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Chromium Availability in Market Economy Countries and Network Flow Model Analysis of World Chromium Supply

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°	degree	Mmtpy	million metric ton per year
°C	degree Celsius	mt	metric ton
km	kilometer	mtpy	metric ton per year
kmt	thousand metric ton	MV·A	megavolt ampere
kmtpy	thousand metric ton per year	MW	megawatt
kV·A	kilovolt ampere	pct	percent
kW·h	kilowatt hour	pct/yr	percent per year
lb	pound	$	U.S. dollar
m	meter	wt pct	weight percent
mm	millimeter	wtd avg	weighted average
Mm^3	million cubic meter	yr	year
Mmt	million metric ton		

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CHROMIUM AVAILABILITY IN MARKET ECONOMY COUNTRIES AND NETWORK FLOW MODEL ANALYSIS OF WORLD CHROMIUM SUPPLY

By Edward H. Boyle, Jr.,[1] Deborah J. Shields,[1] and Lorie A. Wagner[1]

ABSTRACT

This report analyzes the availability of chromium in the form of ferroalloy products (high-carbon and low-carbon ferrochromium and ferrochromium-silicon) and chromite products (metallurgical, chemical, refractory, and foundry sands) in market economy countries (MEC's). A total of 873.5 Mmt of in situ material, containing 202.5 Mmt of chromium, in 10 MEC countries was analyzed for availability as of the January 1989 study date. Extraction and beneficiation of this in situ material would result in 475.4 Mmt of marketable chromite products. As analyzed, 288.5 Mmt of these chromite products would be available for export or for internal chemical and refractory use and 186.9 Mmt would be smelted in-country to produce 74.3 Mmt of high-carbon ferrochromium, 3.9 Mmt of low-carbon ferrochromium, and 2.0 Mmt of ferrochromium-silicon, all available for export.

A network flow model, which includes centrally planned economy countries (CPEC's), was also constructed to analyze world chromium supply and demand interactions for the period 1986 through 1994 and to address a hypothetical North American embargo on direct imports of all South African chromium products beginning in mid-1990.

The model shows capacity constraints developing in the MEC high-carbon ferrochromium industry in 1987 and a possible subsequent overreaction by the industry in terms of new capacity additions. The results suggest that sufficient chromium is available to North America should an embargo on direct imports from South Africa be imposed by its governments. However, the effect on export revenues in South Africa is relatively small, and timely increases to world ferrochromium, chemical chromite, and foundry sand chromite capacities would be required.

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INTRODUCTION

This study of the world chromium industry is an update of Bureau of Mines IC 8977, entitled "Chromium Availability—Market Economy Countries," (*1*),[2] which was published in 1984 and based on 1980-82 data. A complete reevaluation of costs, resources, and industry structure in 11[3] market economy countries (MEC's) was undertaken in 1985 and completed in 1988. An economic model of the world chromium industry, in the form of a network flow model, was constructed during 1989. All costs presented in this report are in terms of January 1989 U.S. dollars, and all resource values are as of a January 1989 study date.

The report presents a commodity overview, followed by a methodology section that outlines the analytic approach used. Presented next are the results of the chromium availability analysis, including summary information on chromium resources. The results of multiyear analysis of supply and demand interaction, made with the chromium network flow market model, are presented and discussed in the last section of the text. Appendixes A and B provide detailed information on the chromium industries, the operating parameters and mining/beneficiation operating cost estimates, and the evaluated properties and units[4] in the MEC chromite producing countries. Appendixes C, D, E, F, and G discuss smelting technologies, economic factors affecting the analysis, demand methodologies, and various aspects of the network flow model.

Since 1980-82 much has happened in the chromium industry. The period up to 1987 was characterized by new high-carbon ferrochromium (high-C FeCr)[5] smelting capacity coming on-line in Greece, the Philippines, and India. Concurrently, chromium ferroalloy capacity in the United States, Europe, and Japan was being shut down. Nearly all sectors of the chromium industry were affected by the economic downturn of the early 1980's that negatively affected most heavy industry.

United States import prices for high-C FeCr reflect this downturn. Figure 1 shows the average annual customs values in actual and in constant 1988 U.S. dollars for the years 1980 through 1989. In actual U.S. dollars, the custom value declined from $0.404/lb Cr in 1980 to only $0.310/lb Cr for all of 1983 and rose slightly to an average of $0.355/lb Cr for 1984.

With the rebound in the MEC economies in late 1987, there was a spectacular increase in the price of high-C FeCr, as shown in figure 1. Prices for low-C FeCr also increased (fig. 2), but less dramatically. This increase in price is related to the previously mentioned decommissioning of substantial amounts of smelting capacity in the United States, Japan, and Western Europe during the early 1980's, which was not matched by the addition of new MEC smelting capacity during the same period.

During 1987, 1988, and 1989, new chromite mines have opened in Indonesia, Brazil, and South Africa, and there have been major high-C FeCr capacity additions in India, Turkey, South Africa, and several European countries. In addition, new high-C FeCr smelting technologies using plasma arc and prereduction techniques for more efficient smelting of chromite ores and concentrates of fine grain sizes have either reached commercial production levels or are under development. By the end of 1989, it appeared that the high-C FeCr industry may have overexpanded in response to the high prices of 1988, raising the possibility of a shakeout in the industry during the early to middle 1990's.

Since passing the Comprehensive Anti-Apartheid Act of 1986, which imposed limited[6] sanctions on South African products, the Congress of the United States has continued to examine the possibility of more encompassing and stringent sanctions on South African products. Extension of the materials covered by the Comprehensive Anti-Apartheid Act could result in the embargo of chromium imports from South Africa.

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

[3]The 1986 reevaluation of reserves for the one major producing property in New Caledonia resulted in an estimate that allowed production only into late 1988. For that reason, the analyzed MEC tonnage available as of the January 1989 study date includes only 10 MEC's and does not include any analyzed chromite reserve for the country of New Caledonia.

[4]The basic resource evaluation groupings used for this study are either as "properties" or as "units." In this study, the definition of a "property" is primarily related to ownership aspects and to operational considerations. In this context, a property could consist of several different types of chromite deposits and mining operations (i.e., an "operation"). The term "units" has been used in this study to facilitate analysis where ownership within a large geographic area of chromite deposits was either unclear or fragmented; e.g., the analysis for the Great Dyke in Zimbabwe and for the California/Oregon podiform deposits in the United States. The term "units" also applied to the analytical situation for the country of India where the Sukinda Valley chromite reserves consist of a number of individual chromite deposits contained within each of several ownership (lease) areas in the valley. To assess economic differences among the various deposits it was necessary to approach each deposit as a separate "unit."

[5]The following abbreviations for chromium ferroalloy products are commonly used in this report: high-C FeCr for high-carbon ferrochromium, low-C FeCr for low-carbon ferrochromium, FeCrSi for ferrochromium-silicon, and FeCr for ferrochromium.

[6]The sanctions imposed by this act were rather extensive, with some exceptions made for strategic and critical materials such as chromium.

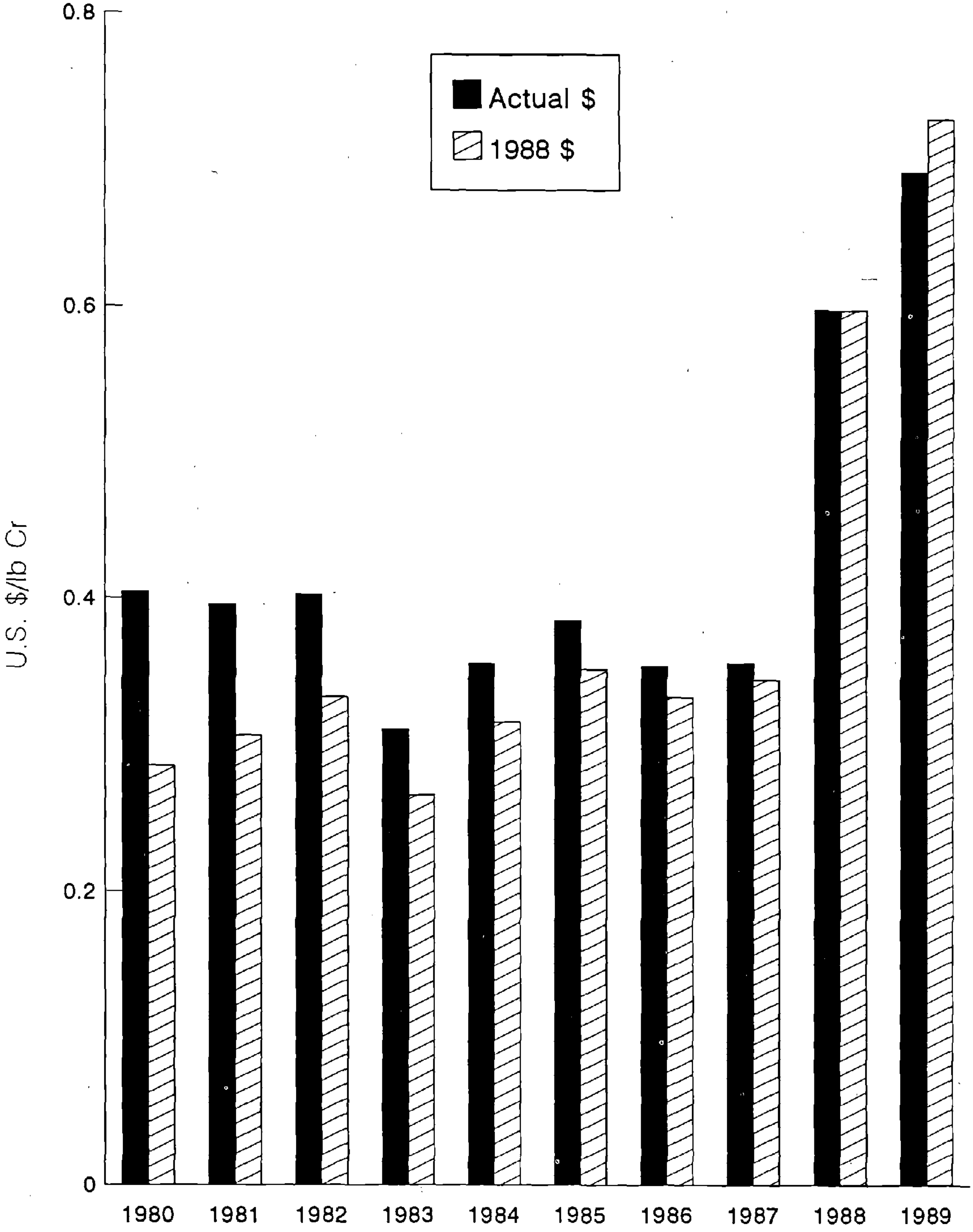

Figure 1.—F.o.b. customs values, high-C FeCr imports to the United States, 1980-89.

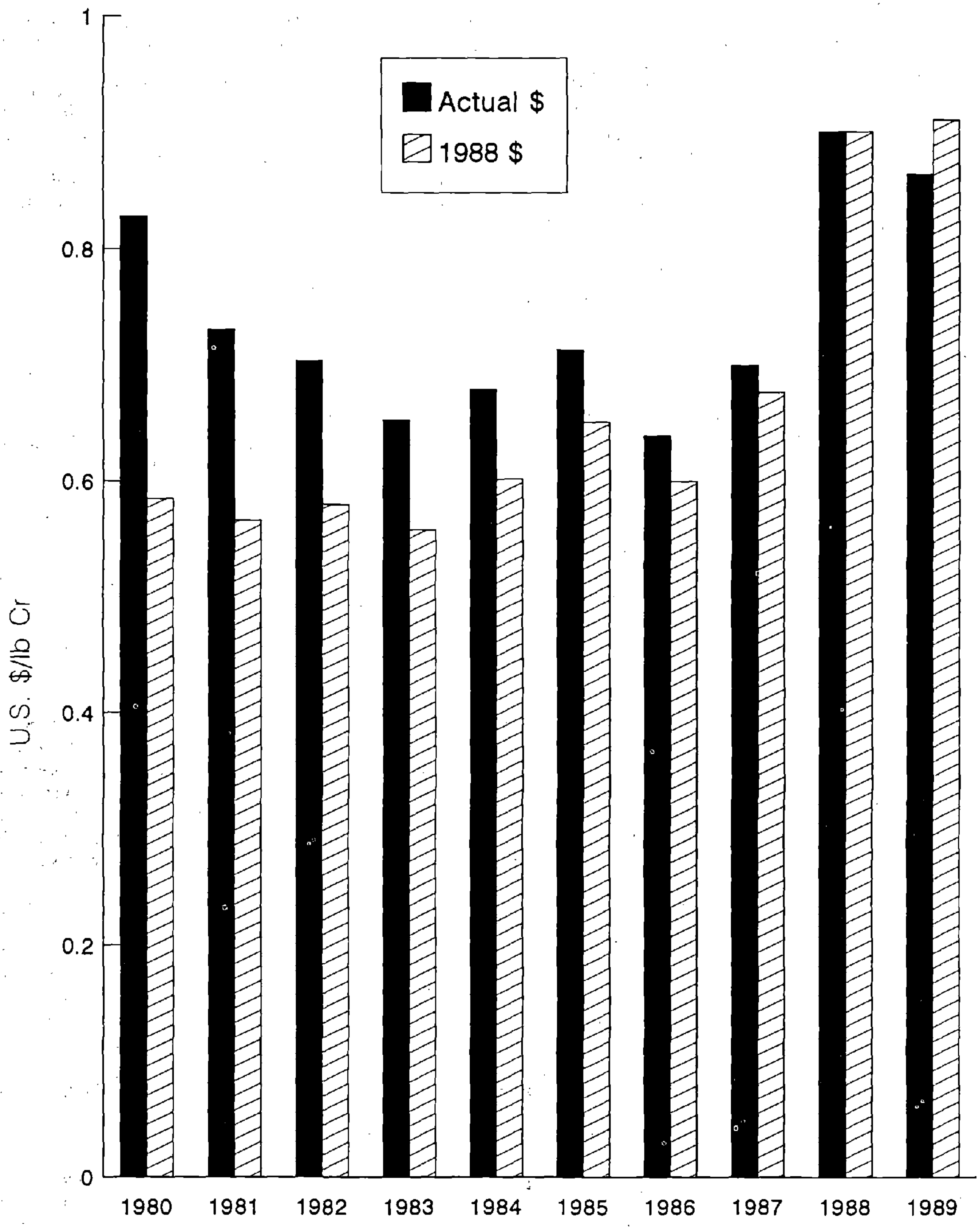

Figure 2.—F.o.b. customs values, low-C FeCr imports to the United States, 1980-89.

The threat of a U.S. embargo on South African chromium products under the Comprehensive Anti-Apartheid Act has probably been greatly reduced by the reforms instituted by the government of the Republic of South Africa beginning in early 1989. However, internal problems, possibly due to the political changes, could also result in disruption of chromium production and exports from this very critical world supplier.

The availability portion of this study will update technologic, economic, and resource information for the major market economy chromite resource countries. Also, a network flow market model will be used to analyze the boom of 1987-88, the potential prospects for all areas of the chromium industry through the year 1994, and effects in the North American markets and in South Africa's chromium industry due to a hypothetical embargo of direct imports from South Africa into North America. Chromium demand will be forecast through 1994, and the network flow market model will be used to examine each issue in a multiyear context.

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The contributions of the following individuals to this overall study are greatly appreciated:

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COMMODITY OVERVIEW

PRODUCTS AND USES

Chromite, the ore and concentrate form of chromium, has many uses, the markets for which are defined as metallurgical, chemical, refractory, and foundry sand. The most significant market for chromite is the metallurgical industry. Historically, metallurgical uses have accounted for 70 to 75 pct of total chromium consumption. The chromium products used by the metallurgical industry are high-carbon (high-C), medium-carbon (medium-C), and low-carbon (low-C) ferrochromium (FeCr) products of varying types and specifications, ferrochromium-silicon (FeCrSi), and chromium metal, all of which are consumed primarily in the manufacture of stainless, carbon, and alloy steels and superalloys.

Chromium is used in the metallurgical industry to enhance such properties as hardenability, impact strengths, and resistance to corrosion, oxidation, creep, wear, and galling. Stainless steel, the main product using chromium, is available in a variety of chemical compositions and microstructures and exhibits a wide range of mechanical properties combined with excellent corrosion and oxidation resistance. These features make these steels highly versatile in a multitude of industrial and consumer products.

Stainless steels may be defined as alloy steels containing at least 10 pct Cr—with or without other elements (2). A minimum of 10 pct chromium is required to ensure passivity[7] in an ordinary environment, with further increases in the chromium content yielding increasingly greater corrosion resistance. However, with an increase in the chromium content of the stainless steel, problems with other properties, such as workability, may occur.

Stainless steels can be classified into two basic types: austenitic and ferritic. At high ambient temperatures, most iron exists in the austenitic form, which exhibits high ductility. When the temperature is decreased, the structure will change to the ferritic form, which exhibits greater strength. The addition of 10.5 pct chromium to the iron results in the formation of ferritic stainless steel, a metal that is difficult to form and fabricate. Moreover, increasing the amount of chromium lowers the temperature at which the austenite-to-ferrite transformation occurs.

Stainless steel in the more convenient and workable austenitic form is more expensive than stainless steel in the ferritic form, since it must contain nickel. The manufacturing cost is higher because of the need for an additional

[7]Passivity is the corrosion resistant behavior produced by the presence of a "passive" oxide film.

alloying agent and because nickel is expensive. With a chromium content of 18 pct, 8 pct nickel is required to ensure an austenitic structure at room temperature. When the chromium content is above or below 18 pct, larger amounts of nickel are required to maintain the austenitic structure. The 18 pct chromium, 8 pct nickel (302 and 304 series alloys) content allows the manufacture of an austenitic steel at optimum cost and, as a result, is one of the most popular grades of stainless steel.

Other grades of stainless steel have been developed for particular uses. The 200 series stainless steels, which are not widely used at present, contain less nickel than the 300 series steels (*3*). The 400 series does not typically contain nickel[8] and is therefore less expensive than the nickel-bearing grades. The chromium content of selected grades of stainless and alloy steels is listed in table 1.

Table 1.—Chromium chemical specifications of selected types of steel

Steel type	Chromium chemical specification (wt pct)	
	Minimum	Maximum
Alloy steels[1] . . .	0.13	1.80
Stainless steels:[2]		
100 Series . . .	12.25	13.25
200 Series . . .	16.00	23.50
300 Series . . .	14.00	28.00
400 Series . . .	10.50	30.00
Type 304	18.00	20.00
Type 409	10.50	11.75

[1]Not all grades require chromium. Range shown is for those grades that do require chromium.
[2]All grades of stainless steel require chromium.

Source: Society of Automotive Engineers, Inc. (*4*).

The chromium chemical industry consumes chromite in the production of sodium and potassium bichromate, which are the base materials from which a wide range of chromium chemicals are made. These chromium-containing chemicals impart color to pigments, provide corrosion protection, enhance mud fluidity, bond copper and arsenic to wood, and promote chemical reactions. Chromium-containing chemicals are also used in chromium plating, etching, and leather tanning. Chromium pigments represent the largest use of chromium in the chemical industry. In this industry, chromium chemicals are used to manufacture chrome green, chrome oxide green, chrome yellow, molybdenum orange, and zinc chromate pigments that are used in paints and inks.

Chromite is used in refractory bricks and mortars to enhance thermal shock and slag resistance, volume stability, and structural strength. Chromic oxide, chromium carbides, and chromium borides are also used in refractories, but to a much lesser extent than chromite. The major application of chromite refractories is in iron and steel processing, nonferrous alloy refining, glassmaking, and cement processing. Chromite sand is used by foundries to make molds for ferrous castings.

REPORTED AND APPARENT CONSUMPTION

Chromite consumption levels for the United States in various years are shown in table 2; comparable figures for other consuming regions are not available. The United States chromite consumption level has fallen from 1.4 Mmt (gross weight) in 1965 to 0.5 Mmt (gross weight) in 1987, primarily as a result of decreased smelting in the United States. Of the total chromite consumed in the United States in 1987, the chemical and metallurgical industries consumed 91 pct and the refractory industry 9 pct. As of 1989, the respective percentages of consumption in the United States are 92 pct and 8 pct.

The main metallurgical use of chromite is in the production of chromium ferroalloys and metal, which is consumed predominantly in the production of stainless and heat-resisting steels. As shown in table 3, the production of stainless and heat-resisting steels accounted for 82 pct of chromium ferroalloy consumption on a gross weight basis in 1987. The various other end metallurgical uses (full-alloy steel, superalloys, etc.) accounted for the remaining 18 pct of consumption.

Apparent consumption of chromium ferroalloys in the major consuming MEC countries for 1985, 1986, and 1988 are shown in table 4. Of importance in this table is that eight countries—Japan, the United States, the Federal Republic of Germany, France, Italy, Sweden, the United Kingdom, and Spain—represent from 84.7 to 88.1 pct of the ferroalloy consumption for these years and only Japan produces any chromite.

With the widespread adoption of new technologies over the last 15 yr, more and more stainless steel is being produced by argon-oxygen-decarburization (AOD) or similar processes. The AOD process is able to remove carbon from molten steel without oxidizing large amounts of valuable alloying elements, especially chromium. The process economically produces stainless steel using lower grade, lower cost high-C FeCr instead of refined low-C FeCr. The adoption of this new technology has resulted in a significant shift away from the consumption of low-C FeCr and ferrochromium-silicon in favor of high-C FeCr as shown in table 5.

Projections of future chromium consumption levels for the various consuming regions are required for the market models used for analyses later in this report. In this study, projections of chromium consumption for metallurgical uses are based on extrapolations of past stainless steel production trends using statistically estimated functions that depend on world economic activity levels. These equations are discussed in detail in appendix E.

[8]Three grades in the 400 series (414, 422, and 431) require Ni; another two grades (409 and 443) limit the Ni content.

Table 2.—Consumption of chromite and tenor of ore used by primary consumer groups in the United States for selected years, 1965-89, gross weight

Year	Chemical and metallurgical industries: Consumption: Chemical (kmt)	Metallurgical (kmt)	Total[2] (kmt)	Average Cr_2O_3 content (wt pct)	Refractory industry[1]: Consumption (kmt)	Average Cr_2O_3 content (wt pct)	Total[2]: Consumption (kmt)	Average Cr_2O_3 content (wt pct)
1965	197	823	1,020	48.9	417	34.7	1,437	44.8
1970	193	827	1,021	47.5	252	35.9	1,273	45.2
1975	151	483	633	44.7	166	34.5	799	42.6
1980	218	520	741	38.8	145	35.8	886	38.3
1985	202	248	449	41.5	59	38.1	508	41.1
1987	W	W	459	41.0	46	39.0	505	40.8
1989	W	W	517	42.8	44	39.5	561	42.6

W Withheld.
[1]Includes foundry sand.
[2]Data may not add to totals shown because of independent rounding.

Source: U.S. Bureau of Mines (5).

Table 3.—U.S. consumption of chromium ferroalloys and metal in 1987, by end use

(Metric tons gross weight)

End use	Ferrochromium: Low-carbon	Ferrochromium: High-carbon	Ferrochromium-silicon	Other	Total
Steel:					
Carbon	2,663	3,325	165	W	6,153
Stainless and heat-resisting	10,746	310,111	8,518	525	329,900
Full-alloy	3,870	25,004	1,074	W	29,948
High-strength, low-alloy, and electric	1,620	1,893	W	W	3,514
Tool	928	2,791	W	O	3,719
Cast irons	787	5,383	24	W	6,195
Superalloys	3,945	4,952	W	2,631	11,529
Welding materials[1]	445	W	O	146	591
Other alloys[2]	535	313	W	1,923	2,771
Miscellaneous and unspecified	311	771	6,514	671	8,267
Total[3]	25,852	354,544	16,280	[4]5,897	402,590
Chromium content	17,427	203,114	5,965	4,483	230,989

W Withheld to avoid disclosing company proprietary data; included with "Miscellaneous and unspecified."
[1]Includes structural and hard-facing welding material.
[2]Includes magnetic and nonferrous alloys.
[3]Includes estimates. Data may not add to totals shown because of independent rounding.
[4]Includes 3,791 metric tons of chromium metal.

Source: (6)

SCRAP AND SECONDARY CHROMIUM

In the United States, the recycling of chromium is important predominantly in the metallurgical industry. The Bureau has estimated that, in 1990, approximately 21 pct of total U.S. chromium demand was provided from recycled stainless steel scrap (*10*). There are no available data on recycled chromium units in the chemical, refractory, and foundry sand industries. For reasons discussed later in this section of the report, the amount recycled in these other chromium industries is probably negligible at present.

Recycling of chromium occurs in the metallurgical industry because the end use markets for chromium are concentrated in the stainless steel industry. Use of stainless steel is fairly heavily concentrated in four major usage categories: (1) the transportation industry, (2) construction and contractors products, (3) containers, packaging, and shipping materials, and (4) machinery and equipment (*9*). When the end use markets for chromium containing materials are concentrated, greater volumes of scrap materials can easily be collected, allowing efficient and economical recycling.

Table 4.— Apparent consumption of chromium ferroalloys by major market economy consuming countries, 1985, 1986, 1988

Country	Apparent consumption[1] (kmt, gross weight)		
	1985	1986	1988
Japan	662	656	774
United States	384	432	522
Germany, Federal Republic of	279	316	396
France	161	159	133
Italy	131	131	142
South Africa	99	49	16
Sweden	84	84	63
Finland	78	57	70
India	78	89	105
United Kingdom	76	95	103
Brazil	67	90	93
Spain	50	78	90
South Korea	8	10	16
Totals	2,157	2,246	2,523

[1]Defined as production plus imports of ferrochromium minus exports of ferrochromium.

Sources: U.S. Bureau of Mines (*7*) (*8*) (*9*).

Stainless steel, unlike basic or so-called carbon steel, is highly alloyed with chromium and often with nickel, molybdenum, and other alloys. It is important that stainless steel scrap be segregated from other types of scrap to facilitate recycling. Contamination of the stainless steel scrap with undesirable alloys from other types of steel must be avoided. The value of the stainless steel scrap is based on the chromium and nickel content, which varies from product to product.

The stainless steel market in the United States is a highly competitive business. Producers must use the most cost-effective raw materials that can be found. Because of its abundance, the fact that it usually sells at a price lower than that for the primary metals it contains, and the availability of technology to recycle this material, stainless steel scrap is an attractive supply source of chromium for use in the production of stainless steel.

The majority of the domestic steel industry, including the stainless steel producers, now uses electric arc furnaces (EAF's) that can take a cold charge of scrap and alloys. Because there is flexibility in making up the charge to the furnace, stainless steel makers use the lowest cost raw materials that can be found, in the form of either primary metals or scrap. With the advent of the EAF's and the minimills (plants that manufacture various types of steel from scrap using these furnaces), more steel companies are making stainless steel with scrap than from the traditional intermediate products containing iron, manganese, nickel, and chromium (*11*). Not surprisingly, EAF steel making has experienced phenomenal growth over the last 20 yr. Only 10 pct of total steel production in the United States was produced by EAF's in 1964. By 1984 the amount had increased to 33 pct and is expected to reach 40 pct by 1990 (*11*).

Stainless steel scrap to feed the furnaces is available from several sources. In order of generation in the product cycle, the three sources are "home," "prompt," and "obsolete" scrap. Prompt industrial scrap is the largest of the three sources. The first two sources listed represent "new" scrap sources; obsolete scrap is also referred to as "old" scrap.

Table 5.—U.S. consumption of chromium ferroalloys and metal in the production of stainless and heat-resisting steel for selected years, 1965-89

(Metric ton gross wt)

Chromium product	1965	1970	1975	1980	1985	1987	1989
Low-carbon ferrochromium	119,548	104,286	39,592	15,715	8,888	10,746	25,018
High-carbon ferrochromium	69,430	57,486	108,209	240,075	250,339	310,111	313,169
Ferrochromium-silicon	59,540	45,356	36,326	14,340	5,689	8,518	16,415
Chromium metal and others	1,949	3,142	184	274	529	525	6,359
Total	250,467	210,270	184,311	270,404	265,445	329,900	360,961

Source: U.S. Bureau of Mines (*5*).

Home scrap, or "run-around" scrap, is generated in the stainless steel mills. This type of scrap is remelted within the facility in which it is generated and never enters the scrap market. The other type of "new" industrial scrap, prompt scrap, is generated from stainless steel as it is processed into consumer or industrial products. Obsolete scrap is derived from worn-out or discarded articles at the end of their useful life. Technologic changes and remodeling of facilities generate large amounts of this "old" stainless steel scrap.

In contrast to stainless steel, the chemical uses of chromium are widely dispersed, and no significant recycling is presently practiced.[9] Chromium containing chemicals are used as pigments and are also used in metal treatments, leather tanning, drilling muds, wood preservatives, catalysts, ceramics, corrosion inhibitors, fireworks, batteries, glass, reagent chemicals, magnetic tape, magnets, textiles, and flame retardants, among other uses. In many cases, such as drilling muds, it is not possible to recover the material for possible recycling. Even if sufficient quantities were available for recycling, the chromium content in many of these chemical end use products is very low, making it uneconomical or technologically unsuitable to reprocess them.

The refractory uses of chromium tend to be concentrated in the iron and steel industries and in the nonferrous alloy refining, glassmaking, and cement processing industries. Little refractory scrap is currently recycled primarily because of unfavorable economics. However, the potential for recovery of chromium is present in this industry because of the accumulated quantities of used refractory brick. Recycling of foundry sands appears to be practiced to some extent, but no detailed statistics are available.

STUDY ASPECTS

Figure 3 is a simplified schematic showing the relationships between the various chromium products and their final markets. The figure is intended to aid in understanding the structure of this availability and supply study with regard to the various chromium products.

The figure shows seven main products that are normally traded in the market; four are chromite products intended for metallurgical, chemical, refractory, and foundry sand uses, and three are the ferroalloy products that are produced from metallurgical chromite (high-C and low-C FeCr and ferrochromium-silicon). The eighth main chromium product shown in the figure is sodium (or potassium) bichromate, which is the initial product from roasting and chemical treatment of chemical grade chromite concentrates. It is subsequently used in producing chromium oxide, chromic acid, chromic sulphates, and chromates that are in turn sold as chromium chemicals.

For the availability portion of this study, price determinations were made for seven of the eight Cr products shown in figure 3. Sodium (or potassium) bichromate was the only major product for which price determinations were not made.

In the network flow model, all eight Cr products were addressed in the design and structure. However, only six of the eight products required individual demand estimates. Metallurgical and chemical chromite products did not require separate demand estimates because demand for chemical chromite products is directly related to demand for sodium (or potassium) bichromate, and demand for metallurgical chromite products depends on the demands for high-C FeCr, low-C FeCr, and FeCrSi alloy products.

In figure 3, the dashed lines indicate that, besides its major role in the Cr ferroalloy industry, high-C FeCr can also be used in making low-C FeCr and ferrochromium-silicon and that ferrochromium-silicon is used in production of low-C FeCr. Not shown in figure 3 is that Cr metal, an important constituent of superalloys that wasn't addressed in either the availability analysis or the network flow model,[10] can also be produced from ferrochromium alloys. Also not shown in the figure is what is commonly referred to as medium- or intermediate-C FeCr. This ferroalloy is typically produced by "blowing down" high-C FeCr in a converter.

METHODOLOGIES

DATA COLLECTION, RESOURCE, AND COST ESTIMATION

The methodology of this updated study is similar to that used for the prior chromium availability study (*1*). One major difference, however, is that all of the various chromite and chromium ferroalloy products that are or could be produced from a property's resources have been differentiated for each property included in the analysis.

[9]The Bureau has developed processes to recover chromium from plating solutions and, with regulations becoming more stringent, it is possible that the level of chromium recycling could increase in the future.

[10]Despite its importance, the amount of Cr metal used annually in the United States is relatively small. Data regarding technology and costs are usually treated as confidential or sensitive. For those reasons, Cr metal was not included in any aspect of these studies.

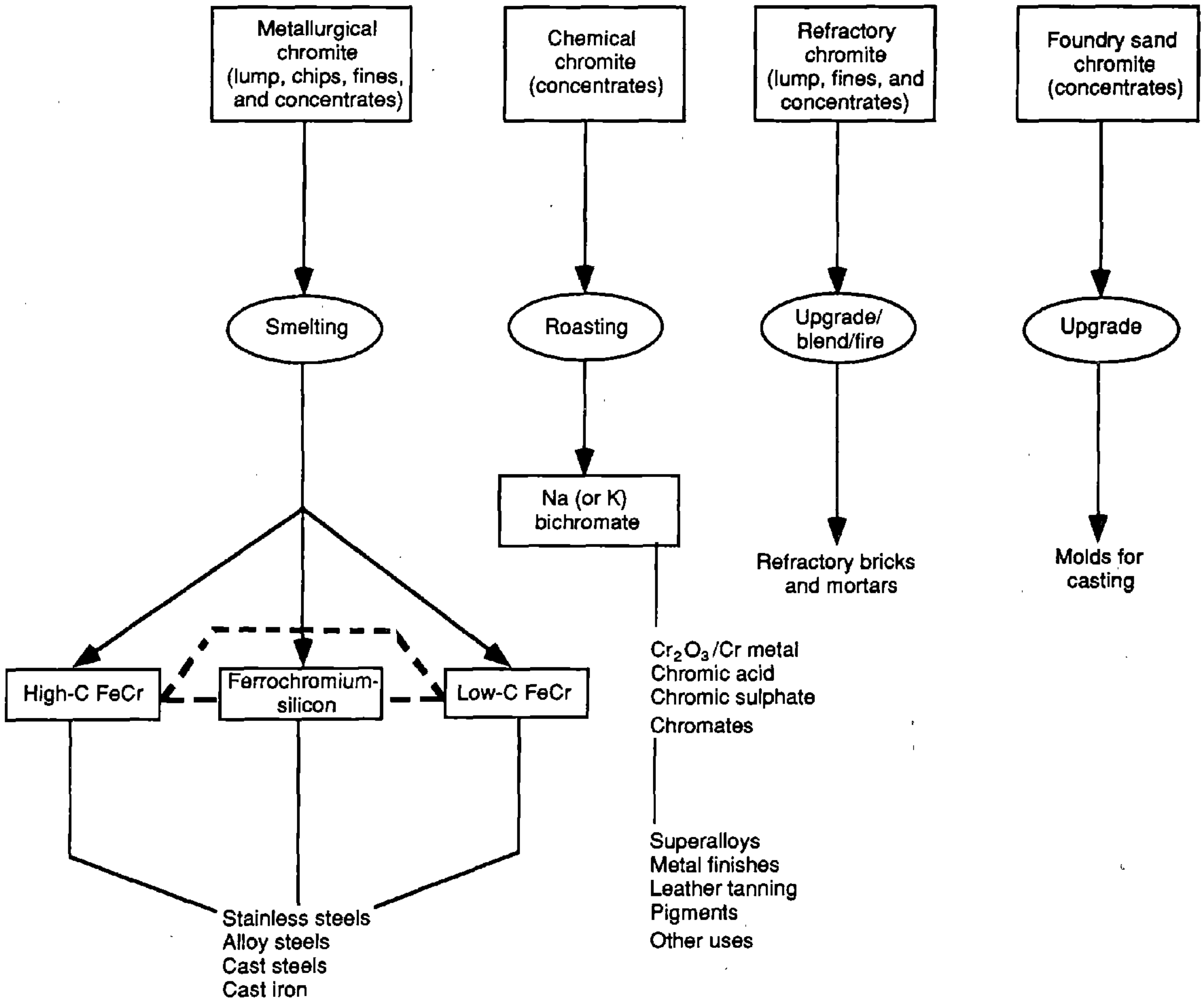

Figure 3.—Summary diagram, chromium products.

All of these chromium products are distinctly represented in the economic analyses.

Some prior availability studies were based on contractor collected data; however, this study was conducted solely by Bureau personnel. Data collection trips were made to the chromite producing countries of South Africa, Zimbabwe, Brazil, Finland, the Philippines, and India, as well as to smelters and/or corporate offices in Sweden, the United States, Japan, and the Federal Republic of Germany. Data and literature obtained from the visits to mining, beneficiation, and smelting operations, from corporate and government offices, and from a variety of other sources were carefully studied and combined with data from the prior study. Based on the decision to conduct the final analysis on a specific product basis, complete mass balances for all actual or proposed ore treatment facilities were developed.

A summary of the updated resource estimates is presented in the section titled "Evaluated MEC Resources." More details on these resource estimates are contained in the specific country sections of appendix B.

Demonstrated resource estimates for the podiform-type deposits were approached with the idea of providing a prudent, yet long-term, assessment of operating life. This meant that assumptions of extension to depth for the podiform deposits were fairly liberal. Conversely, limits were intentionally placed on the demonstrated resource estimates for the stratiform deposits of the Bushveld Complex in South Africa and the Great Dyke of Zimbabwe. These involved (1) limits on the seam depth extensions, (2) exclusion of certain seams from analysis, and (3) limits on assumed strike continuity. In addition, the demonstrated resources of the Sukinda Valley, India, represent estimates of surface minable resources only.

Mine and mill operating cost estimates for the purpose of availability analyses are long-run averages. Therefore, they include both variable (direct) and fixed (indirect) charges. This differs from the methodology for network flow models, where only variable costs are used. The reasons for this difference are discussed in detail in the "Network Flow Market Model" section.

Variable (direct) operating costs include charges for materials, utilities, direct and maintenance labor, and payroll overhead. Fixed (indirect) operating costs include technical and clerical labor, administrative costs, facilities maintenance and supplies, and research. Indirect costs represent a small percentage of total operating costs in the mining, beneficiation, and smelting of Cr. Other costs in the analysis are fixed charges that mainly include local taxes, insurance, depreciation, deferred expenses, and interest payments.

The mining and beneficiation operating costs have been developed in the following manner. First, specific manning levels were estimated and wage rates applied to determine the costs of labor. The evaluator's technical parameter estimates for mining and ore treatment requirements were then entered into the Cost Estimating System (CES) (*12*), which was used to estimate costs for materials and supplies and for equipment operation. All mining cost estimates for this study have been based on complete extraction of the demonstrated resource for the specific property being analyzed. As such, this study's operating cost estimates should be viewed as the average long-run operating costs for extracting a specific resource tonnage.

The operating cost estimates for smelting to high-C FeCr, low-C FeCr, and ferrochromium-silicon were, for the most part, based on actual manning levels, power consumptions, and raw material inputs and on the estimated unit costs for those consumable items. In cases where these input amounts were not known, the requirements for consumables were factored from those operations where actual consumption levels were available, taking into consideration the different furnace sizes, product dedications, and smelting technologies.

Cost items in smelting such as maintenance supplies, miscellaneous, general and administrative costs, and overhead varied greatly in those cases where they were known. Yet, they were a relatively small portion of overall smelting costs. For consistency, these smelting cost items were addressed primarily by applying percentage factors to the overall labor, power, and raw material cost estimates. These percentage factors were similar from country to country.

Capital expenditures were estimated for exploration, acquisition, development, mine plant and equipment, constructing and equipping the mill plant, and all necessary reinvestment. Capital expenditures for mining and processing facilities include the costs of mobile and stationary equipment, construction, engineering, facilities and utilities (infrastructure), and working capital. The facilities and utilities category includes the cost of access and haulage facilities, water facilities, power supply, and personnel accommodations. Working capital is a revolving cash fund required for such operating expenses as labor, supplies, taxes, and insurance. For this study, working capital was estimated as 2 to 3 months of operating costs.

For seam type and surface minable resources, costs for exploration and development requirements, where applicable, were always estimated and entered into the system separately from the operating costs. Hence, none of the mine operating cost estimates reported in this study for those resource types include the costs for finding and accessing the ore. In contrast, the estimates of mine operating costs for the underground mining of podiform-type resources do include estimates of ongoing exploration and stope development.

Because of the generally small size of chromite operations and the relative dearth of information regarding actual infrastructure requirements, this study's estimates of capital requirements for infrastructure usually involved applying a certain dollar amount requirement per year based on the ore capacity of a particular property.

Capital cost requirements for mine equipment, mine plant, and mill plant and equipment were estimated in most cases using the CES model. However, there were a number of cases in which lists of major plant equipment items for specific chromite extraction operations were available. In all such cases, capital cost estimates were based on these detailed lists. When applicable, these detailed lists were also used as a base from which to factor the estimated requirements for other similar properties.

Whereas the previous IC analyzed high-C FeCr production economics based on the inclusion of smelter capital costs, prorated on a property basis, this study does not include smelter capital costs in the availability results. Smelter capital costs were excluded basically because of problems with noncomparative and inconsistent situations regarding individual smelters' capital cost requirements. For example, as of 1988, 15 of the 21 MEC smelters factored into the availability analysis were all at least 10 yrs old; five were from 2 to 6 yr old; and one was nearing completion of construction. In addition there were situations where sufficient ore feed was not available from the analyzed producing chromite properties and units to completely satisfy the full-capacity requirements at certain smelters. For general reference, a table summarizing estimated smelter capital recoupment costs for selected high-C FeCr smelting processes is presented in the "Smelting Capital Cost" section of this report.

The Bureau's Cost Indexation System was used to update cost estimates from the original cost date (1985-86) to a common base date (January 1989 for this report). The index system includes updating factors for 12 separate components of mining cost (e.g., mining labor, equipment and repair parts, diesel fuel, etc.) for foreign countries and 15 components for the United States. The index values for each component in each country take account of whether the expenditure is in local or foreign currency and the traditional sources for needed imports such as machinery. A time series of exchange rates (also part of the index system) is used to translate the cost index values developed in local currencies into values expressed in U.S. dollars. The influence that relative inflation rates and varying exchange rates have on competitiveness is treated more fully in appendix D.

Again, all costs and price determination results presented in the remainder of this report are in terms of January 1989 U.S. dollars. In addition, all price determination results in the availability portion of this report have been analyzed as 100 pct equity; i.e., no loans have been, or are, required for capital investments at any of the analyzed properties.

PRODUCT DIFFERENTIATIONS

Table 6 lists the seven chromium product categories differentiated for economic analysis purposes in this updated availability study. In the economic study itself, the high-C FeCr product category was further split into three subcategories: grade A FeCr (64 pct Cr or greater), grade B FeCr (55 to 64 pct Cr), and grade C FeCr (50 to 55 pct Cr). However, the results for all three subcategories of high-C FeCr products have been combined into the overall high-C FeCr results presented in the availability results of this report.

Table 6.—Types of chromium products differentiated in the availability and network flow model studies

Ferroalloys:
High-C FeCr
Low-C FeCr
Ferrochromium-silicon
Chromite ores and concentrates:
Metallurgical
Chemical
Refractory
Foundry sand

Not listed as a separate product in table 6, nor analyzed separately in this study, is the "medium-C" (also known as "intermediate-C") FeCr product. This product's C content is between the low end of the high-C FeCr grade range (4.0 pct) and the high end of the low-C FeCr C grade range (0.5 pct). It is usually produced by "blowing down" the C content of an initial high-C FeCr product in an oxygen-fed converter furnace.

The lack of detailed cost estimates for the oxygen converter smelting and the very limited size of the overall medium-C FeCr market precluded addressing this product specifically in this study. Rather, in both the availability section and the network flow model section of this report, the high-C FeCr capacity that would be used in producing the medium-C product is treated as if it were used for the high-C FeCr market and not converted to a medium-C product.

PRICE PROPORTIONS

The wide variety of different markets and qualities of the products in the chromium industry, all with different prices, necessitates the use of a price proportioning methodology in the economic analysis. Under this method the total revenues needed to attain a specified discounted cash-flow rate of return (DCFROR) at a property are allocated between all of the property's products according to their relative value in the marketplace as of a specific time period. Thus, each individual product's necessary contribution to the overall economic situation is addressed.

In price proportioning, a proportional (or ratio) factor is determined for each product. These price proportion factors are then used by the economic analysis system to apportion total revenue requirements on a relative value basis.

To accomplish price proportioning for this study, an intensive review was made of the 1984-86 prices of chromite and chromium ferroalloy products in Japanese and U.S. markets. This review resulted in the price proportion factors shown in tables 7 and 8. All of the price proportions shown in these two tables factor off of the following base values: (1) A price proportion factor of 1.00 was assigned as equivalent to a \$100/mt free-on-board (f.o.b.) price in 1984-86 for a typical metallurgical-grade, 48 pct Cr_2O_3, 3:1 Cr-Fe ratio chromite product from Turkey; and (2) a price proportion factor of 0.40 was assigned as equivalent to a \$40/mt f.o.b. price in 1984-86 for a typical metallurgical-grade, 41 pct Cr_2O_3, 1.55:1 Cr-Fe ratio product from South Africa.

Table 7 summarizes the chromite product price proportion factors used in this study. In the table, the first column lists possible Cr_2O_3 contents of the chromite products, and the remaining columns provide the price proportions under differing Cr-Fe ratios, arranged as to major market usage. For example, a chromite product for metallurgical use that contains 45 pct Cr_2O_3 and has a 2.2:1 Cr-Fe ratio would have a price proportion factor of 0.685 in the study, which is equivalent to a 1984-86 f.o.b. port price of \$68.50/mt. As shown by this example, the price proportion factors in table 7 for metallurgical products take into account two of the major pricing factors in the metallurgical market,[11] the Cr_2O_3 content and the Cr-Fe ratio.

[11]The third major pricing factor, a premium for chromite in lump form, has not been included in this methodology.

Table 7.—Chromite product price proportion factors used in analysis, by product type and Cr-Fe ratio ranges

Pct Cr_2O_3 in product	Product types and Cr-Fe ratios						
	Metallurgical				Chemical[1]	Refractory[2]	Foundry[3]
	>3.0	2.5-3.0	2.0-2.5	1.3-2.0	1.3-2.0	1.3-2.0	1.3-2.0
35				0.380			
36				.380			
37				.380			
38				.380			
39				.380			
40			0.610	.390	0.390		
41			.625	[4].400	.400		
42			.640	.410	.410	0.638	
43			.655	.420	.420	.654	
44		0.790	.670	.430	.430	.669	0.477
45		.810	.685	.440	.440	.685	.488
46	0.960	.830	.700	.450	.450	.700	.500
47	.980	.850	.715	.460	.460	.716	.510
48	[4]1.000	.870	.730	.470	.470	.731	.522
49	1.020	.890	.745	.480	.480	.747	.533
50	1.040	.910	.760	.490	.490	.762	.544
51	1.060	.930	.775	.500	.500	.778	.555
52	1.080	.950					
53	1.100	.970					
54	1.120	.990					

[1]Exceptions to the Cr-Fe ratios occur in India with values over 3:1; price proportion of 1.20 used.

[2]Exceptions to typical South African products are the Philippines products with price proportions ranging from 0.75 to 1.20 and the Turkey and India products for which the appropriate metallurgical price proportions were applied.

[3]Exception to Cr_2O_3 content occurs in the Philippines with product grade of 34 pct; a price proportion of 0.60 applied in this case.

[4]All metallurgical price proportion factors use 1984-86 prices of \$100/mt = 1.00 for Turkish chromite products (at 48 pct Cr_2O_3 and a 3:1 Cr-Fe ratio) and \$40/mt = 0.40 for South African chromite products (at 41 pct Cr_2O_3 and a 1.55:1 Cr-Fe ratio) as base values. The base prices used for price proportioning of chemical, refractory, and foundry sand chromite products are for typical South African products at 1.5:1 to 1.6:1 Cr-Fe ratio, using 1984-86 prices.

Table 8.—Selected chromium ferroalloy price proportion factors,[1] by type and grade of ferroalloy product

Chromium ferroalloy product category	Chromium content (wt pct)	Price proportion factor
High-carbon FeCr	52	4.47
Do.	55	4.73
Do.	56	4.82
Do.	64	5.50
Do.	66	5.68
Do.	69	5.93
Low-carbon FeCr	60	8.33
Do.	63	9.59
Do.	69	10.50
Ferrochromium-silicon	38	6.34

[1]Price proportion factors use a 1984-86 price for Turkish metallurgical chromite (48 pct Cr_2O_3 and a 3:1 Cr-Fe ratio) of $100/mt = 1.00 as a base.

The price proportion factors shown in table 7 for the chemical, refractory, and foundry sand chromite products are all based on actual prices for typical South African chemical, refractory, and foundry sand products on the market. Exceptions to the Cr_2O_3 grade ranges and Cr-Fe ratios of these typical South African products are noted in the footnotes to the table. The use of the South African products as the base values reflects that country's dominant position in those markets, particularly in the chemical and foundry sand markets.

Table 8 provides selected price proportion factors for typical chromium ferroalloy products in this study. As an example, the price proportion factor of 5.50 in table 8 for a high-C FeCr product grading 64 pct Cr is equivalent to a 1984-86 f.o.b. port price of $550/mt FeCr. In this methodology the high-C FeCr factor of 5.50 ($550/mt FeCr) is proportional to a factor of 1.00 ($100/mt chromite) for a typical Turkish metallurgical chromite product grading 48 pct Cr_2O_3 and having a 3:1 Cr-Fe ratio.

As a summary example, assume that a South African chromite property, at full capacity, typically produces 50,000 mtpy of 40-pct Cr_2O_3 chromite ore for export to the metallurgical chromium market, 25,000 mtpy of concentrates grading 47 pct Cr_2O_3 for export to the chromium chemical market, and 100,000 mtpy of 38-pct Cr_2O_3 chromite ore, which is transported to an in-country smelter. Also assume that the in-country smelter, using the 100,000 mt of chromite ore from this property, produces about 45,000 mtpy of FeCr grading 52 pct Cr for export.

Finally, with the knowledge that all of the chromite products from this property have Cr-Fe ratios of 1.6:1, reference to tables 7 and 8 results in the following price proportion factors being assigned to this South African property's three products:

Chromite ore for export to the metallurgical market	=	0.39
Chromite concentrates for export to the chemical market	=	0.46
High-C FeCr (52 pct Cr) for export	=	4.47.

With the combination of these price proportion factors and the relative levels of annual output for the three products—50,000 mtpy of metallurgical ore exports, 25,000 mtpy of chemical concentrate exports, and 45,000 mtpy of high-C FeCr exports—the supply analysis model (SAM) system is able to determine the correct proportion of the total revenue requirements for this property that each of the three products needs to provide.

It should be reiterated that the price proportion factors of this study are based on 1984-86 price ranges for Cr products. As such, these factors reflect resource, economic, technologic, and market situations for each of the products involved as of that time period. Over the short, intermediate, and long terms, the relative proportions among the different products may change somewhat in response to changes in those situations.

AVAILABILITY STUDY

The economic evaluation results reported in the "Availability Results" section of this report represent the total costs, f.o.b. major exporting port, to deliver specific products from each of the individual chromite properties and units listed in appendix A. This appendix also includes the chromium product designations for each property in this study.

A unique aspect of the designed structure of this present availability study is that the total costs determined for the chromium ferroalloy products represent the total costs of production from specific ore and concentrate products of individual chromite properties (with smelting at specific in-country smelters). This structure differs from the more conventional approaches that attempt to determine the overall economics of output from individual smelters using chromite feed from several different chromite properties.

After capital and operating costs are determined, deposit data are entered into the SAM (*13*). The Bureau developed the SAM to perform DCFROR analyses to determine the price of the primary commodity required for each operation to obtain a specified rate of return on its investments. This determined value is equivalent to an average total cost of production for the operation over its producing life under the set of assumptions and conditions (e.g., full-capacity production and a market for all output) necessary to make an evaluation. The DCFROR is most commonly defined as the rate of return that makes the present worth of cash flow from an investment equal the present worth of all after-tax investments (*14*). For this study, a 15-pct DCFROR was considered the necessary rate of return for operations to cover the opportunity cost of capital plus risk. A DCFROR analysis for each property was also performed with a 0-pct rate of return. Both sets of results are presented later in the report.

For purposes of the DCFROR methodology, initial capital costs have been depreciated according to the actual investment year, and the undepreciated portion was treated as a capital investment in January 1989, the base year of the analysis. All subsequent investment, reinvestment, operating, and transportation costs are expressed in January 1989 dollars. All cash-flow analyses were performed assuming 100 pct equity.

A separate tax records file, maintained for each state/nation, contains the relevant parameters under which the mining firm would operate. Tax parameters include structures and rates for corporate income taxes, property taxes, and any royalties, severance, or other taxes that pertain to chromite product production. These tax parameters are applied to each mineral in the property or unit under evaluation, with the implicit assumption that each property or unit represents a separate corporate entity.

On completion of product differentiations and development of the price proportions, the individual property DCFROR analyses are conducted for each product. Analyses are grouped by product across all producers and then sequentially aggregated onto total resource "availability curves." The total resource availability curve is a tonnage-cost relationship that shows the total quantity of recoverable product potentially available at each operation's average total cost of production, as determined at the specified (0- or 15-pct) DCFROR. Thus, the curve is an aggregation of the total potential product that could be produced over the entire producing life of each operation, ordered from operations with the lowest average total cost of production to those with the highest. The curve provides a concise, easy-to-read, graphic analysis of the comparative costs associated with any given level of potential output for each product.

Certain assumptions are inherent in the availability curves presented in the "Study Results" section. First, all properties/units produce at full operating capacity throughout the productive life of the deposit. Second, each operation is able to sell all of its output at a price equal to its average total production cost. Third, development of all nonproducing properties and units begins in a base year N (unless the property was developing at the time of the evaluation or definite startup dates were known). No assumption is made about circumstances that might lead property owners to develop the various deposits composing the properties or units. In almost all cases, the preproduction period allows for only the minimum engineering and construction period necessary to initiate production under the proposed development plan. Consequently, the additional time lags and potential costs involved in filing environmental impact statements, receiving required permits, financing, and so on, have not been included in the individual deposit analyses. This assumption is incorporated in all Minerals Availability Program (MAP) studies to show minimum development time in periods of national need.

Because of the assumptions just described, the fact that such cost items as capital and taxes are included, and the lack of market context, the total availability curve should not be interpreted as a supply curve. A supply curve is bounded by demand and consumption constraints at a particular point in time and is based on marginal, not total, costs.

NETWORK FLOW MARKET MODEL

The interpretation of minerals information can be expanded through the use of supply and demand analysis, which allows examination of the interactions between producers and consumers and supports analysis of market equilibria. The impacts on competitive status and trade patterns of changes in costs, exchange rates, tariffs or subsidies, or the development of new capacity are more effectively studied with market models than with the tools of availability analysis. The Bureau's network flow market models are designed to take advantage of the wealth of deposit specific data residing in the Bureau's Minerals Availability System so as to support useful analysis of the minerals industry.

Network flow models are based on the principle of technical economic efficiency, the goal of which is to produce a given level of output with the minimum use of resources, i.e., at the lowest opportunity cost (*15*). The method is a derivative of linear programming: a linear objective function plus a set of linear constraint equations. The goal of the model is to fulfill the objective function, in this case minimization of costs, within the limitations of capacity, demand, and market organization specified in the constraints. The models are called networks because they are initially developed as a series of diagrams, called netmaps, that show the connections between producers and consumers. These diagrams tend to look like transportation systems or networks. The information from the diagrams is translated into a set of linear equations and solved with an optimizing algorithm. The mathematics of networks are addressed in appendix G.

Network market models incorporate both demand and supply. The demand side of the model is based on either an econometric demand function or an estimate of consumption for contained metal in each product. For a single solution of the model, a unique demand-consumption value is assigned to each product in each consuming region. Over a multiyear simulation, the demand functions or the consumption values are updated with statistically estimated growth factors.

Aggregate supply is implicitly defined in the network structure, which is based on the interrelationships between various mining, milling, and processing facilities for the metal in question. The design incorporates the detailed, property-specific engineering and cost data collected or estimated by the Bureau and is intended to represent, as closely as possible, the actual movement, processing, and trade of the metal in question. Vertical integration and contractual obligations are incorporated via arc connections and bounds.

Total production of chromite is equal to the aggregate of annual production from developed properties and units. The individual annual production levels for each property are a function of relative delivered cost and are determined as part of the problem solution.

Figure 4 provides a generalized diagram explaining the basic design of the chromium network flow model. The overall design of the network links suppliers and inventory stockpiles to processors or ports. Ports are connected to other ports and then to further processing facilities or demand locations. Selected details of the chromium network flow model design are presented and explained in appendix F.

Potential movement or processing of metal is represented by flows on arcs in the network design, which in turn connect actual or hypothetical locations represented by the nodes (see figure F-1 for an example of an arc connecting two nodes). The number of distinct products flowing in the system increases as material is processed and traded in different forms. Only one product can be represented by an arc or can pass through a specific node. Thus, some locations are represented by several nodes in the model, each node associated with flow of a different product.

The maximum and minimum levels of annual material flow are set by upper and lower bounds associated with each arc. Each arc has two associated multipliers, one at the beginning and one at the end. These multipliers are used to augment or diminish flow over the arc and are used here to represent processing losses.[12] In addition,

[12]A summarization of the ranges and average recoveries used for smelting, chemical processing, and refractory usage in the availability and the network flow model studies is presented in appendix F of this report.

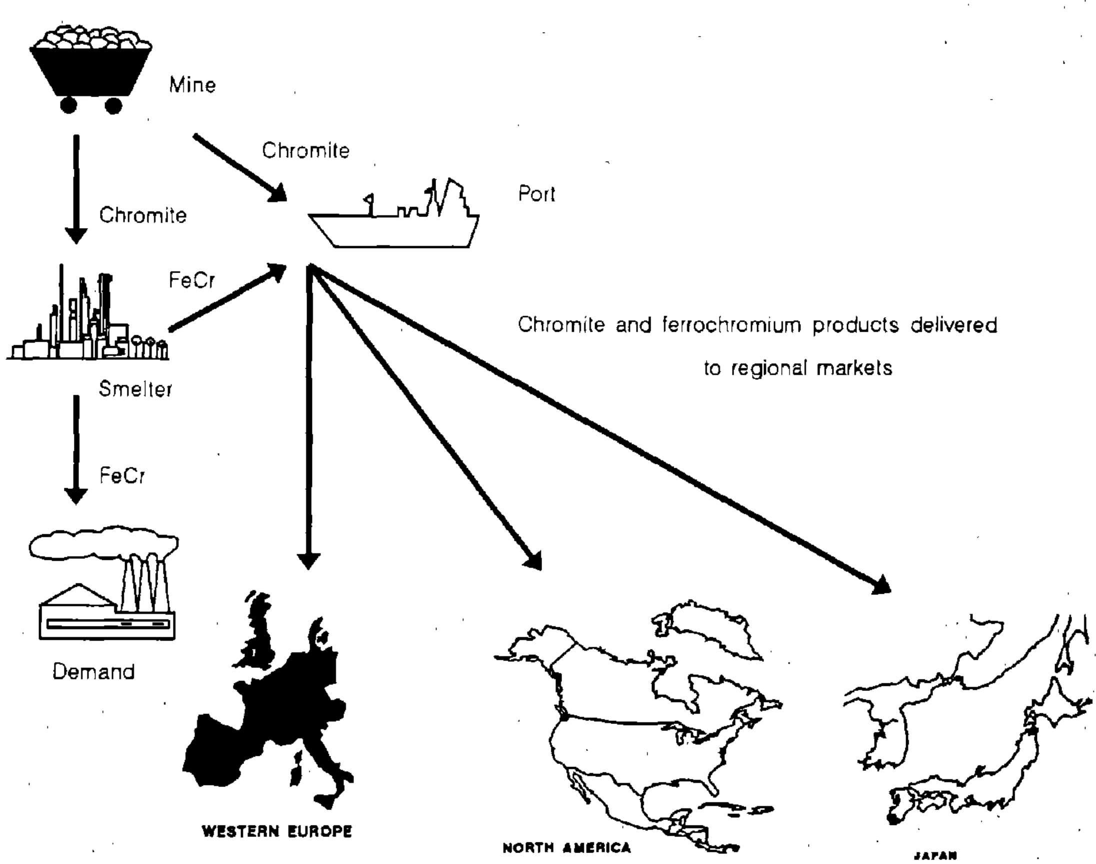

Figure 4.—Generalized diagram of the approach in the chromium network flow model.

each arc has a cost that is set equal to the average variable cost for the process represented by the arc.

Operating costs in the network model are defined somewhat differently from those in the availability analysis. Average total cost estimates for the purpose of availability analyses include both variable and fixed costs. The operating cost estimates used in the network model, however, include only the variable (direct) costs of production. Average variable costs, rather than average total costs, are used because the model solves 1 yr at a time, and, in a 1-yr time frame, a producer will continue to operate as long as average revenues equal or exceed the average variable cost of production. In this type of short-run analysis, investment is viewed as a sunk cost. By comparison, in a long-run analysis, investment costs are yet to be incurred and must be taken into account in any decision to bring a new mine, mill, or other facility into production. But once in production, these newer operations will be faced by the same shutdown and startup considerations as the older mines. In theory, this point of operating indifference occurs when marginal revenues equal average variable cost of production.

When the network is solved as a multiyear model, the estimated production at each deposit is subtracted from the remaining resources after each single-year solution. As ore reserves deplete, properties or units drop out of the active design. New mineral facilities are developed over the period of the simulation, and costs and capacities are changed at existing facilities in response to economic criteria set by the analyst.

Property development is prioritized based on trigger prices. To represent the actual incentive price necessary to start a new facility, the trigger price must be higher than the estimated operating costs of the new facility. For this reason, the trigger price is set equal to a nonproducer's estimated total costs of production, including a return to capital. A new facility will start to be developed in the model when the delivered cost into a particular market of the most expensive supplier is greater than or equal to the set trigger price for that facility.

The solution to a network simulation is provided in two parts: (1) the objective function value and (2) the optimal flows by arc. The first of these is a single dollar value equaling the minimum total system cost required to fulfill predetermined demand (i.e., total delivered cost for all products consumed worldwide). The objective function value for the base year of a simulation is used as a point of reference. In subsequent simulations, this base value is compared to the newly determined objective function value to ascertain the impact a change in the network design or constraints has had on the minimum total system cost.

For each solution of the model, optimal flow on each arc is reported. Examination of flows allows the analyst to predict which facilities will be producers and which will be idle. Flows on arcs between countries or regions indicate potential levels of trade. Comparison of bound constraints and optimal flow levels indicates relative cost competitiveness. Since the model solves to minimize cost, flow equal to the upper bound indicates relative cost competitiveness on a particular arc, say into a specific regional market. Flow at or near the lower bound may imply that the producer is relatively less competitive in a market than other producers and that alternative markets are more attractive to the producer than the one in question.

The results of the basic network model can also be interpreted as a transportation problem. The optimal solution of the primary cost minimizing problem is fed to a shortest-path transportation algorithm, the output of which is a list of the suppliers of each product into each region, ranked by delivered cost. The initial program results provide insight on production by facility, supporting analysis on a site-specific basis. The transportation algorithm program places these output levels in a market context, allowing the analyst to examine the competition between potential suppliers into different regions. The transportation results can be used to identify changes in suppliers and in delivered cost for various products, either over a multiyear horizon or between market scenarios.

The delivered cost of the most expensive supplier of a product in a region can be used as a proxy for equilibrium price in a quasi-competitive market. Comparison of the reported market price to the solved-for delivered cost will provide information on the level of market concentration or the degree of cost competitiveness into a region.

It is important to remember that any single solution to the transportation problem represents just one way in which markets could be supplied with material, consistent with the optimal solution. The transportation solution is guaranteed to be optimal, but not to be uniquely optimal. However, solutions obtained from running the transportation algorithm numerous times have resulted in very similar solutions.

Even though the solution from the transportation algorithm is not unique, insights can be gained, especially into the shifts away from high-cost to lower cost suppliers. Over time, new low-cost facilities and expansions may come on line that are able to force the higher cost suppliers out of specific markets. Conversely, low-cost, high-grade Cr ore sources in one region may deplete over time, allowing another more expensive supplier to gain market share.

The network flow model is well-suited to answering questions related to regional competition, production, and trade flows. Since detailed material flows are solved for, such aspects as regional trade barriers can be incorporated into the model directly as constraints. The model is also useful for examining questions of resource adequacy over the medium to long term, under various scenarios concerning likely future demand levels. The magnitude and the timing of new capacity requirements are monitored. The delivered cost of the marginal, or most expensive, supplier of a given product will correspond to a minimum market price in a quasicompetitive market.

Network models incorporate a variety of assumptions, some of which are more limiting than others. Networks are, by definition, linear models, although the world is seldom linear. Further, it is assumed that variable costs are constant over a wide range of production levels. This is not unreasonable for firms with minimal shutdown or restart costs because production can be varied by increasing or decreasing the work hours. Difficulties arise for firms that use factors of production with significant diminishing marginal returns.

Products are assumed to be homogeneous. For example, in the chromium network, all metallurgical grade chromite is viewed by the model as identical in character (i.e., as metric tons of Cr). This limitation can be overcome by placing a cost penalty on lower quality or impure materials or by placing bound constraints on the arcs.

The network model is a static optimization model. That is, it optimizes 1 yr at a time. In contrast, a dynamic model would perform a simultaneous optimization over the entire multiyear horizon. The benefits gained from allowing interyear updates of the static model outweigh the loss of dynamism. With the current structure, the analyst can vary the development triggers in a series of simulations and observe the market, development, and delivered cost effects.

The demand equations or consumption values are currently updated with exogenously developed growth factors. They are not recalculated each year with prior year results, as would be the case in a recursive econometric model. This limitation can be overcome through sensitivity analyses, using alternative demand growth rates.

Finally, by using unique consumption values, an initial assumption is made that markets are competitive and in equilibrium at the forecast consumption rate. However, this constraint is not binding, and, in fact, examination of the simulation results has indicated that ferrochromium markets are not perfectly competitive. This issue will be covered in the discussion of the network results.

