cr is anticipated. (See table 35.)

The metallurgical industry, accounting for 79 pct of 1973-82 annual average apparent consumption (365 kt-Cr), increased market share to 87 pct of 1983-92 annual average consumption (347 kt-Cr), a decline of 18 kt-Cr representing 5 pct of the metallurgical industry share of 1973-82 annual average apparent consumption. The Primary Metals domestic industry reported 1987-91 annual average releases plus transfers of 14,797 t-Cr. Assuming that these releases and transfers are typical, the metallurgical primary consumer industry average release plus transfer rate was 43 kt-Cr/kt-Met-AC. Thus, the 5 pct decline in metallurgical chromium average apparent consumption from the 1973-82 time period to the 1983-92 time period is estimated to have accounted for a release reduction of 768 t-Cr. Assuming similar performance for the next 10 years (i.e., a 5 pct reduction of metallurgical average chromium apparent consumption between the 1983-92 time period and the 1993-2002 with unit release unchanged), a reduction of domestic releases plus transfers of 730 t-Cr is anticipated. (See table 35.)

These estimates are probably conservative because it has been the time period under study here that environmental awareness has increased resulting in voluntary and legally mandated action to reduce environmental releases.

Table 35.—Estimated U.S. chromium releases and transfers from 1973 through 2002

	Primary consumer industry			Chromium
	Metallurgical	Chemical	Refractory	industry
1987-1991 average: (metric tons)				
Releases	5,531	7,895	257	13,684
Transfers	9,265	1,012	650	10,927
Total	14,797	8,907	907	24,611
Apparent consumption: (thousand metric tons)				
1973-1982	365	51	43	459
1983-1992	347	41	12	400
1993-2002	330	33	3	349
Rate: (metric tons/thousand metric tons of industry apparent consumption)				
Releases	16	193	21	34
Transfers	27	25	54	27
Total	43	217	76	61

Table 35.—Estimated U.S. chromium releases and transfers from 1973 through 2002--continued

	Primary consumer industry			Chromium
	Metallurgical	Chemical	Refractory	industry
Estimated annual average: (metric tons)				
Releases				
1973-1982	5,818	9,821	921	15,702
1983-1992	5,531	7,895	257	13,684
1993-2003	5,258	6,347	72	11,925
Transfers				
1973-1982	9,746	1,258	2,331	12,539
1983-1992	9,265	1,012	650	10,927
1993-2003	8,808	813	182	21,447
Releases plus transfers				
1973-1982	15,564	11,079	3,252	28,241
1983-1992	14,797	8,907	907	24,611
1993-2003	14,067	7,161	253	21,447
Estimated annual average changes: (metric tons)				
Releases				
1973-1982--1983-1992	-287	-1,926	-664	-2,018
1983-1992--1993-2002	-273	-1,548	-185	-1,759
Transfers				
1973-1982--1983-1992	-481	-247	-1,680	-1,612
1983-1992--1993-2002	-457	-198	-469	-1,405
Releases plus transfers				
1973-1982--1983-1992	-768	-2,172	-2,344	-3,630
1983-1992--1993-2002	-730	-1,746	-654	-3,164

SUMMARY AND CONCLUSIONS

International global chromium processing plus product losses of chromium in 1989 were estimated to have been about 2.593 Mt-Cr. This amount of chromium is equivalent to about 60 pct of chromium contained in 1989 chromite ore production. The loss attribution was distributed as follows: mining and beneficiating, 26 pct of total loss in 1989; chemical industry, 19 pct; refractory industry, 13 pct; and metallurgical industry, 41 pct. Breaking the 41 pct loss down further; ferrochromium, 20 pct; stainless steel, 9 pct; and unrecovered and unaccounted for chromium contained in metal scrap, 13 pct. Together, these losses amounted to about 2.593 million tons of chromium in 1989. Industry losses (i.e., process plus product losses) exceed environmental losses (i.e., chromium lost to the environment) because industry recovers chromium from substantial amounts of process and product losses.

Chromium material flow in the United States in 1989 was 452 kt-Cr, based on net trade (i.e., imports minus exports) of chromium materials (including chromite ore, chromium ferroalloys and metal, and chromium chemicals) and purchased stainless steel scrap. Scrap accounted for 22 pct of domestic chromium supply in 1989. The remainder came from net trade adjusted for stock changes. Chromium losses were 31 kt-Cr, disposal was 13 kt-Cr, and recycling was 363 kt-Cr. Losses were distributed among economic sectors as: mining and milling, 3 kt-Cr; processing, 17 kt-Cr; fabrication and manufacturing, 2 kt-Cr; and use, 9 kt-Cr.

An analysis of domestic chromium material flow in 1989 showed that domestic chromium releases plus transfers were about 7 pct of domestic chromium apparent consumption. From 1987 to 1990, releases and transfers change as a percentage of releases plus transfers within a 40 pct to 60 pct range. So, releases and transfers each accounted for roughly the same amount of material during that time period. In 1991, however, the balance shifted to transfers which accounted for 77 pct of releases and transfers in that year. Studies predating the TRI and the TRI data indicate that the primary metals industry and the chemical industry are the major sources of chromium releases and transfers in the United States. Of the possible destinations of chromium releases (land, water, air, and underground), land release was consistently equal to or in excess of 90 pct or the material released from 1987 to 1991. This fact suggests that recovery of that material may someday be possible because land releases are probably the least mobile form of release. Of the possible destinations of transfers (publicly owned treatment works, treatment, and disposal), transfers for disposal ranged from 59 pct to 73 pct of material transferred during the 1987-90 time period. When transfers for recovery were introduced in 1991, that category dominated with 76 pct of material transferred.

