

# Chromium in South Africa

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## SYNOPSIS

The locations of potential reserves of chromite ores throughout the world are discussed. Reference is made to the marked changes in international trade in chromite ores during the past ten to fifteen years, and to the change in locality of the production of ferrochromium alloys, which is currently largely carried out in the country of origin of the ores. The influence of these changes has been very profound in South Africa, which has the largest smelting capacity and the largest production of ferrochromium alloys in the world.

A proportion of South African ore is still exported to meet the demands for the production of chromium chemicals and refractories, including a large tonnage of foundry sands.

Ferrochromium smelters in South Africa have a capacity of virtually 1 Mt of alloy per annum. Nearly all this development has taken place since the introduction of the argon-oxygen decarburization (A.O.D.) process for the smelting of stainless steels. Formerly, expensive low-carbon ferrochromium alloys were required as raw materials, but the A.O.D. process, which is being used world wide, permits the use of high-carbon ferrochromium, the main product of the smelters in this country.

The production in South Africa of chromium-containing corrosion- and heat-resistant steels is still on a relatively small scale, but serious attention is being paid to the exploitation of low-carbon weldable ferritic chromium steel.

## SAMEVATTING

Die ligging en moontlike reserwes van chromietertse oor die hele wêreld word bespreek. Daar word verwys na die duidelike veranderinge in die internasionale handel in chromietertse gedurende die afgelope tien tot vyftien jaar en die verandering in die plek waar die ferrochromlegerings geproduseer word wat op die oomblik hoofsaaklik die lande is waar die ertse voorkom. Die invloed van hierdie veranderinge was baie verreikend in Suid-Afrika wat tans die grootste smeltvermoë en die grootste produksie van ferrochromlegerings in die wêreld het.

'n Gedeelte van die Suid-Afrikaanse erts word nog uitgevoer om in die vraag van die produksie van chroomchemikalië en vuurvaste materiale te voldoen, en dit sluit in groot tonnemaat gieterysand in.

Ferrochromsmelters in Suid-Afrika het 'n vermoë van feitlik 1 Mt legering per jaar. Feitlik al hierdie ontwikkeling het plaasgevind sedert die invoering van die argon-suurstof-dekarbuseringsproses (die ASD-proses) vir die uitsmelting van vlekvrystaal. Vroeër was die nodige grondstowwe duur laekoolstof-ferrochromlegerings, maar die ASD-proses, wat tans wêreldwyd gebruik word, het dit moontlik gemaak om hoëkoolstof-ferrochrom, wat die vernaamste produk van die smelters in hierdie land is, te gebruik.

Die produksie in Suid-Afrika van chroomhoudende korrosie- en hittebestande staal geskied nog op 'n betreklik klein skaal, maar daar word ernstige aandag geskenk aan die gebruik van sweisbare ferritiese chroomstaal met 'n lae koolstofinhoud.

## Introduction

Lead chromate ( $PbCrO_4$ ), an orange-red mineral found in the Beresof Mine on the eastern slopes of the Ural Mountains in the U.S.S.R., was the first known and mined source of chromium. Originally used as a pigment, this 'Siberian red lead' was mined and shipped to Europe and the U.S.A. In 1798 Nicholas-Louis Vauquelin finally succeeded in extracting a minute quantity of chromium metal from a sample of Siberian red lead. A deposit of the black mineral chromite was found in Maryland in the U.S.A. in 1827, and for twenty years this deposit was the only available source of chromite ore. In 1848 high-grade chromite deposits were discovered in Turkey, and these constituted the main source of supply until the discovery of chromite ore in India and Rhodesia in about 1906.

The world production of chromite ore showed no significant expansion until 1932, but from that year to 1980 there was a fiftyfold increase in production, from 200 kt to 10 Mt per annum.

Chromite ore is obtained from major sources in ten different countries, the largest quantities being supplied

by the Republic of South Africa and the U.S.S.R. (Table I). In 1980, the year of maximum production, the respective output of ore from South Africa and the U.S.S.R. was 35,3 and 25,3 per cent of the world's total of 10 Mt. A significant drop in the world total (from 10 to 8,4 Mt) occurred from 1980 to 1983. Albania was the only producing country that increased its output, and the U.S.S.R. the only one that maintained its production at a constant level. In 1982, production in South Africa dropped by 35 per cent, but estimated figures for 1984 show a recovery to 3 Mt.

## World Reserves of Chromite Ores

### *South Africa and Zimbabwe*

Of the world's total reserves of chromite ore, which amount to 3330 Mt, 68 per cent or 2270 Mt are in the Republic of South Africa and 30 per cent or 1000 Mt in Zimbabwe. For many years, the ores from the Shurugwi deposits in Zimbabwe, which are hard and lumpy and have a chromium-to-iron ratio of 3,0 and higher, were the principal raw material used by the ferrochromium industry of the Western World. The depletion of these resources led to the exploitation of the chromite ores from the Great Dyke, which currently contains the entire reserves of chromite ore in Zimbabwe. The ore from the

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TABLE I  
WORLD PRODUCTION OF CHROMITE ORE (EXPRESSED IN KILOTONS)

Country of origin	Average annual production of ore per decade					Annual production of ore				
	1930 to 1939	1940 to 1949	1950 to 1959	1960 to 1969	1970 to 1979	1980	1981	1982	1983	1984
Albania	—	6	119	315	735	760	850	875	898	N.A.
Brazil	1	3	4	15	159	313	236	276	281	N.A.
Finland	—	—	—	11	256	566	631	610	510	890
India	38	39	57	100	334	319	336	340	363	N.A.
Philippines	28	144	519	528	504	496	439	354	363	N.A.
South Africa	92	240	613	973	2207	3414	2870	2164	2232	3000
Bophuthatswana	—	—	—	—	—	433	480	258	239	300
Turkey	122	199	672	445	525	399	423	372	363	N.A.
U.S.S.R.	148	358	647	1343	2022	2450	2400	2450	2450	N.A.
Zimbabwe	130	245	420	439	574	554	536	426	454	N.A.
Others	216	401	516	430	493	408	280	288	318	N.A.
World total	775	1635	3567	4539	7809	10 112	9481	8413	8471	

N.A. = Not available

Lower Group seams of the Great Dyke is of high grade (43 to 54 per cent  $\text{Cr}_2\text{O}_3$  with chromium-to-iron ratios of 2,6 to 3,5), but is much more friable than the ore from Shurugwi, and is not readily amenable to mechanized mining.