SUMMARY OF COST RELATIONSHIPS

The methodology sections just presented for the availability and the network flow market model studies have made reference to numerous different types of costs. The results sections to follow and the appendixes to this report also contain references to various types of costs. Table 9 is presented to summarize—in one section—all of

Table 9.—Summary of relationships, representations, and discussions of costs in the chromium availability and network flow market model studies

Availability Study	Network Flow Market Model Study
"Total costs" include—	"Network model costs" include—
(1) Variable (direct) and fixed (indirect) operating costs[1] for: (a) mining (table 12, appendix B) (b) beneficiation (table 12, appendix B) (c) smelting (tables 14-17). (2) Transportation costs for chromite to smelters (no discussion in report). (3) Transportation costs for FeCr and chromite to port facilities (no discussion in report). (4) Costs related to capital investments required for mining and beneficiation needs (figures 4-7). (5) Royalties, taxes, insurance; as applicable or known (no discussion in report).	(1) Variable (direct) operating costs[1] for: (a) mining (table 12, appendix B) (b) beneficiation (table 12, appendix B) (c) smelting (tables 14-17). (2) Transportation costs for chromite to smelters (no discussion in report). (3) Transportation costs for FeCr and chromite to port facilities (no discussion in report). (4) Ocean transport to markets (appendix F).
"Total costs" exclude—	"Network model costs" exclude—
(1) Ocean transport to markets (appendix F). (2) Costs related to capital investments required for smelting needs (table 18). (3) Tariffs and duties (no discussion in report).	(1) Royalties, taxes, insurance; as applicable or known (no discussion in report). (2) Costs related to capital investments required for mining, beneficiation, and smelting needs (figures 4-7 and table 18). (3) Tariffs and duties (no discussion in report).
"Total costs" equal "price determination results" (tables 19-23; figures 4-7).	"Network model costs" for specific products into regional markets equal "delivered costs" (tables 35-43; figures 10-17).

[1]Because fixed (indirect) costs represent a small percentage of the mining, beneficiation, and smelting operating costs, the same operating costs values were used for both the availability and the network flow model studies of this report.

the costs (and terminology) applicable to the two types of studies described in this report. Included in the table is a notation as to tables, figures, and sections of the report where the costs are either presented or discussed in some detail. Table 9 is intended to explain the relationships between the various types of costs involved in these two studies.

EVALUATED MEC RESOURCES

A summary of the in situ, demonstrated resources in 10[13] MEC's evaluated for this availability study is provided in table 10. Appendix A lists all of the individual chromite properties and units composing the country totals shown in table 10. More detailed descriptions of all U.S. resources and of the evaluated resources for these major MEC chromite producers is presented, by country, in appendix B.

Table 10.—Summary, evaluated MEC chromium resources, January 1989

Country	Cr-bearing ore (kmt)	Cr grade (wt pct)	Cr resource (kmt)	Cr_2O_3 grade[1] (wt pct)
Brazil	26,170	15.88	4,156	23.35
Finland	37,790	18.09	6,835	26.60
Greece	3,424	11.30	387	16.62
India	53,665	27.79	14,915	40.87
Madagascar	9,210	23.09	2,127	33.96
Philippines	65,487	6.23	4,078	9.16
South Africa	549,022	25.95	142,449	38.16
Turkey	13,822	24.69	3,413	36.31
United States	45,306	8.39	3,803	12.34
Zimbabwe	69,616	29.25	20,361	43.01
Total or wtd avg	873,512	23.19	202,524	34.10

[1]In situ Cr_2O_3 grades calculated by dividing in situ Cr grades by a factor of 0.68.

As in the prior study (*1*), chromite resources in the minor market economy producing countries of Iran, Oman, Sudan, Pakistan, and Japan have not been analyzed for availability in this update because of lack of data. Additional, major MEC chromite resources, discussed in the "Other MEC Chromite Resources" section, have also not been included in this availability analysis because of the lack of adequate data for complete costing.

The contained Cr in evaluated resources listed, by country, in table 10 can be compared to the following contained Cr reserve values from table 15 of the Bureau's 1989 Mineral Yearbook chapter for chromium:

Country	Reserves, kmt
Brazil	2,300
Finland	8,900
Greece	400
India	18,100
Madagascar	2,100
Philippines	2,300
South Africa	295,200
Turkey	2,500
United States	0
Zimbabwe	43,500

Comparison reveals that the largest tonnage differences are, not surprisingly, in the two southern Africa countries of South Africa and Zimbabwe. The differences are due to the large extent (and multiple seam nature) of the stratiform chromite deposits contained in the Bushveld Igneous Complex in South Africa and in the Great Dyke of Zimbabwe. It is noted that such large, extensive geological structures as these present the probability of wide variations in separate estimates of contained chromium resources, depending on the method or approach that is used in estimation.

Even though the evaluated chromium tonnage listed in table 10 for both South Africa and Zimbabwe is only about half the size of the reserve value reported for the two countries in the Minerals Yearbook, it still represents 80.5 pct of the contained Cr in all of the evaluated MEC resources. Together, India and Finland account for an additional 10.6 pct of the contained Cr; another 7.7 pct of the contained Cr is fairly evenly split among Brazil, the Philippines, Turkey, and the United States; and the remaining 1.2 pct of the contained Cr is in Greece and Madagascar.

Based on in situ Cr_2O_3 content, the 10 MEC's can be split into two groups. The high-grade group, with grades ranging from 33.96 pct to 43.01 pct Cr_2O_3, includes the countries of India, Madagascar, South Africa, Turkey, and Zimbabwe. The low-grade group consists of Brazil, Finland, Greece, the Philippines, and the United States, with grades ranging from 9.16 pct to 26.60 pct Cr_2O_3. The grade differences between the two groups result in a wide disparity in the respective weighted average Cr_2O_3 contents; the high-grade group averages 38.76 pct Cr_2O_3, and the low-grade group of countries averages only 15.90 pct Cr_2O_3.

[13]The 1986 reevaluation of reserves for the one major producing property in New Caledonia resulted in an estimate that allowed production only into late 1988. For that reason, the analyzed MEC tonnage available as of the January 1989 study date includes only 10 MEC's and does not include any analyzed chromite reserve for the country of New Caledonia.

OTHER MEC CHROMITE RESOURCES

Table 11 provides a listing and brief descriptions of the major MEC chromite resources, as of the late 1980's, which were not included in the availability analysis because of lack of data to estimate detailed costs. The two producing operations listed in the table, the Wosu sand operation in Indonesia and the Vila Nova operation in Brazil, were included in the network flow model by making rough estimates of mining and beneficiation operating costs.

Most of the resources listed in table 11 have in situ Cr_2O_3 grades below 15 pct Cr_2O_3. Exceptions are the Coobina deposits in Australia (28 to 49 pct Cr_2O_3), the Vila Nova deposits in Brazil (35 pct Cr_2O_3), and the UG2 chromite in South Africa (33 to 38 pct Cr_2O_3).

Table 11.—Major MEC chromite resources not included in availability analysis

Country	Deposit/operation name	Summary data
Australia	Cork Tree Well	Explored deposit discovered during the 1980's. Reported reserve of 31 Mmt grading 45 pct Fe and 3.6 pct "chromium in iron oxides (not in chromite)" (*16*).
Do.	Wilson River	Located in Tasmania. Reports in 1988 of 112,000 mtpy operation under consideration for development (*17*).
Do.	Coobina	No major developments during the 1980's. Identified resource of 2.1 Mmt at 28 pct to 49 pct Cr_2O_3 and 1.5:1 Cr-Fe ratio.
Brazil	Vila Nova	Operation began production in 1988. Mill has capacity to treat 270,000 mtpy ROM for production of 160,000 mtpy of 50-pct-Cr_2O_3 concentrates. Estimated 3 Mmt ROM at 35 pct Cr_2O_3 to 100-m depth in a 7-m-thick ore horizon (*18*). Other deposits are in the area.
Canada	Bird River	Updated resource estimates and results of smelting tests available in 1986 (*19*). Measured plus indicated tonnage at 18.58 Mmt and additional 21.39 Mmt inferred. All tonnages grade 9.6 pct Cr_2O_3. Results of six smelter tests gave Cr in FeCr grade ranges of 45.9 pct to 51 pct.
Greenland	Fiskenaesset	No major developments during the 1980's. Identified resource of 20 Mmt at 14 pct Cr_2O_3 with low (1.2:1) Cr-Fe ratios. Possible interest as an ore feed to direct steelmaking methods presently being researched.
Indonesia	Wosu	Operation began production in 1987. In situ reserve estimated at about 12.5 Mm^3 of sand at 3.1 pct Cr_2O_3. Annual capacity of 40,000 mtpy concentrates at 43 pct Cr_2O_3 and less than 1 pct SiO_2 for foundry sand market.
New Caledonia	Offshore sediments	Drilling during 1980's at Pirogues, Ngo, and Ouie Bays by Australmin Pacific (*20*). As of 1988, 100 Mm^3 of material grading 3.5 pct Cr_2O_3 (by volume) defined at Pirouges Bay (*21*). Deposits in very shallow water.
Papua New Guinea	Ramu River	Cr, Ni, Co laterite deposit. The upper layer of 4-m-thick sandy clay contains 100 Mmt in situ material at 6.5 pct Cr_2O_3. About 15 mt of low SiO_2 concentrates grading 49.6 pct Cr_2O_3 and 1.66:1 Cr-Fe ratio smelted to as high as 53 pct Cr FeCr in conventional smelting tests by the Bureau in 1981 (*22*). Prefeasibility studies prior to 1986. Other Ni, Co, Cr deposit based on 2 pct Cr_2O_3 cutoff grade.
South Africa	UG2 seam chromite	Mined and milled for production of PGM's (Platinum group metals) since 1980 with chromite tailings stockpiled. High-C FeCr of about 47 pct Cr has been produced in various smelting tests. Presently being used for limited production of FeCr. Indicated 207.7 Mmt at about 33-38 pct Cr_2O_3.

MINING AND BENEFICIATION OPERATING PARAMETERS AND COSTS

This section presents a brief country-by-country summary of the overall mining and beneficiation recoveries, run-of-mine ore (ROM)[14] and chromite product capacity levels, and associated operating cost estimates of this availability study. Table 12 summarizes total annual ROM and chromite product capacities, average beneficiation recoveries, and weighted average ROM mining and beneficiation operating costs for the 10 MEC's included in this availability study. Annual capacity is the total annual production capacity for all properties and units analyzed for each country. As such, the total annual ROM and chromite product capacity values in table 12 include both actual (for producers) and proposed (for nonproducers) capacities. Appendix A provides a listing of individual properties and units along with their general ownership ties, study status, annual chromite product output capacities, and chromium product assignments. It is noted that the total capacity values in table 12 for South Africa *do not* include any chromite production capacity from UG2 reef material.

[14]In the context of this study, ROM is equivalent to the feed material to any further beneficiation, including sorting. It is distinguished from the in situ material by the inclusion of any applicable mine recovery and dilution factors.

Operating costs in the table are weighted on the basis of a country's total annual ROM capacity. The beneficiation recoveries listed in the table represent the average for all analyzed properties and units in a given country.

Mine and mill operating cost estimates are long-run averages. Therefore, as explained in the "Methodology" section, they include both variable (direct) and fixed (indirect) charges. All mining cost estimates for this study have been based on complete extraction of the demonstrated resource being analyzed.

With the exception of the Philippines and Turkey, the annual chromite product capacity values in table 12 represent a good measure of the total chromite production potential in these MEC's as of the mid-1980's to late 1980's. Reasons for possible understatement of the Philippines and Turkish capacity levels are discussed in the individual country sections of appendix B.

Table 12.—MEC annual capacity summary, average recovery data, and weighted average mining and beneficiation operating cost data

Country	Annual capacity[1] (kmtpy)		Recovery[2] of Cr_2O_3 (pct)	Operating costs[3] (Jan. 1989 \$/mt ROM)	
	ROM	Chromite products		Mining	Benefi-ciation
Brazil	1,035	472	78.6	17.88	3.95
Finland	1,148	607	75.6	W	W
Greece	298	90	81.5	W	W
India	1,568	1,177	83.7	46.53	1.42
Madagascar	228	115	71.7	W	W
Philippines	2,810	493	65.9	8.93	3.15
South Africa	8,254	6,498	87.8	19.62	2.45
Turkey	912	614	88.9	20.79	6.23
United States	2,305	546	81.7	13.76	5.20
Zimbabwe	1,254	1,046	90.1	71.18	5.31
Total or averages	19,812	11,658	84.3	22.31	3.41

W Withheld because only one mining operation in the country; included in totals.

[1]Combined total for all producing and nonproducing properties/units in each country. Annual chromite product capacities for individual properties/units (actual for producers, proposed for nonproducers) are given in appendix A. Total country annual chromite product capacities can be compared to estimated 1988 chromite production as follows: Brazil—240 kmt, Finland—700 kmt, Greece—63 kmt, India—759 kmt, Madagascar—107 kmt, Philippines—190 kmt, South Africa—4,245 kmt, Turkey—625 kmt, United States—none, and Zimbabwe—562 kmt (23).

[2]Recovery of contained Cr_2O_3 in ROM into final chromite products; straight average for all units in a country.

[3]Weighted on basis of annual ROM capacity.

NOTE.—Similar values on a chromite product basis can be calculated by multiplying the ROM basis costs by the ratio of ROM to chromite product annual capacities.

For comparison, it is noted that the total annual chromite product capacity of 11.7 Mmt for all 10 MEC's in table 12 is 57.2 pct larger than the estimated 7.5 Mmt of chromite produced from these 10 MEC's in 1988 (see footnote to table 12). This indicates that a major expansion potential exists in some of these MEC's; e.g., India, South Africa, the United States, and Zimbabwe. Also of interest is that nearly 75 pct of the total MEC annual chromite production potential of this availability study is in only three countries: South Africa, Zimbabwe, and India.

In table 12, the average beneficiation recoveries for the individual countries range from 65.9 pct in the Philippines to 90.1 pct in Zimbabwe. Beneficiation recoveries are directly related to the amount of gravity concentration required; those below 85 pct indicate that a high proportion of material, usually low in Cr_2O_3 content, must be upgraded significantly.

The mining and beneficiation operating costs in table 12 have been weighted on the basis of the ROM annual capacities. These ROM operating costs can be converted to a chromite product basis using the ratio of the ROM to chromite product annual capacities given in the table. The cost estimates for the countries of Finland, Greece, and Madagascar have been withheld in the table because they represent results for a single mining operation.

On a country-by-country basis, there is a wide range in both the mining costs (from \$8.93/mt ROM in the Philippines to \$71.18/mt ROM in Zimbabwe) and the beneficiation costs (from \$1.42/mt ROM in India to \$6.23/mt ROM in Turkey). Likewise, as a percentage of the mining costs, the beneficiation costs range widely from only 3.1 pct in India to a high of 37.8 pct for the undeveloped properties/units in the United States.

SMELTING TECHNOLOGIES AND COST ESTIMATES

SMELTING TECHNOLOGIES

A number of technologies or methods are available for the smelting of chromite products to high-C ferrochromium, low-C ferrochromium, and ferrochromium-silicon ferroalloy products. These are discussed in detail in appendix C ("Smelting Technology"). A brief summary of the technologies is presented here to enable better understanding of the cost discussions that follow.

The smelters included in this study incorporate six individual high-C FeCr production processes. These are conventional electric arc smelting, conventional smelting with briquetting/sintering of fines and concentrates, the Outokumpu Oy process, the solid-state reduction of chromite (SRC) process, the Krupp-CODIR process, and the plasma arc processes.

Differences in smelting operating costs among these processes primarily involve (1) the electrical power consumption per mt of alloy produced, (2) the amount and type of feed pretreatment required, (3) the degree of Cr prereduction achieved, and (4) the type and amount of reductant required. Table 13 shows typical values of these variables for each of the processes.

Table 13.—Comparison of important production factors for various high-C FeCr smelting processes

Process[1]	Total electrical consumption (kW·h/mt FeCr)	Cr prereduction (pct)	Feed preparation	Primary reductant type
Conventional	3,800-4,200	0	None	Coke.
Conventional/briquetting	3,800-4,200	0	Briquetting/sinter	Coke.[2]
Krupp-CODIR	[3]1,400-1,500	90-95	None	Coals.
Outokumpu Oy	3,100-3,200	40	Grind/pelletize/sinter	Coke.
Plasma arc	4,000-4,500	0	Grind portion[4]	Coke/coals.
SRC[5]	2,100-2,200	70-75	Grind/pelletize/sinter	Coke.
SRC[5]	2,600-2,700	55-60	Grind/pelletize/sinter	Coke.

[1]See appendix C for detailed discussion of the different high-C FeCr smelting processes.

[2]Exception is Brazil, which uses charcoal as major reductant.

[3]Original claims or goals (circa 1987) were for furnace power consumptions of 875 kW•h/mt FeCr for a "hot" charge of prereduced material to the furnace and 1,200 kW•h/mt FeCr for a "cold" charge. To be conservative in the costing of a process that has not yet been proven as commercially feasible, the values shown in the table were used as representing total power consumption for the process.

[4]In Swedish method only.

[5]Separate listings for SRC process show how power consumptions differ with higher degrees of Cr prereduction, which depends mainly on retention time in the prereduction kiln.

Two basic processes are represented in these analyses of low-C FeCr smelting cost estimates. The most common, used in all but the estimate for the United States, is the Perrin process. The basic Perrin process involves the reaction of a molten slag of chromite ore and lime with ferrochromium-silicon produced by smelting chromite ore, SiO_2, and a reductant (usually metallurgical coke) in a separate electric arc furnace. In the costing for this study, only Brazil and the Federal Republic of Germany involved variations on the basic Perrin process. In Brazil, the costing was based on producing ferrochromium-silicon by smelting high-C FeCr with SiO_2 and a reductant instead of smelting chromite ore, SiO_2, and a reductant. In the Federal Republic of Germany, the costing was based on the addition of 40 pct (by weight) SiO_2 to the chromite-lime slag, effectively eliminating the need to produce ferrochromium-silicon in a separate furnace. The low-C FeCr cost estimates for the United States are based on the use of the Simplex process, where a high-C FeCr product is mixed with a solid metal oxide, briquetted and dried, then heated in vacuum conditions to 1370° C at a programmed rate.

SMELTING OPERATING COST ESTIMATES

In this section, the estimated high-C and low-C FeCr smelting operating costs used both in the availability study and in the network flow model are presented, as indexes, by country. The smelter operating cost estimates include labor, power, raw material, maintenance supplies, miscellaneous, overhead, and general and administrative costs at the smelters included in the study. They *do not* include the costs of chromite ore feed for smelting, taxes, or costs associated with major initial capital investments such as depreciation, amortization, and interest. The operating cost estimates are presented as indexes (South Africa = 1.00) and as country averages for the study date (January 1989 U.S. dollars).

The smelting operating cost estimates for the two portions of this study (the availability study and the network flow model) consist of two groups, based on the relative detail of the estimates. Detailed cost estimates were made for the major chromite producing MEC's of Brazil, Finland, Greece, India, the Philippines, South Africa, Turkey, Zimbabwe, and the proposed U.S. smelters. Detailed estimates were made for these countries because of their importance to the availability study results.

The network flow model required that additional smelting cost estimates be made for the present U.S. producers and for the countries of Canada, France, Italy, Japan, Mexico, Spain, Swaziland, Taiwan, Venezuela, Federal Republic of Germany, and Yugoslavia. These smelting cost estimates were made in somewhat less detail.

Electrical energy, raw materials (including reductants, slag forming materials, coal, fuels, and electrodes), and labor constitute the three major items in the smelting operating cost estimates. In the high-C FeCr estimates, electrical energy accounted for 20 to 54 pct of the total smelting cost, raw materials (excluding chromite ore) for 15 to 35 pct, and labor for 9 to 27 pct. In the low-C FeCr estimates, electrical energy accounted for 22 to 54 pct of the total smelting cost, raw materials for 17 to 34 pct, and labor for 14 to 28 pct.

In this section, detailed data are presented and discussed for only two of these three major cost components in FeCr smelting: electrical energy and labor. It is important to present details of this study's estimates for these two components because power rates and labor policies (as to employment levels and wages) are the most variable and negotiable of all of the cost items in FeCr smelting.

High-Carbon Ferrochromium

Table 14 summarizes, by country, the study's estimated operating costs for smelting chromite to high-C FeCr. The estimates have been indexed in the table, for comparative purposes, to an average South African smelting cost estimate, which equals 1.00. The labor and power percentages of these cost estimates are also shown in the table.

Table 15 provides the average annual labor rates (also indexed to the South African average) and the average labor productivities for each country as well as a measure of the combination of the labor rates and productivity estimates, referred to as a "unit labor cost index." In addition, table 15 provides the average power costs used in the estimates, both in terms of U.S. \$/kW•h and indexed to the South African average.

As shown in table 14, the smelting cost estimates for Swaziland, the United States, Venezuela, and Yugoslavia are all below the average for South Africa. The very low cost for Yugoslavia reflects a devaluation of the currency in 1988. The Swaziland and Venezuela cost estimates (both at the low end of the indexed scale) are estimates for proposed smelters not expected on-stream until several years into the 1990's. The U.S. smelting operating cost index shown in the table is heavily weighted (close to 70 pct) to the use of extremely efficient prereduction technology at proposed smelters near in-country chromite resources. All of these "low" estimates have either low electricity consumptions or low power costs in common.

Table 14.—Index for estimated high-C FeCr smelting costs,[1] including component cost percents for labor and power

Country	Description of smelting technologies being used and overall smelting cost weightings, circa study period of 1988-89	Smelting cost indexes	Selected component costs (pct of total)	
			Labor	Power
Major chromite producers:				
Brazil	Conventional smelting	1.27	20.7	35.0
Finland	Outokumpu Oy process (30 pct pellets, 70 pct lump ore)	1.41	18.4	38.0
Greece	Outokumpu Oy process (100 pct pellets)	.98	18.5	28.5
India	Conventional (73 pct of high-C) and Outokumpu Oy (27 pct of high-C).	1.37	9.1	50.8
Philippines	Outokumpu Oy process (80 pct pellets, 20 pct lump ore)	1.04	10.4	47.0
South Africa	Conventional (84.5 pct of high-C), SRC process (13.7 pct of high-C) and plasma arc smelting (1.8 pct of high-C).	1.00	10.4	43.7
Turkey	Conventional (31 pct of high-C) and Outokumpu Oy (69 pct of high-C).	1.21	13.1	37.5
Zimbabwe	Conventional smelting	.98	13.8	19.9
Minor/nonchromite producers:				
France	..do.	1.82	23.6	38.1
Italy	..do.	1.60	19.4	36.8
Japan	Conventional (71 pct of high-C) and SRC process (29 pct of high-C).	1.88	15.3	48.0
Mexico	Conventional smelting	1.70	11.7	54.2
Spain	..do.	2.05	12.9	49.6
Swaziland	Krupp-CODIR process; proposed smelter only	.69	14.6	25.2
Sweden	Conventional (66 pct of high-C) and plasma arc smelting (34 pct of high-C).	1.26	22.1	35.4
Taiwan	Conventional smelting	1.82	23.3	48.9
United States	Conventional (31 pct of high-C) and Krupp-CODIR (69 pct of high-C). Krupp-CODIR is for proposed smelters only.	.95	27.1	26.3
Venezuela	Conventional smelting; proposed smelter	.62	11.8	34.8
Yugoslavia	Conventional smelting	.32	11.1	45.6

[1]All values indexed to a value for South Africa of 1.00; index on a common January 1989 U.S. dollar basis. Smelting cost estimates include labor, power, raw materials, overhead, and general and administrative costs. Costs for chromite ore feed, taxes, and costs associated with major initial capital investments such as depreciation, amortization, and interest are not included.

Table 15.—Labor and power values used in high-C FeCr smelting cost estimates, by country

Country	Labor values: Labor cost indexes[1]	Labor values: Labor productivity,[2] person hours/mt FeCr	Labor values: Unit labor cost indexes[3]	Power values: Average power rate, Jan. 1989 U.S. $/kW·h	Power values: Average power indexes[4]
Major chromite producers:					
Brazil	1.49	14.5	21.6	0.029	0.94
Finland	6.05	2.9	17.6	.046	1.48
Greece	1.77	7.8	13.8	.024	.78
India	.33	26.9	8.9	.052	1.68
Philippines	.93	9.1	8.5	.043	1.39
South Africa	1.00	8.2	8.2	.031	1.00
Turkey	.95	7.6	7.2	.036	1.16
Zimbabwe	.71	12.1	8.6	.014	.45
Minor/nonchromite producers:					
France	5.60	6.3	35.3	.046	1.48
Italy	4.82	5.3	25.6	.041	1.32
Japan	6.26	3.8	23.8	.072	2.32
Mexico	1.67	9.8	16.4	.061	1.98
Spain	4.23	5.1	21.6	.070	2.26
Swaziland	.94	8.8	8.3	.031	1.00
Sweden	5.51	4.1	22.6	.042	1.36
Taiwan	3.82	9.1	34.8	.058	1.87
United States	5.59	3.4	19.0	.029	.94
Venezuela	1.11	5.4	6.0	.015	.48
Yugoslavia	.58	5.2	3.0	.010	.33

[1]Unweighted average of the annual wage or salary levels used in the estimates for all employee and management categories; includes estimate of fringe benefits. All values indexed to a value for South Africa of 1.00; index on a common January 1989 U.S. dollar basis.

[2]Calculated on basis of total employees, including contracted and company employees and management. For consistency of comparisons, productivities for all countries have been calculated on the basis of 2,100 hours per year per employee.

[3]Unit labor cost indexes represent the labor cost index times the productivity value for each of the countries listed.

[4]Power rates of previous column indexed to a value for South Africa of 1.00.

The smelting cost estimates for all of the other minor or nonchromite producing countries are significantly higher than the average of the South Africa estimates. They are also significantly higher than the estimates for nearly all of the major MEC chromite producers. This apparent smelting cost advantage for the chromite producing countries is in addition to inherently lower chromite ore feed costs, which are not reflected in the estimates of table 14.

Several reasons for the smelting cost advantages in the major chromite producing countries are clearly shown in table 15. For example, the average annual labor rates for the chromite producing countries outside of Western Europe range from 0.33 to 1.49 times the average South African labor rate, and the power rates for those same countries are nearly all at or below \$0.043/kW·h, the exception being India. These compare to average annual labor rates that are 1.67 to 6.26 times the average South African labor rate and power rates all at or above \$0.041/kW·h for the countries of France, Italy, Japan, Mexico, Spain, Sweden, and Taiwan.

The power rates used in these FeCr smelting cost estimates (and their comparison to the South African rate) have been included in table 14 because of their importance to the overall smelting cost estimates. The assumed power rates are also important to note, since that is the one major cost item in FeCr smelting that is most "negotiable" in terms of subsidies. For example, the \$0.014/kW·h power rate used in this study for Zimbabwe resulted in it having one of the lowest average smelting cost estimates of the major chromite producing countries. This low power rate appears to be subsidized.

The extreme sensitivity of overall FeCr smelting costs to the electrical power rates can also be seen by comparing the estimates for India and Venezuela. India had the second highest smelting cost of the major chromite producers solely because of the very high power rate of \$0.052/kW·h used in the estimates. By comparison, the estimated smelting cost for the proposed Venezuelan ferroalloys complex is very low because of an assumed

\$0.015/kW·h power rate based on the country's low cost hydroelectric power sources.

As shown in table 15, Brazil and India have the lowest productivity levels (i.e., a high number of person hours required per mt of FeCr produced). Interestingly, nearly all of the smelters in these two countries are closely tied to state-owned organizations. However, it should be noted that all of the major chromite producing countries, except for Finland, show significant degrees of overstaffing in comparison to the most efficient of the minor or nonchromite producing countries.

One possible reason for overstaffing in most of the major chromite producing countries is shown by the "unit labor cost indexes" column in table 15. This index, which measures the combination of labor rates and productivities, ranges from 7.2 to 8.9 for the countries of India, the Philippines, South Africa, Turkey, and Zimbabwe. These values are still much less than the unit labor cost indexes for the minor or nonchromite producing countries in Europe and Asia. Because of relatively low labor rate levels, these chromite producing countries can afford a certain degree of overstaffing at their high-C FeCr smelters.

Low-Carbon Ferrochromium

Table 16 summarizes, by country, the study's estimated operating costs for smelting chromite to low-C FeCr. The estimates have been indexed in the table, for comparative purposes, to an average South African smelting cost estimate, which equals 1.00. The labor and power percentages of these cost estimates are also shown in the table.

Table 17 provides the average annual labor rates (also indexed to the South African average) and the average labor productivities for each country as well as a measure of the combination of the labor rates and productivity estimates, referred to as a "unit labor cost index." In addition, table 17 provides the average power costs used in the estimates, both in terms of U.S. \$/kW·h and indexed to the South African average.

Interestingly, table 16 shows that, except for the major low-C FeCr exporting countries of Zimbabwe and South Africa, the other major chromite producing countries do not show a decided cost advantage over the minor or nonchromite producing countries. This is a major difference from the high-C FeCr situation shown in table 14. Also, table 16 shows much less variation in the low-C FeCr smelting cost estimates.

One major reason for the relative similarities of the low-C FeCr smelting costs in the chromite producing countries and in the nonchromite producing countries of the Federal Republic of Germany and Japan can be seen in the labor productivity column of table 17, where serious levels of overstaffing are indicated at low-C FeCr operations in all of the major chromite countries. In combination with lower average annual labor rates, the average of the "unit labor cost indexes" for the five chromite producing countries is very similar to that for Japan and the Federal Republic of Germany.

Table 16.—Index for estimated low-C FeCr smelting costs,[1] including component cost percents for labor and power

Country	Smelting cost index	Components costs (pct)	
		Labor	Power
Major chromite producers:			
Brazil	1.47	28.1	23.6
India	1.74	18.0	42.4
South Africa	1.00	15.0	32.8
Turkey	1.63	25.8	29.4
Zimbabwe[2]	.85	21.9	22.1
Minor/nonchromite producers:			
Canada[3]	1.53	14.0	28.2
Germany, Federal Republic of	1.45	19.3	43.0
Japan	1.82	16.5	53.6
United States[4]	1.02	(5)	(5)
Yugoslavia	.30	(5)	(5)

[1]All values indexed to a value for South Africa of 1.00; index on a common January 1989 U.S. dollar basis. Smelting cost estimates include labor, power, raw material, overhead, and general and administrative costs. Costs for chromite ore feed, taxes, and costs associated with major initial capital investments such as depreciation, amortization, and interest are not included.

[2]Cost is relatively low because total smelting costs apportioned to low-C and ferrochromium-silicon for sale. Ferrochromium-silicon smelting costs under this apportioning were \$404/mt.

[3]Proposed smelter; costed as using Perrin process.

[4]Estimate of costs using vacuum heating of an initial high-C FeCr product. Estimate could be very low.

[5]No breakdowns available for the U.S. and Yugoslavia smelting cost estimates because few details known about processes being used.

It bears mentioning that the staffing levels in these estimates are based on either published information or estimates. However, if reasonably correct, the values could be reflecting the much smaller, more stable, and less competitive nature of the low-C FeCr industry in comparison to the high-C FeCr industry. As a result, the chromite producing countries may feel less inclined to rationalize the relative overstaffing at their low-C FeCr smelters.

SMELTING CAPITAL COSTS, HIGH-CARBON FERROCHROMIUM

As noted in the first part of the "Methodologies" section, this updated study did not include smelter capital costs in determining and comparing the price determination results for the MEC availability study. High-C FeCr price determinations that included the costs of smelter capital were only run for the three proposed U.S. smelters, and the results of these runs are reported on separately in the text of the "Availability Results" section.

Table 17.—Labor and power values used in low-C FeCr smelting cost estimates, by country

Country	Labor values: Labor cost indexes[1]	Labor values: Labor productivity,[2] person hours/ mt FeCr	Labor values: Unit labor cost indexes[3]	Power values: Average power rate, Jan. 1989 U.S. $/kW·h	Power values: Average power indexes[4]
Major chromite producers:					
Brazil	1.62	47.3	76.6	0.029	1.00
India	.35	160.5	56.2	.052	1.79
South Africa	1.00	26.5	26.5	.029	1.00
Turkey	1.15	78.8	90.6	.036	1.24
Zimbabwe	.73	47.5	34.7	.014	.48
Minor/nonchromite producers:					
Canada	5.40	5.5	29.7	.025	.86
Germany, Federal Republic of	6.13	8.5	52.1	.046	1.59
Japan	6.61	8.5	56.2	.072	2.48
United States[5]	NA	NA	NA	NA	NA
Yugoslavia	.61	10.4	6.3	.010	.35

NA Not available.

[1]Straight average for all employee categories, including management. All values indexed to a value for South Africa of 1.00; index on a common January 1989 U.S. dollar basis.

[2]Calculated on basis of total employees, including management. For consistency of comparisons, the productivities for all countries have been calculated on the basis of 2,100 hours per year per employee.

[3]Unit labor cost indexes represent the labor cost index times the productivity value for each of the countries listed.

[4]Power rates of previous column indexed to a value for South Africa of 1.00.

[5]U.S. cost estimate values not included owing to lack of details on the vacuum process in use.

Smelter capital costs were excluded from the overall MEC availability study because of noncomparative situations regarding individual smelters' capital cost requirements, as of the study date of January 1989. For example, as of late 1988, 15 of the 21 MEC smelters factored into the availability analysis were all at least 10 yr old; five were from 2 to 6 yr old; and one was nearing completion of construction.

This section provides the reader with a brief perspective on high-C FeCr capital costs, circa the 1980's. This is done to allow comparison of typical smelter capital cost requirements (on a basis of U.S. dollars per pound Cr) to the high-C FeCr price determination results, sans capital, to be presented in the section immediately following.

Table 18 provides actual and estimated capital cost ranges for various high-C FeCr smelting processes. The Krupp-CODIR values in the table are estimates for facilities yet to produce on a commercial scale. All of the other capital cost ranges in the table represent actual or planned expenditures[15] for smelting facilities constructed during 1981 through 1988. These capital cost values and estimates were all updated to a common January 1989 U.S. dollar value and divided by 10 yr[16] of Cr in FeCr production, at capacity. The resulting cost ranges in the table are thus on a common basis of January 1989 U.S. dollars per pound Cr and can be compared to the price determination results for high-C FeCr in the availability

[15]The capital cost requirements used in this compilation were mostly from published literature and many did not include detailed breakdowns of items composing the total. Because of that, it is possible that financial charges, such as interest on loans, have been included in constructing the table.

[16]For the purposes of constructing the table, 10 yr of production, at capacity, was thought to represent a reasonably conservative length of time for payback of the capital investment.

results section. The capital costs for the plasma arc smelting process are very high on a basis of U.S. dollars per pound Cr primarily because they reflect the total cost to develop new smelting processes from the pilot plant scale to commercial size operations.

Finally, to provide a rough idea of the level of total capital investment required to initiate new high-C FeCr production, the following approximations—according to the South African company SAMANCOR (*24*)—are presented. The company estimates that adding a 36 MV•A[17] furnace onto an existing line of furnaces at a South African smelter would cost $30 million (1988 U.S. dollars), while constructing an identically sized furnace as a "greenfield" smelter would cost $43 million (1988 U.S. dollars). Further, should the company want to add a prereduction kiln to feed prereduced pellets to a 36 MV•A furnace, the total "greenfield" investment would be around $100 million (1988 U.S. dollars).

These SAMANCOR values are rough approximations only and, if anything, seem to be somewhat high. However, the significance of the three values is that they address the relative differences among (1) a "greenfield" conventional smelter complex, (2) a simple "add-on" to an existing conventional smelter complex, and (3) the addition of a prereduction kiln to a "greenfield" conventional smelting complex.

Table 18.—Typical high-C FeCr smelter capital cost ranges,[1] by smelting process

(January 1989 U.S. dollars per pound Cr)

High-C FeCr smelting method/process	Capital cost ($/lb Cr)
Conventional smelting, "greenfield" smelter	0.031-0.062
Conventional smelting, "add-on" to existing furnaces	.022- .043
Kiln/smelting, Outokumpu Oy process	.052- .094
Kiln/smelting, Krupp-CODIR process[2]	.052- .067
Plasma arc smelting[3]	.138- .189

[1]Total actual capital expenditures for major MEC smelters constructed during the 1981-88 period, up-dated to a common January 1989 U.S. dollar basis. U.S. dollars/lb Cr value calculated based on 10 yr of production at capacity and assumed Cr in FeCr grades based on likely ore sources. Exceptions are the Krupp-CODIR capital costs, which are estimates for facilities not yet in commercial production. Costs for interest paid on loans may be included in some cases.

[2]Estimates only; for facilities presently under construction or only proposed.

[3]Capital costs extraordinarily high because they represent all costs needed to construct facilities using entirely new processes from the pilot-plant scale to commercial-size operations.

STUDY RESULTS

AVAILABILITY

As noted previously, the availability analysis addressed the economics of producing a variety of chromium products (ferroalloys and chromite) from a total of 873.5 Mmt of in situ material (see table 10) in 10 MEC's. As analyzed, extraction and beneficiation of this in situ material would result in 475.4 Mmt of chromite products, or about 63 yr of production at the 1988 output levels of these 10 countries.

In the structure of this availability study, 186.9 Mmt of the 475.4 Mmt of chromite products were sent to in-country smelters for production of 74.3 Mmt of high-C FeCr, 3.9 Mmt of low-C FeCr, and 2.0 Mmt of ferrochromium-silicon. The remaining 288.5 Mmt of chromite products were analyzed as available for export with the following tonnage breakdown, by market use:

Product	Amount, Mmt
Metallurgical chromite	181.0
Chemical chromite	64.3
Refractory chromite	26.8
Foundry sand chromite	16.4

If the 186.9 Mmt of chromite assigned in the study for in-country smelting is included in the metallurgical category, then the percentage breakdowns, by market, for the entire 475.4 Mmt of chromite products are 77.4 pct for metallurgical use, 13.5 pct for chemical use, 5.6 pct for refractory use, and 3.5 pct for use as foundry sands.

Using Finland as a property specific example of this availability study structure, the 37.8 Mmt of in situ chromite ore grading 26.6 pct Cr_2O_3 (see table 10) would result in a total of 20.9 Mmt of chromite products after mining and beneficiation. Of this 20.9 Mmt of chromite products, 17.2 Mmt of metallurgical chromite products would be used to produce 6.2 Mmt of high-C FeCr, while 2.6 Mmt of "coproduct" metallurgical chromite products, 0.7 Mmt of chemical chromite products, and 0.4 Mmt of foundry sand products would be analyzed for export (f.o.b. port) economics.

[17]In South Africa, a furnace of this transformer size could be expected to produce about 60,000 mtpy of high-C FeCr using conventional furnace technology (with feed of about 30 pct of the Cr contained in fines ore and 70 pct in lump ore) and could produce about 85,000 mtpy of high-C FeCr if using 100 pct of feed as pellets that have had 60 to 65 pct of the Cr content prereduced.

The SAM is used to perform DCFROR analyses in order to determine the price of the primary commodity required for each operation to obtain a specified rate of return on its investments (*13*). The costs discussed in previous sections form the basis of this evaluation. This determined value is equivalent to an average total cost of production for the operation over its producing life. For this study, a 15-pct DCFROR was considered the necessary rate of return for operations to cover the opportunity cost of capital plus risk. A DCFROR analysis for each property was also performed with a 0-pct rate of return, and both sets of results—for all of the chromium products discussed above—are presented in the remainder of this "Availability" portion of the report. The availability results for the exportable chromite products will be presented first, then the availability results for the ferroalloy products will be discussed.

Metallurgical Chromite

The results of price determination analyses for available metallurgical chromite products (f.o.b. port of export) are discussed in this section. The results are presented for two separate metallurgical chromite groupings: "coproduct" and "primary" metallurgical chromite products.

The coproduct group represents exportable chromite available for metallurgical usage where some other Cr product, usually high-C or low-C FeCr, is the product responsible for the majority of the total revenues for the property. Nearly all of the properties and units with coproduct metallurgical products in the study were in production as of the late 1980's.

The primary group represents exportable products from properties and units where metallurgical chromite products are, or are proposed to be, the major revenue source. By design of the study, the vast majority of the properties and units with metallurgical products as the primary revenue source were in nonproducing status as of the late 1980's.

The metallurgical chromite price determination results to be presented in subsequent text, tables, and curves can be compared to the following 1988 f.o.b. port price levels for South African and Turkish metallurgical chromite (*25*):

Country	Price
South Africa	\$40 to \$46/mt for January through June.
Do.	\$50 to \$56/mt for June through December.
Turkey	\$115/mt for January to May.
Do.	\$125 to \$135/mt for May through June.
Do.	\$150 to \$180/mt for July through December.

Table 19 summarizes the metallurgical chromite availability tonnage in each country for coproduct and primary categories. Also included in the table are the weighted average price determinations, at 0- and 15-pct DCFROR's, for each of the countries listed. As analyzed, a total of nearly 181 Mmt of coproduct and primary chromite products are available for metallurgical use from the seven MEC's listed in table 19.

Table 19.—MEC metallurgical chromite product tonnages and weighted average price determination results, by revenue source category

Country	As coproduct revenue source: Recoverable chromite (kmt)	As coproduct: Price determination results, \$/mt, 0-pct DCFROR	As coproduct: Price determination results, \$/mt, 15-pct DCFROR	As primary revenue source: Recoverable chromite (kmt)	As primary: Price determination results, \$/mt, 0-pct DCFROR	As primary: Price determination results, \$/mt, 15-pct DCFROR
Finland	2,582	47.41	47.57	NAp	NAp	NAp
India	4,965	63.74	68.61	21,449	103.07	128.12
Madagascar ...	NAp	NAp	NAp	4,343	52.65	54.94
Philippines	493	63.59	83.57	3,642	97.49	207.50
South Africa ...	27,254	51.33	55.32	94,479	74.26	84.05
Turkey	318	111.78	115.20	1,398	118.14	134.81
Zimbabwe	NAp	NAp	NAp	20,046	233.95	308.38
Total or wtd avg ..	35,612	53.49	57.54	145,357	100.89	124.20

NAp Not applicable.

Of the total metallurgical chromite recoverable, 19.7 pct (35.6 Mmt) is included in the coproduct group. Fully 83.4 pct (29.7 Mmt) of this coproduct tonnage is recoverable from properties and units producing as of the study date. Figure 5 illustrates the recoverable metallurgical chromite versus average price determination for the coproduct group.

Figure 5 shows price determinations for the coproduct metallurgical chromite ranging from \$33/mt to \$117/mt chromite at the 0-pct DCFROR level and from \$35/mt to \$123/mt chromite at the 15-pct DCFROR level. Respective weighted averages are \$54/mt chromite and \$58/mt chromite.

In figure 5, 25.7 Mmt of the available coproduct metallurgical chromite requires prices, f.o.b. port, between \$33/mt and \$70/mt chromite for a 0-pct DCFROR. Of this low-cost tonnage, 98.6 pct is in producing units and 73.5 pct represents South African products. The price requirements for the remaining 9.9 Mmt of the coproduct tonnage ranged from \$75/mt to \$117/mt at a 0-pct DCFROR. Producing units in South Africa, India, and Turkey contain 4.4 Mmt of the chromite in this price determination range. The additional requirement for a 15-pct DCFROR generally does not change the relative position of properties and units on the curve, indicating that capital requirements for these coproduct metallurgical chromite properties and units are fairly even and comparatively low.

The availability of metallurgical chromite from the primary group is shown in figure 6. This group contains 80.3 pct (145.4 Mmt) of the total recoverable metallurgical products evaluated in this study. Approximately 92 pct (134 Mmt) of this primary metallurgical chromite is contained in resources at properties and units not in production as of the late 1980's. These nonproducing properties/units are located in Zimbabwe, India, the Philippines, and South Africa.

In the primary group, price requirements for metallurgical chromite products ranged from \$42/mt to \$705/mt chromite at a 0-pct DCFROR and from \$48/mt to \$904/mt chromite when evaluated at a 15-pct DCFROR. Respective weighted averages were \$100/mt and \$124/mt chromite.

The results shown in figure 6 can be discussed in terms of three groups of price determination results. The range of lowest price determination results (from \$40/mt to \$100/mt for a 0-pct DCFROR) contains 102.8 Mmt, or 70.7 pct, of the available primary metallurgical chromite. A second division can be drawn for 35.2 Mmt available at \$100/mt to \$250/mt chromite; the remaining 7.4 Mmt is available at prices exceeding \$250/mt chromite for a 0-pct DCFROR.

Of the primary metallurgical chromite contained in producing properties and units, 94.5 pct (about 10.8 Mmt) is available at prices below \$100/mt chromite at a 0-pct DCFROR. The other 5.5 pct in producers (only 0.6 Mmt)

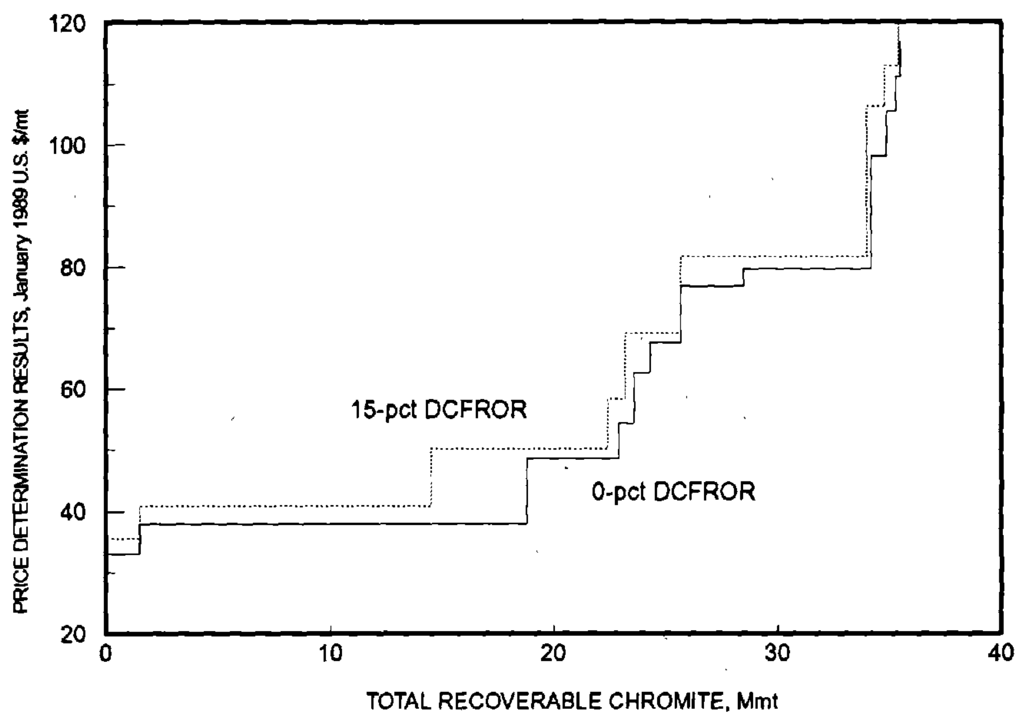

Figure 5.—Coproduct metallurgical chromite potentially available from MEC properties and units (0- and 15-pct DCFROR's).

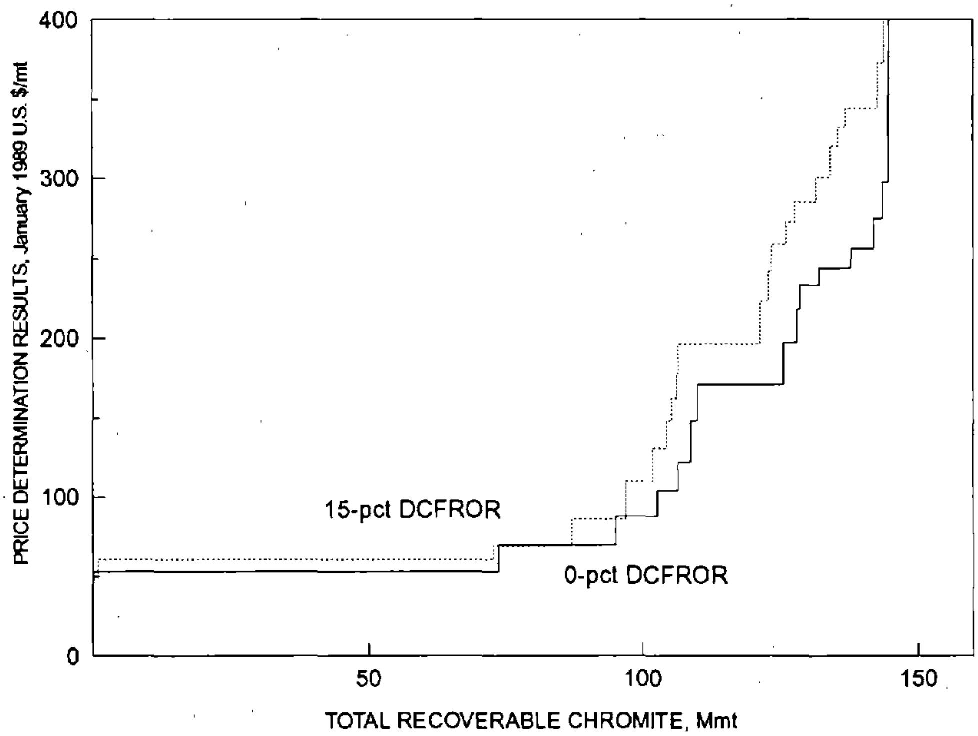

Figure 6.—Primary metallurgical chromite potentially available from MEC properties and units (0- and 15-pct DCFROR's).

was available at average prices between $120/mt and $132/mt chromite.

Most of the nonproducing, primary metallurgical chromite needing prices of less than $100/mt for a 0-pct DCFROR is located in India, South Africa, and Zimbabwe. Primary metallurgical chromite from nonproducing properties and units in the $100/mt to $250/mt chromite price determination range includes properties/units in Zimbabwe, India, the Philippines, and South Africa. The majority of the tonnage in figure 6 shown as available above $250/mt chromite (7.4 Mmt) is contained in nonproducing properties/units in Zimbabwe (89.7 pct) and in India.

Interestingly, figure 6 shows that, in contrast to the coproduct metallurgical chromite, the price determination results for the primary metallurgical chromite group are significantly higher in the highest price range area of the curve when the requirement for a 15-pct DCFROR is added. This can be attributed to the fact that most of the tonnage included in the primary group is contained in undeveloped resources or in past producers that have a consequent need for larger initial capital investments than for the coproduct metallurgical chromite properties and units.

Including a 15-pct DCFROR, 72.5 pct (105.4 Mmt) of the primary metallurgical chromite had price determination results ranging from $48/mt to $150/mt chromite. All of the primary metallurgical tonnage in production as of the late 1980's is contained within this "low-cost" range. The tonnage in this price determination range that was not in production as of the late 1980's is located primarily in India and South Africa.

An additional 18.2 pct (26.5 Mmt)—located in South Africa, India, Turkey, and Zimbabwe—can provide a 15-pct DCFROR at prices between $150/mt and $300/mt. Only a small amount (13.5 Mmt) in Zimbabwe and India requires very high prices ($300/mt to about $900/mt chromite) to obtain a 15-pct DCFROR.

Chemical Chromite

A total of 64.3 Mmt of recoverable chromite concentrates suitable for use in producing chromium chemicals were included in this evaluation. All chemical grade chromite products from South Africa, Madagascar, the Philippines, and Finland were analyzed f.o.b. port, while the Indian and Brazilian products were analyzed for consumption on an internal country market basis.

Of the 64.3 Mmt, a total of 36.1 Mmt is recoverable at operations where the chemical grade chromite product represents the primary revenue generating product. The remaining 28.2 Mmt of chromite for chemical use is contained in properties and units where other Cr products provide the bulk of the total revenue requirements.

Producing properties in South Africa account for 96.7 pct (27.3 Mmt) of the "coproduct" chemical chromite.

South Africa also dominates the total chemical chromite product tonnage with 59.6 Mmt (92.6 pct of the total) contained at eight producing and one nonproducing properties. The remaining 4.7 Mmt is split between the Philippines (50.9 pct), Brazil (18.7 pct), Finland (14.5 pct), India (13.0 pct), and Madagascar (2.9 pct). All of the properties evaluated in Brazil, Finland, and India are presently in production, while two Philippines properties and the Madagascar property are not.

The price determination results showed wide ranges of \$35/mt to \$174/mt chromite concentrate at the 0-pct DCFROR level and from \$37/mt to \$264/mt, including a 15-pct DCFROR. If the highest cost property (a nonproducer) is eliminated, the high ends of the ranges for the 0- and 15-pct DCFROR results are lowered significantly to \$123/mt and \$138/mt, respectively.

Not surprisingly, the lowest price determination results are for the eight South African properties presently in production. The 54 Mmt of potentially recoverable products at these eight properties need prices ranging from \$35/mt to \$60/mt to achieve a 0-pct DCFROR and from \$37/mt to \$68/mt for a 15-pct DCFROR. The non-South African chemical chromite products analyzed as available for the export market had price determination results ranging from \$50/mt to \$174/mt concentrate at a 0-pct DCFROR and from \$54/mt to \$264/mt concentrate for a 15-pct DCFROR.

Refractory Chromite

A total of 26.8 Mmt of recoverable chromite products suitable for use in the manufacturing of refractory bricks, mortars, and other forms of refractories was evaluated. All of the Turkish and Indian refractory chromite was analyzed for in-country usage economics while the South African and Philippines products were analyzed for f.o.b. port economics.

With 22.8 Mmt (85.1 pct of the total) in three producing and two nonproducing properties, South Africa also dominates this major chromite product category. Significantly, 81.8 pct (18.7 Mmt) of the total South African tonnage is contained in the Marico property's underground minable tonnage, which is not currently in production. The 4 Mmt of non-South African refractory chromite is split among the Philippines (55.6 pct), India (24.5 pct), and Turkey (19.9 pct). As analyzed, three producing operations contain all of the refractory chromite tonnage in Turkey and India, while 68.3 pct of the Philippines tonnage is contained in one major producing operation.

The following points are important to an understanding of the refractory chromite price determination results to be presented in this section:

(1) With very high Al_2O_3 grades of 25 to 27 pct and low Cr_2O_3 grades of 30 to 35 pct, the typical Philippines refractory products are unique in comparison to the other MEC refractory chromite products, which usually grade 15 to 22 pct Al_2O_3 and 38 to 45 pct Cr_2O_3.

(2) The South African refractory chromite products analyzed here represent two different types. First, there are the high-Al_2O_3 products (greater than about 19 pct Al_2O_3) that are characteristic of the Marico and Groothoek products. Second, there are the low Al_2O_3 products (in the 15 to 18 pct range) typical of the Winterveld TCL South and the Jagdlust products. Only 9.5 pct of the total analyzed South African refractory chromite tonnage is of the low Al_2O_3 type.

(3) The vast majority of the total refractory chromite product tonnage analyzed here is in properties/units where refractory chromite products are the primary revenue producers. Only 0.94 Mmt (in one South African producer and in a Philippines nonproducer) is present in properties where some other Cr product has been designated as the primary revenue generator.

Table 20 provides a summary of the price determination results for the refractory chromite products. The Indian and Turkish refractory chromite tonnages, which were analyzed for internal usage, have fairly moderate price determination results. The Indian products need prices ranging from \$66/mt to \$91/mt chromite product for a 0-pct DCFROR and from \$77/mt to \$111/mt for a 15-pct DCFROR. Respective weighted averages are \$71/mt and \$83/mt. The Turkish refractory products fall into the same ranges as these Indian price determination results. The actual values have been withheld because only one property was analyzed.

Table 20.—MEC refractory chromite price determination results

Country	Price determination results, \$/mt chromite product			
	0-pct DCFROR		15-pct DCFROR	
	Range	Weighted average	Range	Weighted average
India[1]	66- 91	71.13	77-111	83.29
Philippines ...	103-181	151.77	124-286	197.62
South Africa ..	54- 87	81.95	72-101	85.88

[1]Results for Turkey are within the range given for India.

The f.o.b. port price determinations for the South African and Philippines refractory chromite products show major differences in the price determination results. The South African refractory chromite products need prices ranging from $54/mt to $87/mt chromite product for a 0-pct DCFROR and from $72/mt to $101/mt for a 15-pct DCFROR. Respective weighted averages are $82/mt and $86/mt. The price determination results for the Philippines refractory chromite are much higher, ranging from $103/mt to $181/mt for 0-pct DCFROR's and from $124/mt to $286/mt for 15-pct DCFROR's. Respective weighted averages for these Philippines refractory chromite products are $152/mt and $198/mt.

Foundry Sand Chromite

The availability study addressed the economics of producing a total of nearly 16.4 Mmt of recoverable chromite concentrates suitable for use as foundry sand in terms of SiO_2 content and sizing. The entire tonnage is contained in only eight properties in three countries—South Africa, Finland, and the Philippines. All of these foundry sand products were analyzed for delivery f.o.b. port. The Wosu Sand Project, a significant new producer in Indonesia, was not included in this availability study owing to lack of detailed information. The reader is referred back to table 11 for more information on this Indonesian producer.

Fully 77.3 pct of the analyzed foundry sand chromite tonnage is recoverable as a coproduct at operations where some other Cr product provides the majority of revenue. Only the nonproducing Ntuane property in South Africa was assigned foundry sand chromite as its principal revenue source for this analysis.

As with chemical and refractory chromite, South Africa also dominates the foundry sand product category with 15.9 Mmt (97.3 pct of the total) contained in five producing properties and in one nonproducer. Finland could provide an additional 414,000 mt, and 28,000 mt was estimated to be available from the operation in the Philippines. However, as of 1987, the Kemi mill in Finland was producing only small amounts of foundry sand products on demand, and production of foundry sand had ceased at the Philippines operation.

Of the total South African foundry sand tonnage, 11.1 Mmt was available from four of the five producers at prices ranging from only $38/mt to $48/mt concentrate for a 0-pct DCFROR. By comparison, all of the other MEC properties/units required prices ranging from $51/mt to $83/mt concentrate for a 0-pct DCFROR. Including a 15-pct DCFROR, these same four South African producers required a price range of only $40/mt to $51/mt concentrate, while the other MEC properties and units needed prices of $60/mt to $100/mt concentrate.

High-Carbon Ferrochromium

Figure 7 shows the results of price determinations, at 0- and 15-pct DCFROR's, for high-C FeCr production from chromite resources in the countries of Brazil, Finland, Greece, India, the Philippines, South Africa, Turkey, Zimbabwe, and the United States. Table 21 provides a more detailed breakdown of the total high-C FeCr tonnage, by country, as well as each country's weighted average price determination results at 0- and 15-pct DCFROR's. The price determination results shown in figure 7 and table 21 include mining and beneficiation operating and capital costs, transport to specific smelters, smelting operating costs, taxes, and transport costs to specific port cities for export. Recovery of initial capital costs at the ferroalloy smelters has not been included for reasons discussed earlier in the "Methodology" section.

Table 21.—MEC total recoverable high-C FeCr products and price determination results,[1] by country

(January 1989 U.S. dollars per pound Cr)

Country	Recoverable high-C FeCr (kmt)	Price determination results (wtd avg[2])	
		0-pct DCFROR	15-pct DCFROR
Brazil	3,682	0.55	0.57
Finland	6,237	.46	.46
Greece	421	.44	.52
India	4,207	.40	.42
Philippines	597	.41	.44
South Africa	41,780	.34	.36
Turkey	2,532	.32	.34
United States	4,957	.39	.51
Zimbabwe	9,871	.42	.45
Total or wtd avg	74,284	.38	.41

[1]Price determination results include mining and beneficiation operating and capital costs, taxes, transport to specific smelters, smelting operating costs, and transport costs to specific port facilities for export. Results do not include recovery of smelter capital costs.

[2]Weighted averages are for the entire country, based on chromite feed from specific chromite properties/units to existing smelters as of the study date (January 1989).

Figure 7 shows a total of 74.3 Mmt of high-C FeCr available from these nine MEC's. A large portion (74.6 pct, or 55.4 Mmt) of the total high-C FeCr potentially available can break even (0-pct DCFROR) at prices ranging from $0.28/lb to $0.42/lb Cr. Nearly all (97.8 pct) of the South African high-C FeCr is available in this price range, as is a fair amount of Turkish and Indian production. Portions of the Greece, Zimbabwe, and Philippines production and two of the three nonproducing U.S. units are also in this price range.

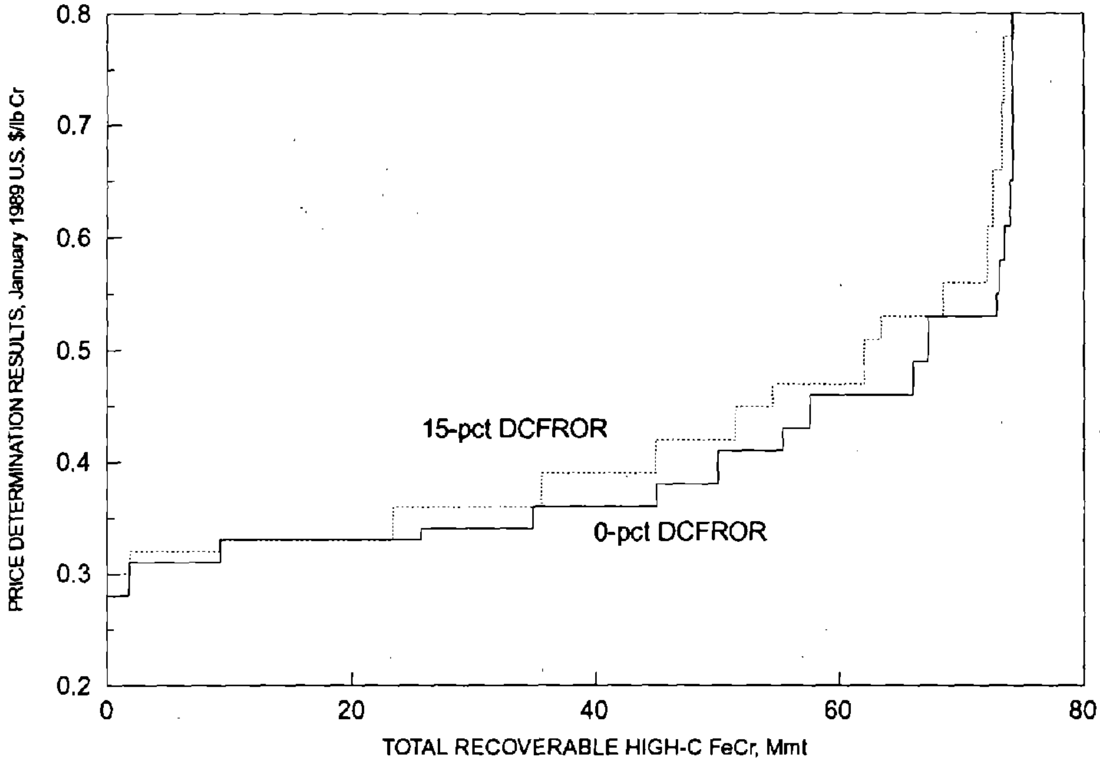

Figure 7.—High-C FeCr potentially available from MEC properties and units (0- and 15-pct DCFROR's).

Nearly 12 Mmt (16.1 pct of the total) required prices ranging from $0.42/lb to $0.49/lb Cr at a 0-pct DCFROR. This group included Finland, fair portions of production from India, the Philippines, Zimbabwe, and the third U.S. nonproducer. Price determinations for the highest cost group ranged from $0.52/lb to $1.07/lb Cr for a 0-pct DCFROR. However, only 6.9 Mmt (9.3 pct) of the total available high-C FeCr falls into this highest cost range. This tonnage was primarily from Brazil and Zimbabwe, with a small portion from Greece and India.

At a 15-pct DCFROR, the price determinations for the low-cost group ranged from $0.30/lb to $0.47/lb Cr. This price determination range contains fully 82.9 pct (61.6 Mmt) of the total and includes all of the Finland and South African high-C FeCr, as well as much of the potential production from Greece, India, and Zimbabwe. This group also contained a little of the Philippines production and one of the U.S. nonproducers.

The middle-cost group for 15-pct DCFROR's ranged from $0.48/lb to $0.57/lb Cr, and the 10.6 Mmt of high-C FeCr in this group included a fair portion of Brazil, India, Zimbabwe, and Philippines production, along with the second of the three U.S. nonproducers. Only 2.1 Mmt (2.8 pct) of the total available high-C FeCr is in the highest cost group for a 15-pct DCFROR, needing prices ranging from $0.60/lb to $1.18/lb Cr. The tonnage in this group is composed of the third U.S. nonproducer, along with portions of the Zimbabwe, Brazil, and Greece production.

As part of this study, price determinations where smelter capital costs were included were made only for the U.S. properties/units. This added smelting capital recoupment requirement raised the weighted average price requirement to produce 5 Mmt of high-C FeCr from $0.39/lb Cr to $0.42/lb Cr for a 0-pct DCFROR and from $0.51/lb Cr to $0.72/lb Cr for a 15-pct DCFROR. In total, it is estimated that $365 million (January 1989 dollars) would be required to develop all the necessary facilities for production of 546,000 mtpy of chromite concentrates and smelting to 247,000 mtpy of high-C FeCr at these three U.S. resource areas. About half of this total represents the costs to construct kilns and furnaces for smelting at the proposed sites.

Low-Carbon Ferrochromium

Figure 8 shows the results of price determinations, at 0- and 15-pct DCFROR's, for low-C FeCr production from chromite resources in the countries of Brazil, India, South Africa, Turkey, and Zimbabwe. Table 22 provides a more detailed breakdown of the total low-C FeCr tonnage, by country, as well as each country's weighted average price determination results at 0- and 15-pct DCFROR's.

Table 22.—MEC total recoverable low-C FeCr products and price determination results,[1] by country

(January 1989 U.S. dollars per pound Cr)

Country	Recoverable low-C FeCr (kmt)	Price determination results (wtd avg[2])	
		0-pct DCFROR	15-pct DCFROR
Brazil	216	$0.94	$0.96
India	162	.77	.78
South Africa	2,592	.61	.64
Turkey	60	.80	.83
Zimbabwe	878	.78	.81
Total or wtd avg	3,908	.68	.71

[1]Price determination results include mining and beneficiation operating and capital costs, taxes, transport to specific smelters, smelting operating costs, and transport costs to specific port facilities for export. Results do not include smelter capital costs.