In this report estimates of chromium loss by primary consumer industry in the United States (i.e., based on reported chromite ore consumption, chromium ferroalloy and metal production, and stainless steel production) indicate that 4.451 kt-Cr was lost in 1989. This is substantially less than industrial releases of chromium reported by EPA as 16.986 kt-Cr in 1989. The difference is thought to result from the fact that losses estimated in this report are for the primary consumer industry while EPA surveys the entire manufacturing industry. The primary consumer industry is a part of the manufacturing industry.

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APPENDIX.—DISCUSSION OF OTHER FACTORS

Major assumptions had to be made to make the estimates of chromium mobilization, loss, and release in this report and in reports referenced herein that made similar estimates. For example, historical information about chromium consumption by U.S. industry has been used to estimate current use because there are too few U.S. primary chromium industry producers to release consumption and production information by industry. In particular, on average from 1973 to 1983 for the U.S. industry, it was found that the metallurgical industry accounted for about 70 pct of U.S. chromium apparent consumption. Over the same time period, the chemical industry accounted for 18 pct and the refractory industry accounted for 12 pct (*67*)[1]. Since 1983, the trend has been to reduce and redistribute chromium consumption yielding a new distribution of 87 pct metallurgical, 10 pct chemical, and 3 pct refractory. It should also be emphasized that these are average values. Because of widely varying metallurgical industry chromium use from year to year, annual use percentages can vary substantially from the averages used here. Similar estimates have been made internationally by the Mintek (Republic of South African). In 1989, Mintek estimated that 79 pct of chromium was utilized by the metallurgical industry, 13 pct by the chemical industry, and 8 pct by the refractory industry (*7*).

Obsolete scrap comes into being at the end of the useful life of a product. Each product has its own lifetime. Average lifetimes have been used to estimate the amount of obsolete scrap generated in a specific year based on production in a previous year. USBM secondary chromium supply is estimated as purchased stainless steel scrap. Purchased scrap includes both obsolete and prompt scrap. Prompt scrap is that generated as part of the production process. For the purpose of this report, processing and product losses were estimated based on 1989 production.

The amount of chromium material flow through the U.S. economy was estimated as domestic production plus net trade plus stock changes. Production included primary and secondary where primary production means supply from mine production and secondary is supply from recycling. There has been no regular domestic mine production since the 1960's. Supply from recycling is complex. Recycled metal is frequently subdivided into home and purchased scrap; run-around, prompt, and obsolete scrap; or new and old scrap. These terms are not always mutually exclusive from a practical process point of view. However, the concept is that home scrap represents a steady, recirculating fraction of production; prompt scrap is material generated as a waste stream from the alloy, mill product, part manufacturing, subassembly, or product manufacturing process; and obsolete scrap results from products that have been used and are worn out. Because estimates are based on chromium flow through the national economy and consumer demand, recirculating or home scrap is not counted. From the point of view of material losses to the environment, however, recirculating material can be the only important factor. If material that would otherwise be released to the environment or transferred to another site is recovered and recycled, it is no longer an environmental release. However, it represents a reduction in consumer demand only once, when the recovery process is started. After that, home scrap is a recirculating load that is part of the production process. From an environmental point of view, home scrap represents a perpetual "savings" of material that might otherwise have been released to the environment. The environmental and demand points of view perceive in-plant recovery quite differently. Secondary supply is here estimated as reported stainless steel scrap receipts. Thus, secondary supply as used here is neither production nor consumption, but is a well-defined transaction somewhere between the two.

The terms mobilization, loss, release, and transfer represent subtle distinctions in material flow. For example, all chromium contained in chromite ore is mobilized when it is mined. When run-of-mine ore is sorted into tailings or waste and product, only product is transported and utilized in commerce. Data are not available for the amount of extracted material returned

[1]Italic numbers in parentheses refer to items in the list of references preceding the appendix.

to the ground from which it was removed. If, as a result of mining, tailings are exposed to natural forces that will transport them, they are mobilized. One such means of transport is acidified ground or surface waters. Metals are leached from tailings and/or underground workings, resulting in contamination of the waters, a process known as acid mine drainage. However, because of its stability and low solubility, chromium in tailings is relatively immobile. The mining of other materials also mobilized chromium when chromium is included among the elemental constituents of the ore, or when chromium is part of the material that must be moved to get at an ore deposit. In the former case, chromium is a constituent. Coal, oil, and phosphate are examples. Thus, when coal is mined, chromium is mobilized. When that chromium will actually be released to the environment is not clear. For the purpose of this report, it was assumed that mobilization and release occurred in the year of extraction.

The term loss is viewed in a variety of ways, objectively and subjectively. Objectively, in order to distinguish what was lost and where the loss ended up, one should distinguish both source and destination. For example, lost from the product stream or lost to the environment. The terminology used by EPA in its TRI is "released and transferred." The only places a release can go is to the environment, so lost to the environment is the same as released. Transferred, as used by TRI, is only for the purpose of disposal.