As shown in Fig. 1, the chromite-ore resources in South Africa are situated within the Bushveld Complex. This geological phenomenon, which consists of an enormous saucer-like intrusive igneous mass, extends for about 400 km from east to west, and roughly the same distance from north to south, and is located in the central and slightly western portion of the Transvaal. The Complex is highly mineralized, comprising deposits of fluorspar and tin in the acidic phase, platinum-group metals and chromite (which are associated with nickel, copper, and cobalt sulphides) in the mafic phase, and magnetites, which occur together with vanadium and titanium in discrete layers. The major reserves of platinum-group metals occur in the UG-2 Reef and Merensky Reef, which constitute the largest known deposits of chromium, vanadium, and platinum in the world.

The four major areas in which chromite ore is mined are the eastern chromite belt, the western chromite belt, the Zeerust district, and the area south of Potgietersrus.

The deposits in the Zeerust and Potgietersrus areas, where the resources are limited, have the highest  $\text{Cr}_2\text{O}_3$  content (52 to 57 per cent) and the highest chromium-to-iron ratios (2 to 2,9). The major deposits are in the western and eastern Bushveld, where the resources are vast but are of lower grade (45 per cent  $\text{Cr}_2\text{O}_3$ ) and have chromium-to-iron ratios of 1,5 to 1,6. Other deposits have slightly lower  $\text{Cr}_2\text{O}_3$  contents and lower chromium-to-iron ratios (1,4). In all, 21 mines have been established in these areas.

#### The U.S.S.R.

The reserves of chromite ore in the U.S.S.R. appear to be fairly substantial and are located almost entirely in the Ural Mountains, where the first chromium-containing mineral was discovered. An early Roskill report estimated the reserves at only 43 Mt. However, careful sifting of the available evidence from German and

U.S. sources indicates that the reserves may be much larger, amounting to over 200 Mt of proven reserves and 180 Mt of potential reserves, i.e. about one-sixth of those in South Africa. On average, the proven resources appear to contain about 50 per cent  $\text{Cr}_2\text{O}_3$ , and to have a chromium-to-iron ratio between 2,8 and 3,0.

#### Albania

Albania is within the Eastern Bloc, and emerged comparatively recently as the third-ranking country in the world in the production of chromite ore. The deposits, which are located in the Dinaric Alps, have estimated reserves of 22 Mt of massive hard ore with an average  $\text{Cr}_2\text{O}_3$  content of 43 per cent and a chromium-to-iron ratio of 3. Most of the ore is suitable for metallurgical and refractory usage, but a substantial proportion of the run-of-mine ore appears to be subjected to beneficiation processes, probably to produce concentrates for the production of chemicals.

#### Localities of Ferrochromium Production

Until 1973, the smelting of chromite ores to produce ferrochromium alloys was carried out extensively in the U.S.A., Western Europe, and Japan, which imported virtually all the ores they required. Electric energy from thermal stations was reasonably cheap, and in Canada and the Scandinavian countries hydro-electric energy was available for smelting. In the past twelve years, however, this situation has been affected by the rapid and unexpected escalation in the price of oil, which began in 1973, and the increasingly stringent regulations promulgated in the developed countries for the control of atmospheric pollution. Difficulties in the recruitment of labour for work in a 'dirty' industry has also adversely affected the situation. As a result, the places where ferrochromium is produced and the demand for imported ores have changed drastically. In a number of the developing countries with resources of chromite ores, e.g. Zimbabwe, the Republic of South Africa, and Brazil, electric energy is being generated by the use of hydro sources or fossil fuels like coal or natural gas. The regulations governing atmospheric pollution are not normally as stringent in

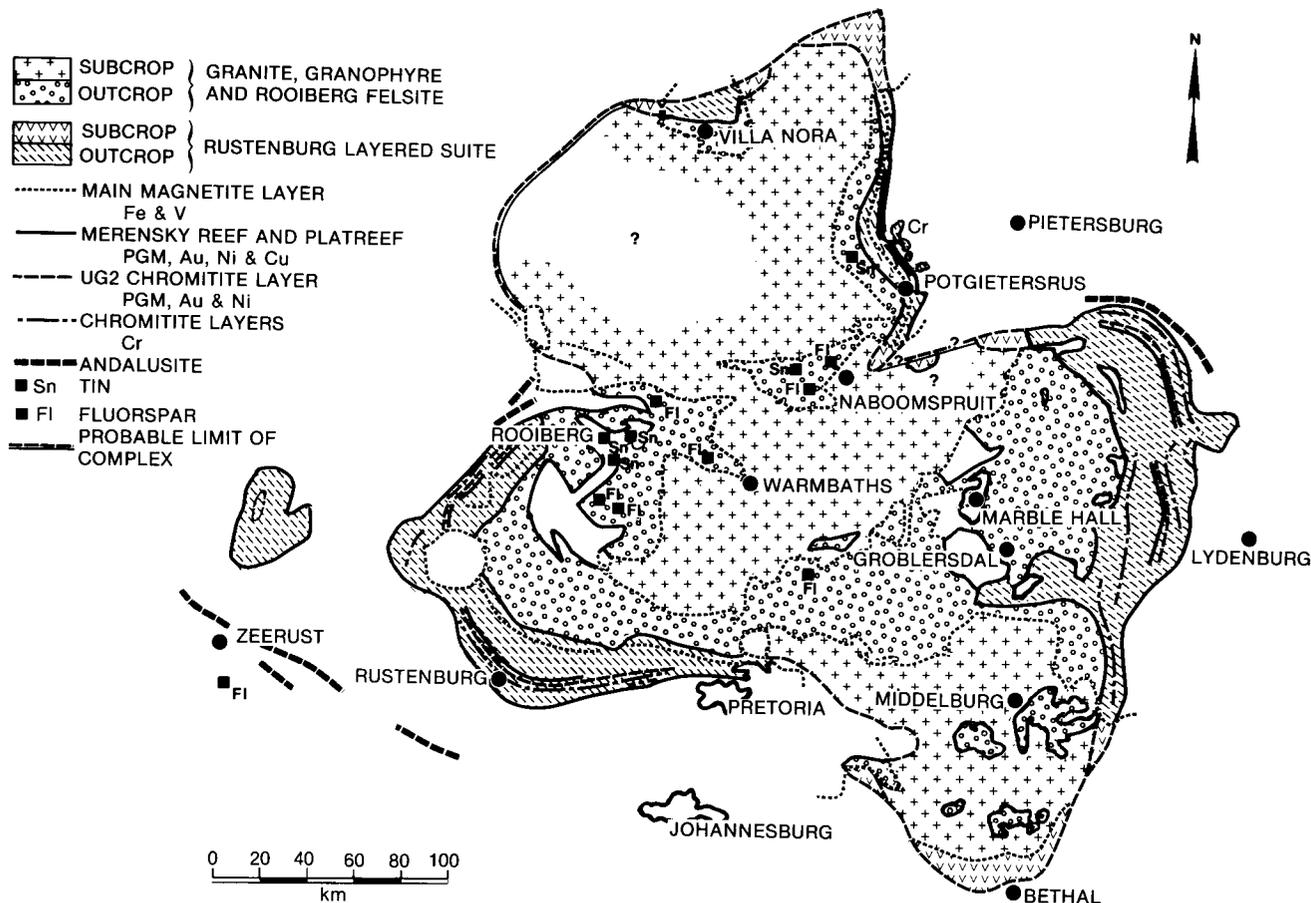


Fig. 1—Distribution of the basic and acid components of the Bushveld Complex (after Von Gruenewaldt)