[2]Weighted averages are for the entire country, based on chromite feed from specific chromite properties/units to existing smelters as of the study date (January 1989).

The price determination results shown in figure 8 and table 22 include mining and beneficiation operating and capital costs, transport to specific smelters, smelting operating costs, taxes, and transport costs to specific port cities for export. Recovery of initial capital costs at the low-C FeCr smelters has not been included because all of the facilities are more than 10 yr old.

Figure 8 shows a total of 3.9 Mmt of low-C FeCr available from these five MEC's. Table 22 shows that South Africa and Zimbabwe represent a very large portion (88.8 pct) of this potential low-C FeCr output. In both of the low-C FeCr cost curves (0- and 15-pct DCFROR's) on figure 8 there is a "low-cost" group that contains 2.7 Mmt of the potential low-C FeCr production. All of the South African production is included in this group. For a 0-pct DCFROR, this group needs prices ranging from $0.48/lb to $0.71/lb Cr. India and Zimbabwe also have some production in this lower cost range. However, most of the India and Zimbabwe production is in the higher cost range, as is all of the low-C FeCr production from Turkey and Brazil. This higher cost group, containing 1.2 Mmt of low-C FeCr, needs prices ranging from $0.73/lb to $0.94/lb Cr for a 0-pct DCFROR.

To obtain a 15-pct DCFROR, the low-cost group required prices ranging from $0.51/lb to $0.73/lb Cr, while the high-cost group's price range is from $0.76/lb to $0.96/lb Cr.

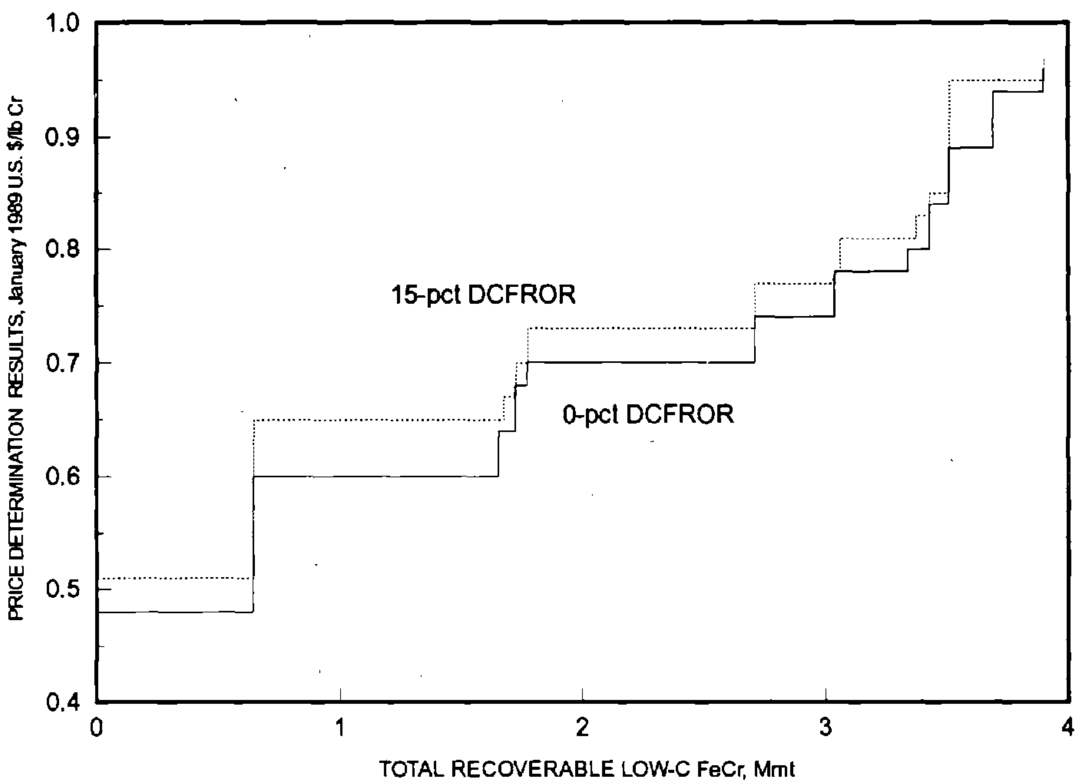

Figure 8.—Low-C FeCr potentially available from MEC properties and units (0- and 15-pct DCFROR's).

Ferrochromium-Silicon

In addition to high- and low-C FeCr, the availability study analyzed the economics of delivering a total of 2 Mmt of Zimbabwean ferrochromium-silicon production to port for export. This export tonnage is available from the smelting of producing Great Dyke seam resources. All ferrochromium-silicon production in this analysis was assumed to have a grade of 38 pct Cr.

The ferrochromium-silicon available for export required prices ranging from \$679/mt to \$822/mt for a 0-pct DCFROR and from \$705/mt to \$871/mt for a 15-pct DCFROR. Respective weighted averages were \$735 and \$755/mt ferrochromium-silicon, which are equivalent to \$0.88 and \$0.90/lb Cr.

Summary

The economics of extracting a total of 873.5 Mmt of in situ chromite ore containing 202.5 Mmt of Cr were evaluated for the availability portion of this study. The tonnage is located in 10 MEC's. On a contained Cr_2O_3 basis, the in situ ore in each of the 10 countries can be assigned to either a high-grade or a low-grade group. The high-grade group, ranging from 33.96 pct to 43.01 pct Cr_2O_3, comprises the countries of India, Madagascar, South Africa, Turkey, and Zimbabwe. The low-grade group, with Cr_2O_3 grades ranging from 9.16 pct to 26.60 pct Cr_2O_3, consists of Brazil, Finland, Greece, the Philippines, and the United States.

Taking into account estimated mining and beneficiation losses, a total of 475.4 Mmt of marketable chromite products would result. Of the 475.4 Mmt of available chromite products, smelting 186.9 Mmt would result in production of 74.3 Mmt high-C FeCr, 3.9 Mmt low-C FeCr, and 2.0 Mmt of exportable ferrochromium-silicon. The remaining 288.5 Mmt of available chromite is composed of 181.0 Mmt for metallurgical uses, 64.3 Mmt for chemical uses, 26.8 Mmt for refractory purposes, and 16.4 Mmt for use as foundry sand. Table 23 summarizes the ranges and weighted averages of the 0-pct DCFROR price determination results for all of the product categories of the availability study.

South Africa and Zimbabwe dominate all resource and product categories in the study. These two nations contain 70.8 pct of the analyzed in situ material and 80.5 pct of the Cr contained in that tonnage. Combined, they also represent 69.5 pct of the potential high-C FeCr tonnage, 88.8 pct of the low-C FeCr tonnage, 100 pct of the exportable ferrochromium-silicon tonnage, 78.3 pct of the metallurgical chromite products, 92.6 pct of the chemical chromite products, 85.2 pct of the refractory products, and 97.3 pct of the potential foundry sand products.

The 181 Mmt of metallurgical chromite is split into two groups: a coproduct group, composed mostly of producing operations, and a primary group consisting mostly of nonproducing properties and units. Respective chromite product tonnages for these two groups are 35.6 Mmt and 145.4 Mmt. The price determination results for the coproduct group are significantly lower than for the primary group. On a country-by-country basis, the coproduct metallurgical chromite can achieve 15-pct DCFROR's at prices ranging from \$48/mt for Finland to \$115/mt for Turkey, with an overall weighted average of \$58/mt. Comparable results for the primary metallurgical products range from \$55/mt for Madagascar to \$308/mt for Zimbabwe, with an overall weighted average of \$124/mt.

Table 23.—Summary of availability study results

Chromium product category	Recoverable products (Mmt)	Price determination results (0-pct DCFROR, Jan. 1989 U.S. dollars)	
		Range	Wtd avg
Chromite:			
Metallurgical, coproduct	35.6	33-117/mt product	54/mt product.
Metallurgical, primary	145.4	42-705/mt product	101/mt product.
Subtotal, metallurgical	181.0	33-705/mt product	92/mt product.
Chemical	64.3	35-174/mt product	53/mt product.
Refractory	26.8	54-180/mt product	87/mt product.
Foundry sand	16.4	39-83/mt product	49/mt product.
Chromium ferroalloys:			
High-C FeCr	74.3	0.28-1.07/lb Cr	0.38/lb Cr.
Low-C FeCr	3.9	0.48-0.95/lb Cr	0.68/lb Cr.
FeCrSi	2.0	0.69-0.98/lb Cr	0.88/lb Cr.

Price determination results for the chemical, refractory, and foundry sand chromite products show a decided cost and tonnage advantage for South Africa. In the chemical chromite results, all of the South African tonnage can achieve 15-pct DCFROR's at prices ranging from \$36/mt to \$68/mt, while all other MEC products require a range of \$54/mt to \$138/mt. In the refractory results, all of the South African products need prices ranging from \$72/mt to \$101/mt for 15-pct DCFROR's, while the other major MEC refractory exporter, the Philippines, requires prices ranging from \$124/mt to \$286/mt. In the foundry sand results, four major South African producing properties, representing 70 pct of the analyzed potential production in South Africa, need prices ranging from only \$40/mt to \$51/mt to achieve a 15-pct DCFROR; all of the other MEC sources outside of South Africa require \$60/mt to \$100/mt.

Including a 15-pct DCFROR, nearly all (97.2 pct) of the high-C FeCr was potentially available at prices ranging from \$0.30/lb Cr to \$0.57/lb Cr, and 82.9 pct would be available at prices up to \$0.47/lb Cr. On a country basis, South Africa and Turkey have the lowest price determination results (15-pct DCFROR), with weighted averages of \$0.36/lb and \$0.34/lb Cr, respectively. Two of the three nonproducing U.S. chromite resource units had results in this \$0.30/lb Cr to \$0.57/lb Cr price range for a 15-pct DCFROR; the third U.S. unit had higher costs.

The low-C FeCr price determinations fall into two main groups: a low-cost group dominated in terms of tonnage by South Africa and a high-cost group dominated by Zimbabwe. For a 15-pct DCFROR, the low-cost group's price determination range was \$0.50/lb Cr to \$0.73/lb Cr, and the high-cost group results ranged from \$0.76/lb Cr to \$0.96/lb Cr. The exportable ferrochromium-silicon, all from Zimbabwe, required prices ranging from \$705/mt to \$871/mt ferrochromium-silicon (\$0.84/lb Cr to \$1.04/lb Cr) for a 15-pct DCFROR.

NETWORK FLOW MODEL

This section of the report focuses on world chromium markets. The network flow model built to examine them is a deterministic, multiyear optimization model and is described in detail in appendixes F and G. It combines a detailed, engineering based supply side with statistically derived consumption forecasts to estimate market equilibrium and country aggregate production levels. Demand methodologies, forecasts, demand levels, and growth rates used in the model for all chromium products are discussed in detail in appendix E.

As opposed to the availability study results just presented, which were only for 10 major market economy chromite resource countries, the network flow model includes all market economy and centrally planned economy chromite producing and smelting countries. In addition, assessments of chromium chemical and refractory plant capacities in MEC's and CPEC's have also been included in the network flow model. Supply-demand aspects of the MEC foundry sand chromite industry were also included in the model.

Over the multiyear simulation, the model is used to predict depletion rates, new mine development, and trends in delivered costs. Specifically, the model is used to examine the basic issues facing chromium markets that were mentioned in the "Introduction": the boom of 1987-88, the prospects for all of the chromium industry through 1994, and the impact on chromium markets of hypothetical North American sanctions against South African imports.

The following paragraphs discuss two very important aspects for consideration as the results of the network flow model solutions are presented in this section of the report. They are (1) the question of what represents the "correct" smelting capacity and (2) the cost minimization aspects of the model.

The question of what total value represents the "correct" FeCr smelting capacity is a difficult one. It involves a determination of operating or proposed furnaces, their sizes (the transformer capacity), the typical power load used in smelting, the product dedication of each furnace (high-C FeCr or ferrochromium-silicon and slag for low-C FeCr), and the technology to be used (conventional or prereduction methods for high-C FeCr, etc.).

The relationship between the transformer capacity of a furnace and the operating power load is very important. For example, at 105 kV•A, the No. 12 furnace at the smelter near Vargon, Sweden, has the largest transformer capacity of any furnace dedicated to FeCr production in the world. This furnace could theoretically be operated with a power load of 85 MW. However, as of the late 1980's, the furnace was being operated at power loads of only 50 to 52 MW for production of about 100,000 mtpy high-C FeCr. In the more normal range of transformer sizes—10 to 40 kV•A—the furnaces will normally be operated at power loads ranging from 8 to 32 MW.

The capacities built into the present network flow model are based on two criteria. First, it includes only operating and proposed furnaces, circa 1986-89, that were dedicated, or were planned to be dedicated, to chromium ferroalloy production. Second, given (or estimated) transformer sizes and power loads, as of that same time period, were used in determining full smelting capacities for these furnaces. Table F-3 (appendix F) summarizes, by country, the full high-and low-C FeCr capacities in this network flow model for the year 1989 and the number of smelters and furnaces composing the total capacity estimates for each country.

Except to a limited degree,[18] the smelting capacity built into the present model does not address two other important aspects for consideration as to the "correct" smelting capacity. The first is the flexibility of any electric arc furnace to be converted—with modifications to the refractories, the shell size, or the transformer capacity—from chromium ferroalloy dedication to, particularly, manganese ferroalloy or ferrosilicon dedication, or vice versa. The second is the existence—particularly in the United States, Japan, and several European countries—of many furnaces that were either idled (decommissioned) or converted from chromium ferroalloy production in the early to mid-1980's that had not been recommissioned or converted back to chromium ferroalloy production by the 1986-89 period.

It would be impossible to include in the network flow model all of the electric arc furnaces in existence that could potentially either be converted to chromium ferroalloy production or be recommissioned. The arguments in favor of the present network flow model's smelting capacity levels; that is, including only announced conversions or recommissions, are many, particularly for the years of 1986-89. For idled furnaces, the main argument is that many of these were very small in size and located in countries that do not have their own chromite resources (i.e., least economical at the time of shutdown). Also, all were shut down during the 1979-85 period and many have probably been "cannibalized." In addition, it does take time—6 months to a year—to restart a furnace that has been idled for some time.

The main argument for limiting the potential conversion of furnaces from other alloy production to chromium ferroalloy production concerns the availability of chromium resources to a particular smelter. For example, the three 18 MV•A furnaces added during 1985-87 at the Pojuca smelter in Brazil were all dedicated to FeSi production at the start. However, in 1987 the company announced plans to convert one of the furnaces to high-C FeCr production. The conversion still hasn't occurred likely because of the company's chromite reserve position.

Another argument is that, as with recommissioning of idled furnaces, conversion takes 6 months to a year to complete. Finally, conversion from manganese ferroalloy production to chromium ferroalloy production requires that a certain amount of technical expertise—specific to chromium—exist within the company and that the layout of the smelter's raw material distribution system should be such that contamination does not occur.

As mentioned in the "Methodology" section, network flow models are based on the principle of technical economic efficiency, the goal of which is to produce a given level of output with the minimum use of resources, i.e., at the lowest opportunity cost. The model's solutions assume that decisions as to whether to produce or not are made rationally and are based on comparative economics. Such is often not the case in the world ferroalloy industry where government (and company) policies may dictate employment levels, operating rates, and prices, especially where government ownership is also involved.

Years 1 Through 4 (1986-89)

Model simulations were first used to examine 1986-89 markets for high-C and low-C FeCr, FeCrSi, SBE,[19] and refractory and foundry sand chromite.[20] A discussion of the model's solutions for the 1986-89 period is useful for three main reasons. First, solutions for these years can be compared with reported import, export, and production data to judge how representative the model is of historic market actions. Second, insights can be gained from consideration of those production allocations that differed from reported production levels. Finally, 1986-89 was an interesting period for the chromium industry, which included a "bust to boom" market, the constant threat of sanctions being imposed on South Africa by various entities, and the development, maturation, or introduction of smelting technologies such as plasma arc smelting, the INMETCO process, and the Krupp-CODIR process.

Initially, 1988 chromite and ferrochromium production estimates from the model solutions will be compared with reported production. Results suggest that the model's least cost criteria (i.e., production coming from properties and units that have the lowest relative delivered costs) lead to consistently acceptable estimates of chromite production and its allocation, by country, for MEC's. The production estimates for ferrochromium products exhibit more variability; they agree with reported production for some producers but not for others. Both of these results are considered in the following sections.

[18]The present network flow model contains only two announced furnace conversion projects. One was a planned conversion of a FeSi furnace in the Philippines; the other was a planned Venezuelan project that would have involved the relocation of three furnaces from Norway and conversion of the furnaces to FeCr production.

[19]In this report chromium chemical plant output capacities are all presented in terms of sodium bichromate equivalent (SBE) tonnages. Sodium bichromate contains 35 pct Cr, by weight.

[20]In the model there are no specific demand points for either metallurgical or chemical chromite; rather, metallurgical chromite demand will be a direct function of the demand for Cr ferroalloys, and chemical chromite demand will be a direct function of demand for SBE.

Chromite

As shown in table 24, the 8.28 Mmt of estimated 1988 chromite production for MEC's (all countries except the U.S.S.R., Albania, Cuba, and Vietnam), based on the model results, rather closely matches the 7.66 Mmt MEC production estimated by the Bureau. However, the network model solution's total worldwide production of chromite was only 10.9 Mmt in 1988, which was 10.4 pct less than the Bureau's estimated production of 12.17 Mmt. This discrepancy is almost entirely the result of differences in the respective estimates for U.S.S.R. and Albanian chromite production.

Table 24.—Comparison of world chromite production estimates for 1988

(Thousand metric tons of chromite products)

Country	Network model solution estimate[1]	Bureau of Mines estimate[2]
South Africa	4,580	4,245
U.S.S.R.	2,010	3,700
India	640	759
Finland	640	700
Zimbabwe	630	562
Albania	570	750
Turkey	560	625
Brazil	460	240
Philippines	350	190
Greece	110	63
Madagascar	100	107
New Caledonia	85	70
Cuba	45	55
Indonesia	42	8
Pakistan	38	3
Sudan	20	8
Oman	11	—
Japan	10	10
Burma	—	—
Iran	—	56
Vietnam	—	4
Yugoslavia	—	12
Thailand	—	1
Total	10,901	12,168

[1]Determined by listing metric tons of Cr flow on all arcs feeding smelters, all arcs flowing into demand nodes, and all export arcs and dividing these Cr flow values by the Cr grade of the chromite product.

[2]Source: U.S. Bureau of Mines (23).

NOTE.—Dash indicates no applicable value.

In the design of this model, the chromite production capacity levels in the model for the U.S.S.R. and Albania were preset at levels commonly reported in the literature. Connections were then made to internal U.S.S.R. and Albanian demand nodes to represent chromite requirements needed to fulfill commonly reported production capacities for ferrochromium, chromium chemicals, and refractory chromite usage. Connections were also made to the MEC markets in the model to allow for exports of chromite products from the U.S.S.R. and Albania.

In the results of the model's simulations, not all of the preset chromite production capacity for both the U.S.S.R. and Albania was needed to fulfill both the preset internal demand levels and the simulation's estimated level of exports. In particular, the model's chromite export levels from the U.S.S.R. and Albania were much lower than the commonly reported values. As a result, much of the U.S.S.R. and Albanian production collected in hypothetical inventory stockpiles.

This model's results for 1988 suggest that reported chromite production levels for the U.S.S.R. and Albania are much larger than the quantities required for internal consumption and for export in competitive worldwide chromite markets. The difference between the estimates using the model's solution and other estimates of U.S.S.R. and Albanian chromite production could be due to several factors, the most significant of which is that chromite production may be overreported in terms of either ROM tonnage or Cr grade.[21] Conversely, trade of chromite between CPEC's may be underrepresented by the model, or internal chromium product use in the U.S.S.R. may be higher than reported. These alternatives all warrant further study.

Of the total worldwide chromite production for the 1988 solution, the model shows that about 34 pct of chromite production is exported and 66 pct is used internally. This result is close to a separate, independent estimate by the Bureau that 38 pct of world chromite production was being exported in 1988 (*26*). The model also estimates that 76.9 pct of total world chromite consumption in 1988 was being used for metallurgical purposes, 13.1 pct for chemical uses, 8.5 pct for refractory uses, and 1.5 pct for foundry sand uses.

The model results give an estimated production level for South Africa that is 7.9 pct higher than the Bureau's production estimate. The difference is not large but does point out that the model is unable to distinguish between differing Cr-Fe ratios in chromite products. Because of this, the model's solutions discriminate in favor of the lowest cost metallurgical chromite products, which are the lower Cr-Fe ratio products typical of South African output. As a specific example, it is noted that the present model's solutions have South African chromite providing nearly all of the metallurgical chromite needs for the Eastern European countries of Czechoslovakia, Poland, and Romania.

[21]For the U.S.S.R., the total ROM capacity in the model is 3.6 Mmt at 30.86 pct Cr (45.4 pct Cr_2O_3) and for Albania the total ROM capacity is 1.7 Mmt at 26.59 pct Cr (39.1 pct Cr_2O_3).

Analysis of model results shows production in Brazil and the Philippines as larger than the reported amounts. The higher levels in the model are mostly due to ore requirements for the reported FeCr smelting capacity in these two countries. It is possible that the Bureau's present estimates for 1988 production in these two countries may be too low.

Ferrochromium

Tables 25 and 26 summarize MEC and CPEC high-C and low-C FeCr production in 1988 according to the network flow model's solution for that year. The tables present the production amounts, by country, in terms of mt FeCr and also present capacity use levels for each country in the model. The total FeCr production in MEC's reported in the tables is a function of the model's demand for Cr in FeCr, with values for the three major regional markets (North America, Asia, and Western Europe) being statistically estimated via the intensity of use (IU) method (see appendix E for details). The FeCr tonnage estimates are calculated from the model's Cr flows on smelter capacity arcs using the percentages of Cr in FeCr that are listed, by country and by ferroalloy product, at the end of appendix F.

In comparing the model's results of tables 25 and 26, by country, to production estimates of the Bureau, it was necessary to combine the model's high- and low-C FeCr production estimates into one overall FeCr total for each country. This comparison of the model's 1988 results to the Bureau's estimates for 1988 is shown in table 27.

In turn, the estimates of tables 25-27 can be compared with two other production estimates as follows:

Company	Production, Mmt
SAMANCOR (24) 1988 MEC high-C FeCr production	2.36
Shearson Lehman Hutton (27) 1988 MEC high-C and low-C FeCr production	2.49

Based on the Cr flow in the model, it was estimated that approximately 2.54 Mmt FeCr was produced in MEC's in 1988 (table 27) and that 2.30 Mmt of this production was high-C FeCr (table 25). It is also of note that the model estimates South African FeCr output at 1,003,000 mt FeCr in 1988, virtually identical to the 997,700 mt reported by the Bureau. These values are all quite close to the other published production estimates, suggesting that the IU method forecasts very reasonable consumption values for metallurgical uses.

In addition to South Africa, the model's FeCr allocations for Brazil, Greece, Finland, the Philippines, Yugoslavia, and Zimbabwe are all different from the Bureau's estimates by only 16 pct or less. On this basis, nearly 70 pct of 1988 MEC FeCr production can be considered as reasonably allocated on a country-by-country basis by the network flow market model.

Table 25.—Estimated world high-C FeCr production for 1988, network flow model solution, by country

Country	Production estimate (kmt)	Capacity use (pct)[1]
Market economy:		
South Africa	937	97.7
Zimbabwe	184	93.9
Finland	181	100.0
India	179	96.0
Sweden	159	100.0
Brazil	118	99.5
Italy	106	100.0
Turkey	106	99.2
Yugoslavia	89	100.0
Philippines	85	100.0
United States	55	[2]100.0
Greece	40	100.0
Japan	26	7.9
France	15	100.0
Taiwan	15	100.0
Mexico	7	100.0
Spain	—	—
MEC total or wtd avg	2,302	86.9
Centrally planned economy:		
U.S.S.R.	295	100.0
China	122	100.0
Poland	68	100.0
Albania	45	100.0
Romania	43	96.4
Czechoslovakia	30	100.0
CPEC total or wtd avg	603	99.8
World total or wtd avg	2,905	89.5

[1]Calculated by dividing the amount of Cr flowing on all ferroalloy production arcs by the upper bound values set on each of those production arcs.

[2]U.S. capacity use calculation does not include furnaces assigned to Defense Department ore conversion program.

NOTE.—Dash indicates no applicable value.

Table 26.—Estimated world low-C FeCr production for 1988, network flow model solution, by country

Country	Production estimate (kmt)	Capacity use (pct)[1]
Market economy:		
South Africa	66	100.0
Germany, Federal Republic of	41	100.0
Zimbabwe	32	100.0
India	30	100.0
Yugoslavia	18	98.5
Brazil	14	100.0
United States	12	100.0
Japan	11	29.9
Turkey	10	100.0
MEC total or wtd avg	234	89.9
Centrally planned economy:		
U.S.S.R.	127	100.0
China	50	100.0
CPEC total or wtd avg	177	100.0
World total or wtd avg	411	94.0

[1]Calculated by dividing the amount of Cr flowing on all ferroalloy production arcs by the upper bound values set on each of those production arcs.

A least-cost allocation of the remaining 30 pct of MEC FeCr output generates results that differ from the Bureau's reported levels and raise interesting questions about ferrochromium markets. The 1988 solution shows Japan's capacity use for high-C FeCr at only 8 pct and for low-C FeCr at 30 pct, a total production level of only 37,000 mt FeCr. These low capacity use rates highlight the fact that the Japanese FeCr smelting industry faces some of the highest costs in the MEC's, particularly for electricity. However, the Bureau reports production to have been approximately 296,000 mt in 1988. There are several possible explanations for this large (259,000 mt) difference in estimated Japanese FeCr production:

(1) All of the Japanese FeCr smelters operating as of 1988 are directly associated, through ownership, with major steel producing companies. With integration, facilities that would otherwise be noneconomic can continue to operate since an integrated firm can choose where to take its profits, for example at either the ferroalloy production or the steel-making level.

(2) Some of the Japanese production of the late 1980's may have been for the country's strategic stockpile program. In such a situation, facilities are operated for noneconomic reasons. Because the network is a cost minimizing model, production estimates will be lower than reported production for properties and units that operate for noneconomic reasons.

(3) The estimated demand levels in the network model could be somewhat lower than actual demand. This explanation appears to be the least likely, given the close correlation between the overall model results and overall production estimates from other sources that were compared earlier in this section.

Table 27.—Comparison of world FeCr[1] production estimates for 1988, by country

Country	Network model solution estimate (kmt)	Bureau of Mines estimate[2] (kmt)
Market economy:		
South Africa	1,003	998
Zimbabwe	216	224
India	209	123
Finland	181	156
Sweden	159	113
Brazil	132	130
Italy	106	55
Turkey	116	54
Yugoslavia	107	93
Philippines	85	76
United States	67	W
Germany, Federal Republic of	41	60
Greece	40	44
Japan	37	296
France	15	18
Taiwan	15	—
Mexico	7	9
Spain	—	20
MEC total	2,536	2,469
Centrally planned economy:		
U.S.S.R.	422	450
China	172	172
Poland	68	45
Albania	45	46
Romania	43	42
Czechoslovakia	30	25
German Democratic Republic	—	23
CPEC total	780	803
World total	3,316	3,272

W Withheld; not included in MEC or world totals.
[1]Includes high-C and low-C FeCr.
[2]Source: U.S. Bureau of Mines (28).

NOTE.—Dash indicates no applicable value.

Detailed, smelter specific explanations for the misallocations can also be found in closer analysis of the results in table 27. For example, assuming that the total MEC demand values in the model are reasonably close to reality, the minimal Japanese production level should result in the model's output for several other countries being larger than would otherwise have been the case. Specifically, nearly all of the lower production estimate in the model solution for Japan is compensated for in the model by 245,000 mt of higher FeCr output than was reported by the Bureau for only four countries: India, Italy, Sweden, and Turkey.

As discussed in appendix B, power and ore availability shortfalls commonly result in actual Indian FeCr production being less than the theoretical capacity (see table B-2). The higher estimate in the model's solution for Turkey is partially the result of a network flow model design that allowed production in 1988 from one of the two new furnaces at the Elazig smelter. In actuality, even though construction of both furnaces was complete by mid-1988 to late 1988, no production came from either of these furnaces until late 1989. With the startup of the two new furnaces, Turkish costs are relatively low, suggesting that output from these furnaces will be competitive on a delivered cost basis.

Similarly, the model's higher production level for Sweden requires that at least one of the two furnaces at the Malmo plasma arc smelting operation be producing at full capacity of about 37,500 mt. In actuality, 31,383 mt were produced in 1988. Finally, the 1988 FeCr smelting capacity estimate presently in the model for the country of Italy (106,000 mtpy of high-C FeCr) could be significantly overestimated.

Basically, the misallocations in the model solutions for 1988 involve underestimation for Japan and overestimation for many Western European countries. Although operating costs in Finland, Sweden, and Italy are lower than in Japan, they are high compared to those in South Africa, Zimbabwe, and Turkey. If the Japanese smelters continue to produce, smelters in these European countries may lose market share and face subsequent rationalizations. In fact, the plasma arc smelter of SwedeChrome AB was closed in January 1990 (*29*).

The results of the model suggest significantly decreased Japanese FeCr production in the 1990's. If this occurs, the countries identified above could temporarily gain market share. However, the results of simulations through 1994 (discussed next) show that if FeCr capacity expansions are made in countries with chromite resources, production in chromite importing countries will be affected. In the long run, FeCr production will probably continue to shift away from countries without chromite resources.

Late in 1987, prices for high-C FeCr jumped dramatically from approximately \$0.40/lb Cr to above \$0.70/lb Cr, eventually reaching \$1.00/lb Cr on the spot market in mid-1988. These price increases were followed directly by a number of announcements in 1988 of new high-C FeCr capacity in South Africa, Zimbabwe, the Philippines, and several European nations. The results of the model simulations for 1986 through 1989 suggest that this price increase was directly related to capacity use levels.

Ferrochromium capacity uses in MEC's for 1986 through 1989 were calculated by comparing the simulation's level of Cr flow to Cr capacity at each furnace (or other type of capacity arc) in the model. Although the production allocations by country do not exactly replicate those reported by the Bureau, this method of capacity use calculation ensures that overall (on an MEC or worldwide basis) capacity use percentages (i.e., the total Cr flow) are still valid. The resulting MEC high-C and low-C FeCr capacity use percentages for the 1986-89 period, given in figures 9 and 10, respectively, show distinct capacity constraints developing for both high-C and low-C FeCr in 1987.

Analysis of the model's solution shows MEC high-C FeCr capacity use at only 83 pct in 1986, jumping to 93 pct in 1987. If the high price levels were related to the capacity constraints, they should have moderated by yearend 1989, when the model's high-C FeCr capacity use declines to only 81 pct. In fact, spot prices for high-C FeCr had already dropped to \$0.715/lb by October of 1989 (*30*).

This decline in the model's percentage of MEC capacity use is due solely to the addition of a large amount of new MEC high-C FeCr capacity (286,503 mt of Cr) in 1988 and 1989,[22] which is a 22-pct increase from the 1987 capacity level (only verified expansions were built into the model for the 1988-89 time period). Meanwhile, the model's Cr in high-C FeCr demand level increased only 18.5 pct from 1,156,852 mt Cr for 1986 (the base year for the simulations) to 1,371,263 mt Cr for 1989.

The MEC low-C FeCr capacity use was 99 pct of capacity in the 1987 solution and represents an increase from 95 pct use in 1986. This very high percentage of capacity use for 1987 appears to explain why the Marietta, Ohio, smelting complex chose—very early in 1988—to restart low-C FeCr production from idled furnaces. In the model, the addition of this low-C FeCr capacity in the United States is a main reason why the capacity use percentages for low-C FeCr in the 1988 and 1989 solutions decrease to the 90-pct level.

As discussed in this section, the model solutions for 1986 through 1989 either replicate the chromium industry production and actions accurately or presage potential or already observed market changes. As these results argue for the validity of the model, it will now be used to forecast future market conditions.

[22]The model's new capacity additions for 1988 and 1989 are estimated to be equivalent to 480,000 mtpy of high-C FeCr, divided between South Africa (153,000 mtpy), Turkey (109,000 mtpy), India (58,000 mtpy), and Western Europe (93,000 mtpy). The remaining 67,000 mtpy of new capacity is in the countries of Japan, the Philippines, and Zimbabwe.

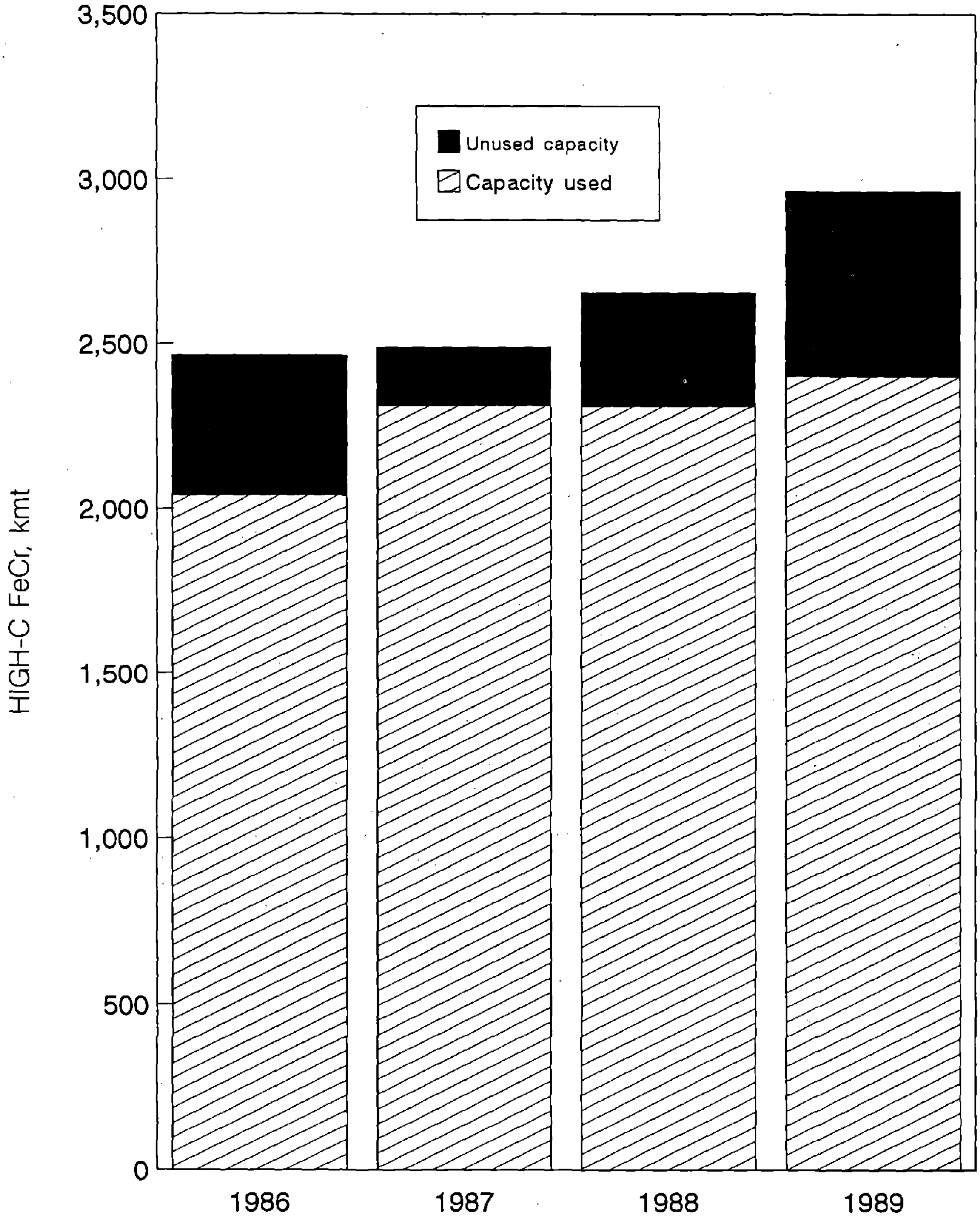

Figure 9.—MEC high-C FeCr capacity use percentages; model solutions for 1986-89.

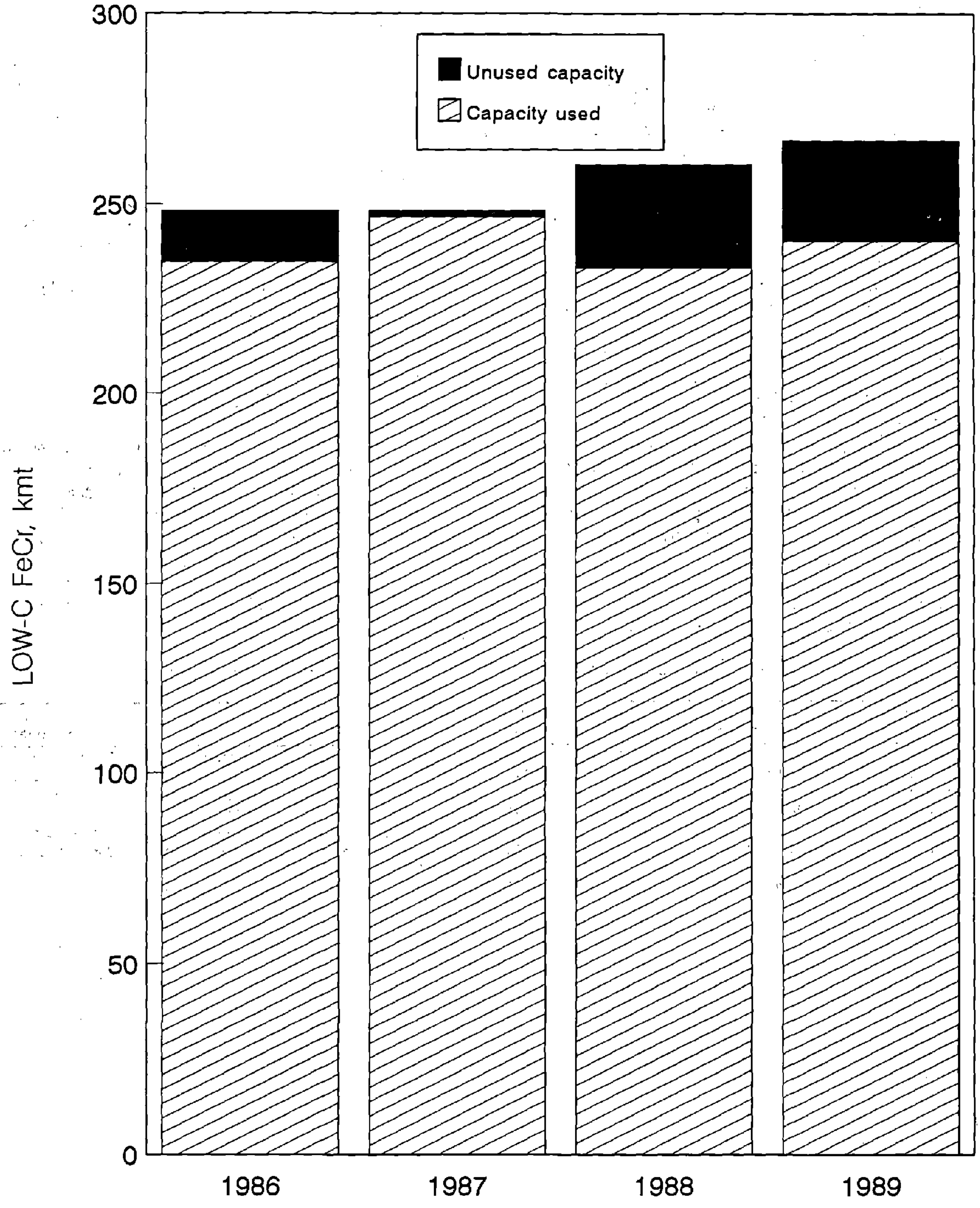

Figure 10.—MEC low-C FeCr capacity use percentages; model solutions for 1986-89.

Years 5 Through 9 (1990-94)

The following section presents selected results of the network flow model's solution for the years 1990 through 1994. Two different scenarios were run, each using the same Cr demand criteria: (1) a normal market scenario where world trade flows are not disrupted and (2) a "cutoff" scenario where it is assumed that all direct imports of South African Cr products into North American markets cease, beginning in the second half of 1990.

The amount of new MEC FeCr capacity built into the model for the 1990-94 period is listed, by country and smelter, in table 28. As shown, the model has an additional 1.12 Mmt of MEC high-C FeCr capacity allowed to come on-line over the 5-yr period (a 38-pct increase). However, only 665,000 mt of this 1.2 Mmt represents capacity increases reported in the press; the other 455,000 mt represents hypothetical capacity additions in Zimbabwe and in the United States, which are proposed only for comparative purposes in this model.

Only two new additions have been made to MEC low-C FeCr capacity in the model over the 1990-94 period. These are a 30,000 mtpy proposed smelter in Canada, which has been discussed in the press, and a 32,000 mtpy hypothetical expansion at the Gweru smelter in Zimbabwe, proposed solely for the runs of this model. It was assumed that both of these low-C FeCr capacity additions would be brought on-line in 1993.

The present network flow model does not include additional actual and prospective FeCr capacity beyond that discussed in the previous paragraphs and shown in table 28. A detailed discussion of this additional FeCr capacity—located in the countries of South Africa, Turkey, Norway, and India—is provided in appendix F.

Chromite

Table 29 summarizes the model's total world chromite production, by country, for the 1994 solutions under both the normal market and the South African embargo scenario discussed later in this section. Also included for comparison are the estimates of chromite production from the model's solution for 1988.

As shown in the table, under undisrupted market conditions and given the demand scenario of this model, total world chromite production grows at an annual average growth rate of 2.5 pct/yr from 10.9 Mmt in 1988 to a total of 12.6 Mmt by 1994. Over this same time period South Africa shows a growth rate of 3.7 pct/yr. Other increases occur in Indonesia, Madagascar, the Philippines, Turkey, the United States, and Zimbabwe, while chromite production decreases in nearly all other countries (Cuba and Greece being the exception). It is not coincidental that much of the increase in chromite production occurs in countries where new, in-country FeCr smelting capacity has been included in the model.

Table 28.—New MEC high-C FeCr capacity included in the network flow model, 1990-94

Country	Smelter name/ location	Capacity (kmt/yr)	Startup year	Nature of expansion	Smelting process	Source of chromite feed
Brazil	Porto de Santana	20	1991	New furnace	Conventional	Company ore.
France	Dunkirk	20	1991	..do.	..do	Purchased ore.
Philippines	ICC	30	1990	Converted furnace	..do	Company ore.
South Africa	Middleburg	120	1991	New furnace	Krupp-CODIR	Do.
Do.	Lydenburg	50	1990	..do.	Conventional	Purchased ore.
Do.	Krugersdorp	25	1990	Expanded transformer capacity.	Plasma arc.	Company ore.
Do.	Tubatse	120	1990	Two new furnaces	Conventional	Do.
Swaziland	Swaziland	120	1992	..do.	Krupp-CODIR	Lebowa homeland, South Africa
United States	Huntley, MT	120	1992	New smelter, for model only.	..do	Company ore.
Do.	Red Mountain, AK	60	1992	..do.	..do	Do.
Do.	Coos Bay, OR	60	1992	..do.	..do	Do.
Venezuela	Puerto Ordaz	160	1994	Relocated and converted furnaces.	Conventional	Purchased ore.
Zimbabwe	Kwe Kwe	215	1993	New furnaces, for model only.	..do	Company ore.
Total		1,120				

Table 29.—Model estimated world chromite production for 1988 solution, 1994 normal market solution, and 1994 "cutoff" solution

(Thousand metric tons chromite products)

Country	Network flow model solutions		
	1988	1994, "normal"	1994, "cutoff"[1]
South Africa[2]	4,580	5,700	5,434
U.S.S.R.	2,010	1,990	1,990
India	640	550	640
Finland	640	470	500
Zimbabwe	630	1,050	1,050
Albania	570	530	580
Turkey	560	600	629
Brazil	460	420	420
Philippines	350	390	390
Greece	110	110	110
Madagascar	100	130	130
New Caledonia[3]	85	—	—
Cuba	45	45	63
Indonesia	42	83	83
Pakistan	38	—	—
Sudan	20	—	—
Oman	11	—	11
Japan	10	—	—
Burma	—	—	—
Iran	—	—	—
Vietnam	—	—	—
United States	—	550	550
Total	10,901	12,618	12,580

[1]Assumes that a ban on the direct imports of chromium products from South Africa was imposed by North America governments beginning in mid-1990.

[2]Includes all chromite and FeCr production and exports from associated Lebowa homeland and Swaziland projects in the 1994 solutions.

[3]Ore depletion in 1990.

NOTE.—Dash indicates no applicable value.

Table 30 presents the amounts of Cr contained in world exports of chromite products for the model's 1988 solution and for the 1994 solutions under both market scenarios. The table shows the total amount of Cr contained in chromite exports in terms of each market use (e.g., metallurgical, chemical, refractory, and foundry sand).

Of note in this table is that, for the normal market scenario, the total amount of Cr in chromite product exports declines by 8.3 pct over the 6-yr period, even though exports for three of the four markets—chemical, refractory, and foundry sand—increase by 4.9 pct. The overall decline in total Cr in exports is due to a 16.4-pct decrease in metallurgical chromite exports and suggests that the nearly 20-yr-old trend of FeCr smelting capacity shifting to the chromite producing countries has not ended.

Table 30.—Model estimated world trade in chromium products, 1988 solution and 1994 solutions for alternative scenarios

Product category	Export tonnages of model solutions		
	1988 Normal market (kmt Cr)	1994 Scenarios[1]	
		Normal market (kmt Cr)	"Cutoff" (kmt Cr)
Metallurgical	670	560	700
Chemical	220	230	230
Refractory	140	150	150
Foundry sand	50	50	50
Total	1,080	990	1,130

[1]Indicates whether or not South African chromium products are cut off from North American markets.

Reference to the 1994 solution results in table 29 shows that the presently nonproducing or undeveloped chromite resources in Alaska, California/Oregon, and Montana operate at full analyzed capacity—550,000 mtpy of chromite—in the present model's simulations. This chromite output would be smelted to about 247,000 mtpy of high-C FeCr at proposed nearby smelters.

The relative attractiveness of the U.S. chromite resources reflects the cost minimization nature of the model, the lack of capital cost recovery and returns in the cost structure, and the importance of installing smelting capacity in the model to use the chromite. The costs are predicated upon use of the most efficient smelting method, now under development in South Africa, at smelters sited close to the resources. As a result, the undeveloped U.S. chromite resources have a very low relative cost structure in the model.

Another reason for the attractiveness of the U.S. resources is that the present chromium model basically represents a "level playing field" in terms of trade (i.e., no tariffs or customs assessments apply under either scenario, and barriers to markets for the South African products are employed only under the cutoff scenario).

As an example, it is noted that in the "normal" scenario's solution for 1994, fully 93.4 pct of the U.S. high-C FeCr output is sent to the Asian market. Similarly, the "cutoff" scenario's solution for 1994 sends 74.2 pct of the U.S. high-C FeCr output to the Asian market. In reality, capturing such a large share of the Asian market could be difficult for the potential U.S. ferrochromium production from domestic chromite resources.

The following items summarize important aspects of the nonmetallurgical chromite product results in the model's solutions:

(1) The Philippines and Madagascar chemical chromite products are capable of competing on an operating cost basis with the South African products. While the resources at the Madagascar property are very limited in size, those at the Philippines operation and in nearby areas are significant in size.

(2) The Indonesian foundry sand operation is also competitive with South Africa on an operating cost basis. However, the present resource at this operation is limited.

Ferrochromium

Tables 31 and 32 provide a summary of world high-C and low-C FeCr production according to the network flow model's solution for 1994. The results in these tables are for the scenario where no disruptions to markets occur and include the 1988 solution results for comparison.

Table 31.—Model estimated world high-C FeCr production, normal market solutions for 1988 and 1994, by country

Country	Solution results, kmt FeCr	
	1988	1994
Market economy:		
South Africa	937	1,310
Zimbabwe	184	325
Finland	181	62
India	179	174
Sweden	159	48
Brazil	118	105
Italy	106	—
Turkey	106	161
Yugoslavia	89	89
Philippines	85	56
United States	55	247
Greece	40	40
Japan	26	—
France	15	—
Taiwan	15	11
Mexico	7	—
Spain	—	—
Swaziland	—	123
Venezuela	—	159
MEC total	2,302	2,910
Centrally planned economy:		
U.S.S.R.	295	295
China	122	149
Poland	68	68
Albania	45	145
Romania	43	45
Czechoslovakia	30	30
CPEC total	603	732
World total	2,905	3,642

NOTE.—Dash indicates no applicable value.

Table 32.—Model estimated world low-C FeCr production, normal market solutions for 1988 and 1994, by country

Country	Solution results, kmt FeCr	
	1988	1994
Market economy:		
South Africa	66	66
Germany, Federal Republic of	41	36
Zimbabwe	32	64
India	30	28
Yugoslavia	18	18
Brazil	13	14
United States	12	18
Japan	12	—
Turkey	10	4
Canada	—	30
MEC total	234	278
Centrally planned economy:		
U.S.S.R.	127	127
China	50	53
CPEC total	177	180
World total	411	458

NOTE.—Dash indicates no applicable value.

Under the present model's demand scenario, MEC high-C FeCr production is predicted to increase at an average annual rate of about 4.0 pct/yr over the 6 yr of 1989 through 1994. This growth rate was forecast using IU methodology and assumes increasing gross domestic products (GDP's) in MEC's. The consumption of Cr in terms of mt per dollar GDP has been decreasing recently in most MEC's, but the drop has been more than compensated for by rising GDP's. If MEC economies slip into a recession in the early 1990's, the growth rate for FeCr production is expected to be much less (see appendix E for an extensive discussion of the relationship between GDP and ferrochromium production).

As discussed previously, the period from 1988 through 1994 will have seen the development of a large amount of high-C FeCr capacity in MEC's. If all of the projects listed in table 28—including the hypothetical U.S. and Zimbabwe expansions—are constructed, overall MEC capacity use for high-C FeCr in the model plummets from 87 pct in 1988 to only 68 pct by 1994. More significant is that this decline in use rates occurs despite a 4 pct/yr forecasted consumption growth rate. Even if the hypothetical U.S. and Zimbabwe capacity additions of table 25 are not included in the calculations of 1994 capacity use, the rate would still be only 76.6 pct. In addition, none of these capacity use calculations include the actual and prospective FeCr capacity not presently included in the model (see appendix F).

As was shown in table 28, the majority of producers who have planned increased high-C FeCr capacity also own chromite resources or have access to a nearby source. The results shown in table 31 suggest that the high-C FeCr producing countries that lack captive chromite resources—most of the European countries and Japan—will have difficulty competing on an operating cost basis with countries that also produce chromite and that a shakeout in the MEC high-C FeCr industry could occur in the first half of the 1990's.

In the present model's demand scenario, MEC low-C FeCr production is predicted to increase at an average annual growth rate of about 3 pct/yr from 1988 through 1994. Without the addition in the model of new Canadian capacity (announced) and an expansion to capacity in Zimbabwe (hypothetical), the model's Cr in low-C FeCr demand in 1994 would be 5 pct higher than total MEC low-C FeCr capacity for that year. However, with these additions, the 1994 MEC capacity use in the model is only 85 pct. Given the positive demand scenario used in the simulations, it would appear that low-C FeCr capacity beyond that already announced will be needed in the MEC's during the first half of the 1990's. Again, if MEC's enter a recession, production and capacity use will likely be lower than in the present model solutions.

For ferrochromium-silicon in this model design, only Zimbabwe has excess capacity to meet export demand; all the other producing countries are constructed as having only sufficient ferrochromium-silicon smelting capacity to meet their own low-C FeCr production requirements. The solution for 1994 shows the Gweru smelter in Zimbabwe producing 82,200 mt of FeCrSi, of which 42,000 mt is available for export. The remainder is used internally for low-C FeCr production. This level of 1994 ferrochromium-silicon production would be 104 pct of the present (1989) capacity of the five furnaces presently available at Gweru for ferrochromium-silicon production. This indicates that, in the case of a hypothetical doubling of low-C FeCr capacity, the Gweru smelter would need to add a new furnace for FeCrSi production or upgrade and expand some of the existing furnaces early in the 1990's. Again, if MEC's enter a recession, production and capacity use will likely be lower than in the present model solutions.

South African "Cutoff" Scenario

The South African "cutoff" scenario to be discussed in this section of the report assumes that a ban on the direct import of South African products into North American markets was imposed beginning in mid-1990. This study's cutoff scenario *does* allow the indirect import[23] of material of South African origin and uses the same demand projections as in the normal market scenario case.

In the South African cutoff scenario, the estimate of total world chromite production according to the model's solution for 1994 is about 0.3 pct less than in the normal market scenario (see table 29). This very slight decrease in chromite tonnage is caused solely by differences in the Cr grade of the ores produced under the normal market scenario and ores produced under the cutoff scenario.

Under the cutoff scenario, South Africa's annual growth in chromite production from 1988 through 1994 is 2.9 pct/yr, somewhat less than the 3.7 pct/yr of the normal market solution. The 266,000 mt of chromite production lost by South Africa under the cutoff scenario is replaced by only 228,000 mt of additional chromite production from Albania, Cuba, Finland, India, Oman, and Turkey.

Tables 33 and 34 provide measures (according to the model) of the production and economic impacts on South Africa's chromium industry in the fifth year (1994) of the model's sanctioning of direct South African chromium product imports into North America. Table 33 provides a complete summary of the South African chromium industry, as described by the model, for 1988 and for the 1994 solutions to both the normal market scenario and the cutoff scenario. Table 34 translates the export tonnages of table 33 into export revenue estimates for each of these solutions, using the chromium prices (in constant January 1989 U.S. dollars) shown.

Table 33 shows that, under the cutoff scenario, South Africa exports more chromite and less ferrochromium. The imposition of sanctions displaces South African ferroalloys from the North American market with alternative imports. Because of insufficient alternative markets for the ferroalloys previously shipped to North America, the South African ferroalloy smelters require less metallurgical chromite feed. As a result, chromite previously used internally is thus available for export. Simultaneously, North American demand for ferroalloys is fulfilled by alternative suppliers, some using imported South African chromite.

This effect can also be seen in table 34 by comparing the forecasted 1994 South African export revenues under

[23]One example of indirect South African imports in the model would be where South African metallurgical chromite is smelted in Western Europe and the high-C FeCr produced is, in turn, exported to the North American high-C FeCr demand node in the model. Another example would be where chemical grade chromite from South Africa is exported to Western Europe for conversion to SBE (in the model) which, in turn, is exported to the model's North American SBE demand node.

the two scenarios. As shown, the cutoff increases South Africa's metallurgical chromite revenues by $23.2 million, while overall chromite product revenues increase by only $16.9 million. The cutoff also causes South Africa's export revenues from high-C FeCr to decrease significantly by $174 million.

Table 33.—Model estimated South African production, consumption, and exports of chromium products, 1988 solution and 1994 solutions for alternative scenarios

Product and destination category	1988 Normal market (kmt products)	1994 Scenarios[1]	
		Normal Market (kmt products)	Cutoff (kmt products)
Total chromite production	4,580	5,700	5,434
Chromite consumption:			
Metallurgical	2,350	3,360	2,810
Chemical	19	100	100
Refractory	16	16	16
Foundry sand	—	—	—
Total chromite consumption[2]	2,390	3,480	2,924
Chromite exports:			
Metallurgical	1,180	1,280	1,654
Chemical	700	630	580
Refractory	200	230	190
Foundry sand	120	87	85
Total chromite exports[2]	2,200	2,230	2,514
Total SBE[3] production	14	71	71
Total SBE consumption	6	7	7
Total SBE exports	8	64	64
Total high-C FeCr production	940	1,430	1,200
Total high-C FeCr consumption	30	40	40
Total high-C FeCr exports	910	1,390	1,160
Total low-C FeCr production	66	66	66
Total low-C FeCr consumption	1	1	1
Total low-C FeCr exports	65	65	65

[1]Indicates whether or not South African chromium products are cut off from North American markets.

[2]Data may not add to totals shown because of independent rounding.

[3]Throughout this study SBE is used as an acronym for sodium bichromate equivalent units of production. Capacities of chromium chemical plants are commonly reported on this basis because it is the intermediate product used to produce a wide variety of other chemical products. Sodium bichromate contains about 35 pct Cr, by weight.

NOTE.—This table includes all chromite and FeCr production and exports from associated Lebowa homeland and Swaziland projects.

NOTE.—Dash indicates no applicable value.

Table 34.—Model estimated South African export revenues from chromium products, 1988 solution and 1994 solutions for alternative scenarios

(Million January 1989 U.S. dollars)

Chromium export products	Prices used for revenue calculations ($/mt product)	Estimated export revenues from chromium products		
		1988	1994 Scenarios[1]	
		Normal market	Normal market	Cutoff
Chromite:				
Metallurgical	62.00	73.2	79.4	102.6
Chemical	67.50	47.3	42.5	39.2
Refractory	70.00	14.0	16.1	13.3
Foundry sand	80.00	9.6	7.0	6.8
Total, chromite		144.1	145.0	161.9
SBE[2]	727.00	5.8	46.5	46.5
High-C FeCr	760.00	692.0	1,056.0	882.0
Low-C FeCr	1,455.00	94.6	94.6	94.6
Total, all products		936.5	1,342.1	1,185.0

[1]Indicates whether South African chromium products are cut off from North American markets.

[2]Throughout this study SBE is used as an acronym for sodium bichromate equivalent units of production. Capacities of chromium chemical plants are commonly reported on this basis because it is the intermediate product used to produce a wide variety of other chemical products. Sodium bichromate contains about 35 pct Cr, by weight.

NOTE.—This table includes all chromite and FeCr exports from associated Lebowa homeland and Swaziland projects.

The following summarizes the effects, according to this model, on South Africa's chromium industry by 1994 if limited sanctions were imposed by North American governments beginning in mid-1990:

(1) Annual growth in total chromite production slows from 3.7 pct/yr to 2.9 pct/yr.

(2) Total high-C FeCr production is 16.1 pct less and high-C FeCr exports are 16.5 pct less than under the normal market scenario.

(3) Metallurgical chromite exports are 29 pct higher under the cutoff scenario because the model uses South African chromite for smelting in other countries.

(4) The net loss of annual export revenues from Cr products (mainly from lower high-C FeCr exports) totals $157 million dollars (11.7 pct). This loss in annual revenue is due to the shift from exporting higher priced, value-added products (high-C FeCr) to the lower priced chromite products.

(5) North American demand for chemical chromite was difficult to fulfill without South African imports largely because chemical chromite has the least number of alternative sources outside of South Africa. Another reason is that, as of October 1988, the Defense Department's stockpile of chemical chromite is the smallest, in relation to overall market size, of the various stockpiled chromium products.

Base Case Trade Patterns and Delivered Costs

In the preceding section, the simulation results were presented from a supplier's perspective, showing who is able to produce and at what level. The trade section will now switch to a consumer's perspective, to determine who is able to supply the material to a given demand region. The purpose is to identify the natural markets for producers' output; i.e., the markets in which they are likely to be most competitive on a delivered cost basis. Estimated trade flows can then be compared over a several-year period to identify potential trends in marginal delivered cost, changes in natural markets, and shifts in supply patterns.

The hypothetical set of trade flows from suppliers to demand regions is derived from the solution to the cost minimizing network flow problem through the use of a transportation algorithm. The result is a set of feasible paths from ore sources to final demand regions, ranked from least to most expensive, the total flow over which fulfills regional demand. The delivered cost of the most expensive supplier to a regional demand node can be considered a proxy for marginal delivered cost in that area. The market shares are reported as percentages by exporting country.

In this section, delivered costs for high- and low-C FeCr are reported as regional weighted averages. All delivered cost results are in terms of January 1989 U.S. dollars per mt contained Cr.

High-Carbon Ferrochromium

The weighted average delivered costs of high-C FeCr for 1986 (the base year of the simulations), 1990, 1992, and 1994 into the major consuming regions of North America, Western Europe, and Asia are presented in tables 35, 36, and 37, respectively. Each will be discussed in turn.

In the base year of 1986, the transportation algorithm solution identifies South Africa as the largest supplier of high-C FeCr to North American markets (43 pct), followed by domestic producers (15 pct), Turkey (14 pct), Zimbabwe (12 pct), Greece (9 pct), and Yugoslavia (4 pct). In comparison with Bureau reported import statistics,[24] the model's allocation is slightly lower than the actual 1986 market shares for South Africa, for domestic producers, and for Yugoslavia, which were 47 pct, 18 pct, and 7 pct, respectively. The model's allocations were slightly higher for the countries of Turkey and Zimbabwe, whose actual market shares were 12 pct and 10 pct, respectively, and much higher for Greece, which had only 1 pct of the actual U.S. market share in 1986.

It must be noted that the model's allocations do reflect upper limits set on South African exports to North America, in the absence of which South Africa would have totally dominated the MEC markets in the model. The setting of upper limits for South African exports is discussed in more detail in appendix F, and the market dominance of South Africa demonstrated by this result will be discussed at more length in this section.

As shown in table 35, the weighted average delivered cost of high-C FeCr to the North American market decreases from \$783/mt Cr in 1986 to \$552/mt Cr[25] in 1994, a 29.5-pct decrease, in January 1989 U.S. dollars per mt Cr. This decrease over time is also shown graphically by the four annual step curves in figure 11. The height of each step in the figure reflects the cost to deliver high-C FeCr to North America. The length of each step shows the magnitude of supply grouped by percentage contribution to the total supply to North America. As new, lower cost producers enter the model's year-by-year simulations, the step curves in figure 11 not only shift down but also become flatter. The difference between high- and low-cost suppliers shrinks, reducing the opportunities to earn economic rent and limiting, to some degree, the market power of individual producers.

As shown in table 35, South Africa is the major supplier to the North American market during the entire simulation period. This country is able to reduce its weighted average delivered cost of high-C FeCr into the North American market from \$605/mt Cr (January 1989 U.S. dollars) to \$563/mt Cr, or 6.9 pct, over the 1986 to 1994 time period. This decrease is predominantly a result of new, lower cost facilities and expansions being brought on-line.

Interestingly, even though their cost to supply the North American market decreases over time in the model solutions, the South Africans do not manage to increase their North American market share over the 1986-94 period.[26] Instead, the model shows new smelting facilities proposed for construction in Swaziland and Venezuela, capturing North American market share because of their lower weighted average delivered costs.

During the 1986-94 time period, Zimbabwe ceases to supply the North American high-C FeCr market in the model's solutions. Based on a total worldwide cost minimization solution, other areas of the world, such as the Western European and Asian markets, become more attractive to Zimbabwe exports (see tables 36 and 37).

A similar shift occurs for Turkey. Even though the transportation analysis shows Turkey losing all of its North American market share by 1994 (table 35), the model still predicts production in Turkey to be at full capacity of 161,000 mt high-C FeCr in 1994. This is because Turkey gains entry into the Western European market and is able to increase market share in this region to 20 pct by 1994 (table 36). If Turkey enters the European Community (EC), if cost increases can be kept to low levels, and if sufficient chromite ore is available to support a further increase to high-C FeCr capacity, this country's European market share could increase even more.

The model shows potential new U.S. producers capable of supplying 23 pct of the North American chromium in high-C FeCr demand on a variable cost basis by 1992. However, by 1994 the percent supplied to the North American market by American producers decreases to 4 pct as the Asian market becomes relatively more attractive to them (table 37).

Interestingly, these potential new U.S. producers are not the most expensive suppliers into the North American market in the 1992 solution. These potential U.S. producers, whose variable costs are below that of the marginal producer, would appear to be able to cover some costs over their variable costs of production and perhaps earn a return to capital.

[24]The model results for delivered tonnages of high-C FeCr into the North American market cannot be compared directly to published Bureau statistics, which show only imports to the U.S. market. For calculation of actual country-by-country market shares in 1986 an estimate of 39,110 mt of chromium in U.S. high-C production was added to the U.S. import total of 179,738 mt chromium in high-C FeCr. Canadian and Mexican imports have not been included.

[25]The transportation algorithm results presented in this section represent just one way in which North America could be supplied with material consistent with the optimal solution. The transportation algorithm solution reported is guaranteed to be optimal, but not uniquely optimal.

[26]In the model, the upper bound restrictions set on South African exports to all markets are allowed to increase 5 pct/yr throughout the multiyear simulation. This aspect of the model design assumes that South Africa will not be overly aggressive in increasing their domination of regional markets for chromium products.

Table 35.—Model estimated weighted average delivered costs and market shares of high-C FeCr in the North American market[1]

(January 1989 U.S. dollars per metric ton Cr)

Supplying country	1986		1990		1992		1994	
	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)
Brazil	1,101	1	0	0	0	0	0	0
Greece	829	9	0	0	0	0	0	0
Mexico	1,111	2	1,040	2	0	0	0	0
South Africa	605	43	604	41	562	42	563	43
Swaziland	0	0	0	0	562	24	562	22
Turkey	921	14	705	33	879	11	0	0
United States	981	15	967	13	824	23	726	4
Venezuela	0	0	0	0	0	0	506	31
Yugoslavia	490	4	0	0	0	0	0	0
Zimbabwe	1,005	12	1,038	11	0	0	0	0
Total or wtd avg	783	100	740	100	658	100	552	100

[1]The supply source distribution reflects the optimal (lowest cost) solution as determined by the transportation algorithm used in the network flow model. The solution shown represents just one way in which the North American market could be supplied with material.

Table 36.—Model estimated weighted average delivered costs and market shares of high-C FeCr in the Western European market[1]

(January 1989 U.S. dollars per metric ton Cr)

Supplying country	1986		1990		1992		1994	
	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)
Finland	967	16	967	14	980	1	980	1
Greece	0	0	813	4	813	4	817	4
Italy	1,034	8	0	0	0	0	0	0
South Africa	706	43	699	43	700	46	708	49
Sweden	951	20	928	26	919	25	951	5
Turkey	0	0	448	4	555	15	643	20
Yugoslavia	407	9	329	9	370	9	412	9
Zimbabwe	668	4	0	0	0	0	583	12
Total or wtd avg	796	100	754	100	711	100	673	100

[1]The supply source distribution reflects the optimal (lowest cost) solution as determined by the transportation algorithm used in the network flow model. The solution shown represents just one way in which the Western European market could be supplied with material.

Table 37.—Model estimated weighted average delivered costs and market shares of high-C FeCr in the Asian market[1]

(January 1989 U.S. dollars per metric ton Cr)

Supplying country	1986		1990		1992		1994	
	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)
Brazil	1,165	3	648	2	0	0	0	0
Greece	952	2	952	1	952	1	952	1
India	1,021	11	783	22	703	13	718	11
Philippines	886	11	942	13	850	6	850	5
South Africa	655	50	655	42	640	41	645	38
Taiwan	893	2	938	2	910	1	921	1
United States	0	0	0	0	632	17	706	20
Zimbabwe	733	21	730	18	796	21	845	23
Total or wtd avg	762	100	742	100	698	100	728	100

[1]The supply source distribution reflects the optimal (lowest cost) solution as determined by the transportation algorithm used in the network flow model. The solution shown represents just one way in which the Asian market could be supplied with material.

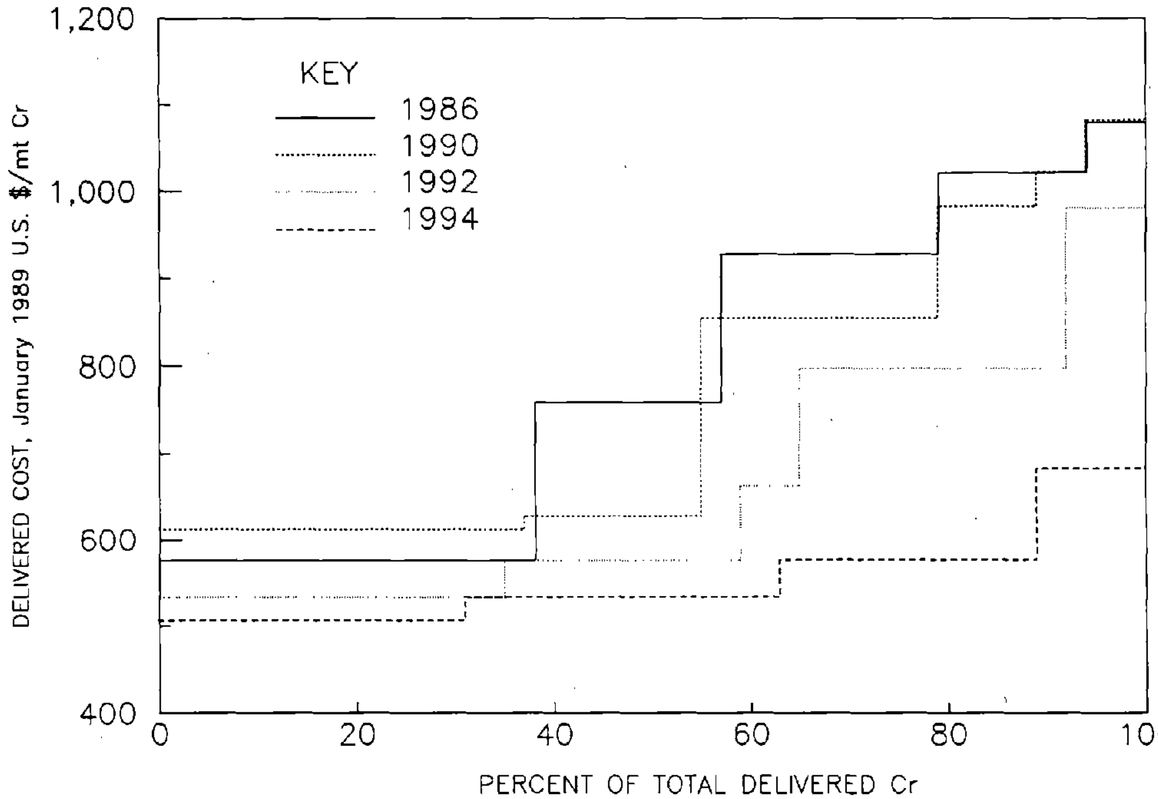

Figure 11.—Delivered cost to supply 100 pct of high-C FeCr demand into North America for selected years; normal market solutions.

As shown in table 36 the weighted average cost to supply the Western European market decreases 15.5 pct, from $796/mt in 1986 to $673/mt in 1994 (January 1989 U.S. dollars per metric ton Cr). As discussed earlier for the North American market, this is predominantly a result of new lower cost facilities and expansions coming on-line. By 1992, in the case of Turkey, and by 1994 for Zimbabwe, significant Western European market share is captured, primarily at the expense of Finland, Italy, and Sweden, which are all higher cost suppliers to the Western European market.

Table 37 shows that the weighted average delivered cost of high-C FeCr to the Asian market (January 1989 U.S. dollars per metric ton Cr) decreases only 4.5 pct from $762/mt in 1986 to $728/mt in 1994. This percentage difference is much less than the decreases in the North American and Western European markets. A portion of this decrease in the weighted average delivered cost to the Asian market can be attributed to the potential new production in the United States. These potential producers allow the United States to gain entry into the Asian market on a cost-competitive basis.

The model's delivered costs for high-C FeCr into North America, Western Europe, and Asia markets are compared in figures 12 (1986) and 13 (1994). The step curve depicting 1986 shipments into North America shows nearly 80 pct of the market being supplied at delivered costs below $950/mt Cr (January 1989 U.S. dollars). Similarly, about 80 pct of the Asian market could be supplied in 1986 for delivered costs at or below $950/mt Cr, but the delivered costs for the last 5 pct are sharply higher. About 75 pct of the Western European market could have been supplied in 1986 for delivered costs at or below $950/mt Cr; however, the delivered cost for the last 5 pct of supply into Western Europe is the lowest of all three of the market regions.

The step curves in figure 13 show delivered costs of Cr in high-C FeCr to Western Europe, Asia, and North America for the 1994 solution. Comparison to figure 12 (the 1986 solution) shows that all of the curves have shifted down and are flatter, reflecting the decreasing costs of supplying high-C FeCr over the time period. The curve representing the North American market is lowest overall, with the entire market forecast to be supplied at delivered costs less than $700/mt Cr. By comparison, only about 55 to 58 pct of the Asian and Western European markets could be supplied at delivered costs below $700/mt Cr in these 1994 model solutions. The results shown in figure 13 support the conclusion that there may be downward pressure on high-C FeCr prices and rationalization of high-cost producers in the early to mid-1990's.

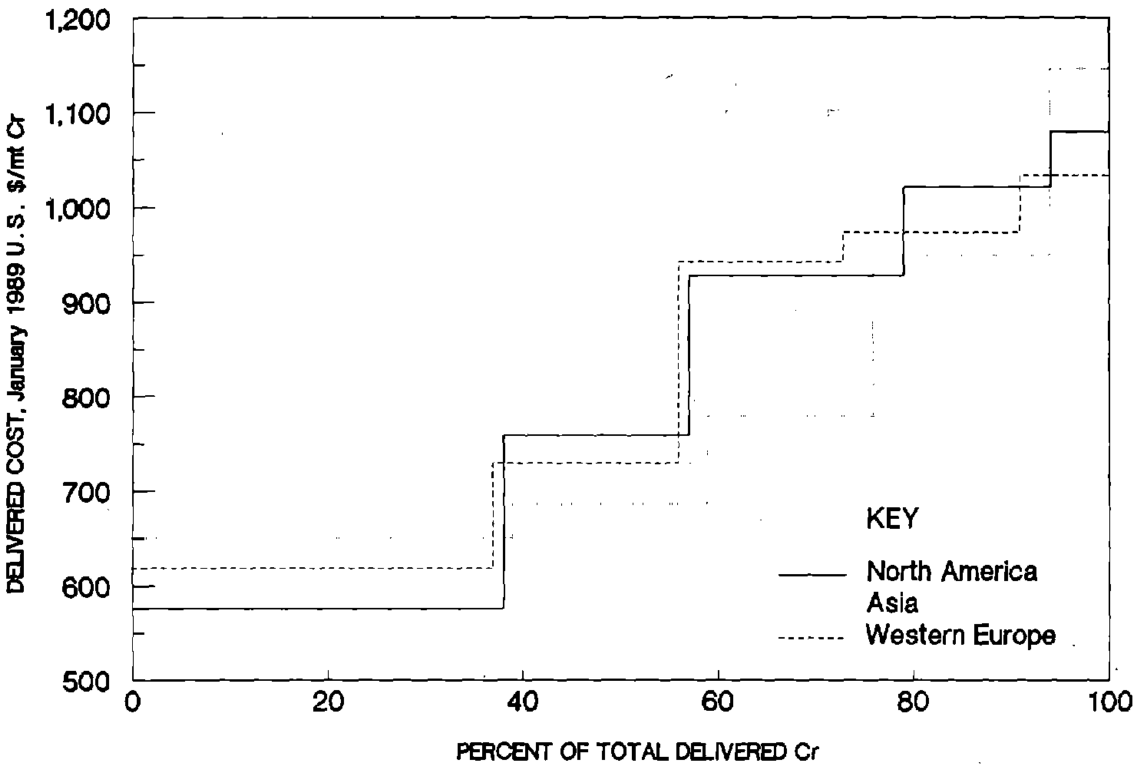

Figure 12.—Delivered cost to supply 100 pct of high-C FeCr demand into North America, Western Europe, and Asia; normal market solution for 1986.

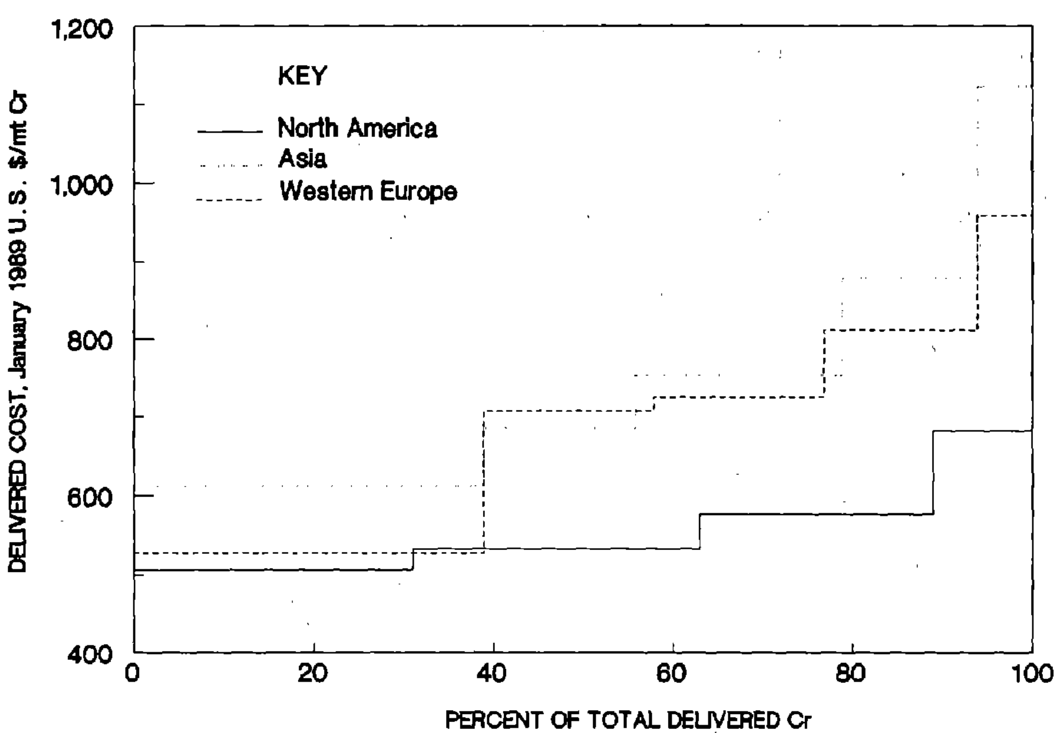

Figure 13.—Delivered cost to supply 100 pct of high-C FeCr demand into North America, Western Europe, and Asia; normal market solution for 1994.

Low-Carbon Ferrochromium

The results of the weighted average delivered costs of low-C FeCr into the three major regions of North America, Western Europe, and Asia are presented in tables 38, 39, and 40, respectively. Each table shows the model's transportation algorithm solution results for 1986, 1990, 1992, and 1994.

Table 38.—Model estimated weighted average delivered costs and market shares of low-C FeCr in the North American market[1]

(January 1989 U.S. dollars per metric ton Cr)

Supplying country	1986		1990		1992		1994	
	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)
Brazil	0	0	0	0	0	0	0	0
Germany, Federal Republic of	1,593	20	1,593	20	1,593	19	1,593	18
South Africa	1,040	37	1,049	26	1,043	30	1,040	34
Turkey	1,948	10	1,948	10	1,948	9	1,808	9
United States	0	0	1,274	44	1,376	42	1,376	39
Zimbabwe	1,689	33	0	0	0	0	0	0
Total or wtd avg	1,458	100	1,349	100	1,373	100	1,341	100

[1]The supply source distribution reflects the optimal (lowest cost) solution as determined by the transportation algorithm used in the network flow model. The solution shown represents just one way in which the North American market could be supplied with material.

Table 39.—Model estimated weighted average delivered costs and market shares of low-C FeCr in the Western European market[1]

(January 1989 U.S. dollars per metric ton Cr)

Supplying country	1986		1990		1992		1994	
	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)
Germany, Federal Republic of	1,523	47	1,523	47	1,523	46	1,528	39
South Africa	1,273	16	1,542	16	1,208	8	1,042	4
Turkey	1,716	9	1,716	9	1,716	9	0	0
Yugoslavia	637	14	624	14	635	14	661	10
Zimbabwe	1,182	14	1,043	14	1,106	23	1,285	47
Total or wtd avg	1,327	100	1,352	100	1,299	100	1,322	100

[1]The supply source distribution reflects the optimal (lowest cost) solution as determined by the transportation algorithm used in the network flow model. The solution shown represents just one way in which the Western European market could be supplied with material.

Table 40.—Model estimated weighted average delivered costs and market shares of low-C FeCr in the Asian market[1]

(January 1989 U.S. dollars per metric ton Cr)

Supplying country	1986		1990		1992		1994	
	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)	Delivered cost	Market share (pct)
Canada	0	0	0	0	0	0	1,342	31
India	1,850	2	1,805	2	1,805	1	0	0
Japan	1,720	39	1,706	26	1,687	40	0	0
South Africa	1,137	43	1,152	42	1,173	41	1,195	39
Zimbabwe	1,397	16	1,476	30	1,587	18	1,588	30
Total or wtd avg	1,421	100	1,403	100	1,460	100	1,359	100

[1]The supply source distribution reflects the optimal (lowest cost) solution as determined by the transportation algorithm used in the network flow model. The solution shown represents just one way in which the Asian market could be supplied with material.

For the base year of 1986, the transportation algorithm solution results shown in table 38 rank South Africa (37 pct) as the largest supplier of chromium in low-C FeCr to North America, followed by Zimbabwe (33 pct), the Federal Republic of Germany (20 pct), and Turkey (10 pct). In comparison with the Bureau's reported U.S. import statistics for 1986,[27] the model's allocations for South Africa, the Federal Republic of Germany, and Turkey are close to the actual import shares, which were 36 pct, 20 pct, and 13 pct, respectively. However, the model's allocation for Zimbabwe is much higher than that country's actual 1986 import share, which was only 16 pct. Much of the additional 1986 market share given by the model to Zimbabwe was, in actuality, provided by imports from Sweden. This low-C FeCr production capability in Sweden was not included in the design of the present network flow model because this smelter's last furnace was decommissioned in the first quarter of 1987, and no indications of possible recommissioning have been indicated. Also, no low-C FeCr production was allocated in the model to the United States in 1986, since no domestic facilities were in production during that year.

[27]Because there was no U.S. low-C FeCr production in 1986, the Bureau's published chromium in low-C FeCr import tonnage of 23,203 mt for 1986 has been used in calculating the actual market shares reported in this section. Canadian and Mexican imports have not been included.

According to the chromium market model, a significant shift in North American low-C FeCr suppliers occurs between 1986 and 1990. As shown in table 38, Zimbabwe is no longer predicted to supply North America. In the model, this change is due mainly to the reopening of shutdown U.S. low-C FeCr capacity. Another reason is that Zimbabwe has a relatively greater cost advantage in Western European and Asian markets than in North America. As a result, tables 39 and 40 show Zimbabwe shifting low-C FeCr exports to its more "natural" markets of Europe and Asia. Although a shift of this magnitude is unlikely to occur, it does highlight the relative strength of Zimbabwe low-C FeCr in European and Asian markets.

The weighted average cost to supply the North American market with low-carbon ferrochromium decreases slightly over the time period of 1986-94. In 1986, the weighted average cost (January 1989 U.S. dollars) is \$1,458/mt Cr, decreasing 8 pct to \$1,341/mt Cr by 1994, as shown in table 38. This decrease is also shown graphically in figure 14 by the downward shifts of the annual step curves for 1986 and 1994.

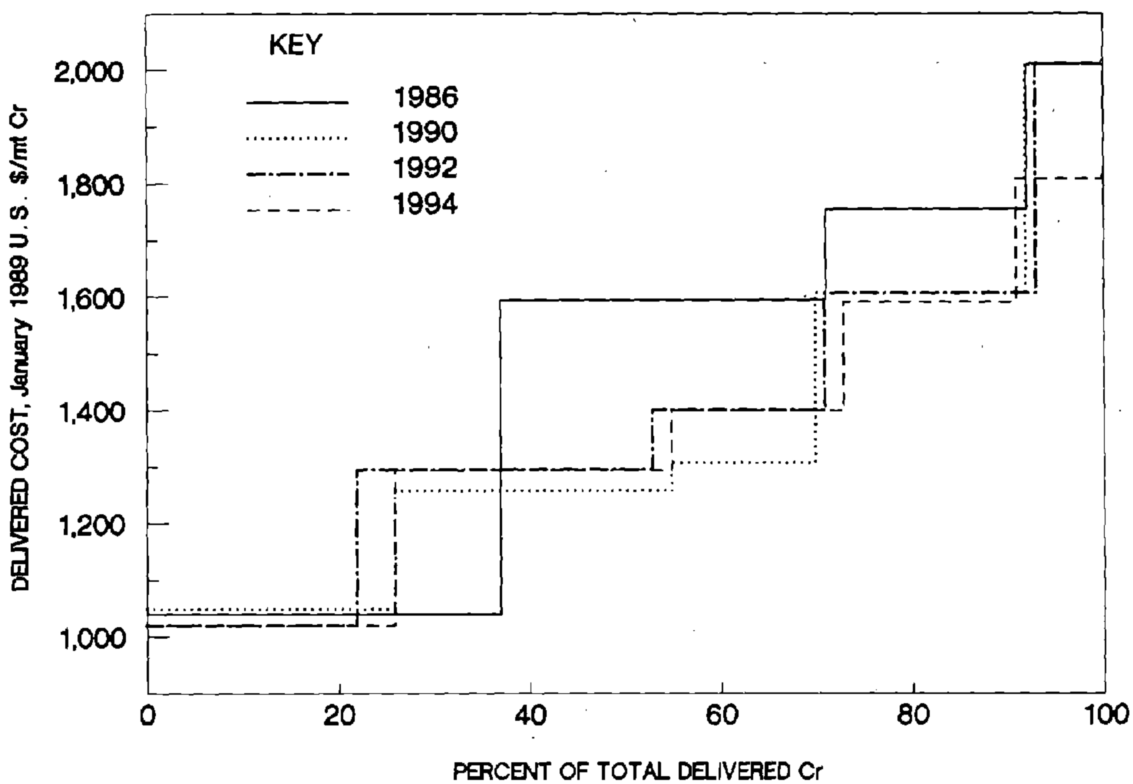

Figure 14.—Delivered cost to supply 100 pct of low-C FeCr demand into North America for selected years; normal market solutions.

Subsequent to 1990, the North American low-C FeCr market sees no major shifts in suppliers. Based on a total, worldwide, least-cost principle, the model predicts that the United States will supply around 39 to 44 pct, South Africa 26 to 34 pct, the Federal Republic of Germany 18 to 20 pct and Turkey 9 to 10 pct of North American demand during the 1990 to 1994 time period.

Table 39 shows that the model predicts no major change in the weighted average delivered cost of low-C FeCr to Western Europe between 1986 ($1,327/mt Cr) and 1994 ($1,322/mt Cr). However, a major shift in the market share occurs over the time period with Zimbabwe's market share increasing to 47 pct in 1994 from only 14 pct in 1986. This is a result of the increased availability of exports from Zimbabwe due to the hypothetical expansion of capacity that was built into the model. The exports from Zimbabwe are able to gain substantial market share in the Western European market, displacing relatively higher cost suppliers such as Turkey, West Germany, and South Africa. Turkey, in particular, may be affected unless relative costs can be lowered and productivity increased. The low-C FeCr smelter cost index (see table 16) emphasizes this point. In this table, which indexes the smelting operating cost estimates of this study, Turkey's cost index value is nearly two times higher than Zimbabwe's and is even higher than the Federal Republic of Germany's.

The weighted average delivered cost of low-C FeCr into the Asian market declines only 4.4 pct over the simulation period, from $1421/mt Cr in 1986 to $1359/mt Cr in 1994 (see table 40). Again, the cost decline is a result of new lower cost facilities and expansions coming on-line.

The transportation algorithm predicts several major changes in the Asian market by 1994. For example, Zimbabwe nearly doubles its market share from 1986 levels; again, this is due to the hypothetical doubling of Zimbabwe low-C FeCr production capacity that was built into the model. Concurrently, the model predicts that the proposed new Canadian low-C FeCr smelter would gain almost one-third of the Asian market because of its competitive cost structure presently in the model. An important result of these two hypothetical capacity increases is the predicted complete shutdown of Japanese low-C FeCr capacity because of its relatively high cost structure in the model.

The step curves for delivered cost of low-C FeCr into the three major markets are presented in figures 15 (1986) and 16 (1994). Delivered costs for the last 10 pct, or so, of the market are highest in North America in both 1986 and 1994; even though the cost curve has shifted down and flattened for 1994 (fig. 16). In the 1986 results, Western Europe, with about 90 pct of the low-C FeCr able to be delivered for costs below $1,600/mt Cr, has the lowest

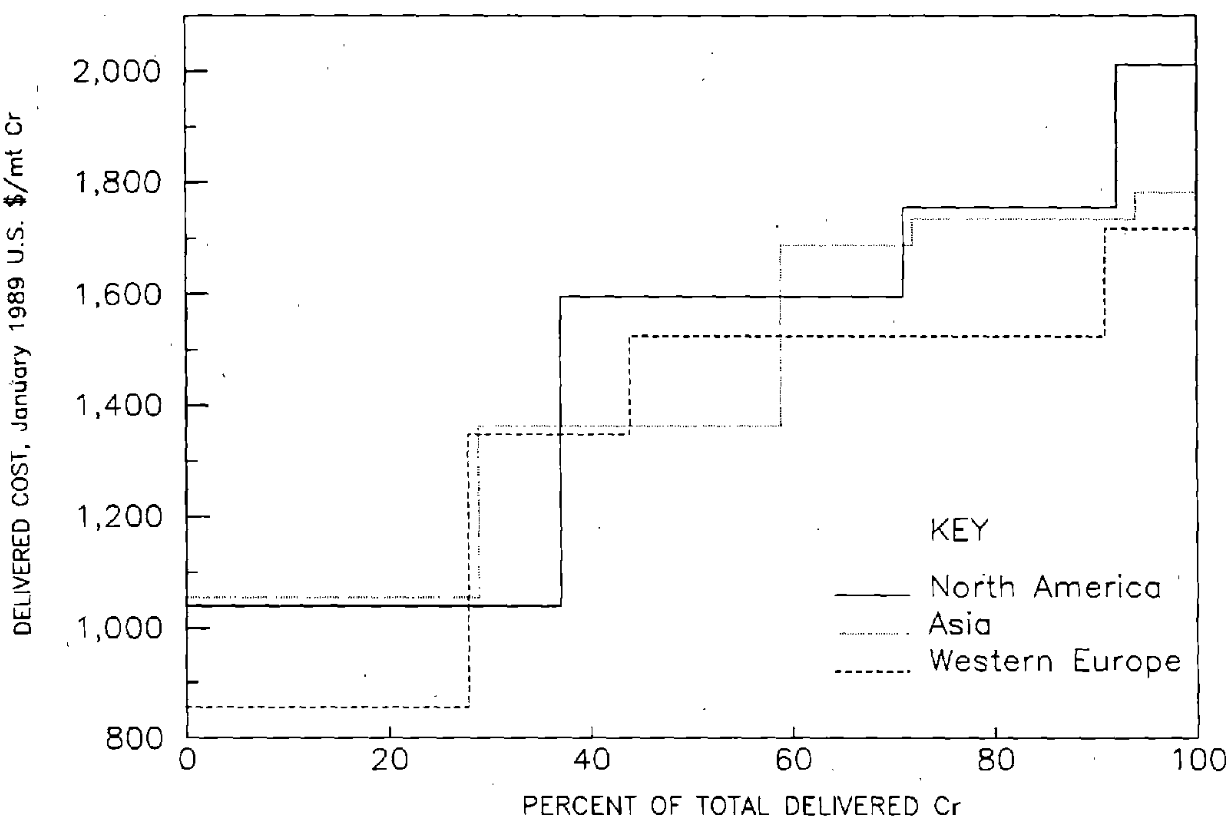

Figure 15.—Delivered cost to supply 100 pct of low-C FeCr demand into North America, Western Europe, and Asia; normal market solution for 1986.

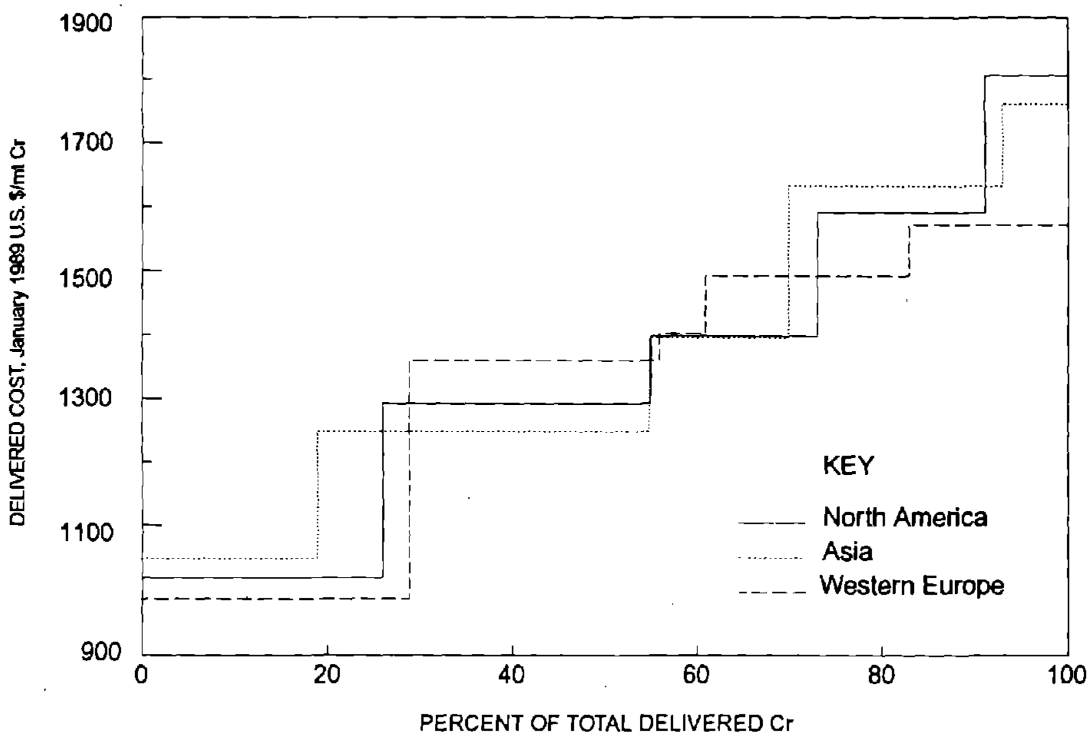

Figure 16.—Delivered cost to supply 100 pct of low-C FeCr demand into North America, Western Europe, and Asia; normal market solution for 1994.

overall delivered cost curve. By 1994 the delivered cost curves for low-C FeCr in all three regions are closer together, with 90 to 100 pct of the needs in all three regions being delivered at costs of less than about $1,650/mt Cr.

Trade Patterns and Delivered Costs, 1992 and 1994

Tables 41 and 42 show the overall total weighted average delivered costs and percent of market share for all suppliers to the North American market in 1992 and 1994 for both the cutoff and the normal market scenarios. The high-C results are given in table 41, and the low-C results are in table 42.

It is stressed that the results shown for the cutoff scenario in this analysis reflect only a ban on the *direct* import of South African products into the North American market; ore of South African origin can be processed in other countries, and the higher value-added material can be imported from these countries into the North American market. The Department of Defense (DOD) stockpile is allowed to supply a portion of the demand but at artificially high prices to indicate its position as a supplier of last resort.

Table 41.—Model estimated shares of North American high-C FeCr market and weighted average delivered costs, 1992 and 1994 solutions[1] under different scenarios

(Percents and January 1989 U.S. dollars per metric ton Cr)

Supplying country	North American high-C FeCr market shares			
	1992 Scenarios[2]		1994 Scenarios[2]	
	Normal	"Cutoff"	Normal	"Cutoff"
Brazil	0	8	0	4
South Africa	42	0	43	0
Swaziland	24	23	22	22
Turkey	11	22	0	13
United States	23	27	4	14
Venezuela	0	0	31	31
Zimbabwe	0	20	0	16
Total	100	100	100	100
Delivered costs[3]	658	723	552	663

[1]The supply distribution reflects the optimal (lowest cost) solution as determined by the transportation algorithm. The distributions shown are guaranteed to be optimal but not uniquely optimal.

[2]Indicates whether or not South African chromium products are cut off from North American markets.

[3]Weighted average delivered cost for all tonnage into market; January 1989 U.S. dollars per metric ton Cr.

Table 42.—Model estimated shares of North American low-C FeCr market and weighted average delivered costs, 1992 and 1994 solutions[1] under different scenarios

(Percents and January 1989 U.S. dollars per metric ton Cr)

Supplying country	North American low-C FeCr market shares			
	1992 Scenarios[2]		1994 Scenarios[2]	
	Normal	"Cutoff"	Normal	"Cutoff"
Germany, Federal Republic of	19	0	18	0
South Africa	30	0	34	0
Turkey	9	14	9	0
United States	42	42	39	40
Zimbabwe	0	44	0	60
Total	100	100	100	100
Delivered costs[3]	1,373	1,436	1,341	1,431

[1]The supply distribution reflects the optimal (lowest cost) solution as determined by the transportation algorithm. The distributions shown are guaranteed to be optimal but not uniquely optimal.

[2]Indicates whether or not South African chromium products are cut off from North American markets.

[3]Weighted average delivered cost for all tonnage into market; January 1989 U.S. dollars/mt Cr.

High-Carbon Ferrochromium

Comparison of the high-C FeCr imports to North America under both scenarios for 1992 (table 41) shows Brazil, Turkey, Zimbabwe, and U.S. producers all increasing their market shares to make up for the loss of South African imports. An important technicality to note in these results is that the proposed smelter in Swaziland, which, according to the model, supplies around 23 pct of North American demand under the cutoff scenario, does process ore of South African origin in the model's solution. The same technicality applies for the new smelting facility proposed to be built in Venezuela, which, according to the model, also processes ore of South African origin. This proposed smelter is able to gain market share, by 1994, at the expense of Brazil, Turkey, Zimbabwe, and U.S. producers in both scenarios. Interestingly, in the cutoff scenario solution, Turkey maintains some high-C FeCr market share in North America through 1994, as opposed to losing all of its share under the normal market solution.

Of particular note in table 41 is that Zimbabwe and Turkey high-C FeCr imports provide the most "replacements" for the North American market in the case of the cutoff. However, U.S. and Brazilian high-C FeCr production also play major roles in the cutoff scenario solution.

Comparison of the weighted average total delivered costs for high-C FeCr (table 41) shows that in 1992 the delivered cost of high-C FeCr under a South African cutoff situation is 9.9 pct higher than in the normal market scenario. Nonetheless, this higher value ($723/mt Cr) is still 17.6 pct less than the actual 1986 c.i.f.[28] import value into the United States of $877/mt Cr in terms of January 1989 U.S. dollars.[29] By 1994, the weighted average cost to supply the North American market under the cutoff scenario is forecast to be $663/mt Cr, which is 20.1 pct higher than the weighted average cost for delivery under the normal market scenario's solution. This 20.1 pct increase to the weighted average delivered cost under the South African cutoff scenario solution for 1994 represents an additional cost for delivery of all high-C FeCr into the North American market of $32.4 million.

Low-Carbon Ferrochromium

Of note in table 42 is that, under the cutoff scenario, low-C FeCr imports from Turkey and Zimbabwe replace material previously supplied by South Africa for the 1992 solution. By 1994, mainly because of the hypothetical doubling of Zimbabwe production capacity built into the model, the lost South African imports are forecast by the model to be replaced entirely by imports from Zimbabwe. In both years, and under both scenarios, domestic U.S production provides a major share of the North American low-C FeCr demand.

These low-C FeCr results stress the importance to the North American low-C FeCr market of imports from Turkey and, particularly, from Zimbabwe. They also point out the importance of maintaining at least some domestic low-C FeCr smelting capacity as a contingency source.

Table 42 shows that a direct ban on the importation of low-C FeCr from South Africa causes the weighted average delivered cost into the North American market to be only 4.6 pct higher in 1992 and 6.7 pct higher in 1994 than would be the case without an embargo. The model's weighted average 1992 and 1994 delivered cost results for low-C FeCr under the cutoff scenario are actually 7.8 and 8.1 pct less than the actual 1986 weighted average delivered cost into the United States of $1,557/mt Cr in January 1989 dollars.[30]

The model shows little difference in total delivered costs under the two varying scenarios for low-C FeCr delivered into the North American market. For example, the 6.7 pct increase to the weighted average delivered cost

[28]Cost, insurance, and freight; a value designation that represents the cost of delivering the commodity to the port of entry.

[29]For comparison purposes, the actual weighted average 1986 cost, insurance, and freight (c.i.f.) value for all high-C FeCr imports into the United States of $823/mt Cr was converted to a constant average 1988 (January 1989) U.S. dollar value of $877/mt Cr using a GNP price deflator.

[30]For comparison purposes, the actual weighted average 1986 cost, insurance, and freight (c.i.f.) value for all low-C FeCr imports into the United States of $1,461/mt Cr was converted to a constant average 1988 (January 1989) U.S. dollar value of $1,557/mt Cr, using a GNP price deflator.

under the South African cutoff scenario solution for 1994 represents an additional cost for delivery of all low-C FeCr into the North American market of $2.5 million. However, the solution for the cutoff scenario required the inclusion of a hypothetical doubling to Zimbabwe's production capacity and the addition of sizable new low-C FeCr capacity in Canada.

Summary

The above results indicate that North American high-C and low-C FeCr markets would not be severely affected by a direct embargo of South African products, as long as new capacity is developed and indirect imports are allowed. The existing and proposed U.S. ferrochromium smelters, combined, could supply approximately 27 pct of high-C and 42 pct of low-C FeCr demand in North America if hypothetical high-C FeCr capacity built into the model is installed. The model's ability to obtain solutions under the "cutoff" scenario without the addition of new hypothetical smelting capacity in such countries as Zimbabwe, Swaziland, Venezuela, and the United States was not tested for this study. It is likely that under such a test the delivered cost results would increase dramatically from those shown, provided a solution could be obtained. Under such circumstances, the impact of an embargo such as the one tested here could be tempered by releases from the DOD stockpile, though not indefinitely.

Comparison of Delivered Costs and Market Prices

Industry prices emerge from the interaction between demanders and suppliers of goods, with market equilibrium occurring when the amount offered for sale is the same as the amount that consumers are willing and able to purchase. In a quasicompetitive market,[31] the delivered unit cost of the last unit supplied to the market (the marginal cost of the marginal supplier)[32] basically sets the equilibrium price of the commodity. This equilibrium price can be interpreted as a likely minimum price in a competitive market. Producers with delivered costs below the market equilibrium price would earn additional return.

Comparisons can be made between the estimated delivered costs of the model's solution and the actual market prices of high-C and low-C FeCr into various regions to test the hypothesis that the markets are quasicompetitive. For this study's purpose, the model's transportation algorithm solutions were used to determine the marginal cost of the marginal supplier for delivery of high-C and low-C FeCr into the three major MEC demand regions of the model for 1986. The resulting values, in January 1989 U.S. dollars, are presented in table 43.

Table 43.—Model estimated marginal cost of the marginal supplier[1] for delivered FeCr products into major consuming regions, 1986 model solution

(January 1989 U.S. dollars per metric ton Cr)

Demand region	Marginal cost	
	High-C FeCr	Low-C FeCr
Asia	1,034	1,753
North America	1,045	2,011
Western Europe	1,025	1,716

[1]In this study, the marginal cost of the marginal supplier is represented by the cost to deliver the most expensive 5 pct of each region's demand, as determined by the model's transportation algorithm. This method prevents skewing of the marginal cost of the marginal supplier by a very high-cost producer that may supply only 1 or 2 pct of the estimated demand.

Because of the lack of data on FeCr market prices in the Asian and Western European markets, this section compares the transportation algorithm's marginal cost of the marginal suppliers of high- and low-C FeCr into the North American market to actual FeCr market prices in the U.S. market. It must be noted that there is no single "market price" for either high-C or low-C FeCr. Ferrochromium products vary in terms of chromium contents, with higher grade products commanding higher market prices on a basis of U.S. dollars per pound Cr. Because the model cannot differentiate between the various grades of high-C or low-C FeCr, the model's marginal cost of the marginal supplier results will be compared to a variety of reported U.S. market prices and c.i.f. import values.

As shown in table 43, the marginal cost of the marginal supplier of high-C FeCr into the North American market was estimated to be $1,045/mt Cr. By comparison, actual 1986 c.i.f. import values into the U.S. market (on a country-by-country basis) ranged from $767 to $996/mt Cr in terms of 1986 dollars or $818 to $1,062/mt Cr in terms of January 1989 U.S. dollars. Again, it is important to remember that these customs values are *not* transaction prices and are presented only as a guide to the valuation of the products as they enter the U.S. market.

For further comparisons, the following tabulation presents selected 1986 U.S. high-C FeCr prices in terms of both average 1986 prices (first value listed) and January

[31]A quasicompetitive market is comparable to a competitive market except that producers face differing costs because of either physical location or quality of resources.

[32]In this study, the marginal cost of the marginal supplier was determined by the transportation algorithm solution of the model. The producer(s) shipping at least the last 5 pct of regional demand is designated as the marginal cost supplier. This approach excludes any unrealistically high cost paths that may be selected by the solution algorithm to balance the final 1 or 2 pct of flow into a market.

1989 U.S. dollars (second value listed). The average 1986 values represent the averages of the January and December 1986 prices (*31*), and the January 1989 dollar values represent these 1986 average prices converted to a January 1989 dollar basis using a GNP deflator:

Imported charge chromium (50-55 pct Cr)—	$904/mt Cr; $964/mt Cr
Imported charge chromium (60-65 pct Cr)—	$980/mt Cr; $1,045/mt Cr
U.S. charge chromium (66-70 pct Cr)—	$1,190/mt Cr; $1,268/mt Cr.

As shown, the average 1986 price for imported charge chromium grading 50 to 55 pct Cr—the grade category that constitutes the largest amount of high-C FeCr imports into the U.S. market—averaged $904/mt Cr in average 1986 dollars, which converts to $964/mt Cr in January 1989 dollars. Comparison back to figure 11 shows that nearly 80 pct of the high-C FeCr supplied to the North American market in the model's solution has a delivered cost below this $964/mt Cr price level.

Comparison to figure 11 also shows that 95 pct of the high-C FeCr delivered to the North American market in the model's solution has a delivered cost (in January 1989 dollars) below the reported price level for imported charge chromium grading 60 to 65 pct Cr ($1,045/mt Cr in January 1989 dollars) and that 100 pct can be supplied below the 1986 U.S. charge chromium (66 to 70 pct Cr) price of $1,268/mt Cr in January 1989 dollars.

At $1,045/mt Cr, the marginal cost of the marginal supplier (as determined by the transportation algorithm solution) in the model's solution for the 1986 North American high-C FeCr market is equal to the price of imported charge chromium grading 60 to 65 pct Cr ($1,045/mt Cr in January 1989 dollars). Therefore, it appears that nearly all suppliers to the U.S. market were able to earn returns in excess of delivered costs in 1986; however, some may have been at or slightly above the breakeven point.

Reference back to table 43 shows that the marginal cost of the marginal supplier of low-C FeCr into the North American market was estimated to be $2,011/mt Cr. This value compares to actual c.i.f. import values into the U.S. market for 1986 ranging (on a country-by-country basis) from $1,014 to $1,822/mt Cr in terms of average 1986 dollars or to $1,081 to $1,943/mt Cr in terms of January 1989 dollars.

For further comparisons, the following tabulation presents selected 1986 U.S. low-C FeCr prices in terms of both average 1986 prices (first value listed) and January 1989 U.S. dollars (second value listed). The average 1986 values represent the averages of the January and December 1986 prices (*31*), and the January 1989 dollar values represent these 1986 average prices converted to a January 1989 dollar basis using a GNP deflator:

U.S. low-C FeCr (0.025 pct C)—	$2,205/mt Cr; $2,350/mt Cr
U.S. low-C FeCr (0.05 pct C)—	$2,094/mt Cr; $2,232/mt Cr
Imported low-C FeCr (0.05 pct C)—	$1,879/mt Cr; $2,003/mt Cr
Simplex low-C FeCr—	$2,205/mt Cr; $2,350/mt Cr.

Comparison back to figure 14 shows that 92 pct of the low-C FeCr supplied to the North American market in the model solution has a delivered cost below the average 1986 price for imported low-C FeCr grading 0.05 pct C, which was $2,003/mt Cr in terms of January 1989 U.S. dollars. Further, the remaining 8 pct has delivered costs below the 1986 price for U.S. low-C FeCr grading 0.05 pct C, which was $2,232/mt Cr in terms of January 1989 dollars. Finally, reference back to table 43 shows that the marginal cost of the marginal supplier for the model's 1986 solution was $2,011/mt Cr, which is nearly the same as the reported average price of imported low-C FeCr grading 0.05 pct C ($2,003/mt Cr in terms of January 1989 dollars). As was the case for high-C FeCr, it appears that nearly all suppliers to the U.S. market were able to earn returns in excess of delivered costs in 1986; however, some may have been at or slightly above the breakeven point.

Because of improved market prices in 1988, a comparison of the model's 1988 marginal delivered costs into the North American FeCr markets to actual U.S. c.i.f. import values and prices shows a drastic improvement in the position of the marginal supplier. In the model's solution for 1988, the marginal cost of the marginal supplier of high-C FeCr into North America, at $1,090/mt Cr, is not much different from the 1986 model solution value of $1,045/mt Cr. There is little difference because during this time period (1986-88) very little new, lower cost high-C FeCr smelting capacity came on-line in the model. Yet, the reported c.i.f. import values for high-C FeCr into the U.S. market for 1988 ranged from $1,094/mt Cr to $2,234/mt Cr,[33] 33.7 pct to 110.4 pct higher than the country-by-country ranges for 1986. Meanwhile, the reported prices for imported charge chromium grading 50 to 55 pct Cr had increased 71 pct from 1986 levels (in January 1989 dollars), and the reported prices for imported charge chromium grading 60 to 65 pct Cr had increased 66 pct from 1986 levels (in January 1989 dollars) (*25*).

[33]On a country-by-country basis; excludes a small amount of imports from one country valued at an extremely high $4,700/mt Cr.

A similar, but much less spectacular, increase in U.S. import values and prices occurred for low-C FeCr. The reported c.i.f. import values for low-C FeCr into the U.S. market for 1988 ranged from $1,346/mt Cr to $2,872/mt Cr,[34] 24.5 pct to 47.8 pct higher than the country-by-country ranges for 1986. Also, the average price for imported low-C FeCr grading less than 0.05 pct C increased 23.9 pct from 1986 levels (in January 1989 dollars) (*25*). Yet, the model's marginal cost of the marginal supplier for the 1988 solution is no different (at $2,011/mt Cr) than in the 1986 solution. Therefore, it appears that as a result of increased prices in 1988, MEC FeCr producers were able to earn returns much in excess of delivered costs into the North American market.

Figures 17 and 18 show the step curves of the model's delivered costs for high-C and low-C ferrochromium into North American markets for the 1986 year solution. Superimposed on each graph are reported average 1986 c.i.f. customs values for countries that accounted for 98.2 pct of U.S. high-C FeCr imports (fig. 17) and for countries that accounted for 98.4 pct of U.S. low-C FeCr imports (fig. 18). All values shown in the figures are presented in terms of January 1989 U.S. dollars. Comparison of the customs values in these figures to the list of Cr in FeCr product grades given at the end of appendix F shows a general relationship between the higher customs values and the increasing Cr grades of FeCr products.

Customs values reflect the buyer's valuation of material in the country of origin; they are *not* the transaction price. In addition, the variation among customs values may be caused by numerous factors, including relative shipping cost from country of origin to North America, varying product quality or chromium content, and exchange rate levels. Nonetheless, as shown in the figures and in the preceding text discussion, the actual c.i.f. customs values for imports into the U.S. market generally exceed the model's estimates of delivered costs for FeCr products into the North American markets. This implies that the vast majority of ferrochromium suppliers are able to earn returns in excess of variable costs even in years when some capacity is idle and the pricing environment is poor, as was the case in 1986.

It is of note that, with this network flow model, reasonable market solutions could be obtained only by limiting the quantities exported by South Africa to all of the major markets. This suggests that, based only on relative cost and size of potential supply, South Africa could dominate any major MEC chromium ferroalloy market if so desired.

[34]On a country-by-country basis; excludes a small amount of imports from one country valued at an extremely high $3,849/mt Cr.

Assuming that South Africa does show restraint in the chromium markets, the reasons for such action may be economic and/or political. If the segment of market demand faced by South Africa is inelastic, its chromium industry could be able to maximize profit by decreasing quantity supplied. Alternatively, the South African industry may be acting to maintain market share rather than to maximize short-run monopoly profits. Consistent with this rationale, the industry may prefer to sell in several markets, even though any single market could be dominated, to limit risk. Or, the South African chromium industry may limit exports into a particular market so as not to be perceived as driving other firms out of the market. It is also worthy of note that in markets where capacity use decisions are seen as particularly important—a characteristic of minerals markets—dominant firms are frequently quantity leaders.

The preceding information demonstrates several important characteristics of North American ferrochromium markets:

There is no single "market price" for either high-C or low-C FeCr.

Ferrochromium products vary in terms of percent chromium content with higher grade products commanding higher market prices (on a $/lb Cr basis).

Delivered costs vary significantly from country to country; prices appear to reflect relative delivered costs into major markets.

Nearly all sellers in ferrochromium markets appear to be able to earn at least some return to capital, even in "down" years such as 1986.

South Africa appears to act as a dominant supplier in the North American market. Given the assumption of the installation of certain low-cost capacity in several other countries, this situation could change by 1994.

These results suggest that ferrochromium markets resemble the oligopolistic model more closely than the quasicompetitive one. There are few producers, each is aware of the actions of its rivals, and price exceeds marginal delivered costs.

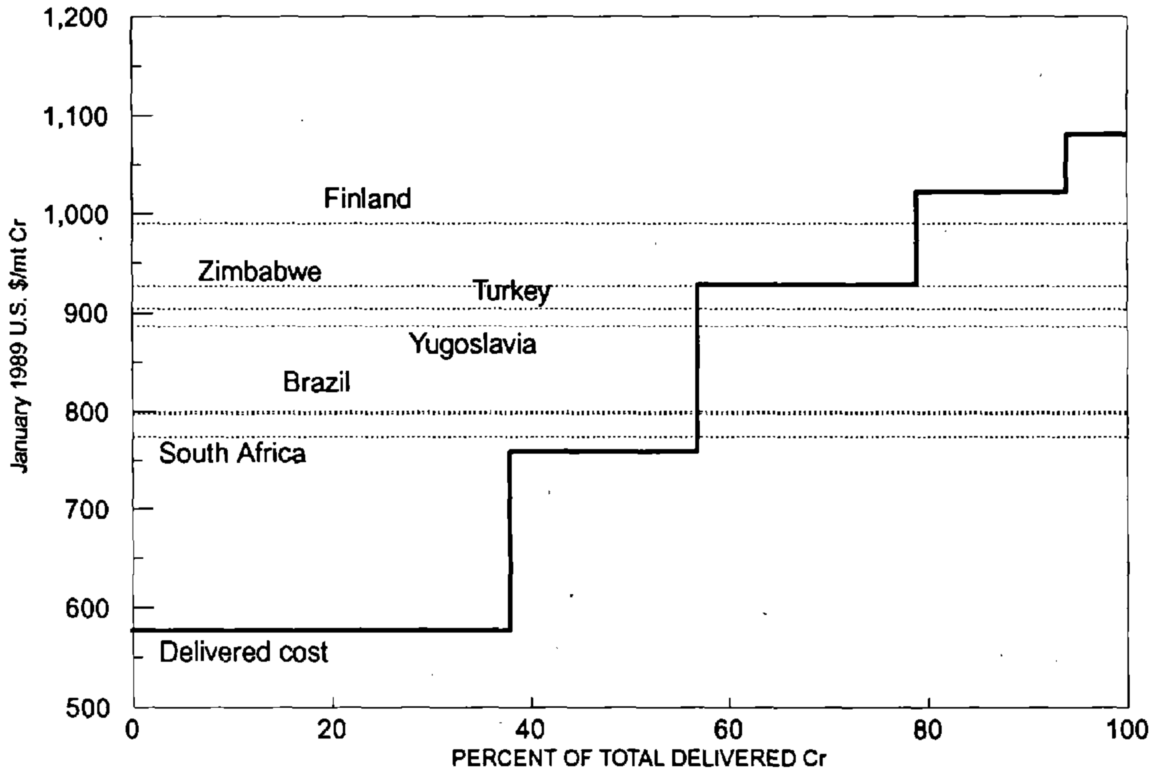

Figure 17.—Comparison of delivered cost to supply 100 pct of 1986 high-C FeCr demand into North America and selected 1986 c.i.f. import values, January 1989 U.S. dollars.

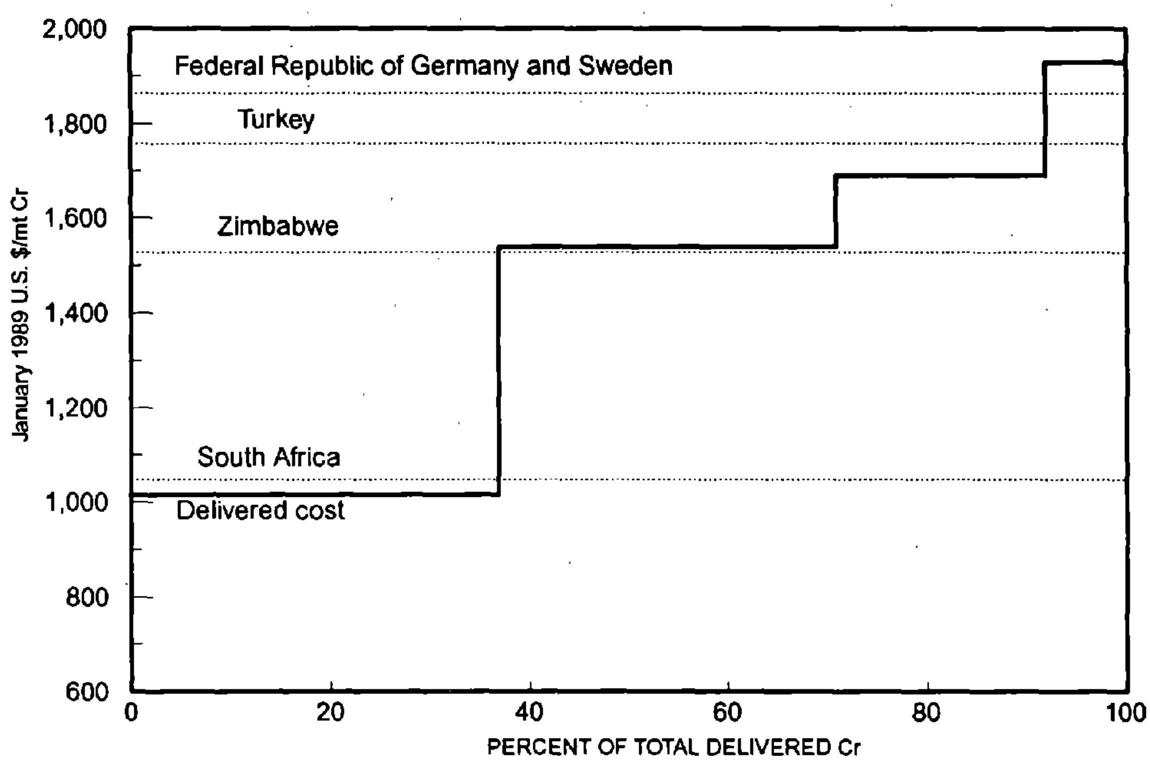

Figure 18.—Comparison of delivered cost to supply 100 pct of 1986 low-C FeCr demand into North America and selected 1986 c.i.f. import values, January 1989 U.S. dollars.

CONCLUSIONS

The following are the main conclusions resulting from the availability study portion of this report:

(1) The size, occurrence, and quality of its chromite resources is an important factor in South Africa's position as a tonnage and cost leader in the MEC chromium industry. Other factors contributing to this position are its level of economic development, the availability of capital and technical skills, and the ability of its chromium industry to introduce and develop the latest technologies. In the results of this study, South Africa is the tonnage leader in every category of chromium product analyzed and had the lowest overall price determinations in every chromium product but one. Only in high-C FeCr is it ranked second (behind Turkey) according to the price determination results of this study. The South African dominance would be even greater if potential future output and economics of UG2 seam chromite resources had been considered in the study.

(2) There is no shortage of chromium resources in MEC's. The producing and nonproducing units in the countries included in this analysis would be capable of beneficiating 19.8 Mmt of ROM to produce 11.7 Mmt of chromite products. This level of potential annual output of chromite products is 57 pct higher than the 1988 output of these countries as a group.

(3) The countries of South Africa and Zimbabwe still dominate in terms of total MEC chromium potential as of the late 1980's. This is despite additional MEC potential being established, particularly in India and Turkey, since the late 1970's.

(4) In terms of tonnage and Cr_2O_3 content, the three U.S. resource areas included in this analysis are of world class level, although in the bottom range in terms of Cr_2O_3 content. Using the most efficient smelting technology currently under development, the Alaska and Montana resources are well within the overall range of the MEC high-C FeCr price determinations of this study. However, their appropriate role should be considered in the context of an industry not short of available chromium resources.

The following are the main conclusions resulting from the network flow model study portion of this report:

(1) The rise in the price of high-C FeCr of late 1987 and early 1988 reflected capacity constraints experienced by the industry. The large amount of new smelting capacity added during the 1988-90 period has caused capacity use percentages to decline to more normal levels, resulting in a price decline from the peaks of 1988.

(2) The capacity additions of 1988-91 should cause a stabilization of prices for the short term, but the level at which the price stabilizes is in question. The model results indicate that under a rather optimistic scenario—a demand growth rate of about 4.0 pct/yr from 1988 through 1994 and a conservative inclusion of additional smelting capacity—the percentage of capacity use in MEC's for the year 1994 would be only 76.6 pct. Should MEC's enter a recession, however, production and capacity uses will likely be lower than in the present model solutions.

(3) In contrast, given the model's growth rate for Cr in low-C FeCr of about 3.0 pct/yr in MEC's from 1988 through 1994 and the smelting capacities presently built into the model, some new low-C FeCr and ferrochromium-silicon MEC production capacity will need to be added early in the 1990's. Again, should MEC's enter a recession, however, production and capacity uses will likely be lower than in the present model solutions.

(4) Using the demand levels and growth rates of this model, it appears that the commonly accepted levels of U.S.S.R. and Albanian chromite production may be overstated. In particular, the model suggests that chromite export levels from the U.S.S.R. are not consistent with reported chromite production levels of 3.3 to 3.8 million mtpy. All aspects of the U.S.S.R. and Albanian chromium industries warrant further study.

(5) The nearly two-decades-long trend for new MEC FeCr capacity to be constructed in chromite producing countries should continue. In a competitive market, relatively free of constraints, the smelters in countries without chromite resources appear to face a cost disadvantage in the future.

(6) The present network flow model has obtained a solution indicating that an embargo of direct imports of South African Cr products into North

America could be feasible, assuming that *indirect* imports of South African origin are allowed. However, the solution requires a series of very timely and specific capacity increases. In addition, this cutoff results in South Africa losing only $157 million (11.7 pct) of the export revenue that they could normally expect to receive from Cr product exports in 1994.

(7) The high-C and low-C FeCr markets are dominated by South Africa, which appears to act as a quantity limiting market leader.

(8) Ferrochromium markets are not quasicompetitive. Market prices in North America differ between suppliers and exceed delivered costs.

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APPENDIX A.—SUMMARY DATA, EVALUATED MEC CHROMITE PROPERTIES AND UNITS

This appendix consists of table A-1, summarizing the names, ownerships, and January 1989 status for the 149 chromite properties and units analyzed for the availability portion of this study. The table also includes the major type of mining (surface, underground, or combined), the predominate type of beneficiation, the chromium product assignments, and the annual chromite product capacities for each of the properties and units. The table lists 4 properties in Brazil, 1 in Finland, 2 in Greece, 2 in Madagascar, 1 in New Caledonia, 13 in the Philippines, 26 in South Africa, and 7 in Turkey. There are 53 properties/units listed for India, 3 United States properties/units, and 37 properties/units in Zimbabwe.

The basic resource evaluation groupings used for this study are either as "properties" or as "units." In this study, the definition of a "property" is related primarily to ownership aspects and to operational considerations. In this context, a property could consist of several different types of chromite deposits and mining operations (i.e., an "operation").

The term "units" has been used in this study to facilitate analysis where ownership within a large geographic area of chromite deposits was either unclear or fragmented. This was the case for the analysis of the Great Dyke in Zimbabwe and for the California/Oregon podiform deposits in the United States. The term "units" also applied to the analytical situation for the country of India, where the Sukinda Valley chromite reserves consist of a number of individual chromite deposits contained within each of the ownership (lease) areas. To assess economic differences among the various chromite deposits it was necessary to approach each deposit as a separate "unit."

Table A-1.—Summary data, evaluated MEC chromite properties and units

Country/property or unit name	Ownership	Status (Jan. 1989)	Type of mining	Type of benefi-ciation	Chromium product assign-ments	Annual chromite product capacity (kmtpy)
Brazil:						
Ipueira I, II, and III	Min.Vale do Jacurici	P	U	G	H, L	181
Limoeira	Cia.de Ferro Ligas da Bahia	N	S	G	H	85
Pedrinhas/Casabulhos	..do.	P	C	G	H	180
Pedrinhas (COMISA/Coitzeiros)	Coitzeiro Mineracao (COMISA)	P	C	G	C, H	26
Total, Brazil						472
Finland:						
Kemi	Outokumpu Oy	P	S	G	H, M, C, F	607
Greece:						
Skoumsta (Type A ore)	Hellenic Ferro Alloys	P	U	G	H	68
Skoumsta (Type B ore)	..do.	P	C	G	H	22
Total, Greece						90
India:						
Bhimtanagar; No. 3, Pit 1	Tata Iron and Steel Co. Ltd.	P	S	S	M, R	46
Bhimtanagar; No. 1	..do.	N	S	S	M	9
Bhimtanagar; No. 2	..do.	N	S	S	M	90
Bhimtanagar; No. 3, Pit 2	..do.	N	S	S	M	46
Bhimtanagar; No. 3A	..do.	N	S	S	M	9
Bhimtanagar; No. 4	..do.	N	S	S	M	5
Bhimtanagar; No. 5A	..do.	N	S	S	M	7
Bhimtanagar; No. 5B	..do.	N	S	G	M	6
Bhimtanagar; No. 6A	..do.	N	S	G	M	8
Bhimtanagar; No. 6B	..do.	N	S	G	M	3
Bhimtanagar; No. 7	..do.	N	S	G	M	11
Bhimtanagar; No. 8	..do.	N	S	G	M	4
Bhimtanagar; No. 9A1	..do.	N	S	G	M	8
Bhimtanagar; No. 9A2	..do.	N	S	S	M	20
Bhimtanagar; No. 9B	..do.	N	S	G	M	4
Bhimtanagar; No. 10A	..do.	N	S	S	M	24

See footnotes at end of table.

Table A-1.—Summary data, evaluated MEC chromite properties and units—Continued

Country/property or unit name	Ownership	Status (Jan 1989)	Type of mining	Type of benefi-ciation	Chromium product assign-ments	Annual chromite product capacity (kmtpy)
India—Continued						
Bhimtanagar; No. 10B	Tata Iron and Steel Co. Ltd.	N	S	S	M	40
Bhimtanagar; No. 10C	..do.	N	S	S	M	40
Bhimtanagar; No. 10D	..do.	N	S	S	M	24
Bhimtanagar; Nos. 11A-11E	..do.	N	S	G	M	4
Bhimtanagar; No. 12A	..do.	N	S	G	M	11
Bhimtanagar; No. 12B	..do.	N	S	G	M	8
Bhimtanagar; No. 13A	..do.	N	S	S	M	10
Bhimtanagar; No. 13B	..do.	N	S	S	M	20
Bhimtanagar; No. 14A	..do.	N	S	S	M	12
Bhimtanagar; No. 14C	..do.	N	S	S	M	14
Bhimtanagar; No. 14C1	..do.	N	S	S	M	12
Bhimtanagar; No. 16A	..do.	N	S	S	M	8
Bhimtanagar; No. 16B1	..do.	N	S	S	M	16
Bhimtanagar; No. 16B2	..do.	N	S	G	M	6
Bouala, High Grade	Ferro Alloys Corp. Ltd.	P	U	S	H, L	108
Bouala, Low Grade	..do.	P	U	G	H	45
Byrapur	Mysore Minerals Ltd.	P	U	S	H	14
Gurjang; No. 1	Govt. of India	N	S	S	M	3
Gurjang; No. 2	..do.	N	S	S	M	7
Gurjang; No. 3	..do.	N	S	S	M	16
Jambur	Mysore Minerals Ltd.	P	S	G	M, C	34
Kaliapani	Orissa Mining Corp. Ltd.	P	S	S	H, M	166
Kalrangi	..do.	P	S	S	R	21
Kamarda; Nos. 2A, 2B	B. C. Mohanty	N	S	S	M	2
Kamarda; Nos. 3, 3A	..do.	N	S	S	M	7
Kamarda; Nos. 4, 4A	..do.	P	S	S	M	3
Kathpal District	Ferro Alloys Corp. Ltd.	P	S	S	L	13
Kathpal District	Orissa Mining Corp. Ltd.	P	S	S	L	14
Nausahi, Low Grade	M/S Serrajuddin	N	S	G	M	10
Nausahi, High Grade	..do.	P	S	S	H	9
Saruabil; Nos. 4, 4A, 2	Misrillal Mines Pvt. Ltd.	P	S	S	M, C	38
Saruabil; No. 4B	..do.	N	S	S	M	5
Saruabil; No. 5	..do.	N	S	S	M	18
Saruabil; No. 5A	..do.	N	S	S	M	27
Saruabil; No. 6	..do.	N	S	S	M	3
Sukerangi	Orissa Mining Corp. Ltd.	P	S	S	H	47
Tagadur	Mysore Minerals Ltd.	P	S	G	M, C	42
Total, India						1,177
Madagascar:						
Andriamenha District	Kraomita Madagascar	P	S	G	M	102
Ranomena	Govt. of Madagascar	N	S	G	C	13
Total, Madagascar						115
New Caledonia:						
Tiebaghi Massif	Various	P	U	G	M, R	85
Philippines:						
Acoje (Santa Cruz)	Acoje Mining Company, Inc.	P	U	G	H	72
Batang-Batang	Philchrome Mining Corp.	N	S	G	M	21
C-Square Consolidated	C-Square Consolidated Mines	N	S	G	R	20
Candelaria	Intercontinental Mng & Oil	N	C	G	R	21
Coto (Masinloc)	Consolidated Mines, Inc.	P	U	G	M, R, F	113
Irahuan	Palawan Consolidated Mining Co.	N	S	G	M, C, R	39
Isabela (eluvial)	Island Mining & Indust. Corp.	N	S	G	M	52
Laganoy (low grade)	Cam-Meta Minerals Ltd.	N	S	G	M	11
Lagonoy (high grade)	..do.	N	S	S	M	4
Llorente	Alamag Processing Corp.	P	S	G	C	33

See footnotes at end of table.