developing countries as they are in developed countries, and local labour is available at reasonable rates. To a very considerable degree, therefore, the position has changed from one in which the producing countries exported chromite ores to the developed countries, which smelted the ore and absorbed the ferrochromium alloys in their metallurgical industries, to one in which the developing countries mine and smelt their ores and export ferrochromium alloys to the developed countries.

#### The Pattern in the U.S.A.

Data relating to the U.S.A. clearly show the extent of this change in the pattern of imports and exports for chromite ore and the production of ferrochromium. In the decade 1950 to 1959, U.S. imports of chromite ore reached a maximum of just over 1,5 Mt/a or 65 per cent of the world exports of this commodity; in the decade 1970 to 1979, the imports of chromite ore were 1,06 Mt/a or only 23 per cent of world exports. South Africa is still the main supplier of chromite ore to the U.S.A., accounting on average for 44 per cent of all the U.S. imports of this commodity from 1977 to 1980.

As shown in Table II, the apparent consumption of ferrochromium in the U.S.A. rose from 190 kt in 1970 to 293 kt in 1981. During that period, the imports of ferrochromium as a percentage of the apparent consumption rose from 12 to 76 per cent. The figures for 1982 are abnormal because of the severe recession in the steel industry, when the consumption of the alloy was only 45

per cent of that in 1981. In 1972 the installed capacity for ferrochromium production in the U.S.A. was about 390 kt/a, but this had declined to 145 kt/a by 1982.

The figures given in Table III, although somewhat distorted by the severe recession in the steel industry, show the general decrease in the production of ferrochromium alloys in the U.S.A. and Western Europe.

TABLE II  
FERROCHROMIUM IN THE U.S.A., 1970 TO 1982 (IN KILOTONS OF CONTAINED CHROMIUM)

Year	Domestic shipments	Imports	Apparent consumption	Imports as % of apparent consumption
1970	187	24	195	12
1971	155	49	189	26
1972	148	82	217	38
1973	220	95	315	30
1974	199	93	296	31
1975	101	180	235	76
1976	119	136	242	56
1977	122	122	245	50
1978	112	165	275	60
1979	137	123	260	47
1980	112	158	255	62
1981	81	224	293	76
1982	45	77	134	58

TABLE III  
WORLD PRODUCTION OF FERROCHROMIUM ALLOYS

Country of origin	Average annual production of ferrochromium per decade, kt					Annual production of ferrochromium, kt				
	1930 to 1939	1940 to 1949	1950 to 1959	1960 to 1969	1970 to 1979	1980	1981	1982	1983	1984
South Africa	—	—	—	27,4	314,6	720	630	450	700	900
Sweden	9,9	1,8	8,6	20,6	63,7	158,3	143,1	111,9	—	—
U.S.S.R.	—	—	1,9	23,6	46,0	630	640	600	—	—
West Germany	—	—	—	—	38,8	90	60	60	—	—
Finland	—	—	—	2,0	32,5	52,7	51,6	54,5	—	—
Japan	—	—	3,5	11,6	31,0	426,9	334,6	355,4	—	—
Yugoslavia	0,5	—	3,6	7,8	29,2	80	90	70	—	—
Zimbabwe	—	—	4,2	8,1	27,2	225	220	200	—	—
Norway	9,8	8,1	20,0	33,5	25,3	11,0	14,0	12,0	—	—
Brazil	—	—	—	—	24,6	93,4	128,8	96,6	—	—
U.S.A.	—	2,2	2,5	11,2	14,1	167,3	149,6	65,1	—	—
France	0,9	0,2	9,0	18,7	13,9	86,3	11,6	34,8	—	—
Italy	—	—	1,5	6,1	12,5	41,1	10,3	11,2	—	—
Turkey	—	—	—	4,3	12,3	46,0	40,9	39,9	—	—
Spain	—	—	—	—	6,3	18,0	17,6	15,6	—	—
India	—	—	—	—	4,3	16,3	15,0	15,0	—	—
China	—	—	—	—	0,4	70,0	70	90,0	—	—
Poland	0,2	—	—	—	—	52,0	52,0	52,0	—	—
Total Western World						2232,3	1827,1	1592,0		
South African production (% of total)					32,2	34,4	28,2			
Total world production	22,9	20,0	75,8	176,4	706,2	3047,3	2662,1	2407,0		
South African production (% of total)	—	—	—	15,5	44,5	23,6	23,6	18,7		

Fig. 2 illustrates the change in places where ferrochromium is produced. In addition to showing the very rapid rise in the total world production of ferrochromium over the fifty-year period 1930 to 1980, the graphs delineate the proportions of the alloy produced by

- countries with relatively cheap hydro-electric energy (Norway, Sweden, and Canada) smelting *imported* ores,
- developed countries smelting *imported* ores to produce ferrochromium that is absorbed by the national industries, and
- countries smelting *locally produced* ores and exporting most of the ferrochromium.

If hydro-electric energy is assumed to be the lowest-cost source of energy, the data shown in Fig. 2 suggest that, under present conditions, the locality where smelting is done depends largely on the costs involved in transportation of the ore.

A recent calculation by the U.S. Bureau of Mines indicated that the weighted average cost per pound of contained chromium in high-carbon ferrochromium smelted in South Africa from local chromite ore is \$0,32 f.o.b. Durban, whereas that for the same ore smelted in the U.S.A. would be \$0,43 f.o.b. Pittsburg. As transportation costs to the U.S.A. could range from \$0,04 to \$0,12 per pound, the difference is not considered to represent a major competitive advantage for producers in South

Africa. However, the depreciation in the exchange rate of the rand versus the dollar has undoubtedly contributed materially to increased exports of ferrochromium from South Africa.