Table A-1.—Summary data, evaluated MEC chromite properties and units—Continued

Country/property or unit name	Ownership	Status (Jan 1989)	Type of mining	Type of benefi-ciation	Chromium product assign-ments	Annual chromite product capacity (kmtpy)
Philippines—Continued						
Omasdang	Acoje Mining Company, Inc.	P	S	G	H	12
Narra (Lapu-Lapu Project)	Trident Mining & Industrial Corp.	N	S	G	M	66
Palawan Joint Venture	Golden Arrow Mining Co., Inc.	N	S	G	M, C	29
Total, Philippines						493
South Africa:						
Chrome Chemicals (Rustenburg section).	Chrome Chemicals S.A. (Pty)	P	U	G	C, M	157
Chroombronne	Chromecorp Technology (Pty)	P	U	G	H	249
Dilokong	Lebowa Devel. Corp. Ltd.	P	U	G	M, C	188
Grasvally	SAMANCOR Ltd.	N	U	G	H, L, M	173
Groothoek	..do.	P	U	G	H, M, R, C	163
Henry Gould	Rand Mines Ltd.	P	U	G	H, M, F	583
Jagdlust	SAMANCOR Ltd.	P	U	S	M, R	192
Kroondal	..do.	N	U	G	M	358
Lavino (Grootboom)	Lavino South Africa (Pty)	P	U	G	M, C, F	335
Marico (Surface)	SAMANCOR/Vereeniging Refractories.	P	S	G	R, M	104
Marico (Underground)	..do.	N	U	G	R, M	104
Millsell	Rand Mines Ltd.	N	U	G	M, F	114
Montrose	SAMANCOR Ltd.	P	U	G	H, M, F	390
Mooinooi	..do.	P	U	S	H	598
Ntuane	Sherwood Chrome Mines Ltd.	N	U	G	M, C	46
Ruighoek	Bathlako Mining Ltd.	P	U	G	H, C	101
Rustenburg Minerals Development Corp.	Associated Ore & Metals Corp.	P	U	S	L, H, M	279
Tweefontein	SAMANCOR Ltd.	P	U	G	H, C, F	566
Waterkloof	..do.	P	U	G	H, C	158
Winterveld TCL (North)	Rand Mines Ltd.	N	U	S	M	446
Winterveld TCL (South)	..do.	P	U	G	H,L,M,C,R,F	788
Zeerust	Associated Ore & Metals Corp.	P	U	G	H	100
Zwartkop:						
Compound Seam	SAMANCOR Ltd.	N	U	G	M	48
Intermediate Seam	..do.	N	U	S	M	44
Magazine Seam	..do.	N	U	S	M	164
New Seam	..do.	N	U	G	M	50
Total, South Africa						6,498
Turkey:						
Kandak	Sitke Kocman Mines	P	U	G	M	22
Kapin	ETIBANK	P	U	S	R	18
Kavak	Turk Maadin Sirketi AS	P	U	G	M	52
Kefdag	ETIBANK	P	U	G	H	298
Kopdag West	Various	N	U	G	M	19
Soridag	ETIBANK	P	U	G	H	124
Uckopru	..do.	P	U	G	L, M	81
Total, Turkey						614
United States:						
Mountain View Mine	Various	N	U	G	H	254
Red Mountain	Cook Inlet Region Inc.	N	S	G	H	145
Northern Klamath Mountains	Various	N	C	G	H	147
Total, United States						546
Zimbabwe:						
Bat Claims/Ngezi Cooperative	Various, unknown	N	U	G	M	17

See footnotes at end of table.

Table A-1.—Summary data, evaluated MEC chromite properties and units—Continued

Country/property or unit name	Ownership	Status (Jan 1989)	Type of mining	Type of benefi-ciation	Chromium product assign-ments	Annual chromite product capacity (kmtpy)
Caesar Section:						
Shallow Mining	Zimbabwe Alloys (ZIMALLOYS)	P	C	G	L	13
Company Claims	do.	N	U	G	M	16
Tributed Areas	do.	N	U	G	M	27
Central (Midlands)	Various, unknown	N	U	G	M	38
Crown/Divide North	Zimbabwe Mining & Smelting (ZIMASCO).	P	U	S	H	10
Divide/Francis	Various, unknown	N	U	S	M	18
Glenapp/Ivo	Zimbabwe Mining & Smelting (ZIMASCO).	P	U	S	H	10
Great Dyke	Zimbabwe Alloys (ZIMALLOYS)	P	U	G	L, S	7
Greenvale	Various, unknown	N	U	S	M	18
Hay/Noro	Zimbabwe Mining & Smelting (ZIMASCO).	P	U	S	H	10
Impinge	do.	P	U	S	H	10
Inyala	Zimbabwe Alloys (ZIMALLOYS)	P	U	G	L	22
Iron Ton	Zimbabwe Mining & Smelting (ZIMASCO).	N	U	S	M	18
Ironsides	do.	N	U	S	M	33
Lalapanzi	do.	P	U	G	H	43
Magazine Hill	Zimbabwe Mining & Smelting (ZIMASCO).	N	U	S	M	25
Magundi	Various, unknown	N	U	S	M	33
Maryland	Zimbabwe Mining & Smelting (ZIMASCO).	P	U	S	H	19
McGowan	do.	P	U	G	H	13
Mdindi/Mapanzuri/Chrome Hill	Various, unknown	N	U	G	M	33
Netherburn	Zimbabwe Alloys (ZIMALLOYS)	P	U	G	L, S	40
Ngezi Cooperative	Ngezi Cooperative	P	U	S	M	1
Ore Recovery Tribute	Various, unknown	N	U	G	M	24
Pons	Various, unknown	N	U	G	M	8
Railway Block	Zimbabwe Mining & Smelting (ZIMASCO).	P	U	G	H	172
Rose/Seymore/Makamisa	Various, unknown	N	U	G	M	11
Rutala	Various, unknown	N	U	G	M	14
Shurugwi Peak	Zimbabwe Mining & Smelting (ZIMASCO).	P	U	G	H	119
Spot	Various, unknown	N	U	G	M	18
Sutton/Rodcamp	Zimbabwe Alloys (ZIMALLOYS)	P	U	G	L, S	30
Umsweswe	Various, unknown	N	U	G	M	13
Umsweswe/Bee	Various, unknown	N	U	G	M	13
Umvukwes	Zimbabwe Mining & Smelting (ZIMASCO).	P	U	S	H	49
Valley Chrome	do.	P	U	G	H	55
Vanad	Zimbabwe Alloys (ZIMALLOYS)	P	U	G	L, S	27
Windsor/York/York West	Various, unknown	N	U	G	M	19
Total, Zimbabwe						1,046

Status: P = producer, N = nonproducer.
Type of mining: S = surface, U = underground, C = combined.
Type of beneficiation: S = sorting and/or screening only, G = gravity (includes heavy media and magnetic separation) for any percentage of ROM feed from 0 to 100 pct.
Chromium product assignments: M = metallurgical chromite, C = chemical chromite, R = refractory chromite, F = foundry sand chromite, H = high-C FeCr, L = low-C FeCr, S = ferrochromium-silicon.

APPENDIX B.—INDUSTRY OVERVIEWS, RESOURCES, AND MINING AND BENEFICIATION OPERATING PARAMETERS AND COSTS, MEC'S

This appendix provides individual overviews of the chromium industry within each of the 11 MEC's that has had chromite resources evaluated for the availability portion of this study. Each country's overview section discusses changes or developments in chromite, ferrochromium, chemical, and refractory industry production, capacities, and ownership since the late 1970's.

All country sections include a discussion of chromite resources. However, detailed discussions of operating parameters and cost estimates are provided for only seven of the countries; there are no operating parameter and cost discussions for the four countries where the analysis involved only one operation or company.

The information given in this appendix provides explanations for many of the design and structural aspects incorporated in both the availability and network flow market model portions of this study.

BRAZIL

Industry Overview

Chromite Production

Brazilian chromite production was estimated to be 313,000 mt in 1980 (*32*),[1] declining to only 155,000 mt in 1983 (*31*). By 1988, production was estimated to have recovered to 240,000 mt (*23*). However, based on normal ore requirements for smelting, the estimate for 1988 chromite production appears to be too low if Brazilian chromium ferroalloy production was at, or close to, the reported production level of 130,000 mt of FeCr (*28*).

Mining and Beneficiation

At the mining and processing level there have been four developments of note during the 1980's. First, the Limoeira mine in the Campo Formosa District, which produced 100,000 mt of products in 1978, its best year, was closed down in late 1983. As of 1989 it had still not reopened and was classified as a nonproducer for this analysis. Also in the Campo Formosa District, the surface mining of primary ores at FERBASA's Pedrinhas/Cascabulhos operations was reportedly halted in late 1984. The company planned to feed the mill with stockpiled ore and tailings during 1985 and 1986 while new underground mining facilities were under development. No updated information is available to indicate whether the transition to full underground production was completed as planned.

A major exploration campaign in the vicinity of the Jacurici River Valley resulted in the 1981 opening of the Ipueira underground mining operations near the town of Medrado. This operation is capable of treating 250,000 mtpy of ROM[2] to produce about 180,000 mtpy of various chromite products.

The fourth development was the discovery of a major chromite deposit in Amapa state. The deposit was delineated during an intensive exploration program from 1983 to 1986 and contains from 3 Mmt to 4 Mmt of surface minable ROM at a grade of 35 pct Cr_2O_3. As of 1989, a mill with the capacity to produce about 150,000 to 160,000 mtpy of concentrates from 270,000 mtpy ROM had been installed on the property. This operation, called Vila Nova, was not analyzed for the availability portion of this study but was included in the network flow model design. The table in appendix A lists the four Brazilian properties included in this availability analysis and the product designations for each. The chemical chromite product shown in the table was assumed to be used internally by the chromium chemicals plant located at Belford Roxo. Thus, as designed for the availability portion of this study, all Brazilian chromite output is used internally.

Smelting

There does not appear to have been any new furnaces or furnace conversions for chromium ferroalloy production at FERBASA's Pojuca smelter since the early 1980's. The smelter did add three 18-MV·A[3] furnaces during the 1985-87 period, but all three of these furnaces have been assigned to ferrosilicon production.

The Pojuca smelter uses five furnaces, ranging in size from 12 MV·A to 16.5 MV·A, for production of about 130,000 mtpy of high-C FeCr at full capacity. For this study it was estimated that about 7,000 mt of this high-C FeCr would be smelted to ferrochromium-silicon in a sixth furnace and the ferrochromium-silicon used along with

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

[2]In the context of this study, run-of-mine (ROM) material is equivalent to the feed material to any further beneficiation, including sorting.

[3]In this report, the relative sizes of electric arc furnaces at smelters are reported in terms of the installed electrical transforming capacity for the furnace. The units for this transforming capacity are given in terms of MV·A's. In some smelting discussions the report includes references to MW units. This unit is the "power load factor," which is the amount of electrical power applied in the smelting process.

slag from two additional furnaces to produce approximately 14,000 mtpy of low-C FeCr at full capacity.

Chromium Chemicals Industry

There have been no changes during the 1980's at the chromium chemicals plant located in Belford Roxo. This plant, constructed in the late 1960's, is estimated to have a production capacity of 20,000 mtpy of sodium bichromate equivalent (SBE)[4] and receives all of its feed from the COMISA/Coitzeiros operation in the Campo Formosa District. No information is available on major refractory chromite or foundry sand chromite users in the country.

Resources

For Brazil, the evaluated in situ demonstrated chromite resources totaled 26.2 Mmt at a grade of 23.4 pct Cr_2O_3. The extraction and beneficiation of this in situ tonnage would result in an estimated production of 10.14 Mmt of marketable chromite products, with 92.1 pct of the chromite products available from the three producing units. The Cr_2O_3 grade of this 10.14 Mmt of chromite products would be about 40.2 pct. This tonnage represents 42 yr of production at the Bureau's estimated 1988 production level of 240,000 mt.

The 1989 in situ estimate of 26.2 Mmt at 23.4 pct Cr_2O_3 can be compared to the prior study's estimate of 18.6 Mmt at 21.0 pct Cr_2O_3. The higher tonnage in the 1989 estimate is a result of 4.84 Mmt of additional tonnage from the Ipueira unit, which is new to this study, and 4.34 Mmt of increased potential at the Limoeira and Pedrinhas units in the Campo Formosa District. The chromite resource of the new Nova Lima mine in Amapa state is not included in the 26.2 Mmt total.

Mining and Beneficiation Operating Parameters

Four major properties were analyzed in Brazil. The Ipueira operation in the Vale do Jacurici District is new to the study and was developed in the early 1980's. The other three evaluated properties are all located in the Campo Formosa District and include the operations of COMISA and FERBASA and the Limoeira (Serjana) property. Intermittent production from numerous smaller operations in the Jacurici River Valley area were not included in this evaluation.

[4]In this report, chromium chemical plant output capacities are all presented in terms of sodium bichromate equivalent (SBE) tonnages. Sodium bichromate contains 35 pct Cr, by weight.

The Ipueira operation was analyzed as a totally underground mining operation, while nearly 100 pct of the FERBASA tonnage and 76 pct of the COMISA tonnage was analyzed as underground minable. The Limoeira property was evaluated as a surface mining operation.

Based on FERBASA's 1985 plans to convert from surface to underground mining, the Campo Formosa District operation was evaluated for complete underground mining. However, information received in 1989 indicates that surface mining is still being used at this property.

As analyzed, the three producing properties account for a total of 725,000 mtpy ROM to produce 387,000 mtpy chromite products, with the majority coming in nearly equal amounts from the Ipueira and FERBASA's Campo Formosa operations. The nonproducing Limoeira property could provide an additional 310,000 mtpy ROM and 84,500 mtpy of chromite products. The ROM to chromite product ratio for all four properties is relatively high at 2.2:1. As a group, the three producers have a lower ROM to product ratio of 1.87:1. These relatively high ratios are the result of fairly low Cr_2O_3 grades and relatively low overall Cr_2O_3 recoveries into final chromite products.

In terms of Cr_2O_3 content, the average ROM grade for all four properties is only 23.8 pct and only 26.0 pct for the three producers. Beneficiation recoveries for the four properties range from 76.4 pct to 82 pct, with an average of 78.6 pct. These low overall recoveries are due to the requirement for gravity concentration of anywhere from 72.3 pct to 96.4 pct of the total ROM at individual properties.

Mining and Beneficiation Operating Costs

Table B-1 shows the estimates of mining and beneficiation operating costs for the Brazilian properties. The table also shows the labor component percentage of these operating cost estimates. The average of the estimated mining costs was \$17.88/mt ROM, and the average of the estimated beneficiation costs was \$3.95/mt ROM. Labor costs average nearly 49 pct of the mine operating cost estimates and 68 pct of the beneficiation operating cost estimates.

Table B-1.—Ranges and averages of mining and beneficiation operating cost estimates, including labor components, Brazil

Range/ average	Mining		Beneficiation	
	Operating cost[1] ($/mt ROM)	Pct labor[2]	Operating cost[1] ($/mt ROM)	Pct labor[2]
High	22.19	52.4	5.56	72.4
Low	13.25	43.3	3.56	65.3
Average ...	17.88	48.9	3.95	68.2

[1]Weighted average; weighted on annual ROM capacity.
[2]Straight average for all producing and nonproducing properties.

FINLAND

Industry Overview

Chromite Production

According to Bureau estimates, chromite production at the Kemi mine and mill in Finland has varied greatly during the 1980's. From a level of 362,000 mt in 1980 (*32*), its production declined to a level of only 246,000 mt in 1983 (*31*). Production has climbed steadily ever since, with an estimate of 700,000 mt for 1988 (*23*). The very low level of production for 1983 was mostly due to interruptions caused by the addition of a large heavy media plant to the Kemi mill. For 1986, the operation produced about 612,000 mt of all chromite products from 1.4 Mmt of ROM, with the 1986 ROM tonnage reflecting greater than average dilution (*33*). By comparison, this availability analysis was based on a long-run production level averaging 1.15 Mmtpy ROM for production of 607,000 mtpy of chromite products with an overall beneficiation recovery of 75.6 pct.

Mining, Beneficiation, and Smelting

The Kemi mill is one of the most sophisticated chromite mills in the world. In the past they have produced foundry sand chromite products, chemical grade chromite products, metallurgical grade chromite concentrates, ROM lump ore, and upgraded lump ore. As of 1987, the company planned to completely phase out the production of lump ROM, and was producing small amounts of foundry sand on demand and only about 12,000 mtpy of chemical grade concentrates.

Since 1988, this operation has been completely integrated, from mining and milling at the Kemi facilities to FeCr smelting and hot and cold rolling of stainless steel at the Tornio Complex, about 20 km from the mill. As a result, developments at both complexes will be described in this one section.

During the 1983-85 period, a large two-stage heavy media plant was added at the Kemi mill to upgrade the lump ROM product to a higher grade lump product. Upgrading of the lump ore was in preparation for the addition of a new 75-MV·A furnace, installed in 1985 alongside the existing 33-MV·A furnace at the Tornio Complex. The original intent was to use this upgraded lump material as 100 pct of the feed to the new furnace; however, by 1987 both furnaces were being fed with a mix of about 30 pct pellets and 70 pct lump ore.

By late 1986, the Viia pit, which includes the Viianranta and Viianlahti orebodies, had reached a depth of 100 m, and the waste-to-ore ratio was approaching 4:1 (*33*). As a result, in early 1987, the company started to prestrip a new area to mine the Viianmaa and Perukka ore bodies.

In late 1987 to early 1988, the Tornio Complex completed construction of a hot rolling mill as a companion to their existing 150,000 to 160,000 mtpy cold rolling mill for stainless steel production. Further expansion is expected to give the operation the capability to produce 100,000 mtpy of hot rolled stainless steel and 250,000 mtpy of cold rolled stainless steel by 1991.

Early in 1989 the company announced that the Kemi mill was to undergo a major revamping with the gravity concentration facilities being increased to 300,000 mtpy of concentrates. The company also planned a related increase to 300,000 mtpy of pelletizing and sintering capacity at the Tornio smelter. This development is likely related to ongoing smelting problems the company has had with the upgraded lump material.

Resources

The in situ demonstrated chromite resource evaluated for Finland totals 37.8 Mmt at a grade of 26.6 pct Cr_2O_3. Extraction and beneficiation of this tonnage could result in the potential production of 20.9 Mmt marketable chromite products. This tonnage is all present in the producing Kemi operation. The 20.9 Mmt of chromite products would have a weighted average grade of about 36.5 pct Cr_2O_3 and represents about 30 yr of production at the Bureau's estimated production level for 1988.

This updated resource estimate is about 30 pct higher than the previous study's estimate of 29.2 Mmt at 26.0 pct Cr_2O_3. The new estimate has higher waste-to-ore ratios than previously estimated because the surface minable resources have been estimated to deeper levels. This study estimates that the long-term average waste-to-ore ratio to extract the entire surface minable resource will be 8.5:1 for mining to vertical depths of 250 m at the Viia pit, to 60 m at the Viianmaa/Perrukka pit, and to 100 m at the proposed Nuottijarvi/Surmanjoa pit.

GREECE

Industry Overview

Chromite Production

Bureau chromite production estimates for Greece show much the same pattern as most other MEC's. Production, which was 41,700 mt in 1980 (*32*), dropped to 27,200 mt by 1983 (*31*), only to have steadily increased thereafter. Production for 1988 is estimated at approximately 63,000 mt (*23*).

Mining and Beneficiation

In terms of chromite producing companies, there have been no changes since the early 1980's. There are two companies, the Hellenic Ferroalloys metallurgical operation in the Skoumsta region and the FIMISCO refractory chromite operations at Eretria, Rodiani, and Domokos.

The new Skoumsta mill of Hellenic Ferroalloys was brought on-stream in late 1983. This new mill replaced an older, inefficiently located mill and has the capacity to treat about 300,000 mtpy of ROM ore for production of about 90,000 mtpy of concentrates from two different ores. In addition, a tunnel connecting the new mill with the underground workings was developed simultaneously with the mill construction.

Smelting

The Hellenic Ferroalloys high-C FeCr smelter at Tsingeli began production in 1983, with a capacity of about 40,000 mtpy. This smelter uses the Outokumpu Oy pelletizing/preheating process. It has a pelletizing capacity of about 100,000 mtpy to prepare fines and concentrates for feed to the single 20-MV·A furnace.

Refractory Industry

The refractory chromite operations were not included in the availability study but were included in the design of the network flow model. Estimates of capacities range anywhere from 11,000 mtpy to a high of 34,000 mtpy. The company is reported to have its own brick plants in the country.

Resources

The two metallurgical grade ore types of the Skoumsta operation included in this update study contain a total of 3.42 Mmt of in situ material at a low Cr_2O_3 content of only 16.6 pct. Mining and beneficiation of this tonnage should result in production of an estimated 1.02 Mmt of marketable chromite products grading 45.5 pct Cr_2O_3 on a weighted average basis. This tonnage represents about 16 yr of production at the Bureau's estimated 1988 output level for the entire country.

The updated resource estimate is larger and has a slightly lower grade than the prior study's estimate of 2.2 Mmt at 18 pct Cr_2O_3. This is due to the inclusion in the new estimate of a second, lower grade ore type, which is produced from deposits north of the main Skoumsta operation.

Mining and Beneficiation Operating Parameters

About 81 pct of the total evaluated resource is minable by underground methods with the remaining 19 pct extractable by surface mining. All of the tonnage is present in producing operations and requires upgrading by gravity concentration at the Skoumsta mill. As analyzed, the Skoumsta mill could treat 298,000 mtpy ROM for production of about 90,000 mtpy of chromite products for metallurgical use. Beneficiation recovery is estimated at 81.5 pct, which, combined with the relatively low ore grade, results in a very high ROM-to-product ratio of 3.31:1.

INDIA

Industry Overview

Chromite Production

India's reported chromite production has increased steadily during the 1980's. The Bureau estimates production at 319,000 mt in 1980 (*32*), 360,000 mt in 1983 (*31*), and 759,000 mt in 1988 (*23*).

Mining and Beneficiation

The increase in Indian chromite production since 1985 has been primarily from Tata Iron and Steel Corporation's (TISCO) Bhimtanagar lease area in the Sukinda Valley. The company reports 1985 chromite production of 132,000 mt, 1988 production of 200,000 mt, and planned to produce 300,000 mt during 1989 (*34*). In addition, they expected to start up a beneficiation mill for low-grade material in 1990. This mill was to have a capacity to treat approximately 300,000 mtpy of ROM ore at 20 pct to 30 pct Cr_2O_3 for production of approximately 100,000 mtpy of 50 pct Cr_2O_3 concentrates. As of 1989, the company stated that it was producing from 14 pits in two main areas—the No. 10 and the No. 2 ore bodies. By comparison, this study has only one pit—at the No. 3 ore body—listed as a producer in January 1989 while the No. 10 and No. 2 ore bodies were classified as nonproducers (see appendix A).

Other significant changes in mining operations since the early 1980's are:

(1) In 1984 a mill with the capacity to upgrade 180,000 mtpy of low-grade (16 pct to 20 pct Cr_2O_3) ores to 50,000 mtpy of 44 pct Cr_2O_3 concentrates was installed at FACOR's Bouala operations in the Keonjhar District.

(2) FACOR's Bouala open pit mine was planned to be shut down in 1989 with replacement by 100 pct underground mining.

(3) OMC's Sukerangi pit was planned to be reopened when the company's new smelter came on-stream in 1987.

(4) OMC was to finish construction in 1990 of a new beneficiation plant at the Kaliapani mine to produce about 84,000 mtpy of concentrates grading from 51 pct to 54 pct Cr_2O_3. Because of the inclusion of a pelletizing line at the new Bamnipal smelter, it is believed that this plant is not solely intended to upgrade low Cr_2O_3 ores but instead would both upgrade and enhance quality control on the significant amount of fines material (low, medium, and high grades) produced at Kaliapani.

Of the developments just listed, only the OMC and TISCO beneficiation plants have not been included in the availability analysis. However, the TISCO beneficiation plant was included in the design of the network flow model.

Smelting

Table B-2 summarizes the ownerships and capacities at the FeCr smelters in India, as of 1989. Also included in the table is a description of status changes at the smelters since 1980. Figure B-1 provides the locations of the smelters located in Orissa state (the Bhadravati smelter, located in the western state of Karnataka, is not shown) as well as their locations relative to the two major chromite mining districts and to port facilities in Orissa state.

As shown in the table, India added a total of 218,000 mt of high-C FeCr capacity during 1980 through 1989. The smelters at Shreeramnagar, Jaipur Road, Bhadravati, Therubali, and Randia all use conventional smelting technology. Of these five smelters, only the Randia smelter has briquetting facilities. The Bamnipal smelter, located very close to the company's mining operations, uses the Outokumpu Oy pelletizing/kiln preheat process for 80 pct of its chromite feed. It is believed that the Choudwar smelter, expected to begin production in mid-1989, will also use this pelletizing/kiln preheat process.

The capacities given in the table for the Shreeramnagar, Jaipur Road, Bhadravati, and Therubali smelters are larger than the actual production levels, which, where reported, have always been much lower than the theoretical capacities. Part of the problem for many of the Indian smelters appears to be limited access to chromite feed and the unreliability of electrical power sources. In response to this latter problem, the newest of the smelters—the Choudwar smelter—was planned to have its own captive powerplant, and FACOR may be planning the same for its smelter at Randia.

The structure of the industry, as designed for the availability analysis, includes only those smelters with definite ownership ties or affiliation to available chromite resources (Shreeramnagar, Jaipur Road, Randia, Bamnipal, and Bhadravati). However, the network flow model does include the two IMFA smelters at Therubali and Choudwar that do not have "captive" ore sources.

Table B-2.—Summary data, ferrochromium smelters in India as of 1989-90

Smelter/location name	Ownership	Status changes 1980-89	Cr ferroalloy capacity, mtpy	
			High-C FeCr	Low-C FeCr
Shreeramnagar	FACOR[1]	None	25,000	17,000
Jaipur Road	IDC[2]	None	—	13,000
Bhadravati	VIS[3]	None	7,000	—
Therubali	IMFA[4]	Furnace commissioned Feb. 1983, switched to FeCr mid-1983.	50,000	—
Randia (Baudpur)	FACOR	Production started July 1983	55,000	—
Bamnipal	OMC[5]	Production started April 1987	50,000	—
Choudwar	IMFA	Production started mid-1989	63,000	—
Total			250,000	30,000

[1]Ferro Alloy Corp.; has own chromite operations, located in Orissa state.
[2]Industrial Development Corporation Ltd.; ties to Orissa Mining Corp. ores, located in Orissa state.
[3]Visvesvaraya Iron and Steel Ltd.; ties to Mysore Minerals Ltd. ores, located in Karnataka state.
[4]Indian Metals and Ferroalloys Ltd.; no chromite operations, located in Orissa state.
[5]Orissa Mining Corp.; has own chromite operations, located in Orissa state.

NOTE.—Dash indicates no applicable value.

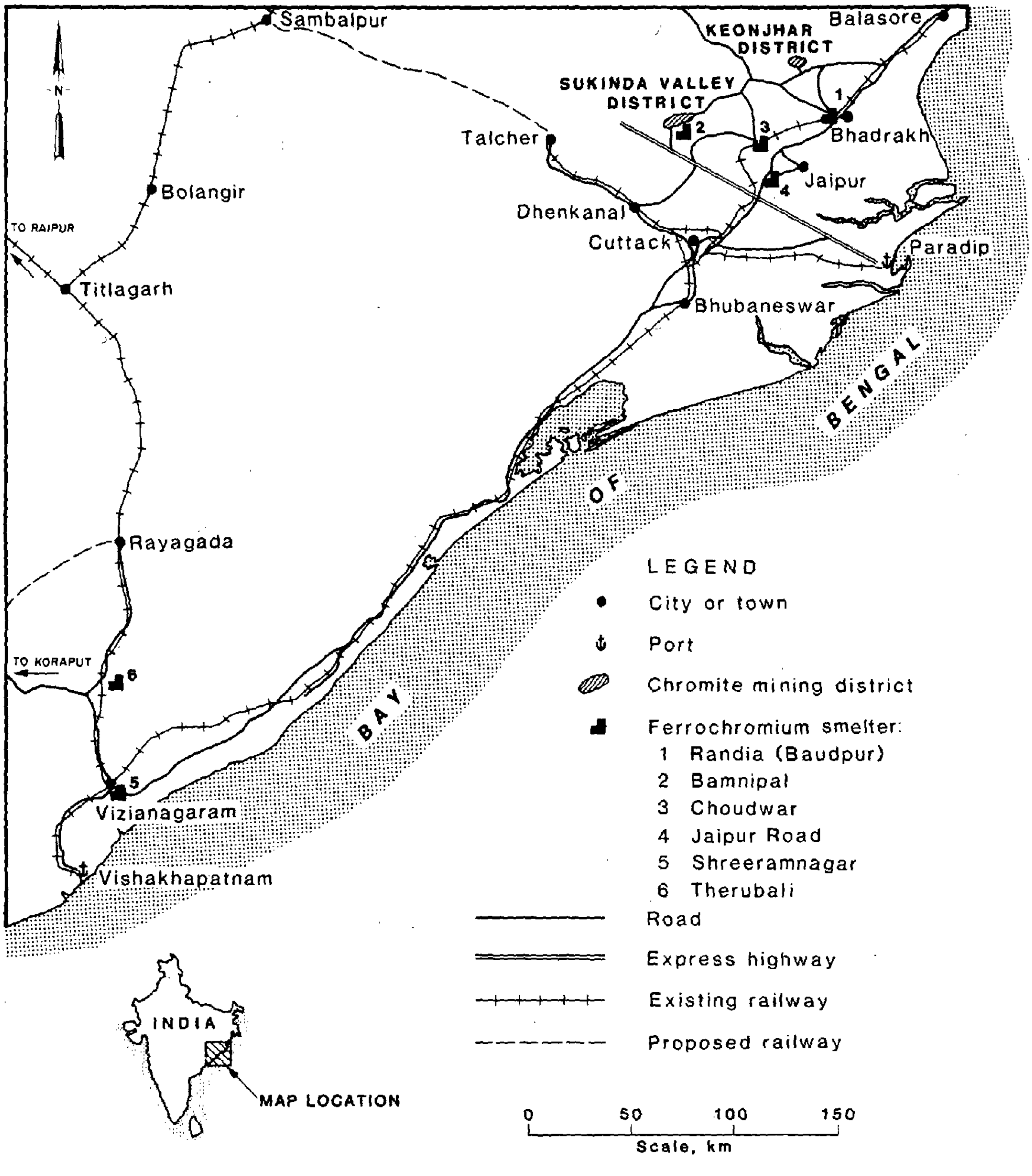

Figure B-1.—Locations of chromite mining districts, ferrochromium smelters, and ports, Orissa State, India.

Chromium Chemicals Industry

The availability and network flow model structures for India are based on eight chromium chemical plants producing an estimated 20,000 mtpy of SBE, requiring about 25,000 mtpy of chromite concentrate feed. The plant names, locations, and sizes are based on an unpublished Indian Government document from 1980; no newer data were available to update this structure.

As designed for both the availability and network flow model studies, the chromite needs of these Indian chemical producers are met by production of concentrates from the Saruabil operation in the Sukinda Valley and by the Jambur and Tagadur operations in Karnataka state. Indian chemical grade chromite was not treated as available for export in the availability analysis design because the indicated internal Indian specifications for these products are not as stringent as those in the other MEC's.

Refractory Industry

The availability and network flow model structures for India were based on five plants using a total of 18,000 mtpy of Cr (about 56,000 mtpy chromite) for production of refractory products. The plant names, locations, and sizes are based on an unpublished Indian Government document from 1980; no newer data were available to update this structure. For study purposes, the chromite for refractory usage in India was assumed to be provided either by the Kalrangi mine of OMC or by the Bhimtanagar operations of TISCO.

Resources

In situ demonstrated chromite resources evaluated for India include 53.7 Mmt at 40.9 pct Cr_2O_3, as of January 1989. This tonnage has the potential for production of 38.4 Mmt of marketable chromite products. The 14 currently producing units account for 47.5 pct of the chromite products available; 52.5 pct would be recoverable from the 39 nonproducing units. The recoverable chromite product tonnage of 38.4 Mmt is estimated to have a weighted average grade of about 46 pct Cr_2O_3 and represents nearly 51 yr of production at India's indicated 1988 level of output.

The 1989 resource estimate is considerably smaller than the prior study's estimate of 81.2 Mmt at only 32.0 pct Cr_2O_3. The main difference is that the prior estimate included a very large tonnage (59.2 Mmt) of low-grade material (averaging 30 pct Cr_2O_3) in the estimates for the Sukinda Valley resource. By comparison, the 1989 "low-grade" tonnage estimate for the Sukinda Valley is much smaller and has a somewhat higher grade range of 30 pct to 40 pct Cr_2O_3. In addition, only 9.4 Mmt of low-grade (average of 15.5 pct Cr_2O_3) material in the Keonjhar District is included in the 1989 resource estimate.

For comparison, in 1981 the official Indian resource estimate totaled 65.5 Mmt of measured plus indicated ore (including the "inferior" grade material), while an updated official estimate of 1982 totaled 103.3 Mmt of proven and probable tonnage. The 1982 official estimate is much higher than the tonnage evaluated for this study because only surface minable material and limited low-grade resources have been included in this analysis.

Mining and Beneficiation Operating Parameters and Costs

The table of properties and units in appendix A lists all 53 of the Indian properties/units analyzed in this update study, along with the ownerships and chromium product assignments for the availability analysis. All 39 of the nonproducing units were assigned to metallurgical-grade chromite production for the availability analysis. Fifty of the properties and units listed in appendix A are located in either the Sukinda Valley or the Keonjhar Districts of Orissa state; the other three properties and units—those owned by Mysore Minerals Ltd.—are located in Karnataka state.

In the designation of units for analysis, ownership was the first factor to be taken into account. The units were then further delineated based on either individual chromite deposits within larger lease areas or high-grade versus low-grade resources. This structure was selected to conform with the individual deposit characteristics, by lease area, in the Sukinda Valley that are cited in a 1982 Indian Bureau of Mines publication (*35*).

An important distinction in assessing Indian chromite resources involves the breakdown of surface minable versus underground minable resources. In this evaluation, a total of 9.7 million mt of in situ material is minable by underground methods. The Bouala operation of FACOR in the Keonjhar District contains 95.3 pct of this underground minable tonnage; the remainder is at the Byrapur operation in Karnataka state.

All resource estimates for the Sukinda Valley units are based on surface mining to vertical depths ranging from 20 m to 70 m, with the limits based on reasonably economic waste-to-ore ratios. A number of technical questions (e.g., water problems beyond the 80 to 100 m vertical depth range, the depth of weathering in the valley, and the strength of the rock types in the area) will have to be resolved before the total potential of the Sukinda Valley chromite resource is realized.

Only 3 of the 53 minable units analyzed in India contain underground minable resources. The remaining 50 units have all been analyzed for surface minable resources only. Two of the underground minable units are the high-grade and the low-grade resources of FACOR's Bouala operation in the Keonjhar District. Beginning in 1989, the company planned to mine both of these ores with a single, large (275,000 mtpy ROM), highly mechanized underground operation. The third underground mining unit is the Byrapur operation of Mysore Minerals Ltd. This is a small (15,000 mtpy ROM), fairly deep mine in Karnataka state.

As analyzed, the 14 producing units account for a total of 764,900 mtpy ROM to produce 601,400 mtpy of chromite products. If all 39 of the nonproducing units were brought into production at the same time, they could produce an additional 802,800 mtpy of ROM for 575,700 mtpy of chromite products. Combined, all 53 units could mine 1.6 Mmtpy of ROM to produce 1.2 Mmtpy of chromite products, giving India the potential to be the third largest world chromite producer.

Table B-3 provides the ranges and weighted averages of the mine operating cost estimates for these producing and nonproducing units. Within the producing group, the weighted average for the underground minable tonnage is only \$13.79/mt ROM, while the weighted average for the surface minable tonnage is much higher at \$47.91/mt ROM.

Table B-3.—Ranges and weighted averages of mining and beneficiation operating cost estimates, India, by status

Status/ranges and averages	Operating cost estimate	
	Mining	Beneficiation
Producers:		
High	\$151.38	\$5.20
Low	11.28	0.00
Wtd avg[1]	34.91	1.79
Nonproducers:[2]		
High	396.50	7.80
Low	16.30	0.00
Wtd avg[1]	57.60	1.07
Producers and nonproducers:		
Wtd avg[1]	46.53	1.42

[1]Weighted on basis of annual ROM capacity.
[2]All surface mining.

The average waste-to-ore ratio for the producing surface units is 10.3:1, and the average vertical depth to which the surface minable tonnages were estimated is 47 m. Only two of the producing surface operations had waste-to-ore ratios higher than the average.

All of the resource contained in the 39 nonproducing units was evaluated as surface minable. The average waste-to-ore ratio for the nonproducing units is 11.9:1, and the average vertical depth to which the surface minable tonnage was estimated is 40 m. Nine of the 39 nonproducers have waste-to-ore ratios greater than the average. Not surprisingly, the mine operating cost estimates for these nine units are significantly higher. For example, these nine units have a weighted average mine operating cost estimate of \$167.80/mt ROM and an average waste-to-ore ratio of 32.9:1. By comparison, the other 30 nonproducing units have a weighted average mine operating cost estimate of only \$42.85/mt ROM and an average waste-to-ore ratio of only 5.8:1. Most important, at 713,000 mtpy ROM resulting in 509,800 mtpy of chromite production, these 30 "low-cost" nonproducing units account for the vast majority of the potential future mine capacity in India.

Labor costs account for 36 to 66.8 pct of the total mining cost estimates for the underground producers. Labor costs for producing surface operations account for between 44.7 pct and 70.9 pct of the total mining cost estimates and between 46.6 and 79.3 pct for the nonproducing surface mining units.

The ratio of ROM to chromite products for all 53 Indian units is 1.33:1. The ratio for the producers is lower (1.27:1) than it is for the nonproducers (1.40:1). The differences in this ratio reflect different Cr_2O_3 recovery percentages into final chromite products. For example, the producers' average beneficiation recovery was 90.4 pct, and the nonproducers' average beneficiation recovery was 81.3 pct. These differences in Cr_2O_3 recoveries are, in turn, reflective of a significantly larger amount of "low-grade" (average 30 pct Cr_2O_3) material present in the nonproducing units.

Much of the Indian chromite resource requires only hand-sorting, crude sizing techniques, and hand-panning. In many cases, employees involved in these labor intensive beneficiation activities also participate in mining activities. For these operations, the costs for beneficiation labor (representing nearly all of the beneficiation cost) were included in the mine operating cost estimate, and no separate beneficiation cost was estimated.

Because some mining and beneficiation costs were combined, only 25 of the operations have had specific beneficiation costs assigned to them. These estimates ranged from \$0.79/mt ROM for a simple sort/screen operation to \$7.80/mt ROM for total gravity concentration in a small 30,000 mtpy ROM mill. Where assigned, labor costs account for 61.5 pct to 63.3 pct of the total beneficiation costs for mechanized gravity concentration and 100 pct for those operations using hand-sorting, screening, and hand-panning methods.

MADAGASCAR

Industry Overview

Chromite Production

According to Bureau estimates, Madagascar produced a total of 180,000 mt of chromite in 1980 (*32*) with a drastic decline to only about 45,000 mt in 1983 (*31*). Production rebounded to a level of 107,300 mt for 1988 (*23*).

Mining and Beneficiation

The one major change in the Madagascar chromite industry since 1980 was the closure of the Befandriana operations in 1981 which leaves the Andriamenha District as the only producing area in Madagascar as of the late 1980's.

Smelting

In 1984-85, and again in 1990-91, studies were made of the resource potential in the Andriamenha District and of the feasibility of building a smelter using the Outokumpu Oy pelletizing/preheating process for high-C FeCr production. The earlier proposed project failed to obtain financing. A development decision resulting from the most recent study has yet to be made as of this writing.

Resources

The evaluated in situ demonstrated chromite resources for Madagascar include 9.21 Mmt grading 34 pct Cr_2O_3. This updated resource estimate is comparable to the prior study's estimate of 10.25 Mmt at 31.5 pct. The difference mainly reflects the exclusion of the Befandriana operations (because of ore exhaustion) and a reexamination of new data available on the Andriamenha District resource situation.

The extraction and beneficiation of this resource tonnage could result in the potential production of 4.48 Mmt of marketable chromite products grading 47.7 pct Cr_2O_3. This tonnage would represent about 42 yr of production at output levels of 1988.

Mining and Beneficiation Operating Parameters

The chromite resource evaluated for this update study primarily represents the surface minable tonnage in the producing Andriamenha District, with only a small amount of surface minable tonnage contained in the nonproducing Ranomena deposit. Combined, both properties would have the annual capacity to mine 228,000 mtpy of ROM for production of 115,000 mtpy of products with an average beneficiation recovery of only 71.7 pct of the Cr_2O_3. At 1.98:1, the ROM-to-product ratio is relatively high, which reflects the need to beneficiate nearly 80 pct of the ROM using gravity methods and the fairly high Cr_2O_3 contents of the typical Andriamenha concentrate products.

NEW CALEDONIA

Industry Overview

Chromite Production

Bureau production estimates for New Caledonia basically chronicle the development of the rehabilitated Tiebaghi Massif underground operation, which began production in 1982. Bureau estimates show total New Caledonia chromite output at only 2 mt in 1980 (*32*), rising to 50,000 mt in 1982 and reaching a peak for the decade of 92,000 mt in 1983 (*31*). For 1988, the Bureau's production estimate for New Caledonia was only 70,341 mt (*23*).

Resources

The longevity of the reserves at the Tiebaghi operation has been a problem since its startup in 1982. The updated estimates made for this study were based on the 1985-86 reserve situation that resulted in a theoretical depletion of reserves at Tiebaghi occurring in 1988. Hence, there are no January 1989 availability results to report on for the Tiebaghi operation. In fact, one of the joint venture companies involved in the Tiebaghi operation has indicated that production would likely cease during 1990 because of exhaustion of reserves.

Beginning in about 1983 or 1984, there has been ongoing sampling of chromite sand deposits at various sites offshore of New Caledonia (see table 11). Some results on qualities and tonnages of the potential offshore resources are available in the literature and from other sources. However, they have not been included either in the availability study or in the network flow model portions of this study.

THE PHILIPPINES

Industry Overview

Chromite Production

Bureau estimates for chromite production in the Philippines show a steady decline during the 1980's. Production, estimated at 496,000 mt for 1980 (*32*), fell to 272,031 mt in 1985, 187,900 mt in 1987, and 190,000 mt in 1988 (*23*). However, based on full-capacity production of high-C FeCr and minimum levels of refractory and chemical chromite exports from the Coto (Masinloc) and Llorente operations, respectively, Philippines production in 1988 was probably 300,000 mt of chromite products, or higher.

Mining and Beneficiation

The table of properties and units in appendix A lists the 13 Philippines properties included in this analysis, their production status, and the chromium product assignments. The two newer producers—Omasdang and Llorente—began production in 1982 and 1985, respectively. Production levels at both operations have seen increases through 1989.

The two long-term producers have not experienced the same prosperity. The Coto (Masinloc) operation, which produced 344,000 mt chromite products in 1980, was hit hard by the market decline for refractory chromite, and its 1986 production amounted to only 115,000 mt of all products. However, recent improvements in the refractory market have likely helped the Coto operation. Production at the Acoje (Santa Cruz) metallurgical chromite operation, which was more than 92,000 mt of concentrates in 1980, had declined to only 70,500 mt by 1986, and production has continued to fall. Lower production levels are a result of constantly declining ore grades related to reserve, technical, and economic problems.

Although the Laganoy high-grade operation produced about 4,000 mtpy of chromite ore in 1986, production has been sporadic, and it has been characterized as a nonproducer for this study. The availability portion of this study does not include the chromite resources of the numerous small producers who presently sell their products (mostly hand-sorted lump ore) to the Philippine FeCr smelters.

Smelting

As of 1989, there were two existing FeCr smelters in the Philippines, with a third beginning production in late 1989. The largest, owned by Ferrochrome Philippines, Inc., began production in late 1983 and consists of a single 30-MV·A furnace with the capacity to produce about 55,000 mtpy of high-C FeCr. The smelter was designed to use the Outokumpu Oy method, with a capacity to pelletize 125,000 mtpy of fines and concentrates and the preheating of all feed (pellets and lump ore). If used at full capacity, the installed pelletizing capacity would represent 100 pct of the furnace needs in the form of pellets. However, lower production levels at the Acoje operation and the semimechanized nature of the Omasdang operation have resulted in lower levels of concentrate feed than was expected. As of 1986, only about 80 pct of the total chromite feed used by the smelter was being pelletized.

The second smelter is owned by Integrated Chrome Corp., which bought out the previous owner—Ferrochemicals Inc.—in 1989. It comprises a small 7.5-MV·A furnace commissioned in December 1981 and a 10-MV·A furnace completed in June of 1985. The smelter, capable of producing 30,000 mtpy of high-C FeCr, has typically smelted ores from chromite operations located in the southeastern part of Mindinao Island, which have not been included in this availability analysis. During 1989, Integrated Chrome Corp. began converting an old 20-MV·A ferrosilicon furnace—purchased from Electro Alloys Corp.—to produce about 30,000 mtpy of high-C FeCr. Both Integrated Chrome Corp. smelters are, or would be, of conventional smelting design.

All three of the smelters just described are located on the northern coast of Mindinao Island in the cities of Tagaloan and Manticao. The total production capacity for all three smelters is estimated at about 115,000 mtpy of high-C FeCr.

Resources

For the Philippines, the updated in situ demonstrated chromite resource was calculated at 65.5 Mmt with a very low overall Cr_2O_3 content of 9.2 pct Cr_2O_3. Potentially, 10.1 Mmt of marketable chromite products, grading close to 39 pct Cr_2O_3 on average, could result from the extraction and beneficiation of this in situ tonnage. This 10.1 Mmt of products would represent about 53 yr of production at the Bureau's estimated level of 1988 production. The four producing units account for 53.1 pct of the 10.1 Mmt of chromite products available, and 46.9 pct of the potential chromite production would come from the nine nonproducing units.

Most of the evaluated resource is minable via surface methods with maximum waste-to-ore ratios of 4:1. Underground mining techniques are used at Coto (Masinloc) and at Acoje (Santa Cruz) to recover 9.3 Mmt of ore grading 18.9 pct Cr_2O_3.

The 1989 estimate of 65.5 Mmt at 9.16 pct Cr_2O_3 is significantly smaller than the prior study's estimate of 207.8 Mmt at 5.6 pct Cr_2O_3. This is a result of revised resource estimates for the Omasdang, Llorente, Coto (Masinloc), and Isabela (eluvial) properties.

Mining and Beneficiation Operating Parameters

A total of 13 Philippines properties were included in this study. Four of these—Acoje (Santa Cruz), Coto (Masinloc), Omasdang, and Llorente—were producing at the time of analysis. The existence of numerous, small, scattered podiform deposits throughout the Philippines suggests that these 13 properties do not necessarily reflect the full potential of this country at any particular point in time.

Only the Acoje (Santa Cruz) and the Coto (Masinloc) operations were evaluated as using totally underground mining methods. The Candelaria property was analyzed as requiring both surface and underground extraction methods, and the remaining 10 were all analyzed as surface mining operations only. Estimated waste-to-ore ratios for surface mining ranged from 0:1 for nearly all of the eluvial and alluvial sand/soil deposits to a range of 3:1 to 4:1 for the massive podiform-type deposits.

On an annualized basis, the Acoje and Coto (Masinloc) operations account for 74 pct of the ROM capacity and 80.4 pct of the chromite product capacity for all four of the producing operations. Similarly, a total of 83.7 pct of the ROM capacity and 78.7 pct of the chromite product capacity for the nonproducers is represented by only five of the nine properties in this status category. As a group, the producing properties are, on average, significantly larger than the nonproducing properties in terms of both annual ROM and annual chromite product output capacities. In addition, at 12.4 pct versus 7.0 pct, their weighted average Cr_2O_3 grade in ROM is also significantly higher than the nonproducing group's.

The ratio of ROM to chromite products for all 13 of the Philippines properties is very high at 5.7:1. The ratio for the producers is lower at 4.85:1, while the ratio for the nonproducers is higher at 6.45:1. These high ROM-to-chromite product ratios reflect the very low grades and low recoveries due to significant upgrading requirements.

The beneficiation recoveries of Cr_2O_3 into final chromite products for the Philippines properties range from lows of 36.2 to 44.1 pct for the refractory chromite properties to a high of 95 pct at one of the properties containing massive-type chromite deposits. The average beneficiation recovery for all 13 properties is only 65.9 pct.

Mining and Beneficiation Operating Costs

Table B-4 summarizes the mine operating cost estimates for both producers and nonproducers. The table also includes the percentage of these cost estimates represented by labor costs. The low average for the nonproducers' mine operating costs reflects the fact that over 98 pct of their total annual ROM capacity is minable via surface methods. In addition, as analyzed, five of the nonproducers would have fairly high ROM capacities, ranging from 150,000 to 680,000 mtpy.

A summary of estimated beneficiation costs is shown in table B-5. The values shown represent 12 of the 13 analyzed properties. A producer, which was mainly an ore buying operation, has been excluded from the results shown in the table. The ranges and averages for the labor and electrical power components of these beneficiation operating cost estimates are also shown in table B-5.

On average, labor and electricity compose 80.4 pct of the beneficiation cost estimates for the producers and 79.5 pct for the nonproducers. The electricity costs in these updated estimates are based on a power cost rate of \$0.118/kW·h. Because of the relatively remote locations of the chromite properties in the Philippines, all aspects of electricity availability and costs are critical if sophisticated chromite beneficiation methods are required.

Table B-4.—Ranges and averages of mine operating cost estimates and percentages as labor, the Philippines, by status

Status/range and average	Mine operating cost estimate, \$/mt ROM	Labor component cost, pct
Producers:		
High	21.02	41.1
Low	2.50	29.1
Average	[1]14.22	[2]35.4
Nonproducers:		
High	37.59	43.0
Low	1.39	22.5
Average	[1]5.45	[2]35.1
Producers and nonproducers:		
Average	[1]8.93	[2]35.2

[1]Weighted averages; weighted on basis of annual ROM capacity.
[2]Averages for four producers and nine nonproducers.

Table B-5.—Ranges and averages of beneficiation operating cost estimates and percentages as labor and electricity components, the Philippines, by status

Status/range and average	Beneficiation cost estimate, \$/mt ROM	Component cost, pct	
		Labor	Electricity
Producers:			
High	4.11	39.6	55.7
Low	2.06	23.8	40.6
Average	[1]3.43	[2]33.3	[2]47.1
Nonproducers:			
High	7.37	45.1	51.1
Low	2.22	26.0	27.5
Average	[1]2.96	[2]37.6	[2]41.9
Producers and nonproducers:			
Average	[1]3.15	[2]36.4	[2]43.3

[1]Weighted averages; weighted on basis of annual ROM capacity.
[2]Averages for three producers and nine nonproducers.

REPUBLIC OF SOUTH AFRICA

Industry Overview

Chromite Production

Chromite production in the Republic of South Africa reached a historical high of 3.4 Mmt in 1980 (*32*). Only 2 yr later, in 1982, reported South African chromite production was only 2.4 Mmt (*31*), which proved to be the low for the decade. Production has steadily increased since. The previous 1980 peak was finally surpassed in 1987, when 3.8 Mmt were produced, and in 1988 with 4.3 Mmt (*23*).

Mining and Beneficiation

The table in appendix A lists the South African chromite properties included in this study. Figures B-2, B-3, and B-4 show the locations of the two major Bushveld Complex limbs (fig. B-2) and the farms comprising analyzed chromite properties on the western (fig. B-3) and eastern (fig. B-4) limbs of the Bushveld Complex. Properties on the outlier areas of the Bushveld Complex—Grasvally in the Potgietersrust District and Zeerust and Marico in the Marico District—are not shown in these figures. Figure B-5 is a schematic diagram of rail transport distances among major cities and rail sidings, as well as chromium processing facilities and export outlets in South Africa.

In the table of appendix A the list of analyzed units for South Africa has two individual listings for the Marico property. This split was made to differentiate the surface and underground minable resources for economic analysis. In addition, there are individual listings for four of the five different seams that have been mined in the past at the Zwartkop property. The fifth seam—the Old Seam—was not included in the analysis because of uncertainties regarding actual lateral extent on the Zwartkop property.

Of the producing units listed in appendix A, only the Tweefontein mine is newly developed since 1980. Three of the six nonproducing properties listed in appendix A were shut down prior to 1980: the Winterveld TCL North section in 1978, shortly after initial development, and both Ntuane and Zwartkop in 1979. The Kroondal mine was shut down in March 1981, Millsell in April 1983, and Grasvally in March 1988. The Ruighoek mine was shut down in 1982, but reopened in 1986 to feed the new, small, high-C FeCr smelter of Bathlako Ferrochrome Ltd. The Jagdlust mine was shut down in late 1981, but was reopened in 1989. Also, the Millsell mine was indicated to be back in production as of 1988, and the Grasvally mine may have been reopened in 1989 or 1990.

Since 1988, the development of three new mines—none listed in appendix A—has been announced: SAMANCOR Ltd.'s Mooihoek and Annex Grootboom mines and Purity Minerals Ltd.'s mine, located just north of the city of Rustenburg. The Mooihoek and Annex Grootboom farms are outlined in figure B-4. The city of Rustenburg is shown in figure B-3; however, the figure does not show Purity Minerals Ltd.'s lease holdings in the area.

Interestingly, all three of these new operations appear likely to have annual output capacities of around 240,000 to 250,000 mtpy of chromite products. The annual ROM capacity for Purity Minerals' underground mine is stated to be about 360,000 mtpy, while SAMANCOR's new underground operation at Mooihoek will likely have a 300,000 mtpy ROM capacity. SAMANCOR's Annex Grootboom mine will be a surface mining operation. Its planned ROM capacity is not known but could be similar in size to Mooihoek's.

The reserves of the new Mooihoek mine have been included (as part of the Dilokong property analysis) in the present availability analysis, but the reserves of both the Purity Minerals mine and the Annex Grootboom mine have not. The production capabilities of all three have not been included in the present availability analysis.

The relationship of these three new operations to the present network flow model is that the Mooihoek mine has been included in the design, while both the Annex Grootboom and the Purity Minerals mines have not. The new Purity Minerals smelter, being constructed in conjunction with the company's new mine, has also not been included in the design of the present network flow model.

The only major mining and beneficiation operational development in the South African chromite industry during the 1980's has been the complete, or nearly complete, mechanization of several operations in the Rustenburg-Brits section of the Western Bushveld Complex. Here, the LG6 and LG6A seams dip at shallow angles of less than 15° and can be mined together over a 1.6- to 1.9-m stope height. Mechanization increases the underground mining productivity from approximately 2.5 mt ROM/person-shift, using conventional methods, to as high as 13 to 14 mt ROM/person-shift. However, mechanization is possible only with dips of 15° or less and with a minimum stope height of about 1.6 to 1.7 m. A second development—the increased use of heavy media beneficiation methods—is related to the increased use of mechanization. This is due to the need for separation of much larger amounts of pyroxenite waste, which is mined along with the chromite ore in mechanized operations.

As of 1989, complete or nearly complete mechanized mining was being practiced at Chrome Chemicals S.A.'s Rustenburg mine, at SAMANCOR's Waterkloof mine, and at Chromecorp Technology's Chroombronne mine. Future developments of mechanization in the South African chromite mines should be watched carefully. SAMANCOR's new Mooihoek mine is planned to be fully mechanized. The Lavino (Grootboom) operation has shown interest in attempting to mechanize mining, and the newly developed mine of Purity Minerals is fully mechanized. The prospective Marikana Minerals' operation (to mine UG2 reef material) was also planned to be fully mechanized.

Smelting

In the prior study, the 1980 South African smelting capacity was estimated at 750,000 mtpy high-C FeCr, 46,000 mtpy low-C FeCr, and 24,000 mtpy ferrochromium-silicon for six smelters (*1*, table 13). Installed capacity as

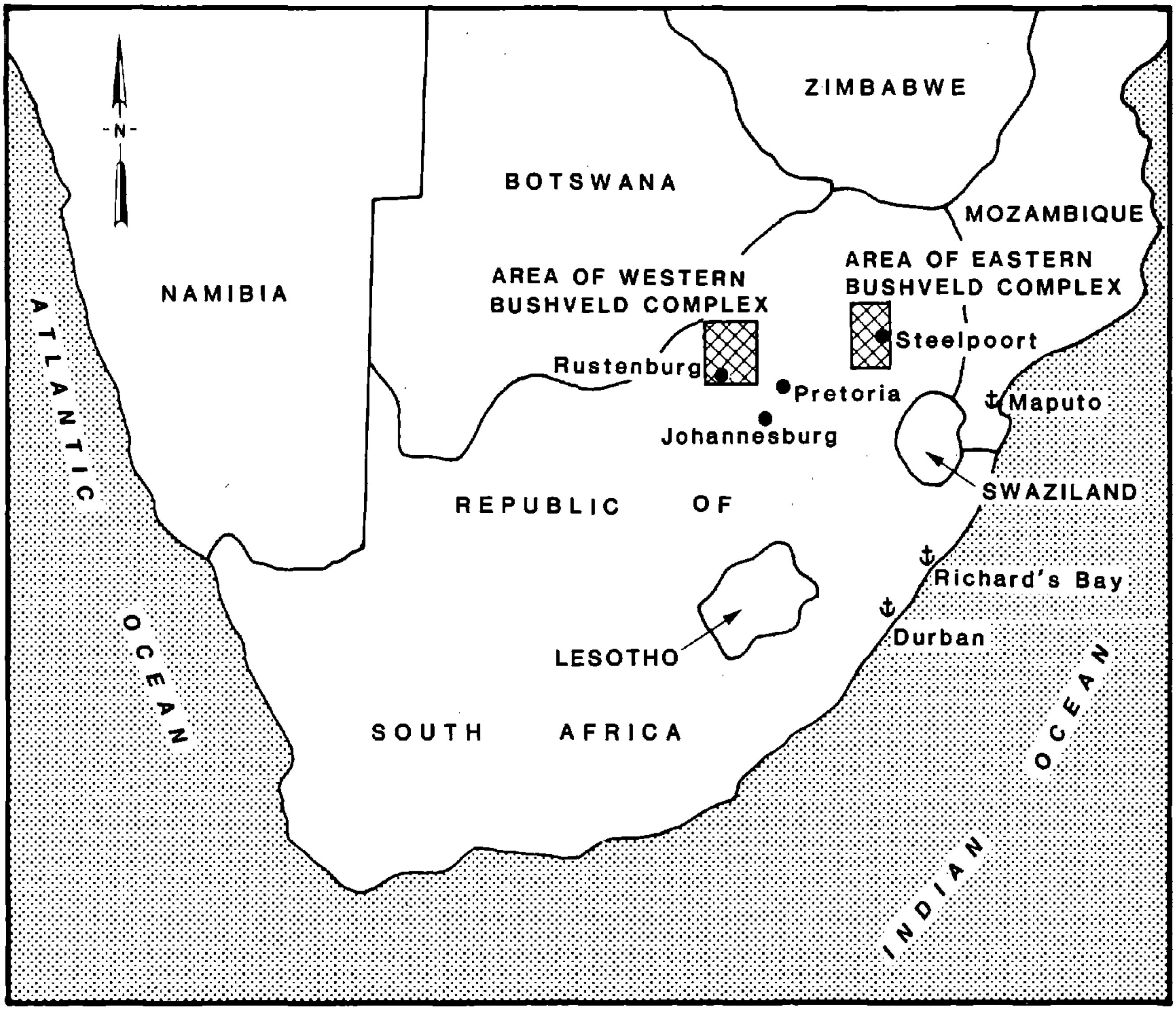

Figure B-2.—General location map, Republic of South Africa.

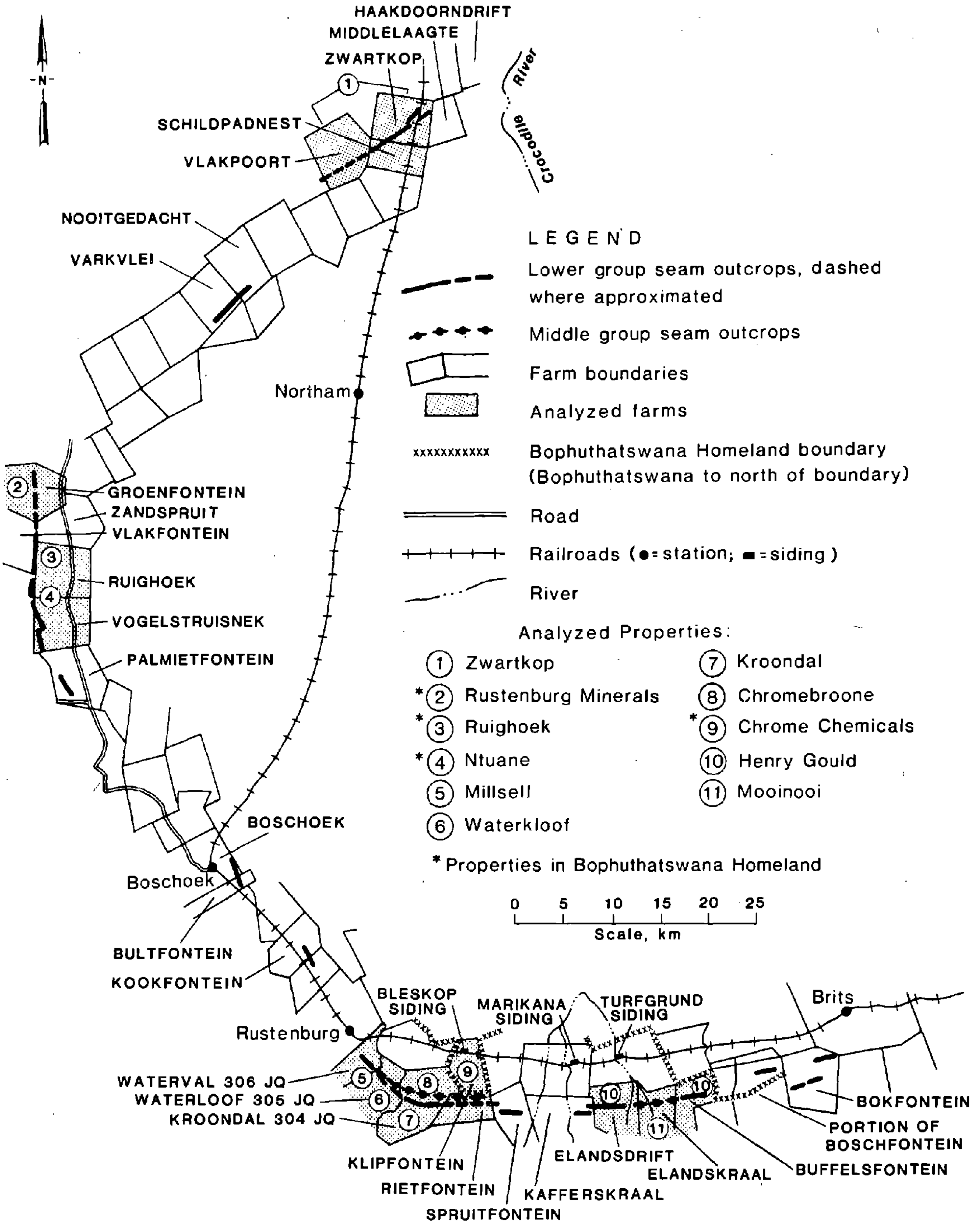

Figure B-3.—Major chromite seam outcrops, farm boundaries, and chromite property locations, western Bushveld Complex, Republic of South Africa.

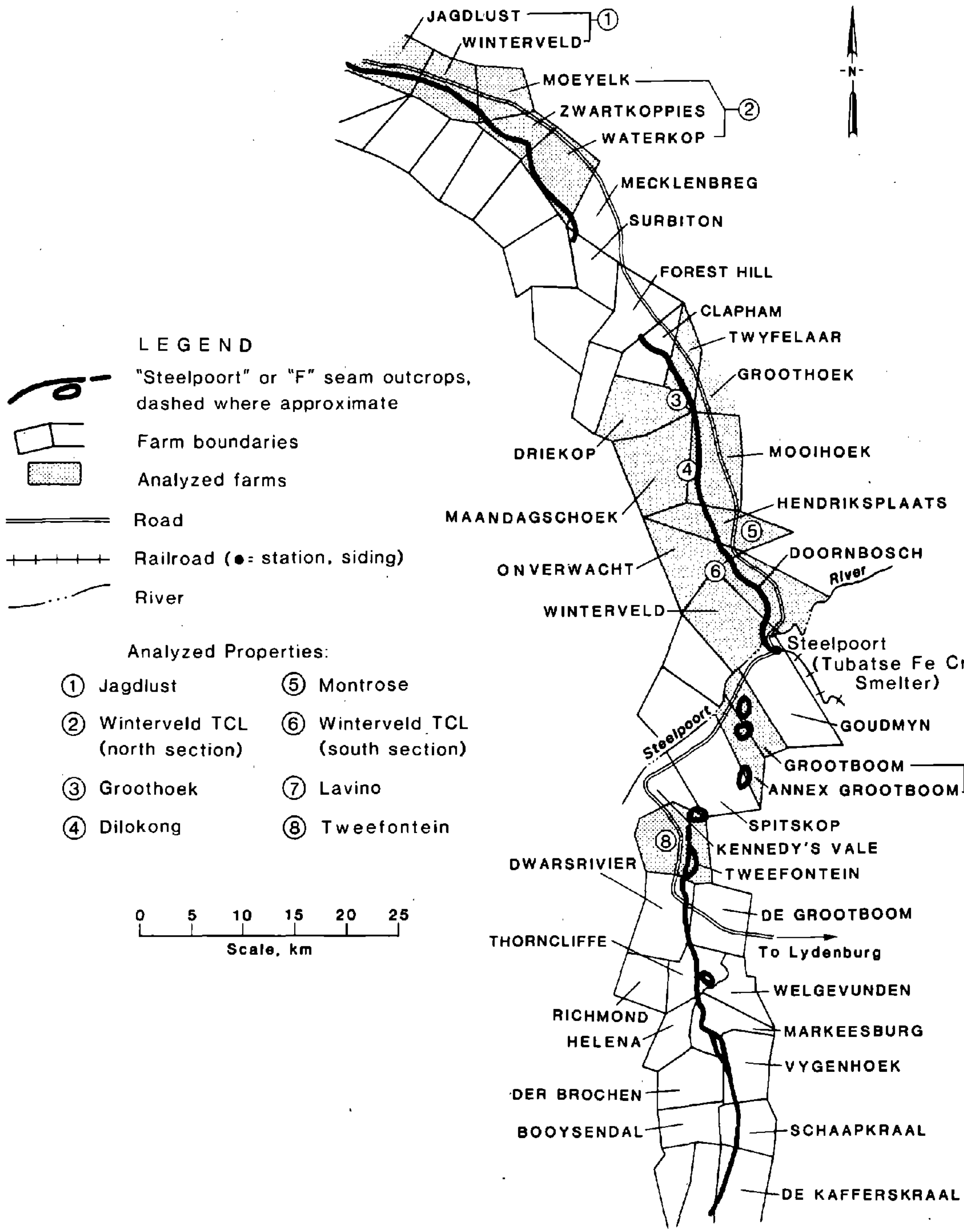

Figure B-4.—Major chromite seam outcrops, farm boundaries, and chromite property locations, eastern Bushveld Complex, Republic of South Africa.