#### The Pattern in Japan

In Japan, which uses some of the most up-to-date and efficient metallurgical processes in the world, the same change in the location of ferrochromium production is becoming evident. Japan's imports of chromite ore ranged from 962 kt in 1979 to 645 kt in 1983, while those from South Africa remaining fairly constant at 42 to 47 per cent of the total. The respective production of ferrochromium in Japan in 1977 and 1983 fell from 380,2 to 297,77 kt, whereas the imports rose from 104,1 to 297 kt. The local production was equivalent to 90 per cent of the consumption in 1977, but fell to 56 per cent in 1983. Except for the low figures for 1981, the production of stainless steel in Japan in this period was fairly constant, being within the range 1,75 to 1,84 Mt/a. There appears to be little doubt that the production of ferrochromium in Japan will continue to fall, since three plants were closed down in 1983/1984. Increased costs of fuel for the generation of electrical energy, possibly aggravated by the imposition of stringent regulations for the control of atmospheric pollution, have resulted in an average production cost in Japan of at least \$0,45 (U.S.) per pound of contained chromium, compared with a c.i.f. cost of

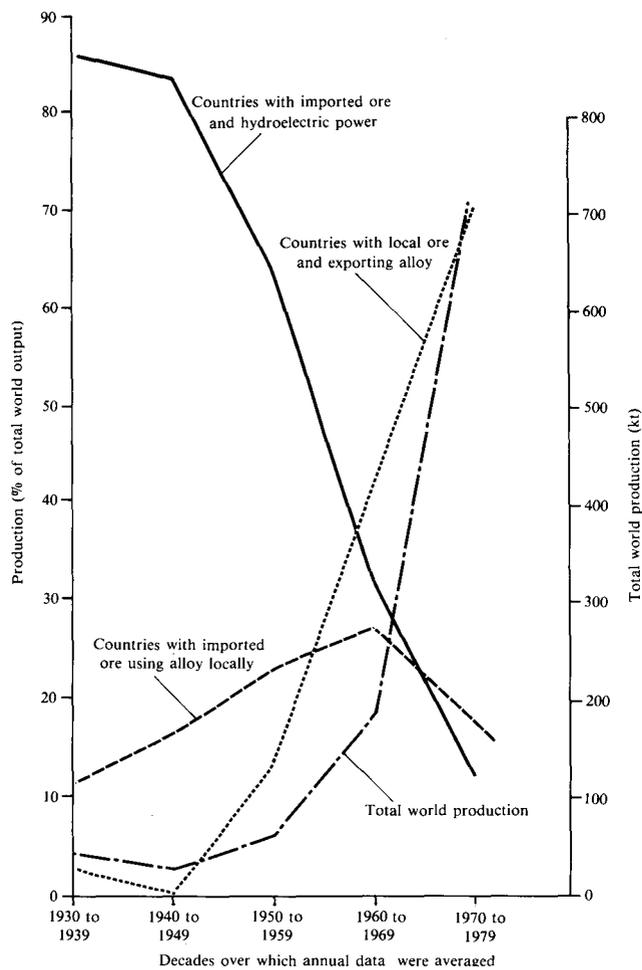


Fig. 2—Production of ferrochromium under various conditions in the countries of manufacture

around \$0,40 (U.S.) per pound of imported alloy.

#### The Pattern in South Africa

Up to twenty years ago, the chromite ores mined in the Republic of South Africa were considered to be suitable mainly for use in the chemical industry since the high iron content is beneficial in the production of sodium dichromate. Smaller quantities of ores with a higher alumina content were used for the production of foundry sands. As will be evident from Table IV, almost all the chromite ore mined up to 1960 was exported, although small quantities were used locally for the production of sodium dichromate.

South African ores were not seriously considered for smelting to produce ferrochromium, mainly because of their low ratios of chromium to iron (about 1,5). World ferrochromium producers preferred to use the ores from Zimbabwe and the U.S.S.R., since these ores were hard and lumpy and had chromium-to-iron ratios of 2,5 to 3,0. In addition, low-carbon ferrochromium was essential for the manufacture of stainless steel. The production of low-carbon ferrochromium is a highly sophisticated metallurgical process. Nevertheless, two South African plants to produce this alloy were commissioned in the 1950s: by Palmiet Chrome at Krugersdorp and by Transalloys at Witbank. As was to be expected, both plants experienced severe teething troubles.

TABLE IV

SOUTH AFRICAN LOCAL AND EXPORT SALES OF CHROMITE ORE

Year	Local sales		Export sales		Export sales (% of total)
	Amount kt	Value R/t	Amount kt	Value R/t	
1960	62,7	7,6	861,1	6,4	93,2
1965	184,7	5,1	701,1	8,6	79,1
1970	330,4	6,1	1021,4	8,8	75,5
1974	567,4	8,5	1072,4	13,9	65,4
1975	745,2	16,4	1246,4	23,1	62,6
1976	899,4	24,7	1196,4	26,4	57,0
1977	1215,4	29,6	1463,4	42,2	54,6
1978	1083,3	25,2	1422,6	43,2	56,7
1979	1309,1	28,4	1269,5	41,0	49,2
1980	1326,5	30,3	1213,3	41,1	47,7
1981	1072,7	31,1	1171,6	45,2	52,2
1982	830,4	24,2	865,6	53,2	51,0
1983	1567,7	31,8	803,2	49,9	33,9

In the early 1960s, Union Carbide Corporation announced the development of a new process (argon-oxygen decarburization or the A.O.D. process) for the production of stainless steel, which involved the simultaneous injection of argon and oxygen into the molten charge in a refining vessel. The injection of argon resulted in a marked reduction in the partial pressure of carbon monoxide in the molten steel, and permitted the reduction of the carbon in the molten mixture of steel scrap and ferrochromium to the very low values required, so that ferrochromium with much higher carbon contents could be used. This new process, together with the variants that were developed subsequently, revolutionized the production of stainless steel and made a major impact on the ferrochromium industry. It became very evident that high-carbon ferrochromium would soon be the major alloy to be used as a raw material for the production of stainless steel, and that only limited quantities of low-carbon ferrochromium would be required for that purpose. The significance of this development is underlined by data from the U.S.A., which show that, of the total 1968 consumption of ferrochromium alloys for the manufacture of stainless steel, 47 per cent consisted of low-carbon ferrochromium and 28 per cent of high-carbon ferrochromium. By 1980, the consumption of low-carbon ferrochromium had decreased to 6 per cent of the total, whereas that of high-carbon ferrochromium had increased to 80 per cent.

However, the ferrochromium industry in South Africa still had some problems to solve. The low chromium-to-iron ratio of about 1,5 in South African ores restricted the chromium content of the alloy to between 50 and 52 per cent, and the ores normally yielded an alloy containing 6 to 7 per cent silicon and 6 to 8 per cent carbon. This product was described as 'charge chrome'. After some aggressive marketing campaigns, this alloy was accepted by stainless-steel producers world wide, which gave a great impetus to the South African ferrochromium industry. As will be clear from Table II, the production of ferrochromium in South Africa really began to escalate in the 1970s, rising from 200 kt in 1973 to 900 kt in 1984, the latter being equivalent to between 20 and 25 per cent of the total world production.

### The Pattern in the U.S.S.R. and the Eastern Bloc

In addition to showing the dominant position of South Africa among world producers of ferrochromium, Table III highlights the increasing influence of the U.S.S.R. in world production. From Table V it appears that production in the U.S.S.R. and the countries of the Eastern Bloc was less severely affected by the world recession in the steel industry than it was in the Western World, and that those countries accounted for about one-third of the total world production in the very early 1980s. China is unusual: it appears to have produced up to 90 kt of ferrochromium but has only minute known reserves of chromite ores. Until 1978 most of the ore required by China was obtained from Albania, but, after a breakdown in relations between the two countries, China had to obtain ore from various alternative suppliers, one of which is reported to be Zimbabwe, which also supplies China with ferrochromium.

TABLE V  
PRODUCTION OF FERROCHROMIUM ALLOYS IN THE EASTERN BLOC  
(EXPRESSED IN KILOTONS)

Country	1978	1979	1980	1981	1982
U.S.S.R.	550	550	630	640	600
Poland	50	52	52	52	52
East Germany	25,4	20,9	20	20	20
Czechoslovakia	30	28	28	28	28
Albania	—	5	15	25	25
China	70	70	70	70	90
Total	725,4	725,9	815	835	815
World total	2473,6	2900,7	3047,3	2662,1	2407,0
Eastern Bloc countries (% of world total)	29,3	25,0	26,7	31,3	33,8

### Usage of Chromium in Industry

The three main areas for the first-use consumption of chromium are the metallurgical industry (ferrochromium alloys and chromium metal), the refractories industry (refractories and foundry sands), and the chemical industry.

Only limited data are available for the absorption of chromium in these three areas, but accurate statistics from the U.S.A. indicate that metallurgical products, refractories, and chemicals account for 76, 13, and 11 per cent of the total U.S. consumption respectively. However, such relative proportions must not be taken as being representative of all countries, particularly the developing countries. What does emerge very clearly is that future growth in the consumption of chromium depends to a very large extent on the progress of the stainless-steel industry. In South Africa, for example, some of the chromite ores are particularly suited to the production of sodium dichromate, and a substantial proportion of these ores are purchased for chemical use, as shown in Table VI, which gives South Africa's exports of chromite ore in 1983 as 804 kt, i.e. 32,6 per cent of the total ore production.

TABLE VI  
EXPORTS OF CHROMITE ORE FROM SOUTH AFRICA IN 1983  
ACCORDING TO END USE

End use	Amount kt	Amount %
Chemical	304	37,8
Metallurgical	207	25,7
Foundry	136	16,9
Refractory	62	7,7
Unspecified	95	11,8
Total	804	100

Hence, in spite of the vast increase in its production of ferrochromium alloys, South Africa still supplies over 50 per cent (390 kt) of the chromite ores used by the chemical industries in the world. Other countries supplying smaller quantities to the countries of the Western World are Finland, the Philippines, and Turkey.

The absorption of chromium in the three areas of consumption is fairly closely associated with grade, chemical composition, and mineralogical and physical characteristics of the ore. Many of the ores throughout the world, particularly in South Africa, are friable and disintegrate relatively easily, at least down to the size of chromite crystals. In addition, the minerals present are invariably in the form of oxides that have the stable structure of chrome spinel. The metallic portion of the spinel always contains chromium and iron together with aluminium and magnesium, and often with zinc.

### Beneficiation of Chromite Ores

The stable structure of these ores implies that processes for their beneficiation are limited to those capable of removing the physically associated gangue minerals, gravity-concentration processes normally being applicable. Some degree of beneficiation treatment is applied to the ore from most of the deposits in the world. The milling costs in Zimbabwe are possibly the lowest in the world because of the nature of the ore, but the mining and freight costs are relatively high.

South African chromite ores all undergo at least rudimentary beneficiation. Several methods are employed, the choice depending to a considerable degree on the type of product desired. Simple screening and hand-sorting operations may be adequate in some cases, but complex heavy-medium, magnetic, and gravity separation may be necessary in others. Intermediate and more widely used operations comprise crushing, washing-screening, hand-sorting or crushing, and washing-grinding-gravity separation. For gravity separation, mainly spiral concentrators are used, although shaking tables are used in a few instances.

Recoveries are usually within the range 80 to 85 per cent but, with the limitations of the beneficiation process, the Cr<sub>2</sub>O<sub>3</sub> grade can be increased by only 1 to 4 per cent. The operating costs of beneficiation are relatively low, probably in the range R3,50 to R12 per ton of feed, of which the labour component accounts for 40 to 50 per cent. Precise data are not available for the tonnages of ore treated by the various beneficiation processes

employed, but only about 30 per cent of the chromite ore mined in South Africa can be classified as 'lumpy ore' (a production of just under 1 Mt/a), most of which is presumably used for the production of ferrochromium in submerged-arc furnaces. At an 85 per cent recovery of the chromium in the ore into the ferro-alloy, 2 t of ore are needed to produce 1 t of ferro-alloy, and about 2 Mt of ore containing 44 per cent  $\text{Cr}_2\text{O}_3$  are needed to produce 900 kt of alloy. Therefore, a substantial proportion of the beneficiated ore is absorbed by ferrochromium producers, leaving about 1 Mt of beneficiated ore for other purposes. A large proportion of the beneficiated ore is too fine to be fed direct to submerged-arc furnaces, and requires some form of agglomeration before it can be used. Some of the concentrates from the grinding and beneficiation processes constitute the starting materials for the production of chemicals, refractories, and foundry sands.

#### *Production of Chromium Chemicals*

The low-grade chromite ores from the Transvaal with low chromium-to-iron ratios are accepted locally and overseas as being very suitable for the production of sodium chromate, which is accomplished as follows. Finely ground chromite ore is roasted with soda ash and lime, and the lime forms insoluble compounds with the gangue minerals in the ore. The chromate is then leached from the calcined products with water, and is converted into sodium dichromate by being reacted with sulphuric acid. Sodium dichromate has a wide variety of applications in industry, being used in the production of pigments (mainly for paints and glazes), the tanning of leather, the preservation of timber against attack by fungi and insects, and as mordants in the dyeing of woollen and silk fabrics.