SOUTH AFRICAN RAILWAY DISTANCES IN KILOMETERS

(Not drawn to scale)

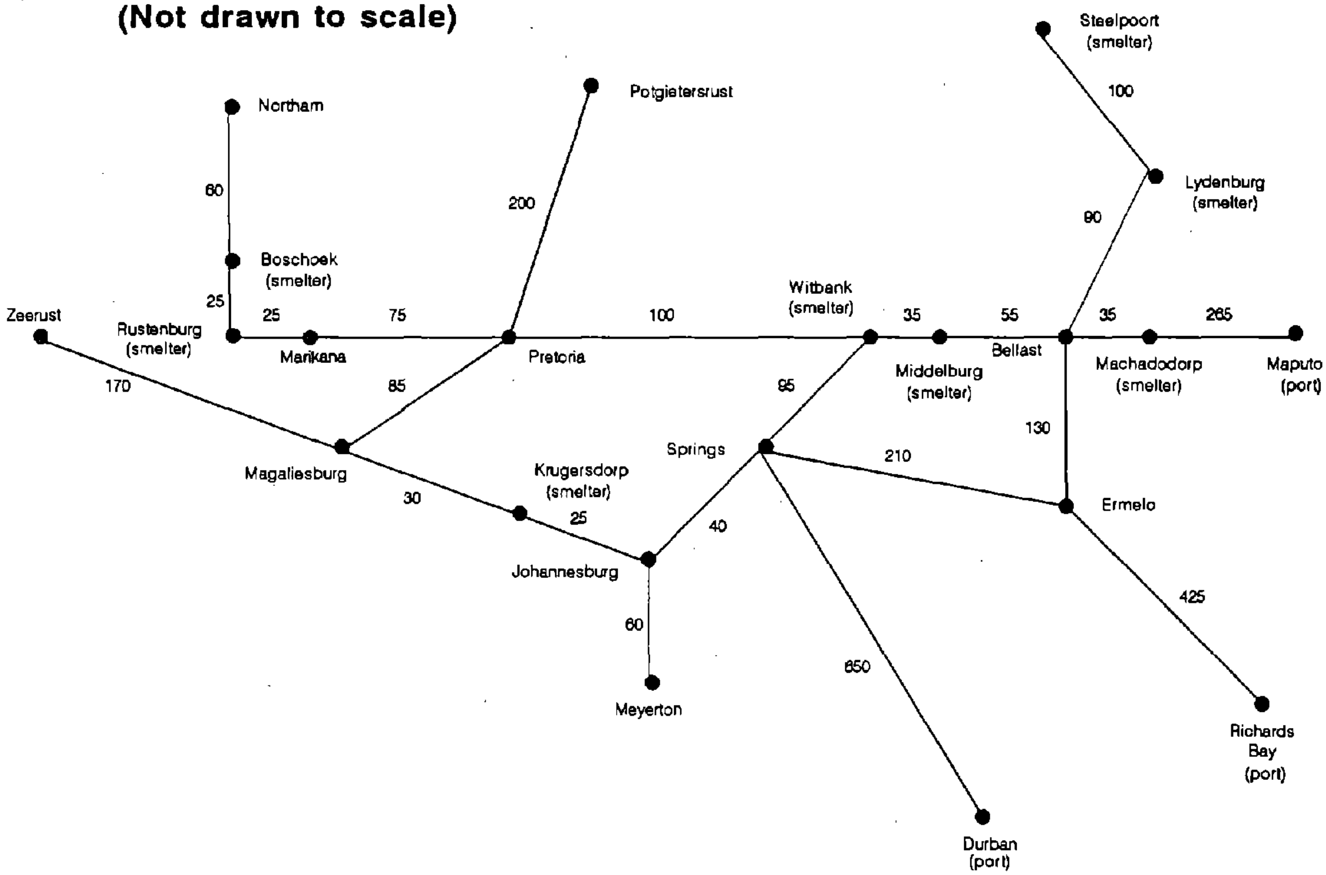

Figure B-5.—Schematic of rail haulage distances between major cities, selected rail sidings, and major chromium processing facilities and export outlets, South Africa.

of late 1988 was estimated for this update study to be 1.14 Mmtpy high-C FeCr, 66,000 mtpy low-C FeCr, and 45,000 mtpy ferrochromium-silicon, for eight smelters, as listed in table B-6.

Of the 391,000 mtpy difference between the high-C FeCr capacity estimates of the earlier study and the present study, the two new smelters of Bathlako Ferrochrome and Chromecorp Technology account for approximately 122,000 mtpy of additional high-C FeCr capacity. Improved efficiencies at the Lydenburg smelter account for an additional 35,000 mtpy, the new plasma arc furnace at Krugersdorp accounts for another 18,000 mtpy, and higher transformer capacities and a slight estimation difference add an additional 10,000 mtpy at Tubatse's Steelport smelter. A slight estimation difference also explains the 6,000-mtpy difference in high-C FeCr capacity at the Machadodorp smelter.

The remaining difference in high-C FeCr capacity of about 200,000 mtpy is due to differences in the estimates of the capacities at the Middelburg and Witbank smelters. The updated high-C FeCr capacity estimate for these two smelters is 500,000 mtpy versus 300,000 mtpy in the 1980 estimates. The difference likely represents a combination of higher transformer capacities, changes in furnace product dedications, and an original estimate that was too low. Similarly, the earlier study's estimates of low-C FeCr and ferrochromium-silicon capacities also appear to have been too low, as no new furnaces have been added during the decade for production of these chromium ferroalloys at the Machadodorp and Middelburg smelters.

The only existing smelter as of 1990 that hasn't been included in either the availability study or the network flow model is Purity Minerals' 120,000 mtpy high-C FeCr smelter. This smelter, which has its own captive mine nearby, is being constructed near the city of Rustenburg and was commissioned in 1990.

Chromium Chemicals Industry

There has been no expansion or change during the 1980's at South Africa's only chromium chemicals plant located at Merebank near Durban. This facility is owned and operated by Chrome Chemicals S.A., a subsidiary of Bayer AG of the Federal Republic of Germany. It has an estimated capacity to produce about 17,000 mtpy of SBE and obtains chromite concentrate feed from the company's own mine near Rustenburg.

It is believed that construction was to start in 1989 or 1990 on a new South African chromium chemicals plant in response to a very tight world market for SBE in 1988. No details as to the location, ownership, source of concentrate feed, or size of this plant are available to the authors as of this writing. However, the plant has been included in the study's network flow model with an assumed location near Richards Bay and a capacity to produce about 60,000 mtpy of SBE.

Table B-6.—Summary data, ferrochromium smelters in South Africa as of late 1988

Smelter location	Ownership	Chromium ferroalloy smelting capacity		
		High-C FeCr (kmtpy)	Low-C FeCr (kmtpy)	FeCrSi (kmtpy)
Ruighoek	SAMANCOR Ltd.—through Bathlako Ferrochrome Ltd.	22	0	0
Krugersdorp ...	Rand Mines—through Middelburg Steel and Alloys Holdings Ltd.	98	0	0
Lydenburg	Johannesburg Consolidated Investment Co.—through Consolidated Metallurgical Industries Inc.	155	0	0
Machadodorp ..	Anglovaal Ltd.—through Ferroalloys Ltd.	86	27	18
Middelburg ...	Rand Mines—through Middleburg Steel and Alloys Holdings Ltd.	200	39	27
Rustenburg ...	Chromecorp Technology (Pty.) Ltd.	[1]100	0	0
Steelport	SAMANCOR Ltd.—through Tubatse Ferrochrome (Pty.) Ltd.	[2]180	0	0
Witbank	SAMANCOR Ltd.—through Ferrometals Ltd.	300	0	0
Total		1,141	66	45

[1]Both furnaces commissioned very late in 1988. Effective 1988 capacity in the network flow model was zero.

[2]Effective 1988 capacity in the network flow model was estimated at only 107,000 mt because of transformer capacity changes being made to two of the three existing furnaces.

Refractory and Foundry Sand Industries

No details are available as to specific South African plants or companies that use chromite for refractory and foundry sand uses. It is known that about 15,000 mt of chromite are used internally for refractory purposes.

Resources

In situ demonstrated chromite resources evaluated for the Republic of South Africa, as of January 1989, were estimated at 549 Mmt at 38.16 pct Cr_2O_3. As evaluated, the extraction and beneficiation of this tonnage could result in potential production of 319 Mmt of marketable chromite products grading about 42.5 pct Cr_2O_3. This amount of chromite products would represent about 75 yr of output at the Bureau's estimated 1988 South African production level. The 16 producing units contain 61 pct of the available chromite products, while the 10 nonproducing units contain 39 pct of the potential chromite production.

As in the prior availability study, the 1989 in situ demonstrated tonnage estimate includes only chromite seams presently being mined (or mined in the past), and the estimates have been taken to specific vertical depths. In contrast to the past estimates, only two of the property estimates involve projections below 300 m vertical depth. These are at the Grasvally property and at the Buffelsontein section of the Henry Gould operation. Other differences from the past estimates involve a few changes in strike lengths of seams on certain properties and a much closer evaluation of past production at the properties.

Table B-7 provides a summary of South Africa's chromite resource situation as of the mid-1980's. The values in table B-7 are compiled from table III of an article by C. F. Vermaak entitled "Summary Aspects of the Economics of Chromium with Special Reference to Southern Africa." The article is a chapter in volume II of "Mineral Deposits of Southern Africa," published in 1986 (*36*). This information is presented to allow comparison with this study's cost-evaluated resources. As shown, the South African chromite resource estimates of table B-7 include estimates of UG2 reef and non-UG2 reef chromite resources. The non-UG2 chromite reserve total of 618.9 Mmt in situ shown in table B-7 is 12.7 pct higher than this study's demonstrated resource estimate of 549 Mmt.

Because of uncertainty regarding future beneficiation and smelting plans, costs, and markets, availability and network flow model analyses of the potential chromite production from the UG2 reef were beyond the scope of this study. However, a discussion of important aspects of this large, potential resource is included in the following paragraphs.

Table B-7.—Published total Bushveld Complex chromite resources, circa 1986[1]

Reserve/resource category	In situ reserve/ resource, kmt
Seams other than UG2:	
Reserves	618,869
Indicated resources	1,506,803
Inferred resources	7,864,471
Total resources other than UG2	9,990,143
UG2 seam:	
Reserves	89,253
Indicated resources	207,743
Inferred resources	1,187,989
Total UG2 resources	1,484,985
Combined totals:	
Reserves	708,122
Indicated resources	1,714,546
Inferred resources	9,052,460
Grand total	11,475,128

[1]Compiled from (36), table III.

The UG2 reef is a disseminated chromite seam with platinum-group metals (PGM's) and sulfides segregated near the top of the seam. About one-third of the ore is chromite grading about 41 pct Cr_2O_3, with Cr-Fe ratios of 1.3:1 to 1.4:1. As of 1989, UG2 milling operations were only extracting the PGM's and sulfides and discarding the chromite with other gangue minerals as tailings of fairly high grade (about 25 to 35 pct Cr_2O_3) and mostly of very fine grain size (less than 325 mesh). To produce a usable chromite product, these tailings would have to be upgraded to at least 38 pct Cr_2O_3 using spirals. As a result, about 1 mt of marketable chromite concentrates could be produced from about 2 mt of tailings. It is possible to separate a certain coarse fraction of chromite (lump material) prior to grinding and flotation for the sulphide minerals. However, the vast majority of potential will come from reprocessing of tailings from PGM processing.

The mining and processing of UG2 reef material for PGM production has increased greatly during the 1980's. Western Platinum Ltd. began using separate mills to treat Merensky Reef and UG2 reef ores in 1980. By 1988 the company had the capability to process 960,000 mtpy of UG2 material and planned to increase this to about 2.9 Mmtpy by March 1990. In addition, Impala Platinum and Rustenburg Platinum both presently mine and process UG2 material for a portion of their PGM production. Finally, the newly developed Crocodile River mine near Brits will mine and process only UG2 material for production of PGM's.

As a result, the amount of chromite tailings from UG2 processing is building up rapidly. Western Platinum estimates that they have generated a total of 4.8 Mmt of chromite tailings from 1980 to 1988. Some South Africans have conjectured that by the years 2005 to 2010 the country's PGM production could be 400 mtpy, with half coming from UG2 reef material, and that this level of UG2 processing could potentially generate 10 to 15 Mmtpy of chromite tailings.

Production costs for chromite products (in lumpy or concentrate forms) from the UG2 seam would be low because of its byproduct nature. The South Africans have demonstrated that a marketable FeCr product can be made from the UG2 concentrates, and limited commercial FeCr production from UG2 chromite has already been instituted by Middelburg Steel and Alloys. A negative economic aspect is possible transport difficulties due to the fine grain sizes of the chromite concentrates. All implications regarding future use and potential of UG2 reef chromite are of major interest to the world chromium industry.

Mining and Beneficiation Operating Parameters

As analyzed, if all 26 of the South African units were in production at the same time, they would account for a combined 8.3 Mmtpy of ROM, which would result in potential annual output of 6.5 Mmtpy of marketable chromite products. The 16 producing operations could mine a total of 6.2 Mmtpy of ROM to produce 4.9 Mmtpy of chromite products; the 10 nonproducers could contribute an additional 2.1 Mmtpy of ROM for 1.6 Mmtpy of chromite products. Average annual ROM capacities for the producers and nonproducers are 386,100 mtpy and 207,600 mtpy, respectively.

The seven largest producing units (ranging in size from 400,000 mtpy to 960,000 mtpy ROM) account, by themselves, for a total of 4.3 Mmtpy ROM and 3.5 Mmtpy of chromite products. These seven—Henry Gould, Lavino, Mooinooi, Montrose, Rustenburg Minerals Development, Tweefontein, and Winterveld TCL South—form the "core" of the South African chromite mining industry. In addition, Winterveld TCL South, Henry Gould, and Montrose all have the capability to add ROM capacity beyond that analyzed here.

Of the 26 South African units analyzed, all but the Marico surface operation are (or are planned to be) mined via underground "bord and pillar" (breast stoping) methods. It is estimated that surface mining at Marico could continue until around the turn of the century, at which time underground mining would commence. As analyzed, the vertical depth of mining has been limited to 600 m at the Grasvally mine and at the Buffelsfontein section of Henry Gould. All of the remaining underground units were analyzed to a maximum depth of only 300 m.

The South African chromite seams included in this analysis range in thickness from 0.15 m to 1.8 m with shallow dips of only 4° to 20°. The minimum stope width used in costing was 0.8 m (for seams from 0.15 to 0.8 m thick), and the maximum was 1.8 m (in most cases for the mining of two seams together, but in one case for what was indicated to be a 1.8-m-thick seam). Development work is "on-seam," and support consists of wide regional support pillars with stick support between pillars.

All of the South African mines with stope heights of 1.3 m and less have been analyzed using the conventional, labor-intensive "bord and pillar" approach. However, since the late 1970's several mines in the southern part of the Western Bushveld have instituted complete or nearly complete mechanization of operations, which has a drastic, positive effect on labor productivity. These "mechanized" mines all have common geologic conditions where two seams are close enough to one another that they can both be extracted with a minimum stope height of 1.6 to 1.7 m and where the dips of the seams are less than 15°. Not all of the mines with seams or seam groups in the 1.6 to 1.9 m thickness range have been costed as mechanized operations in the present study.

The total ROM-to-chromite product ratio for all analyzed properties was 1.27:1, with the 16 producers lower at 1.25:1 and the nonproducers higher at 1.33:1. The lower ROM-to-chromite product ratio for the producers is a result of the somewhat higher Cr_2O_3 grades and because most of their ROM needs only sorting and screening to obtain acceptable lump and fines products for feed to the in-country smelters and for export as metallurgical products.[5]

Related to the above mentioned ROM-to-chromite product ratios are the overall beneficiation recoveries of Cr_2O_3 into chromite products. The South African recoveries are very high, averaging 87.8 pct for all units with separate averages of 89.2 for the producers and 85.5 pct for the nonproducers. Again, the higher recoveries for the producers are because most of their ROM requires only sorting and screening.[6] By comparison, two of the nonproducers will need to have 100 pct of the ROM upgraded by gravity concentration, and a fair amount of the

[5]The present South African producers use gravity methods primarily for the production of chemical, refractory, and foundry sand concentrates for export, which all require low SiO_2 contents of less than 1.5 pct.

[6]Recoveries at those units that primarily sort and screen their ROM range from 91.5 to 96.1 pct; those with a fairly high degree of gravity concentration have recoveries ranging from 82 to 86 pct; and those with total gravity concentration range from 75 to 80 pct overall recovery.

ROM at three other nonproducers will require gravity concentration.

Mining and Beneficiation Operating Costs

Table B-8 summarizes the ranges and averages of the underground mining operating cost estimates. The producers experience lower costs because of larger size (nearly two times larger on average), larger stope heights (1.25 m versus 1.07 m for the nonproducers), and somewhat thicker seams, on average.

The total labor cost estimates include black and white labor as well as administrative and management labor. Total labor accounts for an average of 50.3 pct of the producers' total underground mining costs and for 48.6 pct of the nonproducers' total underground mining costs. Management and administrative costs, which essentially can be viewed as representative of the white component of the labor costs, average 18.0 pct of the total labor cost for the producers and 20.8 pct of the nonproducers' total labor costs.

Table B-8 also summarizes the ranges and averages of the beneficiation cost estimates. The higher average beneficiation cost estimate for the nonproducers is due to smaller size, on average, and a higher proportion of ROM requiring gravity concentration. In the labor portion of these beneficiation operating cost estimates, management and administrative costs average 33 pct of the total labor cost for the producers and 40 pct for the nonproducers.

Table B-8.—Ranges and averages of mining and beneficiation operating cost estimates and percentages as labor, South Africa, by status

Range/average	Mining		Beneficiation	
	Cost estimates ($/mt ROM)	Pct labor	Cost estimates ($/mt ROM)	Pct labor
Producers:				
High	35.63	57.3	5.81	68.6
Low	11.13	41.8	1.36	52.4
Average	[1]17.83	[2]50.3	[1]2.33	[3]57.7
Nonproducers:				
High	91.90	57.3	5.89	79.9
Low	12.08	47.3	1.73	52.6
Average	[1]24.93	[2]48.6	[1]2.82	[3]61.5
Total, Average	[1]19.62	[2]49.7	[1]2.45	[3]59.2

[1]Weighted on basis of annual ROM capacity.
[2]Averages, underground mining units only.
[3]Averages, all properties.

TURKEY

Industry Overview

Chromite Production

According to Bureau production estimates, Turkish chromite output totaled 373,000 mt in 1980 (*32*). The low for the decade was reached in 1983 at 346,000 mt, followed by 487,000 mt in 1984 (*31*). Production has since increased substantially, reaching 600,000 mt in 1987 and 625,000 mt in 1988 (*23*).

Mining and Beneficiation

Most of the mine and mill development in Turkey since the early 1980's has occurred at non-ETIBANK (i.e., owned and operated by private companies) properties. Unfortunately, detailed information on many of these developments[7] was not available in the literature, and travel was not undertaken to Turkey for this update study. As a result, this availability study addresses only seven properties, four of which are owned and operated by ETIBANK, the state-owned company that is the only Cr ferroalloy producer in the country. Six of these seven properties were evaluated in IC 8977 and accounted for the majority of production in the early to mid-1980's. The new property added for this study is ETIBANK's Kapin operation in the Guleman District.

The table in appendix A lists these seven Turkish properties, their present operating status, and their product assignments for the availability and network flow model studies. Of these seven, the only major change during the 1980's occurred at the Kefdag operation, which was shut down in 1982 to undergo a complete mill overhaul and expansion to increase its capacity to almost 500,000 mtpy ore feed (to produce 300,000 mtpy chromite concentrates). This expansion at Kefdag was intended to be closely tied to the startup of the two new furnaces at the Elazig smelter during the late 1980's.

Smelting

Since 1980, there have been no changes in product dedication or in the number of furnaces at the low-C FeCr smelter at Antalya. This smelter produces about 10,000 mtpy of low-C FeCr using a small 6-MV·A furnace for ferrochromium-silicon production and a melt furnace for slag production.

[7]The production not covered involves at least 10 additional companies beyond those listed in appendix A and at least 15 additional mines or operations.

Conversely, ETIBANK's Elazig smelter has recently undergone a large increase to high-C FeCr production capacity. In 1980, the Elazig smelter had only two 17-MV·A furnaces capable of producing about 50,000 mtpy of high-C FeCr. In 1985, ETIBANK began construction of two additional 34-MV·A furnaces, with associated pelletizing lines, to use the Outokumpu Oy pelletizing/preheat process. The new furnaces were originally expected to reach full production by late 1987 or early 1988, but construction was never completed until mid-1988 to late 1988. As of 1990, the Elazig smelter should be capable of producing about 160,000 mtpy of high-C FeCr at full capacity for all four furnaces.

Chromium Chemicals Industry

In October 1984, a new chromium chemicals plant was opened in the port city of Mersin. The plant, with a capacity to produce 22,000 mtpy of sodium dichromate and 3,000 mtpy of chromium sulphate, was built with technical assistance from the Soviet Union. It is believed that the chromite feed (estimated to be about 35,000 mtpy of concentrates) for this plant is received from mines in the vicinity of Adana, which were not included in this availability analysis.

Refractory Industry

New to this study is Turkey's indicated internal demand for chromite at their refractory plants. As of 1987-88, total demand was said to be approximately 80,000 mtpy of bricks and 20,000 mtpy of mortars, with the plants at Kutahya, Konya, and Bozuyuk providing the refractories. It is estimated that the three plants would require a total of 5,473 mtpy of Cr, or about 17,500 mtpy of chromite, all assumed to be supplied by the Kapin operation for the availability analysis.

Resources

The in situ demonstrated chromite resources evaluated for Turkey total 13.8 Mmt at a grade of 36.3 pct Cr_2O_3. According to the estimates of this study, the extraction and beneficiation of this in situ tonnage could result in the potential production of 9.35 Mmt of marketable chromite products grading a relatively high 47.8 pct Cr_2O_3. This 9.35 Mmt of chromite production would represent only 15 yr of production at the Bureau's estimated 1988 output level for the entire country.

The six operations currently producing would account for 95.9 pct of the recoverable chromite products. The updated resource tonnage and grade estimate of 13.8 Mmt at 36.3 pct Cr_2O_3 is very similar to the prior study's estimate of 11.7 Mmt at 38.0 pct Cr_2O_3.

The resource tonnage above does not include any potential ores contained in the 15 or more additional producing operations believed to be in production as of the late 1980's, which have been referred to previously in this section. The analyzed tonnage also does not include a very large, low-grade resource (100 Mmt of ore grading 10 to 15 pct Cr_2O_3) located in Adana province and owned by ETIBANK.

Mining and Beneficiation Operating Parameters

The seven Turkish properties included in this analysis consist of six producers and one small property not in production. Four of the six producers are owned by ETIBANK. As analyzed, all seven properties would account for a total of 887,300 mtpy ROM to produce 595,000 mtpy chromite products, forming the "core" of the Turkish industry. However, many new chromite operations have come into production in Turkey since the early 1980's, and none of these new operations have been included in this study owing to the lack of detailed data sufficient to address costing.

All seven of the properties were evaluated as underground mining operations. Individual ROM capacities range in size from a small 20,000 mtpy to a very large 490,000 mtpy, with the average ROM capacity at 130,240 mtpy.

The ROM-to-chromite product ratio for all seven properties is relatively high (1.49:1). However, this total ratio is strongly influenced by the very large Kefdag operation. This mine has relatively low-grade ore (33.6 pct Cr_2O_3) which requires beneficiation at an estimated recovery of only 80 pct. Excluding Kefdag, the ROM-to-chromite product ratio for the other six properties is much lower (1.342:1), reflecting the higher Cr_2O_3 grades (average of 40.8 pct) and higher beneficiation recoveries (average of 90.4 pct).

Mining and Beneficiation Operating Costs

Table B-9 summarizes the range and average for the mine operating cost estimates; the labor component of these mining cost estimates is also presented in the table. Table B-9 also shows the estimated beneficiation costs and the percentage represented by labor.

Of note in both the mining and the beneficiation cost estimates is the very high percentages, on average, represented by labor costs. This is mainly due to the generally small capacities of the operations in combination with relatively high wage rates for Turkish laborers. In the beneficiation cost estimates, the highest cost is for a small 25,000 mtpy ROM gravity concentration mill, and the lowest cost is for a very large (490,000 mtpy ROM), primarily magnetic separation, mill.

Table B-9.—Ranges and averages of mining and beneficiation operating cost estimates and percentages as labor, Turkey

Range/average	Mining: Operating cost ($/mt ROM)	Mining: Pct labor	Beneficiation: Operating cost ($/mt ROM)	Beneficiation: Pct labor
High	42.35	70.4	13.45	85.3
Low	9.63	53.0	4.30	49.7
Average	[1]20.79	[2]64.9	[1]6.23	[2]75.8

[1]Weighted average; weighted on annual ROM capacity.
[2]Average for all producing and nonproducing properties.

UNITED STATES

Industry Overview

Chromite Production

There was no domestic chromite production during the entire decade of the 1980's. The last chromite production of any significance occurred in 1976 from a California deposit.

Mining and Beneficiation

During the 1980's numerous research projects were conducted by the Bureau on the potential use of domestic resources. Private company exploration activity occurred in the mid-1980's on certain of the northern California deposits and, in 1987-88, on some of the Stillwater Complex deposits. Private company smelting tests were also done on stockpiled Stillwater Complex concentrates. However, as of 1990, there is still no domestic chromite production.

Smelting

Because of increased foreign competition, ferrochromium smelters in the United States, which had produced as much as 224,000 mt of high- and low-C FeCr and 21,505 mt of ferrochromium-silicon in 1979 (*37*), produced only 83,358 mt of high- and low-C FeCr and an unspecified, but low, amount of ferrochromium-silicon for the year 1982 (*38*). One factor in this decline was the 1981 suspension of production of high-C FeCr by Macalloy, Inc. at their Charleston, SC, smelter. This firm, which is one of the two remaining high-C FeCr producers in the United States, as of 1989, filed for chapter 11 bankruptcy in February 1982 and restarted production at one of their furnaces in March 1982 (*38*). In 1983, the U.S. Department of Defense awarded the company a contract to upgrade currently stockpiled chromite to high-C FeCr. From 1984 through 1988, using one furnace, 508,293 mt chromite ore was converted to 196,258 mt high-C FeCr for the stockpile. This contract will likely last at least through the year 1993.

As of 1988, the other furnace at Macalloy was being used to produce high-C FeCr under what could be described as "toll" contracts with owners of chromite ores. According to the company, this arrangement is less expensive than their previous mode of operation because there is no need to account for their own inventories of chromite ores (*39*).

Production of low-C FeCr in the United States was close to zero in 1985 and 1986. This was a decline from 30,869 mt produced in 1979. However, the chromium ferroalloy market rebound in 1987 resulted in the restart of a 12-MV·A furnace at the Marietta, OH, smelter of Elkem Metals Co. With this furnace, which began production in the spring of 1988, the company planned to produce about 20,000 mtpy of high-C FeCr. The high-C FeCr product would then be vacuum degassed to produce an estimated 18,000 mtpy of low-C FeCr.

During the 1988-90 period, preliminary feasibility studies were conducted on the possible construction of a high-C FeCr smelter to be located in Huntley, MT, and a low-C FeCr smelter to be sited in Coos Bay, OR. The low-C FeCr project's site was subsequently changed to a proposed location near Vancouver, British Columbia.

Chromium Chemicals Industry

In 1987, Allied Chemical Corp. closed their chromium chemicals plant in Baltimore, MD. This was the oldest of the U.S. chromium chemicals plants and leaves the United States with two chromium chemical plants operating as of 1989, one located in Corpus Christi, TX, and the other in Castle Haynes, NC. These two plants have the combined capacity to produce an estimated 165,000 mtpy of SBE.

Refractory and Foundry Sand Industries

The U.S. chromium refractories industry, which had 10 plants owned by five companies in the early 1980's, declined to only five plants owned by four companies in 1989. The United States decline reflects the drastic reduction in the amount of chromium used for refractory purposes in MEC's since the late 1970's. This, in turn, is directly attributable to changes in basic steelmaking technology over the same period. As an indication of size, the U.S. refractory industry consumed an average of 65,442 mtpy of chromite in the 5 yr from 1984 through 1988. In 1986, a low of 45,303 mt was consumed; the highest level (88,570 mt) was reported in 1988. There are very little data available on the users of chromite concentrates as foundry sand in the United States.

Resources

As part of ongoing updating activity of the Minerals Availability Program, and in response to a State Department requirement related to the Comprehensive Anti-Apartheid Act of 1986, updated resource and cost estimates were made for the nonproducing U.S. chromite resources considered to be the most economically attractive. The three U.S. chromite resource areas chosen for updating comprised (1) the Mountain View mine property within the Stillwater Complex of Montana; (2) the Red Mountain deposit in Alaska; and (3) selected podiform deposits of the Northern Klamath mountains in the states of Oregon and California.

These chromite resources were chosen for updating primarily because of the large tonnages of potentially minable material and reasonably high Cr_2O_3 contents, ranging from 8.9 pct to 23.3 pct. The tonnages and grades for these three chromite resource areas are given in table B-10. The combined tonnage of 45.3 Mmt at 12.3 pct Cr_2O_3 content could account for production of a total of 11.0 Mmt of marketable chromite concentrate, including 500,000 mt of concentrates already stockpiled. The weighted average grade of the proposed new concentrate production from the three resource areas is 42.7 pct Cr_2O_3.

Table B-10.—Summary, U.S. chromite resources

Property name/location	Tonnage (kmt)	Grade, pct (Cr_2O_3 content)
Evaluated resources:		
Mountain View Mine, MT	10,606	[1]23.3
Red Mountain, AK	23,300	8.9
North Klamath Mountains, CA/OR	11,400	9.2
Total or average	45,306	[1]12.3
Other resources:		
Windy River Placers, AK	37,982	[2]1.3
Claim Point, AK	267	[3]17.8
Red Bluff Bay, AK	30	[3]12.0
Southwest Oregon Beach Sands, OR	80,069	[4]4.8
Benbow, Gish, Nye Basin, MT	27,337	[3]21.5
North Elder Creek, CA	104	[3]11.9
Pilliken Mine, CA	30,975	[3]5.0
Louise Chromite, GA	131	[4]4.0
West placer area, MD/PA	729	[4]1.4
North Caroline area, NC	178	[3]2.1
Renshaw Placer, PA	209	[4]3.5
Casper Mountain, WY	3,774	[4]2.5
Total or average	109,785	7.8

[1]Includes 500,000 mt of 39.0 pct Cr_2O_3 concentrates stockpiled from defense contract production in 1960's.
[2]Inferred level; from evaluation in 1987-88 by the Alaska Field Operations Center, Bureau of Mines.
[3]Inferred level; from table 1, (*40*).
[4]Demonstrated level; from table 1, (*40*).

Also included in table B-10 are the tonnages and grades for other U.S. chromite resources that did not undergo resource or cost updating for this study. It should be noted that only the other Stillwater Complex resources (Benbow, Gish, and the Nye Basin) have comparable size and Cr_2O_3 content to the three U.S. chromite resource areas that were updated for this study.

The resource values shown for the Red Mountain deposits are presently categorized as an identified resource, while the values for the Northern Klamath Mountains resource include both demonstrated and identified resource tonnages. Additional drilling and quality analysis remains to be accomplished before upgrading the confidence level on these resources. The Mountain View mine resources are presently in the demonstrated resource category, and the tonnage shown may be conservative, since the current lessor of the property has conducted much additional exploration activity since mid-1988.

The four Alaskan chromite resource areas listed in table B-10 are part of a larger area defined as the "Border Ranges Fault" chromite deposits. Results of Bureau investigations on the chromite resources of these deposits have been reported in Bureau IC's 8990 and 8991, both published in 1985.

Mining and Beneficiation Operating Parameters

Table B-11 summarizes the proposed capacity data for the major U.S. chromite resources evaluated for this study. At present, none of the three resource areas are in production. However, if all three properties/units were developed at the same time, they could potentially produce a total of 546,000 mtpy of 40 pct to 44 pct Cr_2O_3 concentrates from a combined 2.3 Mmtpy of ROM. This annual chromite production level would be equivalent to 97 pct of the Bureau's estimate for Zimbabwe's 1988 production. Using the resource tonnage estimates and operating rates of this study, the operating lives for the Montana, Alaska, and California/Oregon resources would be 21, 26, and 13 yr, respectively.

Table B-11.—Summary of annual capacity levels proposed for study, evaluated U.S. chromite resources

Evaluated resource	Annual capacities, kmtpy	
	ROM	Concentrates
Mountain View Mine	532	254
Red Mountain	896	145
North Klamath Mountains	877	147
Total	2,305	546

The Mountain View mine resource would be mined using underground methods, the Red Mountain resource would be mined by surface methods, and the Northern Klamath Mountain resource would be extracted with a combination of surface and underground methods. At an average 768,000 mtpy ROM, these three proposed operations are rather small in comparison to most U.S. mining operations for other metals and minerals. However, this average ROM capacity would be at the high end of the range for the South African chromite producers and much larger than the vast majority of the other MEC chromite producers' ROM capacities.

The beneficiation ROM capacities proposed for the three resource areas are also very large in comparison to other MEC chromite producing operations. The ROM from the three areas, grading 8.9 to 22.5 pct Cr_2O_3, would be upgraded using simple gravity methods to concentrates of about 40 pct to 44 pct Cr_2O_3 for feed to nearby proposed smelters. Estimated recoveries for this level of gravity concentration ranged from 80 to 85 pct.

Mining and Beneficiation Operating Costs

The estimated mine operating costs for these three areas range from \$9.16 to \$26.90/mt ROM with a weighted average of \$13.76/mt ROM. As a percentage of the mine operating cost estimates, labor ranges from 31.4 to 68.6 pct with a weighted average of 50.2 pct.

The estimated beneficiation operating costs for the three U.S. resource areas ranged from \$4.77 to \$5.71/mt ROM with a weighted average of \$5.20/mt ROM. As a percentage of the total beneficiation operating cost estimates, labor ranges from 58.5 to 79.8 pct with a weighted average of 68.4 pct.

ZIMBABWE

Industry Overview

Chromite Production

Chromite production in Zimbabwe started the decade with 553,000 mt in 1980 (*32*) and declined to a low for the decade of 420,000 mt in 1983 (*31*). Output has increased steadily since 1983, with production estimated at 570,298 mt in 1987 and 561,477 mt in 1988 (*23*).

Mining and Beneficiation

There have been few, if any, exports of chromite products from Zimbabwe during the 1980's. Virtually all production has been used in producing high-C and low-C FeCr and ferrochromium-silicon. There has also been little change in the number of major mines since the early 1980's, with only the Inyala, Lalapanzi, and Great Dyke operations being rehabilitated.

The Impinge eluvial soil mill shut down operations sometime between 1980 and 1985, most likely because of exhaustion of reserves. The present study does not address Zimbabwe's eluvial soil resources or economics in any manner.

One major development in the chromite mining and beneficiation industry in Zimbabwe since 1980 was the writeoff, in 1984, by ZIMALLOYS, of all capital investments in "deep mining" at their Great Dyke seam operations. The company has since begun purchasing much of their Great Dyke seam ore needs from tributors (independent miners) or from cooperatives mining either surface ores or underground "shallow" ores via adits or inclined shafts. The other major smelting company, ZIMASCO, has also followed this trend. As a result, in ZIMALLOYS' 1986-87 fiscal year, about 41 pct (60,000 mt) of the ore feed to their Gweru smelter was being provided by the cooperatives and tributors. Similarly, in 1988, as much as 15 pct (75,000 mt) of the ore feed to ZIMASCO's Kwe Kwe smelter came from these non-capital-intensive sources.

Another major development was the new tax policy the Zimbabwe government instituted in 1984. This policy allows capital investments to be written off in the year incurred, much like the South African system. This policy change should improve the economics of deep mining the Great Dyke seam resources, but its effects have not been analyzed in this study.

The table of properties and units in appendix A lists the 37 units included in this study for Zimbabwe. Figure B-6 and table B-12 provide the locations and names of all 37 of these analyzed properties and units. Table B-12 also provides a list of the specific Great Dyke chromite seams included in the analyzed resources for the Great Dyke units.

The Great Dyke seam deposits have been split into 30 units for analysis, reflecting 27 individual sections of the Great Dyke (see figure B-6). The three extra evaluated units result from the split of the Caesar section into three separate units and from the split of the Ngezi Co-operative from the Bat Claims section. These separations were made to look at the differences in economics between the so-called "deep mining" operations, which are relatively capital intensive, and the shallower, much less capital-intensive operations of the cooperatives and the tributors on the Great Dyke.

Of the seven evaluated podiform deposit properties, four were in production as of 1989, while 14 of the 30 Great Dyke seam units are in production. Zimbabwe Alloys Ltd. (ZIMALLOYS), the owner of the Gweru low-C FeCr smelter, owns or has ownership ties to the Inyala podiform resource and to the Caesar, Vanad, Sutton/Rodcamp, Netherburn, and Great Dyke seam resources. Zimbabwe Mining and Smelting Ltd. (ZIMASCO), the owner of the Kwe Kwe high-C FeCr smelter, owns or has ownership ties to all of the other podiform resources and to the Umvukwes, Impinge, Crown/Divide North, Maryland, McGowan, Lalapanzi, Glenapp/Ivo, and Hay/Noro seam resources. The ownership within the other Great Dyke seam units is either varied, dated, unclear, or unknown.

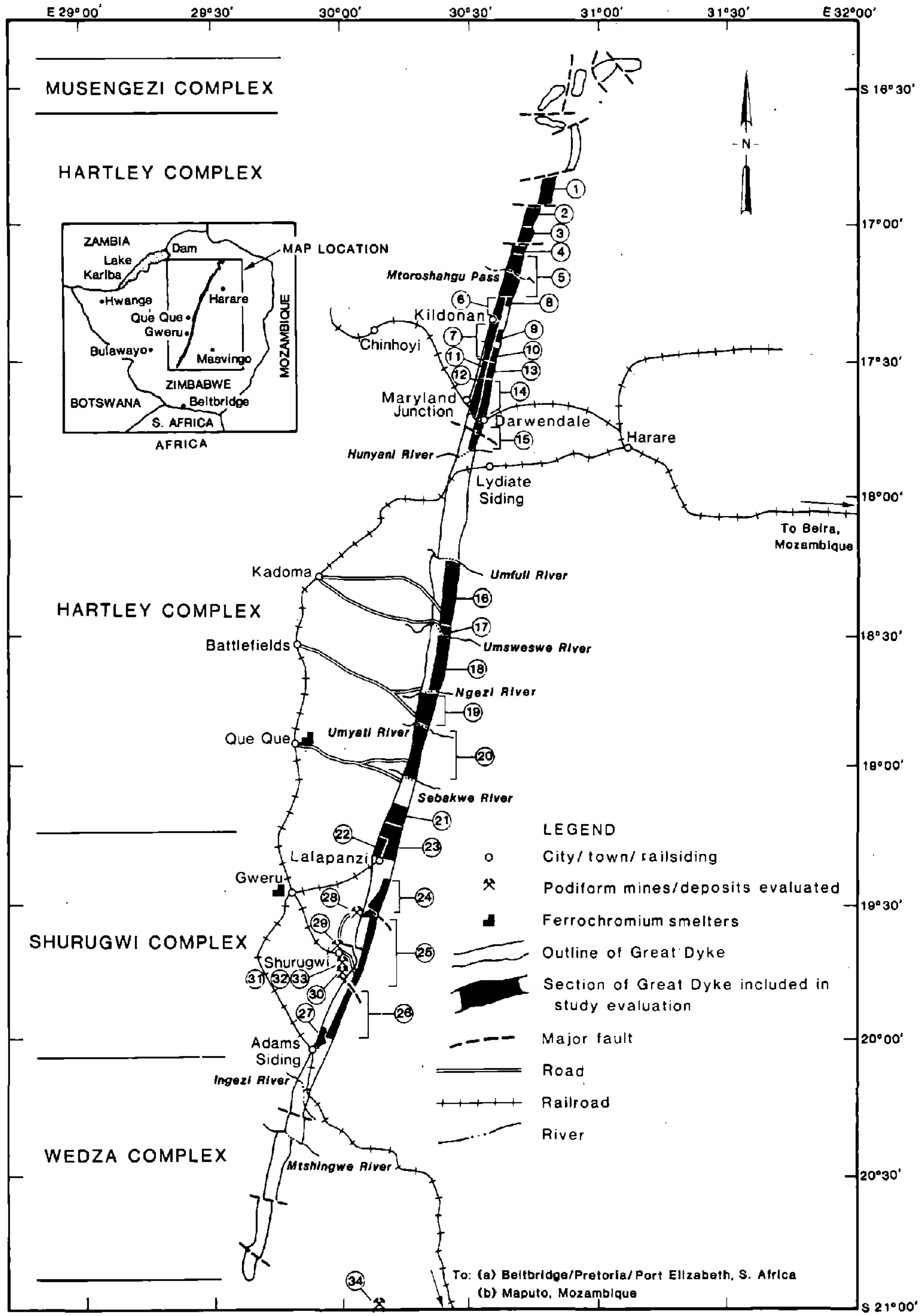

Figure B-6.—Location of evaluated chromite properties and units, Zimbabwe.

Table B-12.—Evaluated chromite properties and units, production status, and seams analyzed, Zimbabwe, by deposit type

Property/units	Production status[1]	Great Dyke seams analyzed	No. on fig. B-6
Podiform properties:			
Inyala	P	NAp	34
Iron Ton	NP	NAp	32
Ironsides	NP	NAp	33
Magazine Hill	NP	NAp	31
Railway Block	P	NAp	29
Shurugwi Peak	P	NAp	30
Valley Chrome	P	NAp	28
Great Dyke seam units:			
Bat Claims/Ngezi Co-operative	NP	1, 2, 5	19
Caesar (Shallow Mining)	P	5, 6, 7, 8	8
Caesar (Company Claims)	NP	6, 7	8
Caesar (Tributed Area)	NP	5, 6, 7	8
Central (Midlands)	NP	2	21
Crown/Divide North	P	4, 5, 6	10
Divide/Francis	NP	4	14
Glenapp/Ivo	P	8, 9, 10	2
Great Dyke	P	4	9
Greenvale	NP	4, 5, 6, 7	13
Hay/Noro	P	7, 9, 10	3
Impinge	P	9, 10	1
Lalapanzi	P	2	23
Magundi	NP	4, 5, 6, 7	11
Maryland	P	4, 6, 7	12
McGowan	P	2, 4	15
Mdindi/Mapanzuri/Chrome Hill	NP	1, 2, 3, 4, 6	24
Netherburn	P	1, 2	22
Ngezi Co-operative	P	2	19
Ore Recovery Tribute	NP	4, 5, 6, 7, 8, 9	6
Pons	NP	1	26
Rose/Seymore/Makamisa	NP	1, 2	25
Rutala	NP	2	16
Spot	NP	2	27
Sutton/Rodcamp	P	6, 7	7
Umsweswe	NP	2	17
Umsweswe/Bee	NP	1, 2	18
Umvukwes	P	5, 6, 7, 8, 9, 10	5
Vanad	P	9, 9A, 10	4
Windsor/York/York West	NP	5	20

NAp Not applicable.
[1]P = producing; NP = nonproducing.

Smelting

Since 1980, only one new furnace has been added at the two Zimbabwe smelters. This is a small remelt furnace added at the Kwe Kwe smelter in early 1988 to remelt high-C FeCr fines being generated in processing and handling. The Kwe Kwe smelter, which obtains about 85 pct of its chromium in ore feed from the three large podiform operations of Shurugwi Peak, Railway Block, and Valley Chrome, has produced high-C FeCr throughout the decade. One furnace was decommissioned in 1986, but was recommissioned in 1988. This study's 1989 estimated full production capacity for the Kwe Kwe smelter, with seven furnaces (including the remelt furnace), is approximately 200,000 mtpy of high-C FeCr.

In the early 1980's, ZIMALLOY's Gweru smelter had the capacity to produce as much as 50,000 mtpy of high-C FeCr in addition to low-C FeCr and ferrochromium-silicon. It discontinued high-C FeCr production in early 1984 and converted this furnace to ferrochromium-silicon production. As a result, using four furnaces, the Gweru smelter produced 31,141 mt of low-C FeCr and 53,527 mt of ferrochromium-silicon in the 1985-86 fiscal year and 33,390 mt of low-C FeCr and 52,298 mt of ferrochromium-silicon in the 1986-87 fiscal year (*41*). However, approximately 20,000 to 22,000 mt of ferrochromium-silicon production should be added to these published values to address the amount of ferrochromium-silicon production that is used in low-C FeCr production. Thus, this study's 1989 full production capacity estimate for the Gweru smelter is for 32,000 mtpy of low-C FeCr and 79,000 mtpy of ferrochromium-silicon, using six existing furnaces in the production of these two chromium ferroalloys.

Because of the importance of Zimbabwe FeCr output to the overall market, a hypothetical doubling of high- and low-C FeCr capacity (with an appropriate increase to ferrochromium-silicon capacity) was built into the network flow model for both the normal and the cutoff scenarios. It was assumed in the model that the hypothetical capacity increases would be on-line by the start of 1993.

Chromium Chemicals, Refractory, and Foundry Sand Industries

There are no chromium chemical plants in Zimbabwe. There could be a small amount of chromite usage in refractory materials, but all indications are that the present chromite production level is essentially used as feed for the two ferroalloy smelters. Therefore, the present availability and network flow analysis do not include provisions for the off-take of any chromite production to an existing chemical, refractory, or foundry sand industry in Zimbabwe.

Resources

The evaluated in situ demonstrated chromite resources for Zimbabwe total 69.6 Mmt at 43.0 pct Cr_2O_3. The seven podiform resource units contain 16.5 Mmt of in situ tonnage at 43.2 pct Cr_2O_3; the 30 Great Dyke seam resource units contain a total of 53.1 Mmt at 42.9 pct Cr_2O_3.

Potentially, 51 Mmt of marketable chromite products, grading about 46.5 pct Cr_2O_3, could be recovered from the evaluated resources. This 51 Mmt of potential production would represent about 90 yr of output at the Bureau's estimated 1988 production level. The 18 producing units account for 60.4 pct of the available chromite products with the remaining potential production in the 19 nonproducing units. Not surprisingly, 43 pct of the recoverable chromite products in producing units is contained in the low-cost podiform resource units, while only 3.4 pct of the recoverable chromite products in nonproducing units is in podiform resource units.

The updated estimate of 16.5 Mmt of in situ podiform material grading 43.2 pct Cr_2O_3 compares with the prior study's estimate of 16.9 Mmt at 46.5 pct Cr_2O_3. In reestimating the potential podiform resource for this update study, more generous assumptions were made regarding potential to depth.

The 1989 estimates of in situ Great Dyke seam material have been significantly reduced from the prior study's estimate of 175.0 Mmt at 49.0 pct Cr_2O_3. Even though the extensions to depth (300 m on-dip) are the same, the tonnage is much lower because the new estimates are based solely on the outcrops shown on B. G. Worst's plan maps from his 1960 publication (*42*). The prior estimates assumed continuity of outcrops across the entire strike length of the section and, in some cases, assumed presence of a seam even though no outcrops showed on the map. Hence, strike lengths of many seams have been greatly reduced, and some seams have been excluded in the new estimates.

It is thought that these estimation changes for the Great Dyke seam material are more cognizant of problems caused by faulting, which are rather common in operations on the Great Dyke. It is noted that such a large, extensive geological structure as the Great Dyke does present the probability of a wide variation in separate estimates of contained chromite resources, depending on the method or approach that is used.

Mining and Beneficiation Operating Parameters

A total of 37 operations, all analyzed as underground mining units, have been included in this study for Zimbabwe. If all 37 units were producing at the same time, nearly 1.3 Mmtpy of ROM could be produced for a total of 1.0 Mmtpy chromite products. On a deposit-type basis, the seven podiform units would represent 526,400 mtpy of ROM for 445,500 mtpy of chromite products, while the 30 Great Dyke seam units would account for 727,400 mtpy of ROM and 600,000 mtpy of chromite products.

The 18 units in production as of January 1989 represent a total output level of 751,500 mtpy ROM for 650,600 mtpy chromite products. This total is composed of four podiform producers (442,000 mtpy of ROM for 369,600 mtpy chromite products) and 14 Great Dyke producers (309,500 mtpy ROM for 281,000 mtpy chromite products).

The 19 units not in production represent a potential output level of 502,300 mtpy ROM for 395,000 mtpy chromite products. The three nonproducing podiform properties could produce 84,400 mtpy ROM for 76,000 mtpy of additional chromite products. The 16 nonproducing units on the Great Dyke represent a potential for 417,900 mtpy ROM and 319,000 mtpy of chromite products.

For all of the Zimbabwe units analyzed, the overall ROM-to-chromite product ratio was 1.199:1. The 18 producing units are lower than the average at 1.155:1, and the 19 nonproducers are higher at 1.271:1. The differences in this ratio between the producers and the nonproducers were due primarily to differences in overall beneficiation recoveries of Cr_2O_3 into chromite products. The overall beneficiation recoveries for the producers ranged from 85.8 pct to 100 pct, with a straight average of 93.4 pct;

estimated recoveries for the nonproducers ranged from 80 to 96.7 pct, with a straight average of 86.9 pct.[8]

Mining and Beneficiation Operating Costs

Table B-13 provides the ranges and weighted averages of the estimated mine operating costs for the Zimbabwe properties and units analyzed in the study. The estimated underground mining costs for the podiform deposit properties are for sublevel and open stope mining methods. The cost estimates for resue mining[9] of the thin seams on the Great Dyke are significantly higher. It is interesting that the weighted average mining cost for the producing Great Dyke units is slightly higher (less than 1 pct) than for the nonproducing Great Dyke units. This difference is due primarily to the relative average annual ROM capacities, which, at 26,100 mtpy for the nonproducers, is 18.1 pct higher than the average for the producers.

Table B-13.—Ranges and weighted averages of mine operating cost estimates, Zimbabwe, by deposit type

Deposit type/ range and average	Mine operating cost estimate, $/mt ROM
Podiform:	
High	49.01
Low	18.44
Wtd avg	[1]36.21
Great Dyke seams:	
High	152.35
Low	32.86
Wtd avg	[1]96.49
Total wtd avg	[1]71.18

[1]Weighted on basis of annual ROM capacity.

Labor costs include black and white employees and management and administrative labor. As a percentage of the average underground mine operating cost estimates for the podiform properties, the labor component ranges from 47.0 to 66.3 pct and averages 57.6 pct. It is not possible to provide a range and average for the labor cost percentage in the Great Dyke underground mining cost estimates because of the inclusion of multiple seams over a single unit. In the base model used for the seam estimates, labor represented 61 pct of the total mining cost estimate for a 10,000-mtpy-ROM unit mining a single 0.10-m-thick seam and 63 pct for a 20,000-mtpy-ROM unit mining a single 0.30-m-thick seam.

Table B-14 presents the ranges and averages of the beneficiation cost estimates for Zimbabwe. The higher cost estimates for the nonproducers are due to lower average annual ROM capacities[10] and the requirement for gravity concentration of a higher proportion of the ROM. The beneficiation operating cost estimates for simple screening/sorting ranged from $3.00/mt to $5.25/mt ROM; for heavy media separation the cost estimates ranged from $4.79/mt to $5.68/mt ROM; the estimates for those units using gravity separation for a portion of the feed ranged from $4.34/mt to $6.24/mt ROM. Not surprisingly, the highest range of beneficiation cost estimates, from $6.44/mt to $9.80/mt ROM, was for those units using gravity separation for 100 pct of their feed material.

Table B-14.—Ranges and weighted averages of beneficiation operating cost estimates, Zimbabwe, by status

Status/range and average	Beneficiation operating cost estimate, $/mt ROM
Producers:	
High	6.24
Low	0.00
Wtd avg	[1]4.88
Nonproducers:	
High	9.80
Low	3.75
Wtd avg	[1]5.94
Total wtd avg	[1]5.31

[1]Weighted on basis of annual ROM capacity.

All labor, including black and white employees and management and administration labor, ranged from 77.5 pct to 88.3 pct of the total beneficiation cost for the simple screen/sort operations. Other labor percentage ranges were 34.2 to 65.4 pct for heavy media and 61.5 to 78.5 pct for partial or complete gravity separation operations.

[8]Only 10 of the 18 producers use gravity concentration and, in all cases, for only a small portion of their total ROM. By comparison, 14 of the 19 nonproducers will need to gravity concentrate significant portions of their ROM.

[9]All cost estimates for resue mining of these Great Dyke seam deposits are based on stope heights from 0.8 m to 0.9 m for extraction of seams ranging in thickness from 0.10 m to 0.30 m to on-dip lengths of 300 to 400 m.

[10]The nonproducers, which include mostly Great Dyke seam units, average 26,440 mtpy ROM. The producing units, at 44,100 mtpy, have a much higher average annual ROM capacity because of the inclusion of the relatively large podiform operations.

APPENDIX C.—SMELTING TECHNOLOGY

HIGH-CARBON FERROCHROMIUM

In conventional smelting technology, high-C FeCr is produced electrothermically in three-phase submerged electric arc furnaces. The chromite ore is fed at the top of the furnace along with various reductants (mostly metallurgical coke) to reduce the contained Cr and Fe in the chromite. Other raw materials are also included in the furnace charge to control smelting conditions such as slag characteristics and to control the constituent grades in the final high-C FeCr product. The most common and critical of these other raw materials are silica (in the form of quartzite or gravel), dolomite for addition of MgO, limestone for addition of CaO and corundum, bauxite, or other aluminosilicates for Al_2O_3 additions. The amounts of these other raw materials that are required to be included (or excluded) in the charge will depend on the SiO_2, MgO, CaO, and Al_2O_3 grades in the chromite feed.

The particle size and friability of the chromite feed is an important element in electric arc smelting. For example, to facilitate the upward escape of furnace gasses during smelting, the high-C FeCr smelter at Kwekwe in Zimbabwe is said to limit the minimum size of chromite feed to 50 to 63 mm (*43*). In contrast, the minimum size of chromite feed to South African smelters appears to be set at only 1 to 1.5 mm. However, chromite particles in this lower size range (1 to about 60 mm) tend to be blown about within the furnace during smelting and lost to the environment or in the slag. As a general rule, a typical South African "fines" chromite ore (in the particle size range from 0.3 to about 10 mm) can be expected to give a smelting recovery of only about 75 pct to 80 pct of the Cr into the Cr ferroalloy product, while a lump chromite ore (greater than about 6 mm) will result in recoveries of 80 to 85 pct.[1]

For these reasons (better smelting efficiency and better recovery) a premium has always been given to chromite in the form of "lumpy" material. However, the trend in chromite production during the 1970's and 1980's has been for increased production of the finer sized chromite ore products, particularly in South Africa and India, as well as for increased production of chromite concentrates in MEC's because of the need to process chromite ores with much lower Cr_2O_3 contents. This trend, combined with the inherently inefficient smelting operations and recoveries when feeding chromite ore "fines" and "concentrates" directly into electric arc furnaces, has led to new directions in the industry's approach to smelting.

The simplest and cheapest approach to this "fines" problem is to make briquettes out of the chromite fines or concentrates by mixing them with various binders. During the 1970's and 1980's, briquetting facilities were installed at two South African smelters, at the Brazilian smelter, and at FACOR's smelter in India. The briquettes are supposed to act somewhat like lump ore in the smelting process. However, in many cases the briquettes do not retain their shape under smelting conditions and have not proved to be the most efficient approach.

A more sophisticated and expensive approach to the problem has been to pelletize the chromite fines and concentrates. The idea of pelletizing a fine chromite concentrate along with a flux and a coking coal reductant to make a composite pellet for feed to an electric arc furnace was thought of as early as 1961 (*44*). Further, it was recognized that with closed-top furnaces the carbon monoxide given off in smelting could be recovered and used to provide heat for the prereduction of the pellets before feeding to the furnace.

At nearly the same time, Union Carbide of the United States piloted a prereduction process, which was then developed, refined, and patented by Showa Denko of Japan during the mid-1960's to late 1960's. This process involved the pelletizing of chromite fines/concentrates, breeze (fine) coke, a binder (usually bentonite), and a flux, sintering (hardening) the pellets in a traveling grate kiln and preheating the sintered pellets in a rotary kiln at 1330 to 1430° C before charging into the electric arc furnace (*45*). This process is called the solid state reduction of chromite (SRC) process.

By 1968-69, two full-scale production plants using the SRC process had been commissioned in Japan by Showa Denko and Japan Metals and Chemicals Company (*45*). In 1975-76, the use of the SRC process was licensed by the Japanese to Consolidated Metallurgical Industries (CMI) of South Africa for their new 120,000 mtpy FeCr smelter at Lydenburg. However, as of 1990, Japan and South Africa are still the only countries with commercial plants using the process.

[1]It is important in the context of this discussion to define the terms meant by "lump (lumpy)," "fines," and "concentrates" material. In South Africa, chromite products with size ranges from larger than 100 mm to a minimum of about 6 to 10 mm are referred to as "lump," "large lump," "small lump," and even "chips," depending on the operation. Chromite products in the general particle size range with a top size of 6 to 10 mm and a minimum size of 0.3 to 2.5 mm have a wide variety of names, including "chips," "nodules," "pebbles," "middlings," and "washed fines." Finally, the third major size category is the "concentrates" category; products in this category have top sizes mostly of 1.0 mm. The middle-size category with a top size of 6 to 10 mm and minimum sizes of 0.3 to 2.5 mm is commonly referred to as "fines" (for smelting purposes) and gives a lower recovery in electric arc smelting without some pretreatment.

At Lydenburg, CMI is now producing 155,000 to 160,000 mtpy of high-C FeCr from the same two pelletizing lines, rotary kilns (60 m in length) and 32.5-MV·A furnaces that were originally constructed back in 1975-76. In Japan, Japan Metals and Chemicals has one 24-MV·A furnace and Showa Denko has one 18-MV·A furnace being fed with prereduced pellets from the SRC process. Thus, as of 1989, about 102,000 mtpy of Japan's total estimated 324,000 mtpy of high-C FeCr production capacity uses this very efficient prereduction method.

In 1988, CMI was achieving 55 to 60 pct prereduction of Cr in pellets, while the Japanese were reported to be achieving 70 to 75 pct Cr prereduction. These results can be compared with demonstrations back in the 1960's that Cr reductions using pelletizing/prereduction methods could be taken, at a maximum, to between 70 and 80 pct with most of the Fe in the chromite being reduced (*44*).

As an example of the extreme efficiency of this process, CMI claims a recovery of Cr into final high-C FeCr products of about 93 pct, and their recoveries have supposedly never been below 90 pct since the plant's start in 1976 (*46*). The company also suggests that they could produce 90,000 mtpy of high-C FeCr using only one of its two 32.5-MV·A furnaces in combination with both of their rotary kilns. This 90,000 mtpy level would compare with an expected 55,000 mtpy from the same size furnace if smelting a feed comprised of 70 pct lump ore and 30 pct fines ore.

There are two other significant pelletizing/prereduction methods either in use or with potential for use in the FeCr smelting industry. One of these, the Outokumpu Oy method, is a pelletizing/preheating method that uses coke as the reductant. The potential process is the INMETCO rotary hearth process, which is touted as being able to use cheaper coal as both the reductant and the energy source (*47*).

The Outokumpu Oy method was initially developed and installed at the startup of the company's Tornio, Finland, smelter in 1968. In this process, the wet-ground chromite concentrate is dewatered and mixed with bentonite and then rolled into pellets. The pellets are fed to a shaft furnace for sintering before undergoing preheating to 1,000° C to 1,100° C in a 55-m long rotary kiln along with the coke and quartz feed. This preheated charge of pellets, coke, and quartz is then fed to the electric arc furnace.

Because of lower preheating temperatures and the fact that the reductant is not intimately mixed with the chromite in the pellets, the Outokumpu Oy method achieves only a fairly small degree of prereduction of the Cr in the pellets. However, because of aggressive marketing, the method has been, or is planned to be, installed at nearly all of the newer (built in the 1980's) MEC FeCr smelters: the Greece smelter, the major expansion at the Elazig smelter in Turkey, the Ferrochrome Philippines smelter, and the Bamnipal and Choudwar smelters in India.

The INMETCO process was initially developed in the late 1970's by International Metals Reclamation Company Inc. (INMETCO), a subsidiary of INCO of Canada, and installed in 1978 at a plant in Ellwood City, PA. The Ellwood City plant uses a rotary hearth furnace to preheat/reduce waste metal oxides with coal as the reductant. The sponge metal is then fed to a submerged electric arc furnace for smelting (*47*). As of 1989, the worldwide licensing rights to the process had been obtained by Mannesmann Demag of the Federal Republic of Germany and work had been conducted on its utility in prereducing chromite. As in the SRC process, the chromite and the coal reductant are mixed together in the green pellets; however, the pellets are not sintered (hardened) before entering the rotary hearth furnace. The pellets are then heated through progressively higher temperatures in the rotary hearth furnace to the desired level of prereduction before feeding to the electric arc furnace. As of 1989, no commercial plant has been constructed to use this process for chromite prereduction.

Besides the three pelletizing/prereduction methods just mentioned, there are two additional processes that do not require that the chromite fines/concentrates be pelletized. In both of these processes, the chromite fines/concentrates are fed directly into the process.

The first of these processes is the use of plasma arc furnaces, now in production at Malmo, Sweden; at Middelburg Steel's Krugersdorp smelter in South Africa; and in the pilot plant development stage at Macalloy's smelter in the United States. The second process is the Krupp-CODIR prereduction process, which involves the prereduction of chromite fines/concentrates with coals as the reductants. The Krupp-CODIR process is now in development on a commercial scale at Middelburg Steel's smelter in Middelburg, South Africa.

In plasma arc smelting for the production of high-C FeCr, the South African and Swedish approaches have been radically different. In South Africa, the furnace (at 16-MV·A transformer capacity in 1988 and being stepped up to 40 MV·A by 1990) contains a single 0.56-m-diameter graphite electrode with an axial hole through its middle. The charge of fine materials (chromite, reductants, and other raw materials) is fed directly through the hole in the electrode along with a continuous feed of nitrogen to stabilize the plasma (*48*). Reduction and melting occur in an open molten bath between the electrode and a copper plate at the bottom of the furnace, which act as the cathode and anode, respectively. At the 40-MV·A transformer capacity, this plasma arc furnace is expected to be capable of producing about 45,000 mtpy of high-C FeCr with Cr recoveries greater than 90 pct.

At the Malmo, Sweden, operation, there are two identical "shaft" furnaces, each planned for a full capacity of about 40,000 mtpy of high-C FeCr. Each furnace is equipped with four 6- to 7-MW plasma generators. The generators produce an electric current through gas that has been blown through the generators. This, in turn, forms an arc directly in front of the generators that acts as the "reaction zone" where reduction and melting take place instantaneously. Fine coal, chromite fines/concentrates, and silica sand are reduced to very fine sizes in an attrition mill and then injected directly into the "reaction zone." Lump coke, limestone, and other raw materials, including lump chromite ore, are fed into the top of the shaft furnace and heated by the generators (*49*).

In 1988, the Malmo operation produced 31,383 mt of charge chrome (high-C FeCr) and the company planned to have a total plant use of over 90 pct by the year 1990. The company reported a total recovery of 92.5 pct based on FeCr cast in ingots and skulls in the ladles (*50*).

A major advantage that the plasma arc methods have over any of the other methods discussed in this section is the capability to produce a much wider range of possible alloy compositions. In plasma arc smelting there is better control of the nitrogen content in the alloy, and the sulfur and phosphorus contents in the alloy can be taken to much lower levels. There is also a more rapid response time in changing the smelting conditions and greater flexibility in process control. However, the advantages of more rapid response time and greater flexibility also require much stricter control measures that can be enforced rapidly (*48*).

The Krupp-CODIR process is a direct reduction process originally developed by Krupp Industrietechnologie of the Federal Republic of Germany for the direct reduction of iron ores. At the suggestion of certain South African companies, Krupp began pilot plant tests in about 1983 on the adaption of their process to the prereduction of chromite fines/concentrates.

In this process, as developed by 1987-88, chromite ore fines or concentrates, along with minus-25-mm reducing coal and silica sand, are introduced to the feed end of an 80-m-long rotary kiln through a hot cyclone. Throughout the prereduction stage, additional coal for further reduction and temperature control is distributed into the kiln through its burner end by the use of a nitrogen fed "slinger." After a residence time of 9 to 10 hours and exposure to maximum temperatures of 1450° C to 1500° C, the "pasty" agglomerate is discharged into a cooling drum, and dolomite is added to bring the "paste" temperature down to 800° C for charging straight into the melting/electric arc furnace.