#### *Electroplating with Chromium*

Sodium dichromate is the essential raw material for chromium electroplating, which is used very widely and is evident in all types of durable goods. Much electroplating is carried out primarily for decorative purposes, although it also supplies substantially increased protection to steel components that are exposed to atmospheric conditions. A very much smaller but very important section of the electroplating industry is 'hard-chrome' plating, which can be used to provide protection against wear and severe surface corrosion, and to refurbish the worn steel components of machines. Hard-chrome plating is usually much thicker (up to 2 mm) than decorative plating ( $0,5 \mu\text{m}$ ), and can be produced to have a hardness of up to  $\text{HR}_c 63$ . Estimates suggest that chromium electroplating accounts for about 3,3 per cent of the total consumption of chromium.

#### *Chromium in Refractories and Foundry Sands*

The chromium-containing refractories—chrome magnesite and 'mag chrome'—are used mainly in the roofs of open-hearth steel furnaces and in fuel-fired reverberatory furnaces for the smelting of copper matte. Changes in the technology of steel production and the major application of the basic-oxygen furnace to steel production have resulted in a marked decrease in the demand for these refractories, except in the U.S.S.R., the countries of the Eastern Bloc, and India, where open-

hearth furnaces are still used fairly extensively.

The production of chromite foundry sands is a relatively sophisticated operation, involving the production of ground ore to fairly strictly specified size limits, chemical composition, and maximum concentrations of impurities. South Africa is the world's largest supplier of foundry sands, the estimated production in 1984 being 175 kt. However, this is markedly lower than the production in earlier years, which was 350 kt. The only other producer of chromite foundry sands is Outokumpu Oy in Finland, where the production amounts to about 20 kt/a.

#### *Production of Ferrochromium*

All chromite ores smelted for the production of ferrochromium alloys contain chromium in the form of chromite, which has the very stable crystal lattice of chrome spinel. The general structure of the spinel can be represented as  $\text{R}^{2+}\text{R}_2^{3+}\text{O}_4$ , where  $\text{R}^{2+}$  can be iron, magnesium, zinc, or manganese, and  $\text{R}_2^{3+}$  can be aluminium, iron, chromium, or vanadium. In virtually no instance does the pure mineral,  $(\text{FeCr}_2)\text{O}_4$ , occur, and the metallic portion of the spinels may be very complex. Of the elements listed, aluminium, magnesium, manganese, and zinc should be oxidized, fluxed, and passed into the slag during smelting. If a carbonaceous reducing agent is used, the thermodynamics of the reduction reactions ensures that the iron and the chromium invariably form carbides and are not reduced to the metallic state.

For the production of a low-carbon alloy, therefore, the chromium oxides must be reduced by a non-carbonaceous reducing agent like the silicon component of ferrosilicon or ferrochromium-silicon. The most common method employed for the production of low-carbon ferrochromium involves the very vigorous mixing of a molten lime-chromite slag with ferrosilicon or ferrochromium-silicon. The iron and the chromium are both reduced from the spinel, and the chromium-to-iron ratio in the ore prevails in the ferrochromium alloy. This fact has a pronounced bearing on the economic aspects of ferrochromium production, since the price of the product is determined by the contained units of chromium present. Former specifications usually called for a chromium content of not less than 60 per cent, but this was waived as a result of the large tonnage of charge chrome sold by South Africa.

#### *Smelting of Chromite Ores*

Major attention is given to smelting practice in South Africa, which is currently the largest producer of ferrochromium alloys in the world. If the exceptionally low figures for 1982 are ignored, it can be seen that the production of ferrochromium alloys by South Africa in the 1980s represented about one-third of the total production in the Western World and almost one-quarter of the total production in the world.

As will be obvious, the essential requirement is the highest possible recovery of chromium as a ferro-alloy with the maximum feasible chromium grade. The non-reducible oxides in the ore, i.e. magnesium oxide, calcium oxide, alumina, and silica, must be absorbed into a slag that has the desired liquidus temperature, viscosity, and optimum electrical conductivity. The reduction of

chromium and iron in the ore is effected by a carbonaceous reducing agent in the form of coke, char or, under certain conditions, coal or anthracite. The thermal energy required to melt the reactants and products and to induce the chemical reaction is provided electrically by three self-baking graphite electrodes in the furnace.

The non-reducible oxides must be absorbed in the slag and, although a self-fluxing charge is sometimes possible, fluxes must usually be added to produce a slag with the desired characteristics. The fluxes comprise quartz (to supplement the quantity present in the ore), dolomite (to control the desired MgO-to-CaO ratio), and serpentine (for the desired MgO to SiO<sub>2</sub> ratio). Basically therefore, the slags can be regarded as multi-component systems containing MgO-SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub>, CaO, FeO, and Cr<sub>2</sub>O<sub>3</sub>; the base diagram for these systems is the ternary system MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>, which has been very well established for many years. Numerous researchers have studied the phases present and the changes effected in the liquidus temperatures when various quantities of CaO, FeO, and Cr<sub>2</sub>O<sub>3</sub> are added to this three-component system.

The three physicochemical properties of slags of particular interest in the smelting of chromium alloys are liquidus temperature, viscosity, and electrical resistivity. The liquidus temperatures of the slags used in submerged-arc furnace smelting have a particular importance in operation. In such a furnace, once the charge has reached the smelting zone and has fused, it drops away from the area of intense heat surrounding the arcs and settles at the bottom of the furnace. Consequently, if the alloy has to be superheated, say to a sufficient degree to permit continuous or machine casting, the slag must have a liquidus temperature considerably higher than that of the alloy. The products of smelting can drain away from the arc zone only when the slag is sufficiently fluid to permit this to happen, and at that juncture the alloy will already have been superheated.

The viscosity of the slag must be low enough to allow diffusion processes to take place at a sufficiently high rate for reactions between slag and alloy to rapidly approach equilibrium and so favourably affect the kinetics of the process. Ease of separation of alloy and slag is another aspect of slag viscosity and is of particular importance because of the turbulent conditions existing in the arc zone.

The transfer of electric current through the charge from electrode to electrode is probably primarily a function of the carbonaceous reducing agent but can also occur to some degree through the slag phase. The very low resistance (1 mΩ or less) across a submerged-arc furnace is probably due mainly to the high conduction through the carbonaceous reductant.

Research has therefore been directed to these three aspects of the physicochemical properties of slags with particular reference to the ternary diagram MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>. Additional data were also required on the effect of the quantities of FeO, CaO, and Cr<sub>2</sub>O<sub>3</sub> on the slag system.

In the middle of late 1960s, the ferro-alloy industry in this country was expanding markedly but was faced with a lack of fundamental information on slag and alloy constitution and properties. In addition, the installation of substantially larger submerged-arc furnaces compound-

ed some of these problems. At that time, the National Institute for Metallurgy established a Pyrometallurgical Research Group in the Department of Metallurgy at the University of the Witwatersrand. This Group began to investigate some of these problems with a view to providing some of the data urgently needed by the rapidly developing industry.

The ternary diagram (Fig. 3) of magnesium oxide, alumina, and silica can be used as the basis for the assessment of slag characteristics in the smelting operation. The proportions of each of the three components normally found in the slag lie within the region ABCD. The silica contents are from 25 to 45 per cent by mass, and the ratios of magnesium oxide to alumina are from 0,7 to 1,5. As can be seen from the isotherms, the liquidus temperatures in this region rise from 1550 to almost 1900°C as the silica content decreases from 45 to 25 per cent. The usual incompatibility is found of rising liquidus temperature with decreased viscosity of the slags in this region. The electrical conductivity of the slags increases as the silica content decreases, and an increase in the ratio of magnesium oxide to silica also raises the conductivity of the slags.

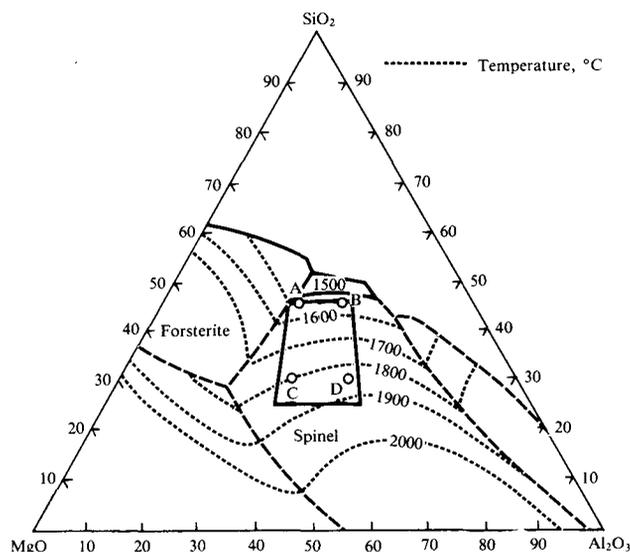


Fig. 3—The system MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>, indicating the region of slag compositions used in the production of ferrochromium

Other components found in the slag in practice are mainly calcium oxide and ferric oxide (about 6 per cent each), and Cr<sub>2</sub>O<sub>3</sub>. Calcium oxide and ferric oxide (mainly in the form of ferrous oxide) normally dissolve completely in the slag and have little effect on the liquidus temperature. Both oxides increase the electrical conductivity of the slag. The presence of Cr<sub>2</sub>O<sub>3</sub> also has this effect, but this oxide causes a rapid rise in the liquidus temperature. All three oxides reduce the viscosity of the slag, probably because of a higher concentration of cations in solution. One of the problems encountered is that most slags contain some undissolved (and unreacted) chromite, with a consequent reduced recovery of the metal; up to 17 per cent of the chromium charged to the furnace is lost to the slag in the form of oxide.

### *Reactions in the Submerged-arc Furnace*

The submerged-arc three-phase furnace is probably one of the most complex high-temperature reaction systems in existence. Theoretically, a mixed charge of ore, fluxes, and reducing agents descends smoothly to the region of the arcs, undergoes reduction and slag formation, and forms a smooth pool of ferro-alloy covered with slag in the bottom of the furnace. This happens only rarely in practice, and is the exception rather than the rule for the reaction processes. Also, the larger the furnace, the less likely is the operation to be completely smooth. The formation of slag occurs in a series of steps over a wide range of temperatures, 'primary slag' forming at a relatively high level in the charge and suffering major changes in composition as it descends towards the arc zone. Reduction of the oxides in the chromite begins with the reduction of iron oxide by carbon monoxide. At higher temperatures, incipient fusion commences with the formation of a slag phase, and this is believed to be a basic condition for the reduction of chromium oxide by solid carbonaceous reducing agent, since these oxides cannot be reduced by carbon monoxide gas. Carbon dissolves in the reduced iron, forming a molten iron-carbide alloy. This alloy diffuses fairly rapidly along grain boundaries and through fissures in the particles of ore, and brings about the reduction of chromium oxides. This sequence of events is facilitated by the diffusion of iron and chromium ions through the partially reduced particles of ore. As the charge descends further towards the zone of intense heat in the vicinity of the arcs, the stable complex carbides melt and accumulate in the molten-alloy phase. Several changes in composition probably take place as successive reactions occur, but the end-product is the relatively stable carbide  $(\text{FeCr})_7\text{C}_3$ . The liquidus temperature of the slag must be controlled so that the alloy is raised to the desired temperature before it falls away from the arc zone into the pool of molten alloy.

The gaseous products of the reactions (mainly carbon monoxide) rise through the descending charge, effecting heat transfer and providing the reducing agent for a proportion of the iron oxide in the ore particles. Clearly, it is essential for the descending charge to have good permeability so that the gases can diffuse and 'blows' and explosions can be avoided. Some of the furnaces used to melt chromite ores are not fitted with roofs, so that any thermal energy in the gases evolving from the charge is lost. In large furnaces, a taphole is provided in line with each electrode, since it is not at all unusual for separate pools of molten alloy and slag to be found in the vicinity of each of the electrodes.

A feature of these submerged-arc furnaces is the very low electrical resistivity of the charge, which ranges from about 0,5 to 1,5  $\text{m}\Omega$ . Therefore, the furnaces operate at relatively low voltage and very high amperage. Ohmic conduction is predominant in the upper part of the furnace, but arcing becomes predominant as temperatures increase in the lower regions. The dissipation of electrical energy from the electrodes is not easily measured, but some simulation testwork has indicated that 50 per cent of the total energy is dissipated from the tip of the electrode and 25 per cent from the last 300 mm of the electrode length. With an electrode penetration of 1800 mm, only 25 per cent of the energy is dissipated from the

1500 mm portion. This results in an intense concentration of thermal energy in the immediate vicinity of the electrode tips, the temperatures in the arc zone probably being about  $2000^\circ\text{C}$ .

All submerged-arc furnaces are equipped with self-baking electrodes of the Söderberg type, electrode paste being added to the top of the circular steel casing, which forms the exterior of the electrode and with which the ring of water-cooled copper contact shoes is forced into intimate contact at a zone just above the top of the furnace charge. Provision is made for the raising and lowering of the electrodes by an electromechanical hoist, or more commonly by hydraulically operated cylinders, the raising and lowering of the electrodes being adjusted so that the desired current supply is maintained at a constant level. Provision must also be made for periodic controlled slipping of the electrode through the ring of water-cooled contact shoes to compensate for the combustion of carbon from the tip of the electrode.