The goals of using this prereduction method are (1) to obtain Cr prereduction levels of 90 to 95 pct, as compared to the 55 to 75 pct being attained with the SRC process, further decreasing the electrical consumption of the electric arc furnace and (2) to use lower cost coals as the reductant in place of metallurgical coke. However, the electrical consumption in the electric arc smelting stage will depend on the degree of Cr reduction in the kiln; 90 to 95 pct Cr prereduction was only a stated goal as of 1988. In fact, Middelburg Steel indicated that, based on their tests, West Bushveld Complex chromites gave 15 pct more Cr reduction than East Bushveld Complex chromites and that the particle size of the chromite feed does play a major role in the amount of Cr reduction in the Krupp-CODIR process (*51*).

All of the five processes just discussed have one result in common. This common aspect is that actual or expected recoveries of Cr from the treatment of chromite fines and concentrates are all very high, with four of the five attaining, or expected to achieve, over 90 pct. The exception is the Outokumpu Oy process, which achieves about 86 pct recovery from the smelting of pellets. It is also of note that, except for the Outokumpu Oy and SRC processes, all of these processes substitute lower cost reductants, either completely or to a high degree, for more expensive metallurgical coke.

When considered as a group, the electrical consumptions and the subsequent costs of electricity in producing FeCr for each of the five processes are varied. Table C-1 presents total, as well as furnace, electrical power consumptions (per mt FeCr) for the Outokumpu Oy, SRC, and Krupp-CODIR processes and for conventional smelting. The table clearly shows the rather drastic decline in furnace (and total) consumptions expected as higher degrees of Cr prereduction are attained.

Table C-1.—Comparison of typical electrical power consumptions for selected high-C FeCr smelting processes

Technology/process	Pct of Cr prereduction	Electrical power consumptions (kW·h/mt FeCr)	
		Furnace	Total
Conventional	None	3,800-4,200	3,800-4,200
Outokumpu Oy	About 40	[1]2,800-2,900	3,100-3,200
SRC	55 to 60	[1]2,200	2,600-2,700
SRC	70 to 75	[1]1,700	2,100-2,200
Krupp-CODIR	90 to 95	[2]1,100	1,400-1,500

[1]100 pct preheated pellet feed; 100 pct hot charging.
[2]100 pct hot charging.

Conversely, the plasma arc techniques are indicated to consume more electrical power than the conventional method. For example, SwedeChrome's initial literature estimated total power consumption of 4,400 kW·h/mt FeCr (*49*), and in 1986 the power consumption of the 16-MV·A furnace at Krugersdorp was said to be between 4,000 and 4,500 kW·h/mt FeCr (*52*).

Each of these plasma arc operations have mitigating aspects to these high power consumptions. First, as has been noted, the Krugersdorp furnace's transformer capacity is being increased to 40 MV·A by 1990, which should result in improved electrical efficiency. Also, the South Africans have not, as yet, attempted to preheat the charge prior to its introduction through the electrode.

On the other hand, the SwedeChrome smelter was sited very close to the city of Malmo, and an extensive gas recovery system was installed at the smelter. As a result, through the sales of recovered gas and of the thermal energy in the cooling water to the local district heating company, the company claims that in 1988 they provided 13 pct of the total distributed energy to the city of Malmo. Further, it is claimed that this "sold" energy was equivalent to an electrical consumption of 4,537 kW·h/mt FeCr (*50*).

The SRC and the Outokumpu Oy processes are fairly old and well-established processes and hence have no major operational questions or problems. However, both plasma arc methods and the Krupp-CODIR process are relatively new and carry their own set of specific operational "question marks."

The major problem in the SwedeChrome PLASMACHROME method appears to be the extremely close tolerances required for the very fine material that is introduced directly into the "reaction zone." This may be the reason why, as of the end of 1988, the company had used only chromite concentrates as feed material in the injection system, not chromite fines ore. In addition, there have been abrasion problems with the attrition mills and in the pneumatic conveying system from the attrition mills to the shaft furnaces (*50*).

The South African plasma arc method appears to have fewer operational difficulties. However, there is presently a physical limit of 1 meter as the maximum diameter of the hollow electrode. Beyond that size, cracking of the electrode occurs (*53*).

The Krupp-CODIR process for chromite prereduction has not yet been operated at a commercial scale. Middelburg Steel of South Africa is now in the process of constructing the first commercial-size kiln. As of late 1988, the company was mainly concerned about two aspects: (1) how well the refractories will tolerate the extreme kiln conditions and (2) management of the buildup of unreacted materials in a "ring" around the kiln (*51*). Another concern is simply how well a "pasty" agglomerate can be made to travel 80 m in a rotary kiln. The following are indicated to be additional aspects to consider in regard to this process:

(1) Certain qualities of the coals used in the kiln are very critical to overall performance. The ash-fusion factors of the coals are most critical with a high-fusion temperature required. Also, the reducing coals should be fairly hard (anthracitic) with bulk densities between 0.75 and 0.80, and the coals must be low in phosphorus and sulfur.

(2) The sizing of the chromite fines/concentrate feed is thought to be an important factor in the degrees of Cr reduction achieved in the kiln. As of 1988, the size range of chromite feed for optimum use was said to be between 1.0 and 1.5 mm; the chromite particles should not be greater than 1.5 mm, but can be less than 1.0 mm (*51*).

This section of the report has attempted to describe all the various approaches now available as of the late 1980's for the production of high-C FeCr. It has not discussed the possible future development of steelmaking procedures that would use chromite ore directly instead of the intermediate FeCr product. Another future trend in the industry could be the increased use of ladle refinement outside of the furnaces to produce more specific high-C FeCr products (*54*).

The decision as to which process is most applicable for a given situation depends on consideration of each of the following factors:

(1) The availability and cost of power supplies.

(2) The amounts, qualities, and costs of the available chromite as well as the amount available in the form of fines or concentrate products.

(3) The existence of a nearby outlet for the sale of any excess energy that is recoverable from the smelting process.

(4) The relative availability, specific qualities, and costs of coals and other reductants in relation to coke.

(5) The decision to serve the FeCr market as a "commodity" FeCr producer or as a "customized" FeCr producer.

Beyond these considerations, these newer processes require considerably more capital than the conventional method and also require a certain minimum level of technical capability in the available work force.

Finally, despite the development of these new FeCr smelting methods, it is significant that the vast majority of the new smelting capacity added in South Africa from 1987 through 1991 will still use conventional smelting technology. Exceptions are the fairly small increase to the Krugersdorp plasma arc furnace and the Krupp-CODIR capacity (120,000 mtpy FeCr) being added at Middelburg Steel.

LOW-CARBON AND MEDIUM-CARBON FERROCHROMIUM AND FERROCHROMIUM-SILICON

This smelting technology discussion of low-C FeCr, medium-C FeCr (or intermediate-C FeCr), and ferrochromium-silicon production methods is intended to provide a broad overview and to relate this to specific aspects in this study's methodology regarding these Cr ferroalloys. It is noted at the start that only two of the processes described in this section are newly developed since the early 1970's. Rather, this portion of the Cr ferroalloys industry tends to constantly modify the same basic process rather than to develop new processes.

Table C-2 provides a summary of typical specifications for FeCr products as of the 1980's. As shown, the C contents of charge chromium and high-C FeCr products (both included in this study's high-C FeCr category) range from 4 to 8 pct while the medium-C FeCr product range is from 1 to 4 pct C, and the low-C FeCr products are all less than 0.5 pct C.

The range of C contents of 1 to 4 pct desired for the medium-C FeCr products can be achieved by simply "blowing-down" the C content in a high-C FeCr product via oxygen refining in top- or bottom-blown converters. It is possible, through the use of multiple stages of oxygen refining, to "blow down" the C contents of high-C FeCr products to the less than 0.5 pct C contents shown in table C-2 for low-C FeCr. However, this is an expensive procedure compared to the silicothermic processes to be described in the following paragraphs.

Ferrochromium-silicon is both an intermediate product used in making low-C FeCr and a final saleable product for charging in steelmaking and other metallurgical uses. It can be produced using three different methods.

Table C-2.—Typical Cr and C specifications in ferrochromium products

FeCr product	Cr content (pct)	C content (pct)
Charge chromium	50-55	8.0 (maximum).
High-C ferrochromium	60-70	4-6.
Do.	58-65	4-6.
Do.	60-70	6-8.
Medium-C ferrochromium	65-75	1.0 (maximum).
Do.	65-75	1.5 (maximum).
Do.	65-75	2.0 (maximum).
Do.	65-75	2-4.
Low-C ferrochromium	60-75	0.05, 0.10 (maximum).
Do.	65-75	0.015 (maximum).
Do.	65-75	0.025 (maximum).
Do.	65-75	0.05 (maximum).
Do.	65-75	0.10 (maximum).
Do.	65-75	0.50 (maximum).

Source: (*55*).

The most common method of producing ferrochromium-silicon is a one-stage smelting in an electric arc furnace of a charge composed of chromite ore (preferably lump ore), silica, and coke or some other reductant. Another method uses a two-stage smelting where an initial high-C FeCr product from smelting is then resmelted with silica and coke in a second furnace. The third method (*44*) was just an experimental method in the early 1970's and has not seen major acceptance over the years. It involves the addition of either FeSi (ferrosilicon) or silicon metal to a molten high-C FeCr, preferably in a ladle.

The earliest common process for making low-C FeCr was the "Triplex" (or so-called "Swedish" process), which involved first smelting to high-C FeCr, smelting the high-C FeCr with SiO_2 to produce a high-Cr, high-Si, low-C alloy and mixing this alloy with a chromite/lime slag produced in a third furnace. This process was superseded by the Perrin (also called the Ugine) process, which was developed during the 1930's and has become—with variations—the most commonly used method.

The basic Perrin process is a two-furnace method (two-smelting-stage) where ferrochromium-silicon is produced in a submerged electric arc furnace and chromite and lime are smelted in an open arc furnace to produce a Cr-rich slag. The ferrochromium-silicon is further refined in a ladle along with an "intermediate" slag from a second refining ladle. The resulting products from this first ladle are an "intermediate" alloy and a final "waste" slag. Meanwhile, in the second refining ladle the Cr-rich slag produced in the open arc furnace is mixed with the intermediate alloy from the first refining ladle. The resulting products from this second refining ladle are the intermediate slag, which is used in the first ladle, and the final low-C FeCr alloy product.

One variation of the Perrin process is called the "Duplex" process. In this variation the molten Cr-rich slag from an open-top tilting melt furnace is reacted with lump ferrochromium-silicon in two steps, but in the same ladle rather than two separate ladles (*44*).

At the West German smelter, which has been producing low-C FeCr since the 1930's, the company uses a method requiring only one smelting stage rather than the two needed in the Perrin process. Details on the process, as practiced by this company, are sketchy, but it is probably similar to the "single stage reduction with ferrosilicon and aluminoferrosilicon" described by Bleloch (*56*).

At the Gweru smelter in Zimbabwe the company followed the Perrin process nearly identically up until 1978, at which time they developed a "single-stage" operation (*57*). The new procedure is similar to the Duplex process. In this new procedure the molten slag is reacted directly with crushed solid ferrochromium-silicon fines as it is poured into a ladle. Preheated, but unmelted, lime and chromite are added at the same time for temperature control. When the ladle is full it is decanted into a second ladle, and the process is repeated to give a total of six decantings. Even if referred to as a single-stage operation, this method still requires two smeltings.

All of the low-C FeCr processes described so far are "silicothermic" methods in which silica is the driver of the reactions. There is one other nonsilicothermic process that should be mentioned. This is the Simplex process in which finely crushed high-C FeCr is mixed with a solid metal oxide, such as oxidized FeCr powder, or with high-purity silica sand. The mixture is then briquetted, dried, and heated in a vacuum to 1370° C at a programmed rate to produce FeCr with C grades as low as 0.008 pct.

The preceding discussion has described all of the common methods with which low- and medium-C FeCr and ferrochromium-silicon ferroalloys have been and are produced. The following paragraphs relate how these methods have been addressed in this study and provide specific details regarding the analysis of these ferroalloy products.

In the availability portion of this study, a total of seven MEC, low-C FeCr producing smelters were subjected to detailed mass balances, detailed cost estimates, and balancing with respect to specific chromite properties and units. Two of these smelters are in South Africa, one is in Zimbabwe, two are in India, and one each is in Brazil and Turkey. The seven smelters have an estimated total production capacity of 150,000 to 155,000 mtpy of low-C FeCr as of the 1986-89 period.

As analyzed, only the Zimbabwe smelter had a high enough level of production to be able to export ferrochromium-silicon. The ferrochromium-silicon production levels at the other six MEC smelters were assumed to be only sufficient to meet their needs for production of low-C FeCr products.

For detailed costing and mass-balancing, the seven MEC smelters were analyzed as using the basic Perrin process in which ferrochromium-silicon and chromite/lime slag are produced in separate furnaces and then reacted in ladles to produce low-C FeCr. In terms of ferrochromium-silicon production, six of the seven smelters were analyzed as using the single smelting method where lump (or briquetted) chromite, coke, and SiO_2 are smelted in an electric arc furnace. Only the Brazilian smelter was mass-balanced and costed on the basis of first producing high-C FeCr in one furnace and then smelting the high-C FeCr with SiO_2 and coke in a separate furnace to produce ferrochromium-silicon.

Power consumptions used in the study for costing were very similar from country to country at around 5,750 kW·h/mt ferrochromium-silicon and about 1,350 to 1,400 kW·h/mt slag. With consumptions of 0.65 mt ferrochromium-silicon/mt low-C FeCr and 3.2 mt slag/mt low-C FeCr, these power consumptions would equate to about 8,150 kW·h/mt low-C FeCr.

Recoveries were assumed at 100 pct for the chromite fines used in making the slag, 80 pct in smelting to ferrochromium-silicon, and 80 to 85 pct in the ladling procedure. In general, the combination of these three recovery values would result in an overall recovery of about 76 pct of the Cr in chromite feed into final low-C FeCr products.

The chromium network flow market model added an additional 115,000 mtpy of existing low-C FeCr capacity for the MEC's of Japan, the Federal Republic of Germany, the United States, and Yugoslavia. Another 175,000 mtpy of existing low-C FeCr capacity was added for the CPEC's of the U.S.S.R. and the People's Republic of China. The model also included a total of about 62,000 mtpy of potential new low-C FeCr production by 1993-94 from a proposed Canadian smelter and a hypothetical expansion in Zimbabwe.

The smelter evaluations for Japan, the Federal Republic of Germany, the United States, Yugoslavia, and Canada low-C FeCr production capacity in the chromium market model are less detailed and more generalized than those made for the availability study. No cost estimates were made for low-C FeCr production in the U.S.S.R. and China, while the proposed Zimbabwe expansion used the same technical and cost estimates made for Zimbabwe in the availability study.

APPENDIX D.—EXCHANGE RATES AND COST INDEX FACTORS

The Bureau's cost indexation system was used to update cost estimates, as necessary, to a base date of January 1989, for this report. The index system comprises updating factors for 12 separate components of mining and processing costs (e.g., mining labor, mining equipment, diesel fuel) for foreign countries and 15 components for the United States. The index values for each component in each country take into account whether the expenditure is in local or foreign currency and the traditional sources for needed imports, such as machinery. A time series of exchange rates, also part of the index system, is used to translate the cost index values developed in local currencies into values expressed as U.S. dollars. This index system is used to measure the differing rates of change in the costs of factor inputs to the mining industry of foreign countries and to quantify the foreign exchange bias that enters into cost conversions from a local to a base currency.

The cost index system allows the Bureau to monitor and evaluate the change in mining costs through time on an individual factor basis as well as on an operating, capital, or total cost basis. It can be used to determine the degree to which the competitiveness of the mining industry in different countries is influenced by the changing value of factor input costs and the host country currency. The indexation system as it applies to South Africa is discussed in detail below.

The major chromite producing country, South Africa, is of particular note, since it has experienced large exchange rate fluctuations during the 1980's. South African price indexes are designed to reflect price changes within South Africa. Domestic prices are influenced by domestic conditions, by prices in countries with which it trades, and by exchange rates. When sales transactions are based on one currency and production costs are incurred primarily in a second currency, severe economic dislocations can occur if there is a significant variation in the relative values of the two currencies. For example, a chromite producer may sell in terms of U.S. dollars but pay for labor and materials largely in South African rands. Generally, if a currency is depreciating, local unit costs will rise, tending to reduce the overall impact. Furthermore, a major part of a producer's purchases may be made in U.S. dollars. Thus, the net impact of exchange rate movements is determined by the proportion of production costs incurred in the local currency and the ability of the company to resist unit cost increases in these items in the face of a depreciating currency (*58*). If the South African rand is devalued relative to the U.S. dollar and there are no unit cost increases, the mining firm benefits substantially from foreign exchange rates.

Cost index and exchange rate trends for South Africa during the 1980's are shown in table D-1 and figure D-1. As shown in the table, South Africa has experienced fluctuations in the exchange ratio over the 1984 to 1988 period.[1]

During this time period, in terms of South African rands, the index for mining wage rates has increased from 399.7 in 1984 to 606.4 in 1988. The index for electric power has increased dramatically from 475.4 in 1984 to 930.0 in 1988. However, of particular note is that the change in inflation appears to have been offset by a simultaneous change in the value of the currency (see figure D-1). This can be seen in table D-1, since even though the local currency indexes reflect the high inflation, the U.S. currency indexes are generally level or declining. As shown in the table, in terms of U.S. currency the mining wage index actually decreased from 203.4 in 1984 to 196.4 in 1988. The electricity index increased from 242.0 in 1984 to 301.2 in 1988, which is not as dramatic an increase as when shown in terms of the local currency. As a result, the overall South African production costs, in U.S. dollar terms, remain relatively unchanged from 1985 to 1989. It is estimated that during this time period, overall production costs for ferroalloys increased by only 3.3 pct in U.S. dollar terms, although they increased approximately 60 pct when stated in rands.

This 3.3 pct production cost increase was determined by updating the costs from January 1985 dollars to January 1989 dollars. The costs for individual components of production cost (labor, electricity, etc.) were all updated to January 1989 (average 1988) terms by using the formula shown below, which uses labor rates in South Africa as the example:

$$A * B * C * D = E$$

where A = 1984 South Africa labor rate (U.S. dollars),

B = 1984 exchange rate (rands per U.S. dollar),

C = 1988 South Africa labor index divided by 1984 South Africa labor index,

D = 1988 exchange rate (U.S. dollars per rand),

and E = 1988 South Africa labor rate (U.S. dollars).

[1]In the methodology of this study, the average 1984 exchange rate is taken to represent that of January 1985, and the average 1988 exchange rate is taken to represent that of January 1989.

Table D-1.—Selected South African cost indexes, 1980-88 (1975 = 100)

Year	Mine wage[1]	Fuel[2]	Transport[3]	Electric[4]	Exchange rate[5]
		LOCAL CURRENCY INDEX			
1980	203.5	334.3	155.4	261.8	0.778
1981	246.5	366.3	178.0	295.3	.870
1982	268.8	422.8	201.4	356.0	1.082
1983	306.0	422.1	245.4	427.8	1.112
1984	399.7	399.4	239.9	475.4	1.438
1985	397.7	501.5	276.0	566.5	2.191
1986	445.1	543.3	305.6	753.9	2.268
1987	539.8	491.7	326.7	841.3	2.035
1988	606.4	499.8	351.0	930.0	2.260

Year	Mine wage[1]	Fuel[2]	Transport[3]	Electric[4]	Exchange rate[6]
		U.S. CURRENCY INDEX			
1980	191.4	314.5	146.2	246.3	0.940874
1981	207.4	308.2	149.8	248.5	.841379
1982	181.9	286.0	136.2	240.8	.676524
1983	201.4	277.9	161.5	281.6	.658273
1984	203.4	203.3	122.1	242.0	.509040
1985	132.8	167.5	92.2	189.2	.334094
1986	143.6	175.3	98.6	243.3	.322751
1987	194.2	176.8	117.5	302.6	.359705
1988	196.4	161.8	113.7	301.2	.323893

[1]Mine and plant labor; includes skilled, unskilled, local, and expatriate labor.
[2]Refined fuel products weighted toward diesel.
[3]Transport based on an assessment of the country's normal freight transport network relevant to the mineral industry. Includes rail, truck, barge, and pipeline.
[4]Standard industrial.
[5]National currency per United States dollar.
[6]1975 exchange rate divided by current year exchange rate.

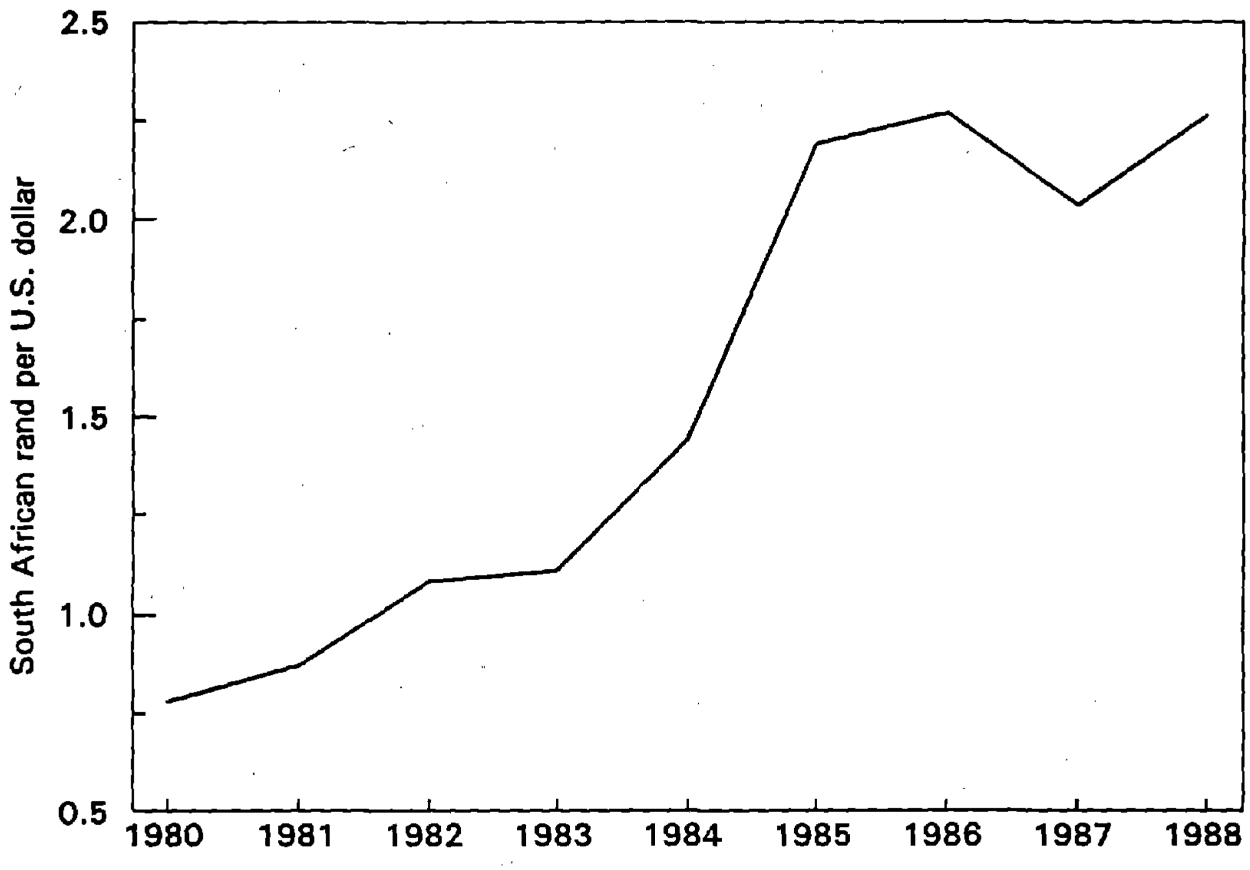

Figure D-1.—Value of the South African rand per U.S. dollar, 1980-88.

The operating costs of underground mining, surface mining, beneficiation, and smelting and the cost of ground transportation in South Africa were updated separately. In each case, the appropriate updated factors were weighted according to their use in the process and combined to give a single update number. When the January 1985 (average 1984) costs are compared to the updated January 1989 (average 1988) costs in the two currencies, the percentage changes are striking. Underground mining costs increased 62 pct in rands and 2.8 pct in dollars; surface mining costs increased 56 pct in rands, but decreased by 1 pct in dollars; beneficiation costs increased 61 pct in rands and 2.7 pct in dollars; transportation costs increased 46 pct in rands, but decreased by 7 pct in dollars; and smelting costs (for which electricity is a major component) increased dramatically, 87 pct in rands and 18.8 pct in dollars. The average change in costs for all five phases of producing FeCr for export calculates to a 62 pct increase in terms of rands, corresponding to a 3.3 pct increase in dollars.

During this time period, the exchange rate changed by 57 pct (1.438 rands per U.S. dollar in 1984 to 2.260 rands per U.S. dollar in 1988). This devaluation of the currency in international monetary markets suggests that the change in inflation is being offset by a somewhat similar change in the value of currency. This is not inconsistent with the statement by the International Monetary Fund that "the authorities of South Africa . . . intervene in the exchange market to affect the rates quoted by the commercial banks for the 'commercial' rand. The principal intervention currency is the U.S. dollar" (*59*).

Therefore, in the end, the costs of production for South Africa do not change significantly when they are updated from January 1985 dollars to January 1989 dollars because the domestic inflation is being offset by a simultaneous currency devaluation. It is believed, however, that this practice of devaluing the local currency (whether intentional or inadvertent) cannot continue indefinitely. If the local currency ceases its devaluation against the U.S. dollar and local inflation increases continue in the double digit per year range, South African production costs must eventually rise in terms of U.S. dollars.

APPENDIX E.—DEMAND METHODOLOGY AND RESULTS

In the chromium model, demand forecasts were required for six individual end-use chromium product markets: high-C FeCr, low-C FeCr, ferrochromium-silicon, refractory chromite, foundry sand chromite, and SBE, which represents chromium chemical usage. Demand for chromium in the form of chromium metal or in medium-C (also referred to as intermediate-C) FeCr was not included.[1]

The discussion of demand has been divided into two parts: an introduction to the forecasting method and a summarization, by chromium product and by selected years, of the demand values used in the model. Readers interested in the final demand values should proceed directly to the section entitled "Demand Results."

METHODOLOGY

Demand for a product can be modeled as a function of the price of that product, the price of products that are used concurrently (compliments), and the price of products that can be used instead (substitutes). For example, nickel is a compliment of chromium in stainless steel production, whereas stainless steel scrap is a partial substitute for virgin chromium in the same production process. Other factors can influence demand as well, including consumers' preferences and expectations, prices in general, consumers' wealth, and other measures of the overall state of the economy. Once data on these factors (production, prices, preferences, etc.) have been gathered, economic, econometric, and mathematical methods can be used to analyze the information and interpret the relationships.

For this analysis, a simpler approach has been taken because of lack of data to support conventional economic evaluation. The intensity of use (IU) technique has been used to estimate chromium ferroalloy consumption (rather than demand) over time for three major MEC consuming regions—North America, Asia, and Western Europe. Expert judgment was used in estimating consumption of chromium ferroalloys in other countries and regions as well as in estimating consumption of chromium for chemical, refractory, and foundry sand uses.

The IU technique has been widely used by mineral economists in recent years to study metal demand issues. This theory of metal use is based on the assumption that the use of a metal depends primarily on the level of national income, the proportion of national income that is spent on final goods containing the metal in question, and the amount of the metal contained in final goods (*60*).

National income, or the volume of economic activity, is measured by the gross domestic product (GDP) of the region of interest. In using GDP as one of the factors effecting chromium demand, the assumption is made that inflation, interest rates, and political policies are taken into account in the model. These issues are in the realm of macroeconomics and are not within the scope of this paper. Therefore, the determinants of GDP will be considered purely exogenous here, and GDP will be forecast using trend extrapolation only.

The second assumption is that the portion of consumer income spent on the final good of interest, called the product composition of income (PCI), reflects consumer tastes and preferences. This includes the selection and characteristics of goods and services, relative prices, consumer wealth, and all other factors effecting consumers' decisions.

The third assumption made in this theory involves the amount of the metal used in making the final good, referred to as the material composition of product (MCP). The assumption is that the MCP describes the current state of product manufacturing technology and its metal requirements. This relationship could change over time as lower cost inputs are found or as the final product itself is replaced by more cost-efficient materials. Since these innovations are at least partially dependent on relative input costs, a further assumption must be made: that firms are behaving rationally and that they will act to operate as efficiently as possible and minimize costs in the long run.

IU is defined as the metric tons of metal consumed in a region per dollar of gross domestic income and is the product of MCP and PCI. When IU is multiplied by GDP, an estimate of the total mt of metal consumed in the region is determined. The IU approach has been applied only to ferrochromium demand because this product group is the single largest consumer of chromium and also because it is the only product group for which reliable production and price data are available.

[1]Although critically important to the superalloys industry, the chromium metal market is relatively small in the United States and little data are available on many aspects of this market. Medium-C FeCr, defined as those products with C grades ranging from 0.5 pct to 4.0 pct C, has only recently become a distinct market and also is very small. Because of relative market size and the lack of data, these two chromium products were not addressed specifically in either the availability study or the network flow model study.

The mathematical form of IU is shown below, followed by a discussion of each component of chromium demand as forecast with IU.

$$D_t = IU_t * GDP_t \quad \text{(E-1)}$$

$$IU_t = PCI_t * MCP_t \quad \text{(E-2)}$$

$$PCI_t = P_{it}/GDP_t \quad \text{(E-3)}$$

$$MCP_t = M_{it}/P_{it} \quad \text{(E-4)}$$

where D = the consumption/demand of Cr in ferrochromium (in mt),

IU = the intensity of use of ferrochromium,

GDP = the gross domestic product for the region in question,

PCI = the product composition of income; the portion of GDP that is spent on stainless steel, the product group containing ferrochromium,

P_i = the total value of stainless steel production, in dollars,

MCP = the material composition of product; Cr in ferrochromium per dollar of stainless steel produced,

and M_i = the metric tons of Cr in ferrochromium used in making stainless steel.

The ferrochromium IU model depicts demand for the MEC's by dividing the world into three regions. These regions are North America, Western Europe, and Asia. The categories are not exhaustive; ferrochromium consumption in MEC's not included in any of the three regions will be addressed later in this discussion. Gross domestic product was calculated for each of the three regions. The nominal values were obtained from the World Bank publication "International Financial Statistics" (*61*) then converted to 1980 U.S. dollars.

To provide differing perspectives, two different GDP growth scenarios were considered. First, a pessimistic forecast was made that real regional gross domestic products would grow at an average annual rate of only 1 pct per year worldwide. A second forecast was more optimistic, that real regional GDP would continue to grow at the average annual growth rate reported by the International Monetary Fund for the 1981-89 period (*62*). In this second forecast, regional growth rates used were North America, 2.89 pct/yr; Western Europe, 2.22 pct/yr; and Asia, 6.94 pct/yr. Estimated future GDP can be calculated by applying the estimated growth rates to the reported base year GDP level.

The product composition of income (PCI) is the portion of GDP that is spent on the product group containing the metal of interest (equation E-3). According to Tilton (*63*), the PCI is a measure of relative consumer preference for a product and is determined by the desired proportion of their income that consumers choose to spend on the item. In this case, stainless steel was chosen as the product group most representative of ferrochromium demand. To calculate PCI, P_i, the value of stainless steel production, must be determined. P_i is the quantity of stainless steel produced times its price and was calculated using stainless steel production figures (table E-1) and stainless steel prices (table E-2). The price time series was obtained from selected publications of the U.S. International Trade Commission (*64-66*), converted to constant 1980 U.S. dollars. PCI, mathematically defined as P_i/GDP, was then calculated.

When plotted against time, PCI suggests that North America is purchasing relatively less stainless steel over time (fig. E-1) in terms of the total dollar value of purchases made. Western Europe and Asia, however, appear to have a slowly rising product composition of income, as shown in figures E-2 and E-3. One explanation for a rising PCI is that stainless steel production is growing at a faster rate than the economy (GDP) is growing. This phenomenon of rapidly expanding stainless steel production is evident from table E-1.

The material composition of product (MCP) is defined as the amount of chromium actually used to produce a given dollar volume for stainless steel. It is calculated by dividing the physical amount of Cr in ferrochromium used in making stainless steel (M_i) by the value of stainless steel production (P_i). To determine M_i, the amount of stainless steel produced is multiplied by the average chromium content in stainless steel. Stainless steel production figures used are those reported in table E-1. An estimate of average chromium content in all stainless steels produced was made, based on the following guidelines and published information on chromium consumption versus stainless steel production for various stainless steel producers worldwide.

Table E-1.—Western world production of stainless steel, 1978-87

(Thousand metric tons)

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Western Europe:										
Austria	74	77	79	71	74	68	78	68	48	54
Belgium	101	147	123	114	113	133	149	151	165	182
Finland	57	80	91	87	109	123	158	176	173	189
France	538	613	594	509	529	544	646	560	611	700
Germany, Federal Republic of	761	821	816	753	680	747	878	808	888	957
Italy	440	502	493	393	438	438	520	509	540	547
Spain	156	156	161	160	192	197	292	271	273	320
Sweden	360	418	379	330	329	372	441	435	436	455
United Kingdom	238	266	144	243	219	229	256	283	294	393
Yugoslavia	98	94	100	107	98	120	160	229	272	332
Total	2,823	3,174	2,980	2,767	2,781	2,971	3,578	3,490	3,700	4,129
Japan	1,978	2,190	2,217	1,862	2,121	2,230	2,595	2,638	2,570	2,882
U.S.A.	1,763	1,913	1,537	1,583	1,119	1,591	1,608	1,527	1,529	1,836
Other countries:										
Australia	14	14	15	16	14	18	24	34	40	49
Argentina	2	2	3	3	2	3	4	6	8	9
Brazil	46	45	47	51	46	57	76	109	129	157
Canada	25	24	25	27	24	30	40	58	69	84
India	50	48	51	55	50	61	82	117	139	170
Mexico	2	2	3	3	2	3	4	6	8	9
South Africa	34	33	35	37	34	42	56	80	95	116
South Korea	17	16	17	18	17	21	28	40	47	58
Taiwan	39	37	40	43	39	48	64	91	108	132
Total	229	221	236	253	228	283	378	541	643	784
Grand total	6,793	7,498	6,970	6,465	6,249	7,075	8,159	8,196	8,442	9,631

Source: World Stainless Steel Statistics (*67*).

Table E-2.—Stainless steel prices, 1980-88

(1980 U.S. dollars per metric ton)

Year	Price
1980	1,653
1981	1,508
1982	1,334
1983	1,276
1984	1,409
1985	1,236
1986	1,324
1987	1,387
1988	1,633

NOTE.—Prices compiled, then converted to constant dollars (*64-66*).

The most popular grade of stainless steel produced in 1986 (40 pct of total U.S. production of stainless and heat resisting steel) (*68*) was series 304, which contains 18 pct chromium. Series 409, the next most popular grade (14 pct of production), contains 12 pct chromium. For the IU demand calculations for these model runs it was estimated that the average amount of chromium contained in all stainless steels produced was 14 pct, hence M_i equals 14 pct of the total mt of stainless steel produced. This chromium consumption level is then divided by P_i (the value of stainless steel produced) to arrive at MCP.

As mentioned previously, MCP describes the current state of manufacturing technology and can be considered a measure of efficiency. This will change over time in response to technical innovations and substitutions by other materials. When the plots of MCP over time for all three regions are considered (figs. E-1 to E-3), there does not appear to be a trend allowing gradual savings of chromium in stainless steel production. There is no identifiable technologic shift away from chromium in stainless steel production, suggesting that currently there are no adequate substitutes for chromium in stainless steels. The results suggest that the amount of chromium consumed will be a function not of technical progress but of the consumer preference portion of the intensity of use relationship.

Now that PCI and MCP are known, the intensity of use (defined as PCI * MCP) can be calculated. According to Malenbaum (*69*), historical evidence in developed regions reveals declines in the intensity of metal use as GDP expands, while in developing countries the intensity of use increases as GDP expands. These tendencies suggest a general pattern in the graphical shape of an inverted U.

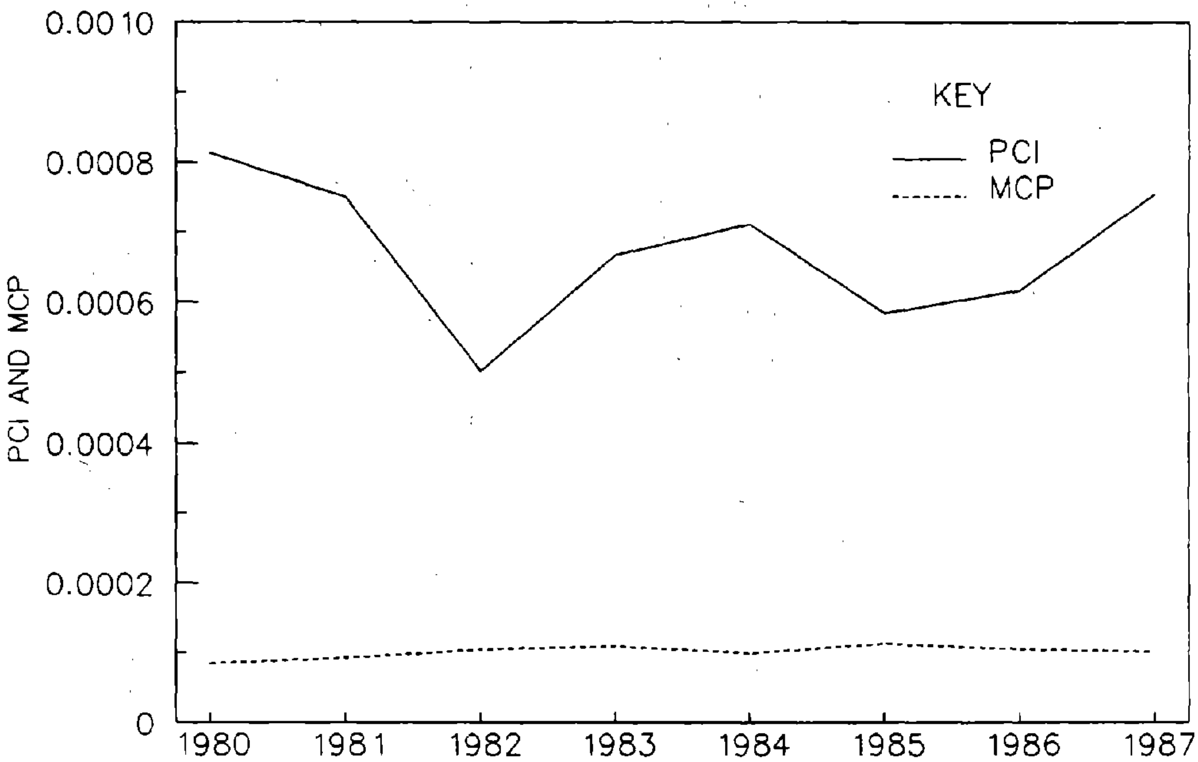

Figure E-1.—PCI and MCP versus time, North America.

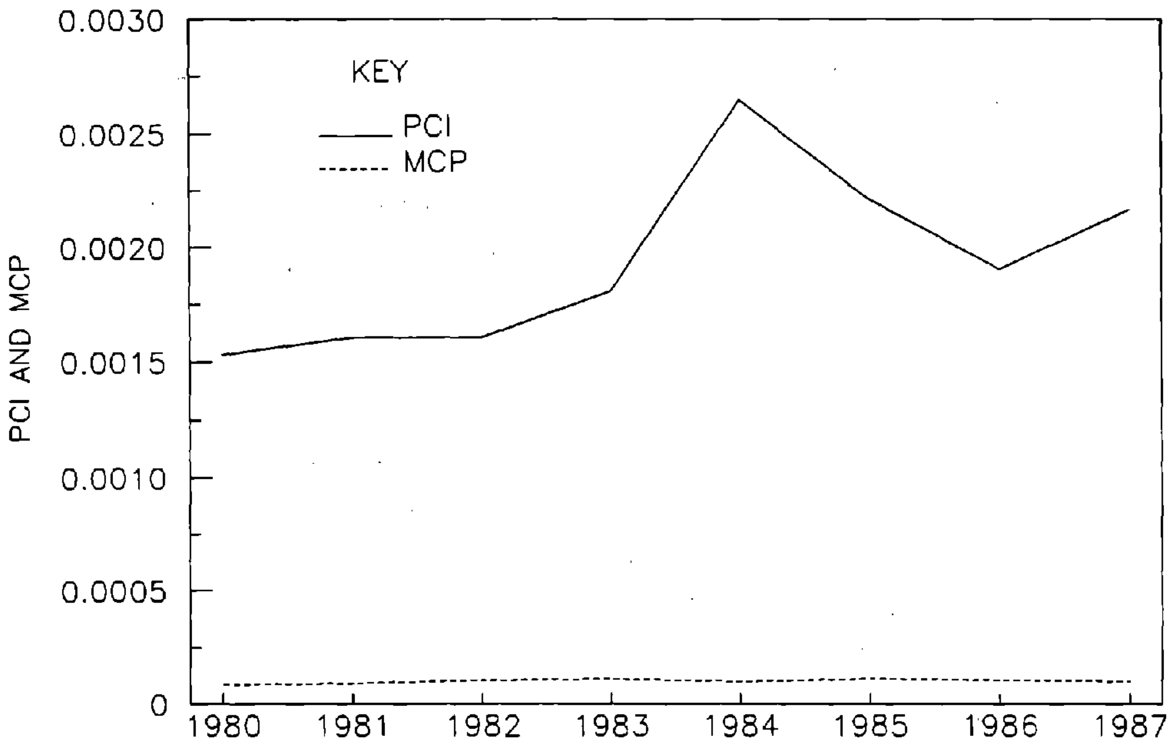

Figure E-2.—PCI and MCP versus time, Western Europe.

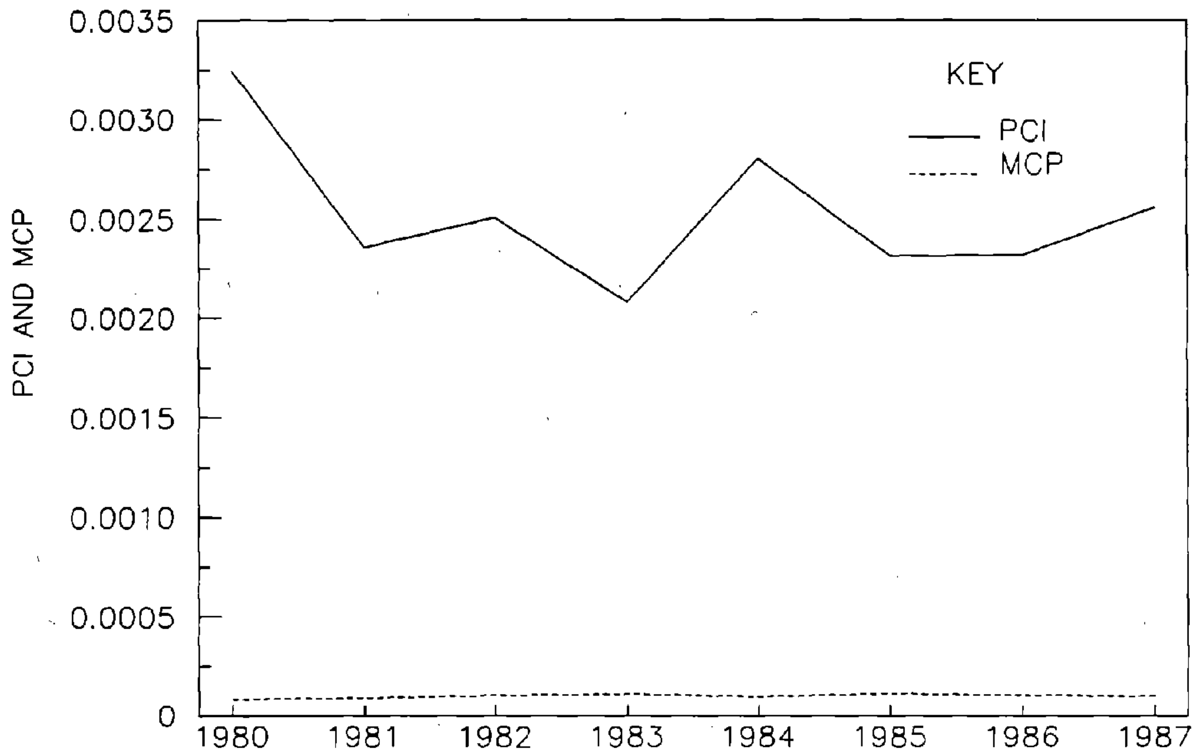

Figure E-3.—PCI and MCP versus time, Asia.

Initially as nations develop, they are material intensive; as the GDP level increases and the nation becomes more developed, a switch is made to a more service-oriented economy thus decreasing the intensity of use.

When the intensity of chromium use in North America is plotted over time[2] (fig. E-4), a relatively constant to very gradual decline in the intensity of use is suggested. One explanation for such a scenario is that for the North American region, of which the United States is the major component, the switchover from a material-intensive to a more service-oriented economy has begun to occur. If most of the switchover has already occurred, the rate of change in the IU should have decreased and be relatively constant. Brown's linear exponential smoothing technique was applied to the historic data, and the resultant equation was used to forecast future (1987-95) levels of IU for North America. The outcome was a relatively constant intensity of use.

Plotting the intensity of metal use for Western Europe against time (fig. E-5) shows an initial period of increasing intensity of use with the stainless steel industry growing at a rate faster than GDP. As the rate of growth tapers off (1984), the intensity of use starts to decline in a manner consistent with Malenbaum's hypothesis. Again using Brown's linear exponential smoothing, which was sensitive to the slowdown in the growth of the stainless steel industry in Europe, Western Europe was forecast to experience a slight decline in its intensity of chromium use in future periods.

The IU plot for Asia (fig. E-6) suggests a slight downward trend in the intensity of chromium use. Even though portions of Asia could be considered as developing regions for which an increasing IU would be expected, the majority of stainless steel production, and therefore chromium consumption, occurs in developed countries. Japan is by far the largest stainless steel producer in Asia. The results suggest a gradual downward trending IU forecast for Asia, extrapolated from historic IU levels via Brown's linear exponential smoothing.

When the forecast IU values for a region are multiplied by the estimated future GDP levels (two scenarios: 1 pct GDP growth and historical GDP growth) the resultant figures are the estimated chromium consumption by the stainless steel industry for that region. However, since these figures were estimated using the compositional basis of stainless steel (the amount of chromium present in the stainless steel that is produced), an adjustment must be made to account for the chromium lost in the production of the stainless steel. This melt-loss was estimated to be 15 pct. Therefore, the amount of chromium actually

[2]This plot could also be considered a plot of IU vs. GDP since GDP has increased over the time period and GDP is forecast to grow at a constant rate in future periods.

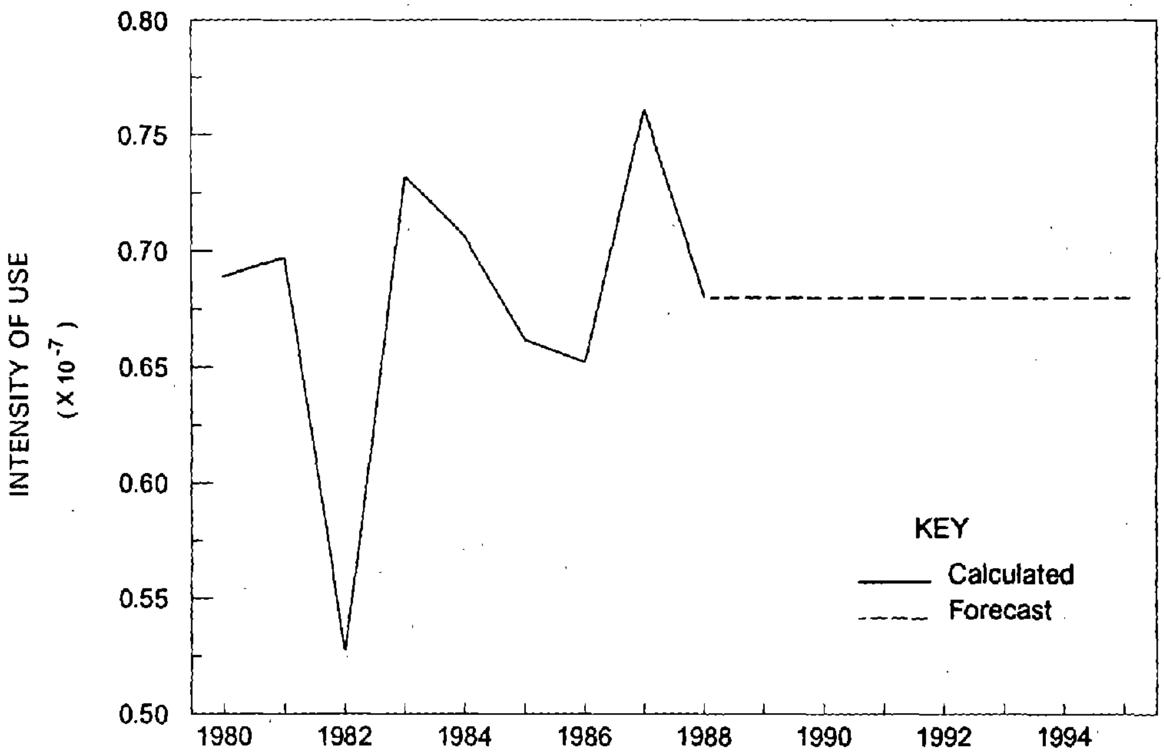

Figure E-4.—Intensity of chromium use in North America versus time.

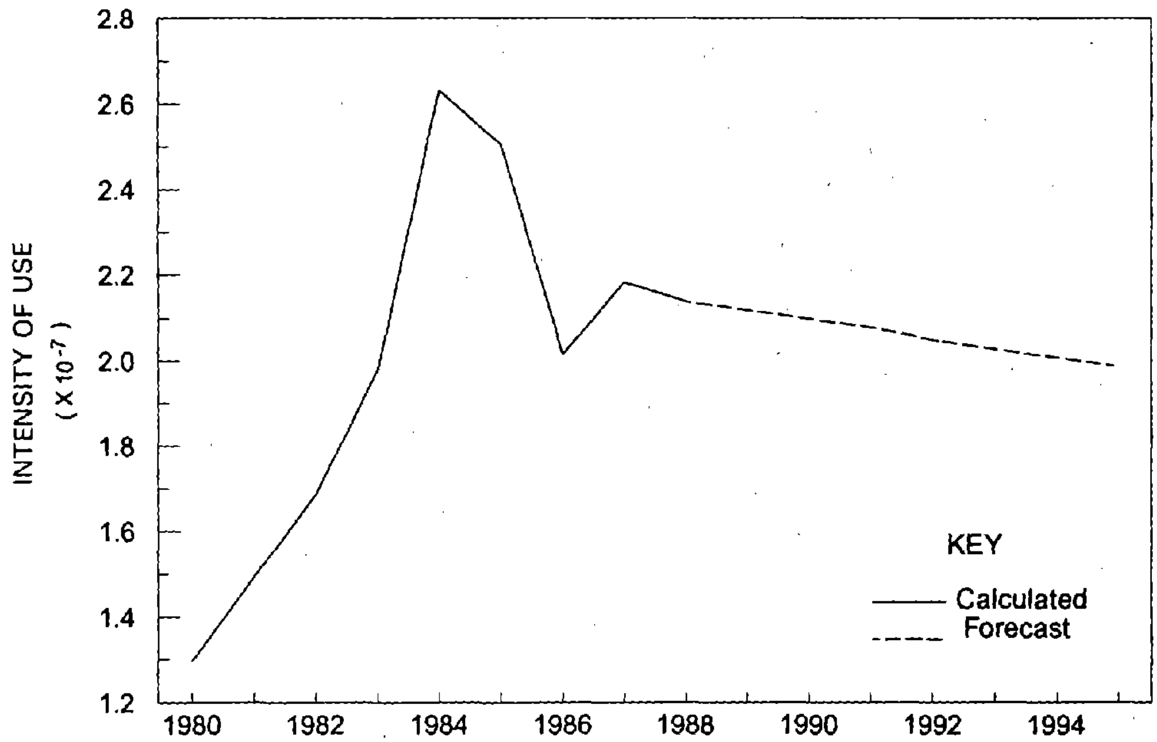

Figure E-5.—Intensity of chromium use in Western Europe versus time.

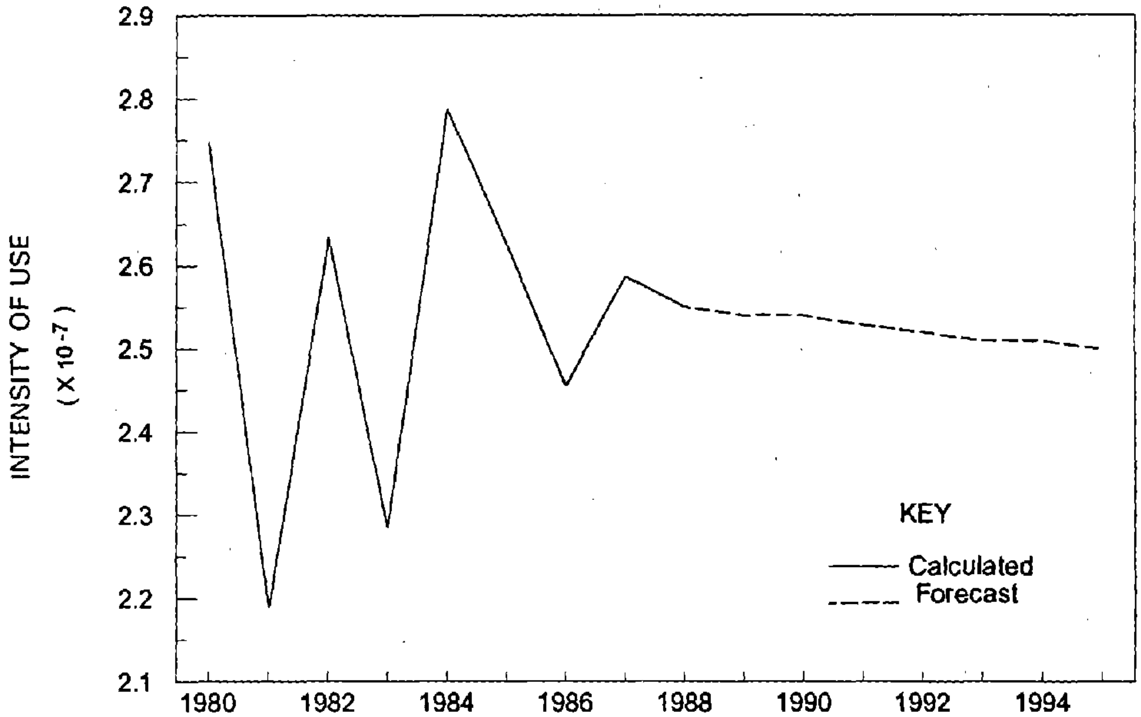

Figure E-6.—Intensity of chromium use in Asia versus time.

demanded would be 15 pct higher than that which was forecast using the IU technique. After adjustment, the estimate reflects total metallurgical chromium demanded by the stainless steel industry.

For the final regional Cr in stainless steel requirements it was estimated that approximately 20 pct of the total chromium used for metallurgical purposes is supplied from recycled material. Therefore, the chromium consumption values calculated with IU were adjusted downward by 20 pct to reflect only "virgin" metallurgical chromium consumption. These virgin chromium consumption amounts for the three main MEC regions were then split 90 pct to high-C FeCr and 10 pct to low-C FeCr plus ferrochromium-silicon, with the latter 10 pct further divided to obtain individual values for low-C FeCr and ferrochromium-silicon.[3]

From the discussion so far, it is seen that the IU methodology requires three critical technologic estimates: the average amount of Cr in the final stainless steel products, the average recovery of virgin Cr in stainless steelmaking, and the percent of Cr requirements that are provided by recycling. The demand values calculated for this study using IU methods assume an average of Cr in stainless steel products and a recovery of 85 virgin Cr in stainless steelmaking. Demand value assume that 20 pct of Cr requirements come fro cycling. A second set of values—17.3 pct Cr as an a grade in stainless steel products (*70*), 85 or 90 pct re in stainless steelmaking, and 30 pct of the Cr require coming from recycling—may be more reasonable for estimating Cr requirements for stainless steel prodı In comparison to the Cr requirements for stainless production determined using this study's assumed f application of this second set of factors would re differences of 8.1 pct (higher), if a recovery of 85 used, and only 2.1 pct (higher) if a recovery of 90 used.

As stated in the consumption section, stainless accounts for 82 pct of total demand for metallurgical mium in the United States. The data to derive inten use for the remaining 18 pct of metallurgical chro are not available. Demand levels must be approxi for other metallurgical chromium uses. The metho chosen makes the assumption that the rate of grow chromium consumption in stainless steel and in othe allurgical uses will be the same. In addition, it w sumed that the ratio of chromium consumption be stainless steel and other uses remains constant ove and that the ratio for the United States is applicable other regions considered. In applying this method

[3]The methodology used for the present model assumes that the 90 pct high-C FeCr/10 pct low-C FeCr plus ferrochromium-silicon breakdown, which is typical of the U.S. market as of 1986, does not shift any further in favor of high-C FeCr. It is possible that the percentage represented by high-C FeCr usage could continue to rise beyond 90 pct.

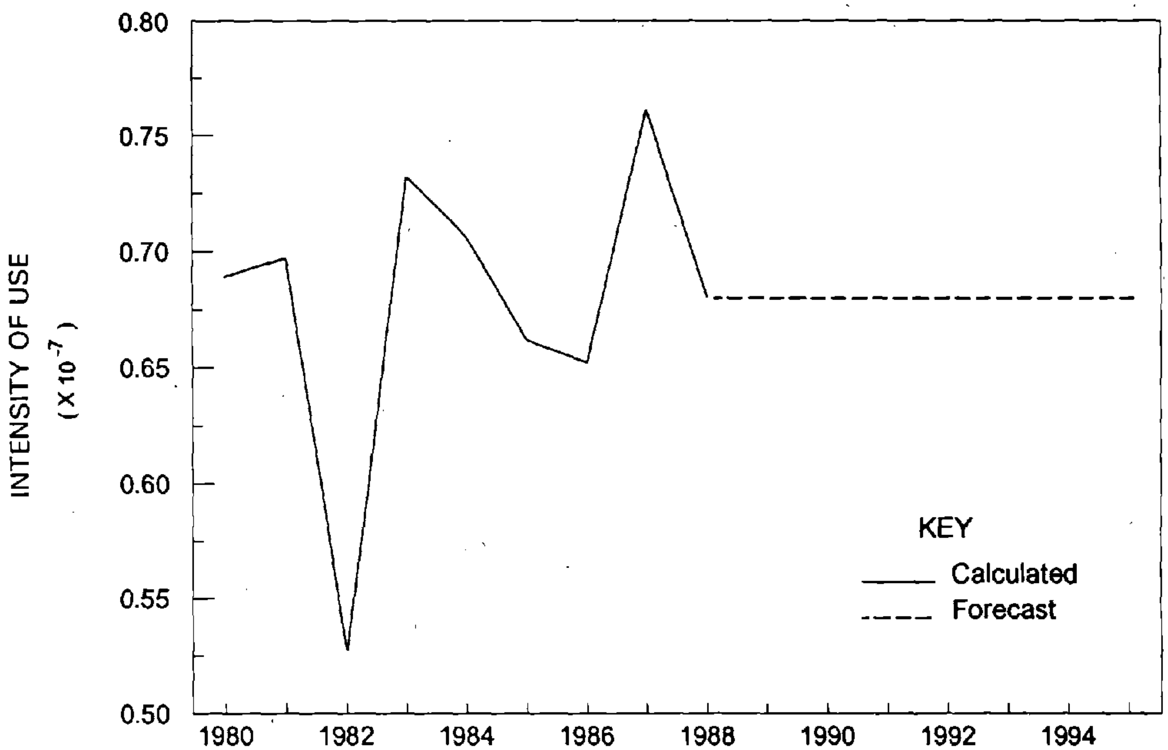

Figure E-4.—Intensity of chromium use in North America versus time.

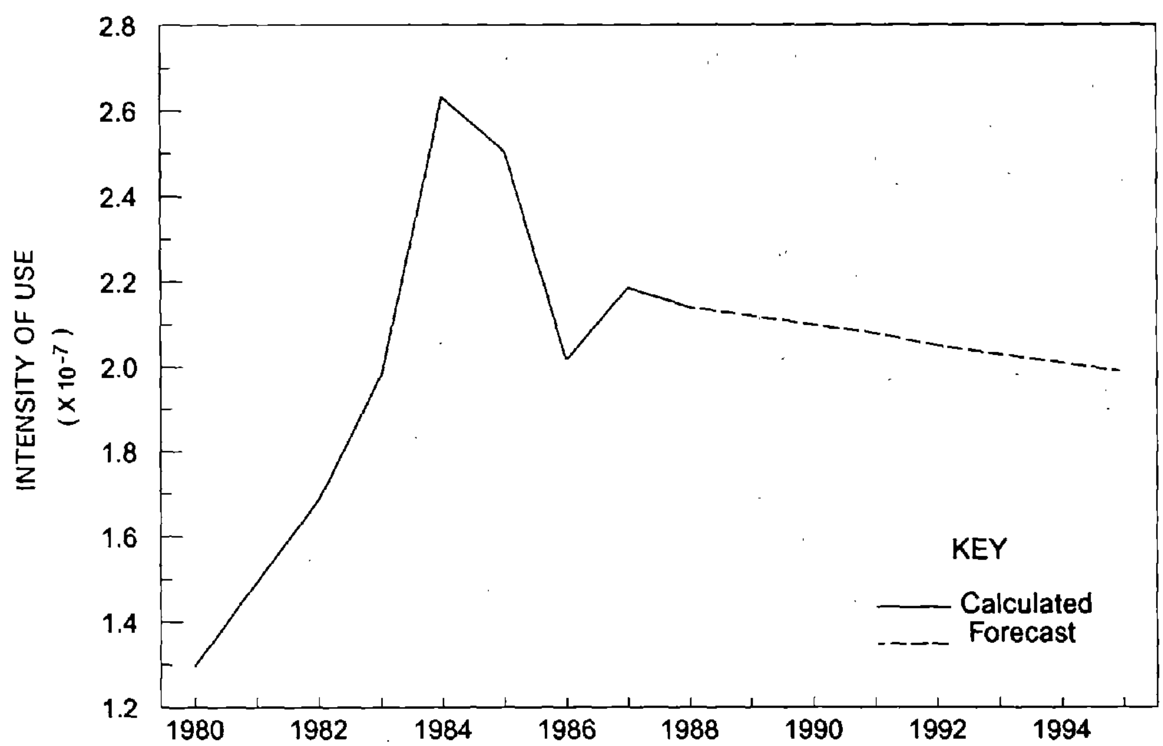

Figure E-5.—Intensity of chromium use in Western Europe versus time.

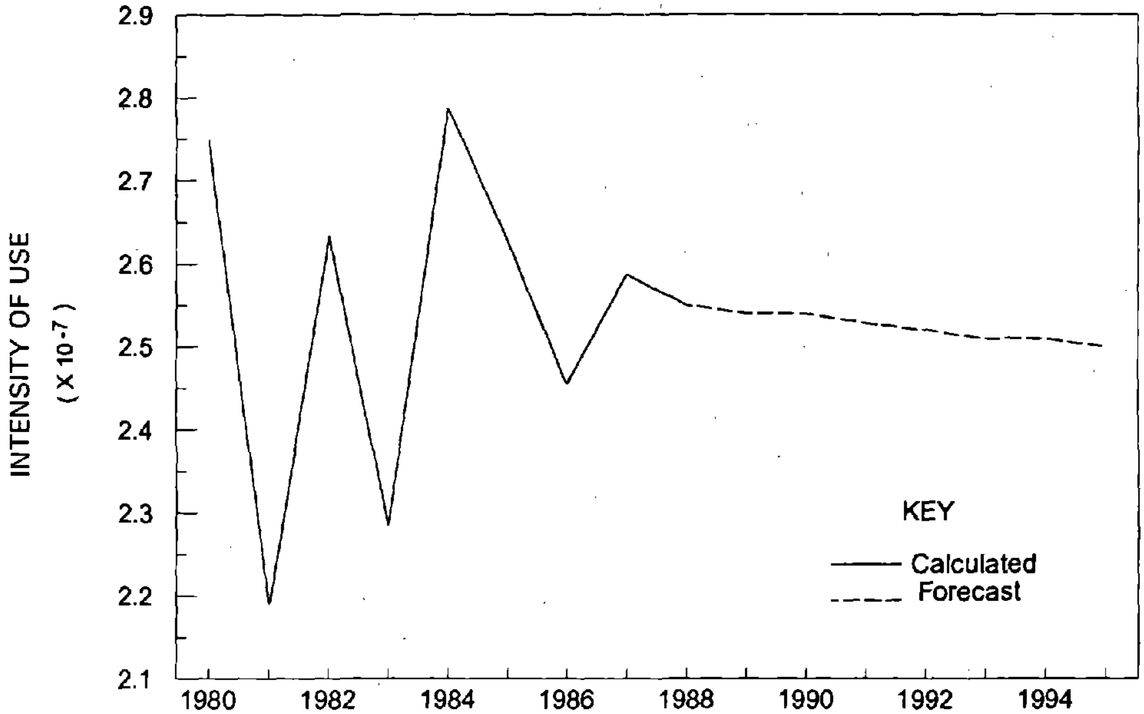

Figure E-6.—Intensity of chromium use in Asia versus time.

demanded would be 15 pct higher than that which was forecast using the IU technique. After adjustment, the estimate reflects total metallurgical chromium demanded by the stainless steel industry.

For the final regional Cr in stainless steel requirements it was estimated that approximately 20 pct of the total chromium used for metallurgical purposes is supplied from recycled material. Therefore, the chromium consumption values calculated with IU were adjusted downward by 20 pct to reflect only "virgin" metallurgical chromium consumption. These virgin chromium consumption amounts for the three main MEC regions were then split 90 pct to high-C FeCr and 10 pct to low-C FeCr plus ferrochromium-silicon, with the latter 10 pct further divided to obtain individual values for low-C FeCr and ferrochromium-silicon.[3]

From the discussion so far, it is seen that the IU methodology requires three critical technologic estimates: the average amount of Cr in the final stainless steel products, the average recovery of virgin Cr in stainless steelmaking, and the percent of Cr requirements that are provided by recycling. The demand values calculated for this study using IU methods assume an average of 14 pct Cr in stainless steel products and a recovery of 85 pct of virgin Cr in stainless steelmaking. Demand values also assume that 20 pct of Cr requirements come from recycling. A second set of values—17.3 pct Cr as an average grade in stainless steel products (*70*), 85 or 90 pct recovery in stainless steelmaking, and 30 pct of the Cr requirements coming from recycling—may be more reasonable for use in estimating Cr requirements for stainless steel production. In comparison to the Cr requirements for stainless steel production determined using this study's assumed factors, application of this second set of factors would result in differences of 8.1 pct (higher), if a recovery of 85 pct is used, and only 2.1 pct (higher) if a recovery of 90 pct is used.

As stated in the consumption section, stainless steel accounts for 82 pct of total demand for metallurgical chromium in the United States. The data to derive intensity of use for the remaining 18 pct of metallurgical chromium are not available. Demand levels must be approximated for other metallurgical chromium uses. The methodology chosen makes the assumption that the rate of growth for chromium consumption in stainless steel and in other metallurgical uses will be the same. In addition, it was assumed that the ratio of chromium consumption between stainless steel and other uses remains constant over time and that the ratio for the United States is applicable to all other regions considered. In applying this methodology,

[3]The methodology used for the present model assumes that the 90 pct high-C FeCr/10 pct low-C FeCr plus ferrochromium-silicon breakdown, which is typical of the U.S. market as of 1986, does not shift any further in favor of high-C FeCr. It is possible that the percentage represented by high-C FeCr usage could continue to rise beyond 90 pct.

metallurgical chromium demanded by the stainless steel industry was increased by 18 pct to reflect these other uses. Total metallurgical chromium demand is then derived by the summation of chromium demanded by the stainless steel industry and chromium demanded for other uses. This total metallurgical chromium demand for various regions based on consideration of various GDP growth rates is shown in tables E-3 and E-4. In each case, the values shown for years 1980 through 1986 have been estimated based on reported stainless steel production, stainless steel prices, and GDP's. The values for 1987 through 1995 have been calculated by multiplying the forecast of IU for a region by its forecast GDP.

Table E-3.—Demand for metallurgical chromium using a 1-pct GDP growth rates

(Metric tons Cr)

Year	North America	Western Europe	Asia
1980 ...	300,833	533,791	437,346
1981 ...	310,044	492,155	370,299
1982 ...	220,372	492,542	470,128
1983 ...	312,263	521,683	443,313
1984 ...	317,727	623,082	518,974
1985 ...	305,989	588,049	536,940
1986 ...	308,726	619,843	530,471
1987 ...	[1]364,177	[1]678,267	599,811
1988[1] ...	328,510	671,048	597,225
1989[1] ...	331,794	671,424	600,831
1990[1] ...	335,112	671,741	606,840
1991[1] ...	338,464	671,997	610,495
1992[1] ...	341,849	668,928	614,163
1993[1] ...	345,268	669,026	617,844
1994[1] ...	348,720	669,058	624,022
1995[1] ...	352,207	669,026	627,750

[1]Forecasted values.

The estimated metallurgical Cr consumption in the three regions of North America, Asia, and Western Europe for the base year of 1986 was 1.46 Mmt, with the largest consuming region (Western Europe) accounting for 619,843 mt or 42 pct. By 1995, total consumption of Cr in ferrochromium for all three regions is estimated to be 1.65 Mmt in the case of 1 pct/yr GDP growth, and 2.15 Mmt in the case of higher GDP growth. The increase over 1986 is 13 pct with slow economic growth, but 48 pct if higher growth is sustained. By 1995, Western Europe remains the largest consumer of ferrochromium in the slow growth scenario, though only by a small margin. However, consumption in Asia far exceeds that of either North America or Western Europe by 1995 if recent economic growth patterns in the region are maintained. In that case, consumption is forecast to increase from the 1986 level by almost 87 pct to 991,603 mt of Cr.

Table E-4.—Demand for metallurgical chromium using various GDP growth rates

(Metric tons Cr)

Year	North[1] America	Western[2] Europe	Asia[3]
1980 ...	300,833	533,791	437,346
1981 ...	310,044	492,155	370,299
1982 ...	220,372	492,542	470,128
1983 ...	312,263	521,683	443,313
1984 ...	317,727	623,082	518,974
1985 ...	305,989	588,049	536,940
1986 ...	308,726	619,843	530,471
1987 ...	[4]370,992	[4]686,459	599,811
1988[4] ...	340,920	687,357	632,349
1989[4] ...	350,772	696,051	673,582
1990[4] ...	360,909	704,789	720,328
1991[4] ...	371,340	713,575	767,286
1992[4] ...	382,072	718,895	817,293
1993[4] ...	393,113	727,687	870,545
1994[4] ...	404,475	736,512	930,961
1995[4] ...	416,164	745,372	991,603

[1]GDP growth rate of 2.89 pct/yr was forecasted for 1987-95.
[2]GDP growth rate of 2.22 pct/yr was forecasted for 1987-95.
[3]GDP growth rate of 6.94 pct/yr was forecasted for 1988-95.
[4]Forecasted values.

These results demonstrate the combined impact of intensity of use and gross domestic product. In all regions, IU is forecast to either remain steady or decrease, but net consumption of Cr is expected to increase. The magnitude of the increase depends largely on the level of economic growth in the region. The implication is that the ability of chromium markets to absorb recent and planned capacity expansions while maintaining the higher prices of recent years depends heavily on macroeconomic conditions beyond the control of ferrochromium or chromite producers. A world recession, or even a significant slowdown in economic growth, could force rationalizations and price decreases. Conversely, strong demand with only 1 pct/yr economic growth would still support considerable capacity expansion.

RESULTS

In the network flow model simulations made for this study the IU metallurgical chromium demand values of table E-4, which reflect historic GDP growth rates, were used along with separate estimates for countries and regions not covered by the IU methodology. This section summarizes all of the resulting demand levels used in the model for all six of the chromium product markets: high-C FeCr, low-C FeCr, ferrochromium-silicon, SBE, refractory chromite, and foundry sand chromite.

Chromium in high-C FeCr consumption values in the model are reported in table E-5. Over the time period covered in the table the annual growth rates for consumption of Cr in high-C FeCr in the three major markets are 7.5 pct/yr for Asia, 3.7 pct/yr for North America, and 2.4 pct/yr in Western Europe. Combined, the annual growth rate for all three regions is 4.7 pct/yr, and these three regions account for 89.8 pct of the total estimated base (1986) MEC Cr requirements in high-C FeCr.

A 3.5 pct/yr growth rate for Cr in high-C FeCr was assumed for South America and Eastern Europe, as well as for the countries of Brazil, Yugoslavia, and the People's Republic of China. A 0-pct/yr growth rate was assumed for U.S.S.R. usage.

The remainder of the high-C FeCr demand nodes in the model address specific steel plant needs in Finland, Western India, and South Africa as well as the special case in Albania. A 0-pct/yr growth rate was assumed for the Finland and the Western India steel plants, since no expansion at these steel plants is known to be planned. A discrete jump of 50 pct by 1991 was assigned to South Africa to address Middelburg Steel's planned expansion to stainless steel production. The demand node for Albanian high-C FeCr contains a very large 15.8 pct/yr increase, from 28,800 mt Cr in the base year (1986) to 92,800 mt Cr by the sixth year (1991). This is due to the decision to match Albania's demand to their planned output level in order to keep this product from entering the present network model's trade flow.

In summary, the annual growth rate for consumption of high-C FeCr through 1994 was estimated to be 4.5 pct/yr in the MEC's, 3.3 pct/yr in the CPEC's, and 4.2 pct/yr on a worldwide basis.

The growth rates for Cr in low-C FeCr (table E-6) in North America, Asia, and Western Europe over the 9 yr of the simulation are, respectively, 1.6 pct/yr, 5.4 pct/yr, and 0.4 pct/yr. Combined, these three regions account for 78.8 pct of the base year (1986) MEC consumption and have an annualized growth rate over the 9 yr of 2.6 pct/yr. A 1-pct/yr growth rate was assumed for South America, Yugoslavia, and the People's Republic of China. Eastern Europe's growth rate in the model is 0.3 pct/yr over the 9 yr, while a 0-pct/yr growth rate for Cr in low-C FeCr usage was assumed for the countries of India and the U.S.S.R. Only one specific steel plant has been assigned its own low-C FeCr demand node in the model. This is Middelburg Steel's plant in South Africa, which was assigned a discrete 50-pct increase in demand by the year 1991 to account for announced expansion of the plant's stainless steel capacity.

Table E-5.—Chromium in high-C FeCr demand values for selected years in the multiyear simulation, by region or country

(Metric tons Cr)

Demand node (region, country)	Base year (1986)	Yr 4 (1989)	Yr 5 (1990)	Yr 7 (1992)	Yr 9 (1994)
MEC:					
Asia[1]	377,526	487,350	521,172	591,328	673,569
North America[2]	219,715	253,791	261,125	276,437	292,646
South America[3]	10,000	11,087	11,475	12,292	13,168
Western Europe[4]	441,130	503,607	509,929	520,135	532,881
Brazil	43,200	47,897	49,574	53,105	56,887
Finland	27,397	27,397	27,397	27,397	27,397
India	18,010	19,554	20,105	21,255	22,508
South Africa	13,384	13,384	13,384	20,076	20,076
Yugoslavia	6,490	7,196	7,449	7,981	8,551
Subtotal, MEC	1,156,852	1,371,263	1,421,610	1,530,006	1,647,683
CPEC:					
Eastern Europe[5]	75,000	83,154	86,064	92,194	98,761
Albania	28,800	49,920	71,360	92,800	92,800
China	72,605	80,498	83,315	89,249	95,605
U.S.S.R.	191,843	191,843	191,843	191,843	191,843
Subtotal, CPEC	368,248	405,415	432,582	466,086	479,009
Total, world	1,525,100	1,776,678	1,854,192	1,996,092	2,126,692

[1]Includes Japan, Taiwan, Australia, Republic of South Korea; excludes India.
[2]Includes Canada, Mexico, and the United States.
[3]Excludes Brazil.
[4]Excludes Finland and Yugoslavia.
[5]Excludes Albania.

Table E-6.—Chromium in low-C FeCr demand values for selected years in the multiyear simulation, by region or country

(Metric tons Cr)

Demand node (region, country)	Base year (1986)	Yr 4 (1989)	Yr 5 (1990)	Yr 7 (1992)	Yr 9 (1994)
MEC:					
Asia[1]	42,165	46,364	49,582	56,256	64,080
North America[2]	24,540	24,144	24,842	26,299	27,841
South America[3]	2,000	2,060	2,080	2,123	2,165
Western Europe[4]	49,270	47,912	48,512	49,483	50,696
Brazil	8,075	8,320	8,404	8,574	8,748
India	19,000	19,000	19,000	19,000	19,000
South Africa	551	551	551	827	827
Yugoslavia	1,600	1,648	1,664	1,697	1,730
Subtotal, MEC	147,201	149,999	154,635	164,259	175,087
CPEC:					
Eastern Europe[5]	5,000	5,152	5,204	5,308	5,415
China	31,590	32,547	32,872	33,532	34,206
U.S.S.R.	82,219	82,219	82,219	82,219	82,219
Subtotal, CPEC	118,809	119,918	120,295	121,059	121,840
Total, world	266,010	269,917	274,930	285,318	296,927

[1]Includes Japan, Taiwan, Australia, Republic of South Korea; excludes India.
[2]Includes Canada, Mexico, and the United States.
[3]Excludes Brazil.
[4]Excludes Finland and Yugoslavia.
[5]Excludes Albania.

In summary, the annualized growth rates for chromium in low-C FeCr during the 9-yr period equate to 2.2 pct/yr in the MEC's, 0.3 pct/yr in the CPEC's, and 1.4 pct/yr on a worldwide basis.

There are only three demand nodes for ferrochromium-silicon in the entire model: North America, Asia, and Western Europe. The growth rates for consumption in these regions were estimated using the IU technique. The annual growth rates during the 9-yr period are 1.6 pct/yr, 5.4 pct/yr, and 0.4 pct/yr, respectively, identical to those for low-C FeCr. Combined, the annual growth rate for these three MEC regions is 2.6 pct/yr.

The base year (1986) demand for Cr in SBE represents estimates of the total Cr content capacity of the chemical plants in existence as of the 1986-87 period. Similarly, the base year demand for Cr in refractory bricks, mortars, and other refractory products is a rough estimate based mainly on known or estimated refractory plant capacities for the same time period. The 1986 Cr demand for use as foundry sand material is a rough, and probably low, estimate based mainly on indicated differences in metallurgical activity levels in four of the five major MEC demand regions. No foundry sand demand estimate was made for Eastern Europe.

Consumption of Cr in SBE in North America, South America, Asia, Western Europe, and South Africa was assumed to grow at a rate of 2 pct/yr, while consumption in Eastern Europe, India, Yugoslavia, and the U.S.S.R. was assumed to have no growth at all over the 9 yr of the simulation (table E-7). The annual growth rates are 1.2 pct/yr in the MEC's, 0 pct/yr in the CPEC's, and 1.0 pct/yr on a worldwide basis.

Growth rates of 1 pct/yr were assumed for refractory products (table E-8) in the regions of North America, South America, Asia, and Western Europe, as well as for the countries of South Africa and Cuba. No growth over the 9 yr of the simulation was assumed for Cr in refractory products in Eastern Europe and in the countries of Albania, India, Turkey, and the U.S.S.R. The annual growth rates over the 9-yr period of this simulation are 0.9 pct/yr in the MEC's, 0 pct/yr in the CPEC's, and 0.5 pct/yr on a worldwide basis.

The use of Cr in foundry sand products is represented in the model by four demand nodes (table E-9), one each for the regions of North America, South America, Asia, and Western Europe. Growth rates of 1 pct/yr over the 9 yr of the simulation were assumed for all four regions.

Separate demand nodes have been included in the model to address the internal consumptions of Cr products in all of the major chromite producing countries (Albania, Brazil, the People's Republic of China, Cuba, Finland, India, South Africa, Turkey, the U.S.S.R., and Yugoslavia).[4] In the model, these demand nodes provide two important functions. First, they address the critical point that any usage within a chromite producing country is not available to the export markets. Second, as described earlier for Albanian high-C FeCr, by matching internal demands to production levels it is possible to "close off" (from the export market of the model) those products that, for whatever reason, have no associated cost estimates.

[4]Even though Yugoslavia presently has no producing mines of its own, it is considered as a chromite producer in this context, since it has a fairly large amount of milling capacity that is used to upgrade imported ores.

Table E-7.—Chromium in sodium bichromate equivalent (SBE) demand values for selected years in the multiyear simulation, by region or country

(Metric tons Cr)

Demand node (region, country)	Base year (1986)	Yr 4 (1989)	Yr 5 (1990)	Yr 7 (1992)	Yr 9 (1994)
MEC:					
Asia[1]	32,000	33,959	34,638	36,038	37,494
North America[2]	55,000	58,366	59,533	61,937	64,438
South America[3]	5,000	5,306	5,412	5,631	5,858
Western Europe[4]	85,000	90,200	92,037	95,823	99,765
India	7,000	7,000	7,000	7,000	7,000
South Africa	2,000	2,122	2,164	2,250	2,339
Yugoslavia	2,000	2,000	2,000	2,000	2,000
Subtotal, MEC	188,000	198,953	202,784	210,679	218,894
CPEC:					
Eastern Europe[5]	13,000	13,000	13,000	13,000	13,000
U.S.S.R.	130,000	130,000	130,000	130,000	130,000
Subtotal, CPEC	143,000	143,000	143,000	143,000	143,000
Total, world	331,000	341,953	345,784	353,679	361,894

[1]Includes Japan, Taiwan, Australia, Republic of South Korea; excludes India.
[2]Includes Canada, Mexico, and the United States.
[3]Excludes Brazil.
[4]Excludes Finland and Yugoslavia.
[5]Excludes Albania.

Table E-8.—Chromium in refractory products demand values for selected years in the multiyear simulation, by region or country

(Metric tons Cr)

Demand node (region, country)	Base year (1986)	Yr 4 (1989)	Yr 5 (1990)	Yr 7 (1992)	Yr 9 (1994)
MEC:					
Asia[1]	35,000	36,061	36,422	37,154	37,900
North America[2]	32,000	32,970	33,301	33,972	34,656
South America[3]	4,000	4,121	4,162	4,246	4,332
Western Europe[4]	55,000	56,667	57,234	58,384	59,557
India	18,000	18,000	18,000	18,000	18,000
South Africa	5,000	5,152	5,204	5,308	5,415
Turkey	5,455	5,455	5,455	5,455	5,455
Subtotal, MEC	154,455	158,426	159,778	162,519	165,315
CPEC:					
Eastern Europe[5]	10,000	10,000	10,000	10,000	10,000
Albania	5,000	5,000	5,000	5,000	5,000
Cuba	1,000	1,030	1,040	1,050	1,050
U.S.S.R.	85,000	85,000	85,000	85,000	85,000
Subtotal, CPEC	101,000	101,030	101,040	101,050	101,050
Total, world	255,455	259,456	260,818	263,569	266,365

[1]Includes Japan, Taiwan, Australia, Republic of South Korea; excludes India.
[2]Includes Canada, Mexico, and the United States.
[3]Excludes Brazil.
[4]Excludes Finland and Yugoslavia.
[5]Excludes Albania.

Table E-10 summarizes this model's MEC, CPEC, and world Cr demand values for years 1, 5, and 9 (1986, 1990, and 1994) of the multiyear simulation. The cumulative effect of the various growth rates on the overall total Cr requirements is shown. Over the 9-yr simulation, total MEC Cr requirements increase 3.7 pct/yr, while total CPEC Cr usage grows only 1.8 pct/yr and the total world usage increases at a rate of 3.1 pct/yr. The resulting grand total is an estimated world demand for 3.1 Mmt of Cr by year 9 (1994) of the simulation. Of particular note in table E-10 is that, of the additional 681,171 mtpy of Cr needed by year 9 of the simulation, fully 635,469 mt (93.3 pct) comes from the increases in metallurgical requirements.

Table E-9.—Chromium in foundry sand demand values for selected years in the multiyear simulation, by region

(Metric tons Cr)

Demand node (region)	Base year (1986)	Yr 4 (1989)	Yr 5 (1990)	Yr 7 (1992)	Yr 9 (1994)
MEC:					
Asia[1]	15,000	15,455	15,610	15,923	16,243
North America[2]	10,000	10,303	10,406	10,615	10,829
South America[3]	2,000	2,061	2,082	2,125	2,169
Western Europe[4]	20,000	20,606	20,812	21,230	21,657
Total, MEC	47,000	48,425	48,910	49,893	50,898

[1]Includes Japan, Taiwan, Australia, Republic of South Korea; excludes India.
[2]Includes Canada, Mexico, and the United States.
[3]Excludes Brazil.
[4]Excludes Finland and Yugoslavia.

Table E-10.—Total world chromium demand for selected years in the multiyear simulation, by major usage category

(Metric tons Cr)

Category	Base year (1986)	Yr 5 (1990)	Yr 9 (1994)
Metallurgical:			
High-C FeCr:			
MEC	1,156,852	1,421,610	1,647,683
CPEC	368,248	432,582	479,009
Subtotal	1,525,100	1,854,192	2,126,692
Low-C FeCr:			
MEC	147,201	154,635	175,087
CPEC	118,809	120,295	121,840
Subtotal	266,010	274,930	296,927
FeCrSi:			
MEC	12,886	13,659	15,846
All metallurgical:			
MEC	1,316,939	1,589,904	1,838,616
CPEC	487,057	552,877	600,849
Total, metallurgical	1,803,996	2,142,781	2,439,465
Chemical:			
MEC	188,000	202,784	218,894
CPEC	143,000	143,000	143,000
Total chemical	331,000	345,784	361,894
Refractory and foundry sand:			
MEC	201,455	208,688	216,213
CPEC	101,000	101,040	101,050
Total refractory and foundry sand	302,455	309,728	317,263
Grand totals:			
MEC	1,706,394	2,001,376	2,273,723
CPEC	731,057	796,917	844,899
World	2,437,451	2,798,293	3,118,622

APPENDIX F.—CHROMIUM NETWORK FLOW MODEL DESIGN

INTRODUCTION

This chromium network flow model is intended to represent the world chromium industry through the smelting and chemical processing level. It has been designed as a thoroughly general network, in which actual or hypothetical locations are represented by nodes and processing or movement by arcs. The network simulates the annual flow of contained Cr, on a metric ton basis, from mines and stockpiles through smelting or chemical processing—as applicable—to regional demand for Cr in the form of high-C and low-C FeCr, ferrochromium-silicon, foundry sand, refractories, and SBE. In essence, the model fulfills a predetermined level of demand at the minimum total system cost.

The final chromium network flow model contains 6,191 arcs and 3,657 nodes. An overview of the design elements of the chromium network flow model will be presented in this section. Interesting or unique features will be discussed; however, no attempt will be made to address the derivation of every arc and node parameter. The demand methodology and resulting values were presented in appendix E.

NODES AND ARCS

All significant ore sources, beneficiation plants, and smelters have been included individually in the design; smaller operations have been grouped together in some countries. Locations and processes were labeled with names designating country, facility name, product, and processing step. As an example, the node name BRAZ-IPUERA LUMP-MNO has been assigned for lump chromite output from the Ipuera mine in Brazil. The flow through this node is in terms of metric tons of Cr contained in lump ore output, and the arc feeding into the node represents the process of mining and sizing, hence MNO for "end of mining process arc." The naming convention allows the user to view or update subsets of the arc data base by searching for key words. For instance, all arcs in Brazil or all arcs associated with the Ipuera mine are easily identified and extracted. The names also facilitate the representation of numerous individual processing steps at a single location.

In the network, material flows from mines or inventory nodes through the system design to final demand nodes on arcs. The arcs have five basic characteristics: upper and lower bounds, cost, and head and tail multipliers. Each of these will be addressed in the following subsections.

UPPER AND LOWER BOUNDS

Bound constraints limit flow in the network system. Upper bounds represent the maximum amount of flow allowable on an arc and are set equal to, or less than, the annual capacity (in metric tons of Cr) of the process represented by that arc. The lower bounds represent the minimum necessary flow and are set at zero or at any level up to the upper bound value. If an arc's lower bound is set at zero, flow occurs on an arc only if it is required by the optimal solution. If the lower bound is set above zero, flow on the arc must be at least equal to the lower bound value, but could be as high as the upper bound value. This is called "forcing" flow.

Upper bound values can be used to limit or "shut off" flow on strategic arcs in the model. For example, it was observed in the first solutions of the Cr model that, because of South Africa's relatively low costs and high production capability, worldwide solution results replicating historic trading patterns could be obtained only when the flow of South African high-C and low-C FeCr and metallurgical and refractory chromite exports to North America, South America, Asia, and Western Europe were constrained by the use of upper bound values. Examples of complete shutoff (using zero as the upper bound value) are the closing off (in the model) of Cuban chromite exports from all but Eastern European markets and of FeCr production in CPEC countries from the overall MEC trade flow.

Upper bound values were also used to address capacity constraints at ports in Southern Africa. For example, the model allows South African exports of high-C and low-C FeCr to flow through the port of Maputo in Mozambique; however, the total flow on this export route is limited by the upper bound values on the arcs leaving those Maputo port nodes.

The forcing of flow by the use of lower bound values is used mainly on trade flow arcs to account for (1) contractual arrangements or long-standing trading relationships between certain suppliers and consumers and (2) ownership relationships. Lower bound values were also used at a few strategic points in particular netmaps to force flow along certain routes.

Tables F-1 and F-2 summarize all of the upper and lower bound values presently assigned in the model to export arcs from producing countries to consuming regions for the base year of 1986. For the South Africa cutoff scenario simulations, all of the low-C FeCr lower bounds shown in Table F-2 were eliminated for the 1990 through 1994 multiyear solutions.

Table F-1.—Upper bound values for export arcs, by product and exporting country, for the base year (1986) of the multiyear simulation

(Metric tons Cr)

Product	Trade flow description	Upper bound value, mt Cr
High-C FeCr . .	South Africa to North America[1]	95,000
	South Africa to South America[1]	20,000
	South Africa to Asia[1]	190,000
	South Africa to Western Europe[1]	190,000
	Zimbabwe to North America	25,000
	Poland, Czechoslovakia, and Romania to North America, South America, Asia, and Western Europe.	0
Low-C FeCr . .	South Africa to North America[1]	9,000
	South Africa to South America[1]	2,000
	South Africa to Asia[1]	18,000
	South Africa to Western Europe[1]	2,000
Metallurgical chromite.	South Africa to Asia[1]	90,000
	South Africa to Western Europe[1]	90,000
	Cuba to North America, South America, Asia, and Western Europe.	0
Refractory chromite.	South Africa to North America[1]	15,750
	South Africa to South America[1]	1,800
	South Africa to Asia[1]	35,000
	South Africa to Western Europe[1]	28,852
	Cuba to North America, South America, Asia, and Western Europe.	0

[1]Combined upper bound values for South African exports from both Richard's Bay, South Africa, and Maputo, Mozambique.

Table F-2.—Lower bound values for export arcs, by product and exporting country, for the base year (1986) of the multiyear simulation

(Metric tons Cr)

Product	Trade flow description	Lower bound value, mt Cr
High-C FeCr	Zimbabwe to Asia	20,000
	Brazil to Asia	10,000
	India to Asia	15,700
	Philippines to Asia	25,000
	Greece to Asia	6,000
Low-C FeCr	Turkey to North America	2,500
	Zimbabwe to Asia	2,345
	Federal Republic of Germany to North America	5,000
	Federal Republic of Germany to Western Europe	5,000
Metallurgical chromite . .	Turkey to Western Europe	35,930
Refractory chromite	South Africa to Western Europe	10,852
	Philippines to North America	6,941
	Philippines to South America	2,013
	Philippines to Asia	4,489
	Philippines to Western Europe	1,153
	Greece to Western Europe	4,500
	Cuba to Eastern Europe	10,000
Chemical chromite	Philippines to Western Europe	9,046
SBE (sodium bichromate equivalent).	Eastern Europe to Eastern Europe	13,000

In early runs of the model, it was found that lower bound values were needed to force flow of the Philippines refractory products to all of the major refractory markets. This was because the model could not differentiate between the two major types of refractory chromite products: the high (21- to 27-pct) Al_2O_3 refractory products and the average (15- to 20-pct) Al_2O_3 refractory products. The model's cost optimization solutions simply asked for the cheapest Cr available. Unfortunately, the least expensive material always turned out to be the average Al_2O_3 refractory products from South Africa rather than the higher cost, high-Al_2O_3 products from the Philippines.

One way to remedy this situation would have been to estimate two separate refractory chromite demand levels, one for the high-Al_2O_3 products and one for the average Al_2O_3 products. This was impossible to accomplish with the present available data. Instead, to force flow, lower bound values were assigned to the Philippines export arcs based on actual export data available for that time period.

The present network model includes the capability to set upper and lower bounds on any arc in the model for specific years of the multiyear simulation. Presently, the modeler is limited to entering only four of these specified year changes for any particular arc. In the Cr model this particular feature was used in four ways, as described in the following paragraphs.

First, this capability was used to allow upper and lower bound values, which had been set in the base year of the simulation, to be adjusted upward or downward over the full 9 yr of the simulation. A major example of this is where the upper bound values used to constrain South African high-C and low-C FeCr and metallurgical chromite exports to major consuming regions (see table F-1) were allowed to rise 5 pct/yr during the full 9 yr of the simulation.

A second use of this capability was in bringing nonproducing properties on-line at appropriate times in the multiyear simulation. Because the model was actually constructed during the fourth year (1989) of the 9-year simulation, it was well known which of the properties/units were producing and which were not producing during the 1986-89 period. Thus, in appropriate years, the upper bound values (representing annual Cr capacity levels) for these properties/units were increased from zero (a shutoff condition) to annual capacity in the year that the property or unit began to produce.

A third example of using this capability was in addressing the staggered effect of new smelting capacity. For example, the years 1988 and 1989 have seen a number of announcements regarding new Cr ferroalloy projects expected to come into production on a staggered basis over the next 4 yr. The ability to set individual arc parameters, in conjunction with design of the model on a furnace-by-furnace basis, allowed for a fairly realistic approximation of the staggered effect of these new projects. Upper bound values were again set from 0 to capacity in the year when individual furnaces were forecast to open.

A final example of use of the "set arc parameters" capability was the case of the South Africa to North America cutoff simulation. In this scenario, it was necessary to shut off particular arcs from South Africa export nodes to North America demand nodes and to open up arcs from U.S. Defense Department stockpiles in specific years. The ability to shut off and open up particular arcs at specific points in a multiyear simulation was critical in accomplishing this.

COSTS

The basic approach to costing in the network model has been presented in the main body of this report. To reiterate briefly, costs are set equal to the variable cost of the process in terms of contained Cr, in constant 1989 dollars. They contain estimates of administrative costs and, in this Cr model, deliberately include all direct and indirect costs. Since indirect costs represent a small percentage of total operating costs in the mining and smelting of Cr, it was not considered to be critical to the results of the model that these indirect costs be removed from the original estimates. All mine, mill, and smelter capital cost estimates have been excluded from the model. The following discussion covers costing aspects required by construction of the Cr network flow model that were different from the detailed costings made for the "more limited" availability study.

For those MEC FeCr smelters without their own associated chromite resources (i.e., not evaluated in the availability study), it was necessary to make rough estimates of smelter operating costs for the model. These estimates are thought to be reasonable in that the technology in use at each smelter and the sizes of the operating furnaces are known. Consumption values from comparable operations that had been costed in detail were used. The "rough" elements in these cost estimates were mainly in the estimates of wage rates and consumables such as power and raw materials.

To get complete balance of world Cr flow, it was necessary to include all known chromite producing countries in the model. The model design required that f.o.b. port costs for chromite be estimated for chromite exporting CPEC's where costing was impossible (Albania, the U.S.S.R., Cuba, and Vietnam) and for small MEC chromite producers that weren't costed for the availability study. Since the Cr_2O_3 content and Cr-Fe ratios of the available products from these countries were known from various publications, it was decided to use the price proportioning table (see the "Methodology" section of the text) and update these prices to determine average 1988 f.o.b. prices for all of these products. These f.o.b. values were then discounted by 30 pct to approximate a variable (direct) cost basis (i.e., no taxes, capital recoupment, etc.) for comparative purposes in the model. Hence, for these countries or operations, f.o.b. prices for typical chromite products act as "proxies" for detailed costing in the present model.

The model includes cost estimates for the transport of all products (high-C FeCr, low-C FeCr, ferrochromium-silicon, SBE, and metallurgical, refractory, chemical, and foundry sand chromites) from ports in producing countries to each of the five major markets (North America, South America, Asia, Western Europe, and Eastern Europe). The distances (in kilometers) of all routes were determined using the Defense Mapping Agency's "Distances Between Ports" (*71*), and average 1988 U.S. dollar transport costs of $0.00123/mt/km for all chromite products and $0.00256/mt/km for all ferroalloy products were applied to these distances. Because of this design, the transport costs of this model simply reflect a distance differential and do not take into consideration any differences due to tariffs, duties, demurrage, and so on.

As mentioned previously, the f.o.b. cost of chromite products from centrally planned economy exporting countries (Albania, the U.S.S.R., and Cuba) was handled in the model by using factored f.o.b. prices as a "proxy" for costs. No cost estimates were made for production of Cr ferroalloy products in the U.S.S.R., China, Albania, Poland, Czechoslovakia, and Romania. Likewise, no cost estimate was made for production of Cr chemical products in the U.S.S.R. This was because no published prices were available for any of these CPEC products that could serve as "proxies" for costs.

Because of this lack of costs, or prices, in the model for these CPEC products, it was necessary to exclude all of these products from the model's overall MEC trade flow. Otherwise, costless CPEC product would displace costed MEC product in world markets. In the case of the U.S.S.R., China, and Albania, this closing off was accomplished by matching the production level to the internal country demand level for each particular product. In the case of the high-C FeCr production of Poland, Czechoslovakia, and Romania, the closing off was attained by allowing the output to flow on only one arc—to Eastern Europe high-C FeCr demand.

The present Cr network flow model contains arcs intended to represent additional potential Cr supply from properties in Turkey and the Philippines that were not addressed individually in the model. F.o.b. port values of $70.00/mt for both the Turkish chromite products and the Philippines chromite products (after discounting 30 pct to approximate a straight operating cost basis) were chosen as representative f.o.b. port costs for these arcs.

In the base runs of the network flow model, no costs were assigned to any of the arcs involving DOD stockpile sources. However, all of the DOD stockpile sources were shut off from the North American markets during these base runs. For the South African cutoff scenario simulations, extraordinarily high ("dummy") costs were put on the DOD stockpile material to keep the material from competing with existing U.S. smelting operations in the simulations. Obviously, the building of these stockpiles has involved costs, but it is difficult to decide exactly how the DOD would handle the accounting for this material in the event of its use.

MULTIPLIERS

The multipliers are used to augment or diminish flow across an arc. The tail multiplier acts on flow as it enters the arc; the head multiplier acts on flow as it leaves the arc. The multipliers can be set to any combination of positive and negative values. They are usually set at -1 (tail) and +1 (head), the result of which is that all flow entering the arc also leaves the arc. No growth or diminution in the amount of flow on the arc takes place in this situation.

In the chromium network, multipliers were occasionally set to values other than -1 and +1. Head node multipliers were used to represent process recovery rates. For example, a head node multiplier of 0.75 signifies that 75 pct of the chromium entering a process is recovered, and 25 pct is lost. The head multipliers, rather than the tail multipliers, are selected to represent process recovery because all tonnage entering a mill is processed, even though some Cr may be lost. To record the cost of a process accurately, it is necessary to diminish flow after the cost of the process has been considered.

Special multipliers were also used on the arcs representing the 250 sources for chromium included in the network design. Doubly augmenting arcs, which have positive multipliers at both ends, were used to address the simultaneous extraction of ores with significantly different physical characteristics. Many chromium ores are a combination of lump and fines, each of which is processed differently, at different cost. Since the network is a cost minimizing model, the ore type with lower beneficiation cost will always be selected over one with higher costs; however, the lump and fines are, of necessity, extracted together. By using doubly augmenting arcs to model ore sources exhibiting a consistent lump/fines split, any flow on the mining arc would exit as both lump and fines, in the proportions set by the arc multipliers.

Figure F-1 shows an example of a doubly augmenting arc. In this particular example, the mine being modeled has natural lump and fines percentages in the chromite ore of 75 and 25 pct, respectively. If 100 mt of Cr in ore is extracted at this property, 75 mt will flow into the lump product stream and 25 mt into the fines product stream. In the final model, 117 individual Cr sources are represented by these doubly augmenting arcs. Their economic reserve values are maintained in a table and decremented by the flow on the mine process arc at the end of each year of a multiyear simulation.

The other 133 individual sources of Cr in the present model are represented by surplus arcs. These arcs begin and end at the mine node and have multipliers of 0 and +1. Flow can leave the surplus arc but cannot enter. Surplus starting arcs were used for those ores that were 100 pct lump/grains, for 100 pct fines ores, for low-grade (or other) ores where 100 pct of the ore requires beneficiation, and for stockpiled sources of Cr.

Inventories were also modeled by manipulating the arc multipliers. Collection of inventory was permitted at properties/units, at smelters, and at many of the port site representations in the model, again by product type. For each inventory location, a maximum annual inventory increase was set, as well as the maximum allowable total inventory. Nodes for annual and total inventory were created for each location and product. Attached to the annual inventory node was a slack arc, the upper bound of which was set equal to the maximum annual allowable inventory buildup. The total inventory node for that location was fed by a surplus arc, with its upper bound set equal to existing inventories for that year of the simulation. At the end of each year of a multiyear simulation, the upper bound on the surplus arc feeding the total inventory node would be recalculated to equal the prior year's total inventory less inventory shipments plus flow into the annual inventory node. The upper bound on the annual inventory slack arc would be set equal to maximum annual buildup or the difference between the upper bound on the surplus arc and maximum total inventory, whichever was less.

PROPORTIONALITIES

Network flow market models do not allow the direct inclusion of ratios or proportionalities, such as would be found in a traditional blending problem. However, proportions were necessary to model the chromium industry accurately. This was handled with linear side constraints, which were solved via a heuristic. Proportionalities allow the modeler (1) to split the flow on each of the arcs *leaving* a particular node into specified proportions or (2) to split the flow on each of the arcs *entering* a particular node into specified proportions. Their application in the chromium network flow model is described below.

Figure F-2 shows examples of the two types (convergent and divergent) of proportionality usage available to the modeler. Proportionalities were used for three basic situations in the chromium network flow model. The most common was for situations where a furnace had two separate arc "streams" (one for lump/grains ores and one for fines/concentrates), which then combined back into a single arc representing overall Cr output from the furnace. This situation is described by the converging proportionality example in figure F-2. The second most common usage was in situations where one of the arcs from the initial doubly augmenting split required a further split to the natural grain distribution by additional screening. This situation is described by the diverging proportionality example in figure F-2. The least common usage of proportionalities occurred where a particular netmap contained a mixture of several ores of different Cr grades that required separation further along in the netmap.

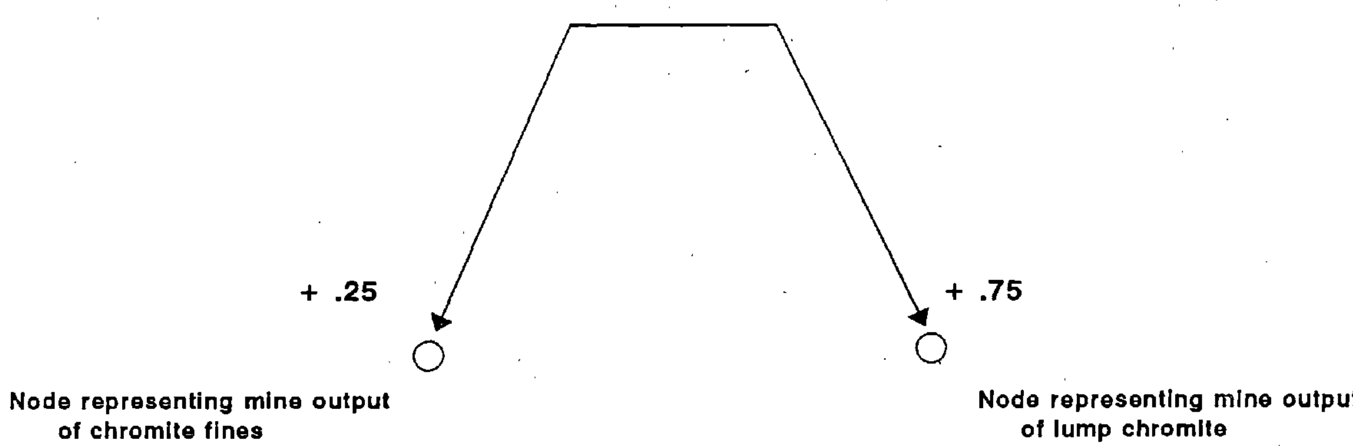

Figure F-1.—Example of usage of a doubly augmenting arc in the chromium network flow model.

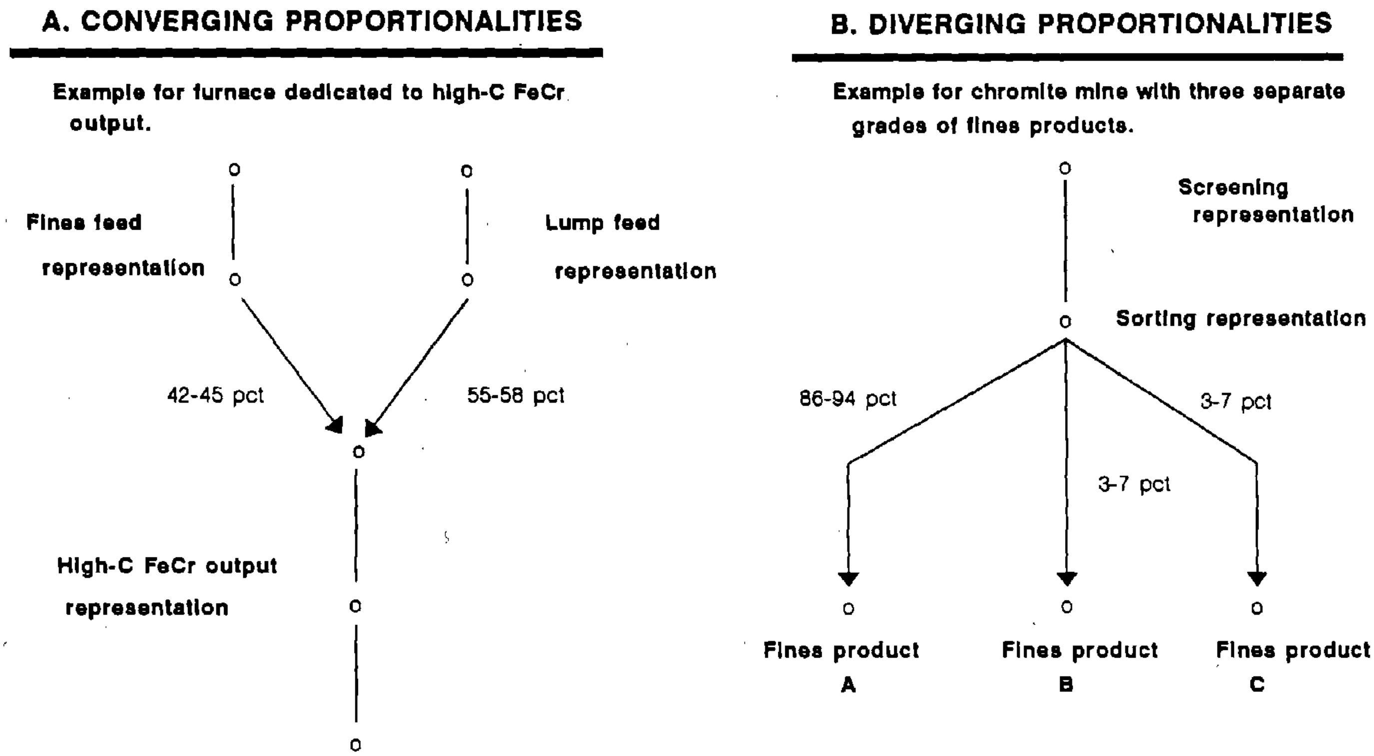

Figure F-2.—Examples of converging and diverging proportionality usage in the chromium network flow model.

Readers interested in site specific information on the chromium network design are encouraged to contact the authors.

MEC SMELTING CAPACITY INCLUDED IN NETWORK FLOW MODEL, YEAR 4 (1989)

Table F-3 provides a summary, by country, of the full high- and low-C FeCr capacities in this network flow model for the year 1989. The number of smelters and number of furnaces in each country that are represented by the capacity values are also included.

MEC RESOURCES AND SMELTING CAPACITY NOT INCLUDED

Table F-4 lists major MEC chromite resources that presently are not included in the Cr network flow model. This table should be compared with table 11 in the availability section of the main text. Each of these resources is discussed in some detail in that table. The exclusion of these resources from the present network flow model is mainly due to a lack of sufficient detailed data to support reliable estimates of costs. Each of these can, depending on future data and priorities, be added at any time to the network flow model.

Even though the present model contains all of the additional furnaces planned by South African producers as of late 1988, it does not contain all of the planned furnaces as of late 1989. The model presently does not contain the new 120,000 mtpy high-C FeCr smelter constructed near Rustenburg and owned by Purity Minerals Ltd. This smelter, whose furnaces were both commissioned in mid-1990, also has its own captive nearby mine for ore feed.

Also in South Africa there have been indications as of late 1989 that Chromecorp Technology Ltd. may have decided to add a third furnace (50,000 to 60,000 mtpy high-C FeCr) to the two furnaces that started production in late 1988. This third furnace has not been included in the model. Also, it was indicated in late 1989 that Tubatse Ferrochrome was planning to add another 40,000 to 50,000 mtpy of high-C FeCr capacity to the present 300,000 mtpy already included in the network flow model for their smelter at Steelport. In total, these three projects would represent 210,000 to 230,000 mtpy of potential new high-C FeCr capacity in South Africa that has not been included in the model.

Table F-3.—MEC FeCr smelting capacity representation in the network flow model for 1989, by country

Country	Number of smelters	Number of furnaces[1]	Ferrochromium capacity, kmt Total	High-C	Low-C
Brazil	1	7	137	123	14
Finland	1	2	180	180	—
France	1	1	25	25	—
Germany, Federal Republic of	1	1	40	—	40
Greece	1	1	40	40	—
India	7	10	260	230	30
Italy	4	4	106	106	—
Japan	7	15	361	323	38
Mexico	1	1	7	7	—
Philippines	2	3	85	85	—
South Africa	8	28	1,206	1,140	66
Spain	1	1	18	18	—
Sweden	2	4	183	183	—
Taiwan	3	3	15	15	—
Turkey	2	6	170	160	10
United States	2	3	73	55	18
Yugoslavia	3	9	108	90	18
Zimbabwe	2	13	232	200	32
Total	49	112	3,246	2,980	266

[1]Dedicated to FeCr production for purposes of the model; includes furnaces for slag and ferrochromium-silicon production used in producing low-C FeCr.

NOTE.—Dash indicates no applicable value.

Table F-4.—Major MEC chromite resources not included in the chromium network flow model

Country	Property, deposit, resource
Australia	Cork Tree Well, Wilson River, Coobina.
Canada	Bird River.
Greenland	Fiskenaesset.
New Caledonia	Offshore sediments.
Papua New Guinea	Ramu River.
South Africa	UG2 chromite.
Turkey	Adana Province (low grade).

In Turkey, there are two high-C FeCr smelting projects that have not been included in the network flow model. One is under construction as of 1990 and the other is only a prospective project. The smelter under construction is located in the Orhaneli area. It is a small facility owned and operated by a South Korean/Turkish joint venture. The size of this smelter is in question; some sources state that it will have a 20,000 mtpy capacity, and other sources give the planned capacity at 40,000 mtpy. The project includes the development of a captive mine to provide ore feed. The prospective smelting project is planned to be a very large (450,000 mtpy) smelting complex. If constructed, it will likely be sited near the indicated primary ore feed source, which is a 100 Mmt chromite resource of low grade (7 to 15 pct Cr_2O_3) located in the Adana-Karsanta area.

The network flow model also does not have any FeCr production capability built in for the smelter located at Mo-i-Rana, Norway. There are two furnaces at this facility: One is in production, and the other is idled as of late 1990. The furnace in production had been commissioned in September 1989 and was producing at an annual rate of 72,000 to 84,000 mtpy of high-C FeCr. Commissioning of the second furnace was scheduled for the second or third quarter of 1991, depending on market conditions.

Finally, a large amount of prospective smelting projects in India were announced during 1989. None of these projects was built into the present network flow model. If all of these planned projects are developed, a total of about 270,000 to 275,000 mt of annual FeCr capacity would be added to the 280,000 mt of FeCr capacity listed in table B-2 that is presently built into the network flow model.

Of these numerous prospective smelting projects in India, the most likely to be developed are those involving companies either presently controlling chromite resources or owning an existing smelter. TISCO planned to convert an existing 12-MV·A furnace—at a smelter in the Keonjhar area—from FeMn production and also planned to construct a new 15-MV·A furnace that would use pellet feed from the SRC prereduction process. These two furnaces would result in an estimated 40,000 to 45,000 mtpy of high-C FeCr production. IDC planned to add a new furnace at its Jaipur Road smelter that would be of a size capable of producing 15,000 mtpy of high-C FeCr. In addition, Misrillal Mines obtained a license to build a new smelter capable of producing 15,000 mtpy of low-C FeCr.

Of those companies not controlling chromite resources, the largest project is Ispat Alloys Ltd.'s planned 37,500 mtpy high-C FeCr smelter that would use the Outokumpu Oy preheating process. The remaining 160,000 mtpy of new, licensed FeCr capacity would be split between 12 other companies. It is very questionable whether all of these small, potential FeCr producers that do not control chromite ore resources will actually get into production.

RECOVERIES OF CHROMIUM

Recoveries in chromite beneficiation used in this study represent individual property characteristics such as ore qualities and beneficiation techniques used or needed. Because of that it is very difficult to provide a generalized summary of the chromite beneficiation recoveries used in both the availability study and the network flow market model study. The following provides a summary of the ranges (or averages) used in these studies for smelting, chromium chemical processing, and refractory usage:

Process or Usage	Percent
High-C FeCr smelting:	
Conventional, Cr in fines ore to Cr in FeCr	75
Conventional, Cr in lump ore/briquettes to Cr in FeCr	80-85
Outokumpu Oy process, Cr in pellets to Cr in FeCr	85-86
SRC process, Cr in pellets to Cr in FeCr	93
Krupp-CODIR process, Cr in fines/concentrates to Cr in FeCr	93
Plasma arc processes, Cr in fines/concentrates to Cr in FeCr	93
Low-C FeCr smelting (Perrin process):	
Cr in fines, concentrates, or lump to Cr in lime slag	100
Cr in fines, lump, or concentrates to Cr in FeCrSi	80
Cr into low-C FeCr in ladling procedures	80-85
Generalized overall average in Perrin process	76
Chemical processing: Cr in chemical grade concentrates to Cr in SBE	85
Refractory usage: Cr in chromite feed to Cr in refractories	100

PERCENTAGE OF CHROMIUM IN FERROCHROMIUM

Table F-5 provides a country-by-country list of the percentages of Cr in FeCr used to convert Cr flow tonnages in the model to FeCr amounts for reporting and analytical purposes. These overall country percentages are provided for both high-C and low-C FeCr products. For the MEC's of Brazil, Finland, France, Greece, India, the Philippines, South Africa, Turkey, the United States, and Zimbabwe, the values are very close to the percentages used in the availability study and are related to the property and ore type. For all of the other countries in the table, the values represent estimates that consider both the typical or probable ore sources and the typical or expected Cr-Fe ratios of those ores.

Table F-5.—Country averages, percentage of chromium in ferrochromium products, high-C and low-C FeCr

FeCr Product/country	Ce in FeCr (wt pct)
High-C:	
Albania	64.0
Brazil	54.0
China	64.0
Czechoslovakia	63.6
Finland	54.4
France	66.0
Greece	64.0
India	[1]58.8
Italy	63.0
Japan	55.0
Mexico	63.0
Philippines	62.5
Poland	55.0
Romania	55.0
South Africa, Republic of	53.0
Spain	55.0
Swaziland	54.0
Sweden	57.0
Taiwan	63.0
Turkey	67.5
U.S.S.R.	65.0
United States	[2]59.0
Venezuela	56.5
Yugoslavia	62.0
Zimbabwe	67.0
Low-C:	
Brazil	63.0
Canada	66.0
China	65.0
Germany, Federal Republic of	69.0
India	67.0
Japan	63.0
South Africa, Republic of	60.0
Turkey	69.5
U.S.S.R.	65.0
United States	60.0
Yugoslavia	65.0
Zimbabwe	68.0

[1]Average; year-to-year percentages vary depending on the solution and ranged from 57.8 to 59.8 pct.
[2]Weighted average for all actual and prospective production.

APPENDIX G.—NETWORK FLOW MODEL SOLUTION ALGORITHMS, OUTPUT, AND INTERPRETATION

The mineral supply network model is based on the principle of technical economic efficiency, adopting the goal of fulfilling specified market requirements (demand) with the minimum use of resources, i.e., at the lowest opportunity cost. Demand for specified mineral commodities in the model is either calculated automatically from an internal set of demand equations or set directly by the user. The supply side of the model is based on the interrelationships between the various mining, milling, smelting and refining facilities for a specific mineral commodity.

Minerals facilities are represented as discrete nodes in the network model and characteristically include mining and beneficiation stages, smelting stages, inventory stockpiles, ports or railheads, and final markets. Arcs represent the processing opportunities or flows of material. They lead from sources or supply points representing mines or existing inventories, through intermediate junctions, to final destinations, representing regional product demand. Units of flow throughout the network are consistently metric tons of contained metal. Mineral commodities marketed as alternative or associated products are modeled with separate paths.

Maximum and minimum admissible values of material flow and processing levels provide upper and lower bounds associated with the arcs. Each arc has an associated objective function cost coefficient equal to the minimum average variable cost (marginal cost) of the activity that the arc represents. Oligopolistic, vertically integrated mineral market characteristics are incorporated into the model via these constraints and the intrinsic network design. The model can be mathematically stated in vector notations as

$$\text{Minimize} \quad cf$$

$$\text{subject to} \quad Mf = b$$

$$0 \leq L \leq f \leq U$$

where c = vector of marginal costs,

f = vector of flows,

M = node arc incidence matrix (constraint coefficient matrix),

U = vector of upper bound constraints,

L = vector of lower bound constraints,

and b = vector of node requirements (predetermined demand).

This problem is solved via a thoroughly generalized network algorithm that uses a phase I-phase II start and progresses toward optimality in the following manner. Imaginary arcs (artificial variables) are introduced and form the basis for an initial feasible solution. During phase I, cost is set to zero on all real variables and a cost of one is assigned to imaginary variables. Using the primal simplex method, real variables are found to accept the flow from the starting imaginary variables. As flow on an artificial variable falls to zero, that artificial is removed from the problem. When all flows have been shifted to real variables, phase I is complete (i.e., there is a set of flows entirely on real variables). This represents a feasible, albeit a nonoptimal, solution. At the start of phase II, actual costs are restored to the real variables. The primal simplex method is again applied to find better (lower cost) flows. When no more flow can be shifted to alternative lower cost arcs, an optimal solution has been found. The solution fulfills technical efficiency since the technical limitations of the market (constraints) are observed and fulfills economic efficiency because output is supplied at the lowest system cost.

The code used by the model is extremely streamlined, requiring significantly fewer iterations and calculations than previous generalized network codes. There are two important benefits derived from this streamlining. First, the program runs faster. Second, fewer numerical operations mean increased numerical stability.

Mineral models occasionally deviate from the structure of cost-minimizing generalized networks through the inclusion of proportionalities. The flows on some (proportional) arcs must be relative to the flow on another (reference) arc. This situation arises when modeling polymetallic ores, process steps with multiple products, and processes requiring blended feed. These problems are handled in the following manner.

The user designates a proportional node between flows to be restricted. Either outgoing flow will be proportional to an incoming flow or incoming flow will be proportional to an outgoing flow. The arc to which other flows must be proportional is designated the reference arc. The user then defines the percent of reference arc flow that must occur on each proportional arc in the final network model solution. These can be discrete levels (e.g., 10 pct) or ranges (e.g., 8 to 12 pct). The upper bounds on proportional arcs are set to the maximum percent.

The problem is solved via a heuristic algorithm. The algorithm solves the initial cost minimizing problem. The flows on reference and proportional arcs are compared and where flows are outside the proportionality constraint bounds, the arcs bounds are adjusted toward the desired level. The algorithm is then reinvoked. This iterative process of optimization and constraint alteration is repeated until the flows in an optimal solution are all within the designated proportionalities.

The solution to the algorithm is provided in three parts: (1) the objective function value, (2) the optimal flows by arc, and (3) the "shadow price" associated with each constraint.

The first of these is a single dollar value equaling the minimum total system cost required to fulfill predetermined demand. The optimal value for the base case is used as a point of reference. In subsequent runs of the model, the optimal value can be compared to the original base case value to determine, ceteris paribus, how a change to the network flow model would affect total cost.

For the second optimal solution, arc flows are defined as the predicted level of flow in metric tons of contained metal for each arc and are segregated into two types: nonbasic arc flows and basic arc flows. Arcs that have an optimal flow equal to either zero, the lower bound, or the upper bound are nonbasic arcs. Arcs with an optimal flow between zero and the upper bound are basic arcs. There is a maximum of one basic arc for each node. (Basic and nonbasic flows can be reported together or separately as desired.)

It is important to keep in mind that the network flow model is solved with a cost-minimizing algorithm; hence, the simultaneous solution represents a system-wide cost minimization as opposed to cost minimization for any single property. Every individual flow is a function of the cost and constraints not only on that arc but also on all other arcs. The solution flows represent the optimal results if the economic world were "rational" and "efficient" and only cost minimizing goals were taken into consideration. As a result, flows can be viewed in two different but interrelated contexts. The levels of flow into a single destination (head node) from several competing sources (tail nodes) are indicative of the relative competitive status of each of the suppliers into that market. Simultaneously, the levels of flow from a single source (tail node) to several destinations are indicative of the relative attractiveness of each of the alternative markets.

To compare the relative competitive position of several suppliers in a single market, it is necessary to compare the optimal flow on each incoming arc to the capacity constraints on that arc. For example, if three arcs are directed into a single port, each corresponding to a different country, it is possible to rank the three source countries in terms of relative competitiveness. If the optimal flow on one arc is at zero units, then that supplier is relatively less competitive than other possible suppliers. Conversely, if optimal flow on an arc is at the upper bound, then that supplier would be considered relatively more competitive than suppliers whose optimal flow is not at the upper bound constraint. Suppliers for whom the optimal solution is between the upper and lower bound have an intermediate competitive position: above those suppliers with flow at zero and below those with flow at the upper bound.

These results can be explained in terms of economic efficiency, but to do so requires the use of the third part of the solution, the shadow prices. Each node in the network is assigned a shadow price pi (or node potential) as part of the optimal solution. Pi represents the value to the system of a unit of flow added to the network at that node. In other words, pi represents the amount by which the objective function value would change if the RHS value of a node constraint were increased by one unit.

Once the shadow price at each node has been determined, the rules of complementary slackness are used to identify which arcs should have increased flow. Where cost minimization is the objective, c_{ij} is the cost on arc ij, m_i is the arc multiplier at node i (or M matrix coefficient for arc constraint i), and m_j is the arc multiplier at node j. The complementary slackness rules are as follows:

1. If c_{ij} is less than $pi_i m_i + pi_j m_j$, it is profitable for arc ij to increase its flow, and, in fact, the unit increase in profitability or marginal profit is $pi_i m_i + pi_j m_j - c_{ij}$.

2. If c_{ij} equals $pi_i m_i + pi_j m_j$, increase or decrease of flow on arc ij does not affect the objective function value.

3. If c_{ij} is greater than $pi_i m_i + pi_j m_j$, it is profitable to decrease flow on arc ij.

Complementary slackness states that if the increase in value of a unit of flow as a result of moving from the tail node to the head node is greater than the cost of doing so, then it is economically efficient to do so. Conversely, if the increase in value of a unit of flow as a result of moving from the tail node to the head node is less than the cost of doing so, no units should be moved. A supplier can be considered relatively more competitive in a specific market to the degree that flow from that source is economically efficient compared to flow from other suppliers. (As stated previously, the model assumes "rational" cost minimizing economic behavior.)

Consider an arc with optimal flow at the upper bound. Flow has been set to the upper bound because it was efficient to do so; i.e., the difference in shadow price at the head node versus the tail node is greater than the unit cost associated with the arc. If optimal flow is set at the lower bound, then the marginal arc cost is greater than the potential increase in shadow price, so it would be inefficient to have flow on the arc. Flow would be greater than zero on such an arc only when the lower bound forces flow. If flow is between the lower and upper bounds, cost equals the potential change in value and the model is indifferent as to level of flow.

If multiple arcs are solving at the upper bound, suppliers can still be ranked by competitive position through the use of sensitivity analysis. Flow out of the head node representing the market in question is decremented and the network flow model solved with the algorithm. As this process is repeated, the reduction in total flow out of the head node forces flow to that node to be reduced. The supplier first losing flow is the least competitive in the market.

TRANSPORTATION ALGORITHM OUTPUT AND INTERPRETATION

The initial optimal solution discussed above (as distinguished from sensitivity analyses) is used to develop regional short-run supply curves for delivered secondary product. A short-run industry supply curve is a schedule of the amount of product all firms are willing and able to offer for sale at each cost and is represented by the horizontal summation of the individual marginal cost curves for each firm. In this model, the quantity-marginal cost relationship representing supply is derived by determining the marginal supplier to each region for a range of quantity levels. The marginal supplier will have an associated marginal cost per unit of delivered secondary product, which is the sum of the arc costs for all arcs (corrected for arc multipliers) in the path from mine to demand point. As was previously discussed, arc costs are considered marginal costs and so a sum of the arc costs over a path is identical to the marginal cost for a unit of delivered product. The marginal supplier is defined as that supplier with the highest marginal cost to a particular demand node. As such, it would be the first supplier to lose market share if demand were reduced.

Because of the complexity of the network model design, in terms of both number of nodes and direction of flow, it is impossible to identify all the paths from mine to demand point by visual examination of the simulation results. Rather, the marginal supplier is identified through the use of the transportation algorithm. This algorithm takes into consideration the combinatorial complications arising from the non-discrete nature of generalized network flows and is applied to the optimal data set from the generalized network solution.

Paths are selected in the following manner with the goal of identifying the alternative distribution paths compatible with the least cost solution. That is, paths must use the optimal network solution. Arcs for which the optimal flow is zero are automatically excluded from the set of possible arcs available to the transportation algorithm. The program then solves for the shortest path from every source to every destination. A simple FIFO, first-in/first-out, shortest path algorithm is used. The program next selects the minimum, or shortest, path distance to each destination as calculated above and sends as much flow as possible (consistent with the optimal solution) along those paths, storing them in memory. Since the algorithm is working only with optimal flows, sending "all available" flow is consistent with the optimal solution. The optimal flows are reduced by the path flow just recorded in memory. This process is repeated until there are no more flows left for which paths are needed. At this point the problem is finished.

Paths are reported by region, by demand type, in order of increasing marginal cost. The most expensive path to each demand type in each region is flagged as a marginal path. The marginal cost on the marginal path is paired with the demand quantity for the associated demand node as the price/quantity coordinate. Output will be as follows:

1. A list of all paths used to fulfill each D_{rji} sorted in order of increasing MC_{ri} for each year in the simulation.

2. A list of the marginal paths for each D_{ri} and the associated MC^*.

Given $i = 1,...,m$ (demand regions),

$j = 1,...,n$ (demand levels),

$r = 1,...,p$ (product type),

$s = 0,...,q$ (supply paths),

D = demand,

MC = marginal cost,

and MC^* = marginal cost on the marginal path.

One output of the model is a graph of unit cost for delivered product versus cumulative quantity, for all paths to a single destination (see the analysis results for examples). It allows the user to visually compare the cost-quantity relationships for all suppliers to a single demand region. This is particularly useful in sensitivity analysis, allowing visual comparison of the cost of suppliers under differing scenarios.

It is important to keep in mind that the transportation solution is guaranteed to be optimal but not to be uniquely optimal. By nature of the design of thoroughly general networks, more than one optimum is possible. (Therefore, the marginal supplier should be viewed as a proxy for the actual marginal supplier.)

To develop the vector of price/quantity coordinates that will be used to represent supply, it is necessary to repeat the foregoing process of determining marginal suppliers, by region, for a series of different demand levels. These demand levels are calculated from the demand equations for each region. For a given scenario (i.e., network design), all variables in the demand equation are fixed by the user except for price and quantity. By varying price, a series of quantities can be calculated. This process is repeated for each of the demand regions, using the same set of prices. The result of solving the problem repeatedly with these demand values is arrays of marginal delivered cost/quantity coordinates by product and by region.

Once a vector of marginal cost/quantity pairs has been calculated, these values are regressed to calculate the short-run supply curve for delivered product. An ordinary least squares regression is used.

MULTIYEAR ANALYSIS

The network flow model can be used for multiyear analysis. Specific demand values or growth rates from a base consumption value are set by the user for each product in each region for each year. Alternatively, annual growth rates for demand equations can be entered. For forecasting simulations, changes in inventory demand are set by the user.

The previously mentioned regression equation representing supply and the equation representing demand can be solved simultaneously to generate a short-run equilibrium delivered marginal cost and quantity. The dollar value should *not* be viewed as a price forecast. Since the model is variable cost based, return to capital is not part of the solution value, but would certainly affect pricing decisions. The equilibrium MC and quantity values have several important uses. Equilibrium MC values from sensitivity analyses can be compared to base year values to give an indication of possible relative movement of price with respect to market changes. Also, demand is set equal to the equilibrium quantities for a final optimization of the network. Optimal flows from this solution are used to identify production levels by property, relative competitive status into specific markets, and marginal suppliers.

The individual production levels identified through use of the price quantity equilibrium for a single year are used to reduce economic reserves of each property prior to the next year's simulation of the multiyear analysis. As a property's economic reserves are reduced to zero, it no longer can supply the network. Exhaustion of reserves is modeled in this manner.

Nonproducers are considered for reclassification as producers between each year of a multiyear run. The criteria for changing a property to producer status are listed below. A positive response to any one of the four would trigger the change.

(1) Reserves at another mine (specified by the user) are exhausted.

(2) Equilibrium MC in the previous time period equals or exceeds a price specified by the user.

(3) Equilibrium quantity in the previous time period equals or exceeds a quantity specified by the user.

(4) The prespecified simulation year is reached.

All nonproducing properties have default values for each of these criteria; however, each can be changed by the user. To bring properties into the simulation, the upper bound on the slack supply arc associated with that property's mining node is reset to equal economic reserves. This does not mean that a property will automatically operate; the cost minimizing algorithm chooses who will produce and at what level. Reclassifying a property merely provides the opportunity to produce.

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