### *Larger Furnaces for Increased Production*

The notable feature in furnace design during the past fifty to sixty years has been an increase in the size of furnaces, both dimensionally and in electrical transformer rating.

The production of ferrochromium in South Africa began in the 1960s on a few small-scale plants. In 1973 the production was 210 kt, but this had grown to 900 kt by 1984. This rapid increase in production was due to the installation of larger submerged-arc furnaces. The earlier ferrochromium furnaces had a rating of only 4,5 MVA, but the industry currently runs four 48 MVA, two 32,5 MVA, and three 30 MVA furnaces, the total number of furnaces being 26. Hence, the total installed transformer capacity is 581 MVA and the total estimated furnace capacity is almost 1 Mt/a. The major advantage of large submerged-arc furnaces is the reduced labour component required per ton of alloy produced. Because of the sharp rise in the wages paid to unskilled operators in the past decade, this reduction in the labour component is of great value in the control of production costs. A recent estimate by the U.S. Bureau of Mines gave the production costs of South African producers f.o.b. Durban as 32 U.S. cents per pound of contained chromium, as compared with 43 U.S. cents per pound f.o.b. Pittsburgh for the same chromite resources smelted to the same grade of ferrochromium in the U.S.A. This fairly significant cost advantage is seriously eroded when shipping costs are taken into account. The most important disadvantage of larger submerged-arc furnaces is the restriction that must be imposed on the percentage of fines (defined as material smaller than 6 mm) present in the charge. A 9 MVA furnace will operate reasonably well with 60 per cent fines in the charge, but a 30 MVA furnace requires a charge that contains not more than 15 per cent fines. The friable character of the ores mined in South Africa therefore presents considerable problems in the operation of large submerged-arc furnaces. As not more than 30 per cent of the ore mined in South Africa can be classed as lumpy ore, a substantial proportion of the charge to a submerged-arc furnace must be subjected to some method of agglomeration.

### *Agglomeration of Fines*

The conventional travelling-grate sintering process, so widely adopted for the treatment of iron ore fines, cannot be used for chromite fines. Some South African producers turn the fines into briquettes, using the well-proven and widely used lime-molasses mixture as the binder, and sometimes incorporating at least a proportion of carbonaceous reducing agent. Like most unfired briquettes, these do not have a very high hot strength, but the addition of bag-filter fines from a ferrosilicon furnace brought about substantial improvements in one case. A ferrochromium producer in India briquettes fines screened from the ore with the product of a gravity-concentration process, which contains a proportion of material smaller than 75  $\mu\text{m}$ . The briquettes develop a reasonably high hot strength after a few hours, a feature probably associated with the fine material in the concentrate. Some of the briquettes produced in South Africa have low hot strength in the range 750 to 1000°C, which is believed to lead to increased losses of unreduced chromite in the slag.

An alternative route for the treatment of fines is provided by the Showa-Denko process, which involves pelletization of the fines and prereduction of the pellets in a rotary kiln. This process is in operation at the C.M.I. plant in the north-eastern Transvaal, where chromite ore fines (smaller than 6 mm) and coke fines are dried by the combustion of carbon monoxide gas from a submerged-arc furnace. The mixture is then finely ground, bentonite is added as a binder, and pellets ranging in size from 10 to 30 mm and having a moisture content of about 7 per cent are formed on a rotating disc. The pellets are dried and preheated on a travelling grate that is heated by the exit gases from a rotary kiln. The fuel-fired rotary kiln is claimed to effect 60 to 70 per cent prereduction of the charge, but requires very careful monitoring and control of the ratio of carbon monoxide to carbon dioxide and the free-oxygen content of the kiln gases. The prereduced pellets are then charged to two 32,5 MVA furnaces. Operational problems have been numerous, one of which is the variable carbon content of the pellets due to changes in the degree of reduction effected in the rotary kiln. As a result, the feed to the furnace must be monitored continuously so that the proportion of reducing agent and fluxes charged can be altered when necessary. Nevertheless, two very important points should be noted: the consumption of electrical energy per ton of alloy produced in the submerged-arc furnace is almost halved, and the recovery of the chromium in the charge to the smelting furnace is over 90 per cent as compared with 70 to 80 per cent by the conventional smelting process.

### *Plasma Smelting of Fines*

The only alternative technology currently in prospect for the direct smelting of fines is plasma smelting, which appears to offer a potentially attractive method for the treatment of chromite ore fines and for the remelting of the ferro-alloy fines that are produced in fairly large quantities during the crushing and screening of the cast alloy to market requirements. Thermal energy is usually generated by the combustion of a fossil fuel with air or oxygen-enriched air, or by an electric arc between a graphite electrode and a charge in a furnace. The plasma-arc torch works on a completely different principle: it

converts electrical energy into thermal energy by ionizing a gas, which becomes electrically conducting at temperatures in excess of 3000°C. The plasma torch has the following characteristics:

- (a) it requires only a small fraction of the gas associated with the combustion of fossil fuels,
- (b) the efficiency of conversion of electrical to thermal energy is very high, and
- (c) the gas used in the torch can be inert, reducing, or oxidizing, so that any desired controlled furnace atmosphere can be achieved.

One essential feature of the plasma process is that fine material can be treated directly, and hence there is no need for agglomeration. Substantial research-and-development investigations involving the plasma-arc technique have been carried out in many countries, including South Africa. An interesting aspect of the work done in Japan has been an attempt to produce stainless steel from mixtures of chromite and iron ore using a transferred-arc d.c. plasma furnace. Practical industrial applications of the plasma-arc techniques have been developed for the smelting of iron ore fines or concentrates to produce pig iron, and for the smelting of prereduced iron ore to produce steel.

The plasma process appears to offer other advantages besides its ability to treat fines, but a 20 MVA unit is the largest industrial unit to be installed so far. In South Africa, for instance, five plasma gas heaters of 8 MW have been commissioned for use in the reforming units of a direct-reduction iron (D.R.I.) plant, and a 10,8 MW unit to melt ferro-alloy fines has been installed on the Metalloys plant at Meyerton by Samancor Management Services (Pty) Ltd. This unit is similar to those used in the VEB Edelmetallwerke in Freital, East Germany.

The Swedish firm ASEA has been involved in the development of a d.c. arc furnace in which the charge is introduced into the arc zone through a hollow graphite electrode. A furnace of this type is reported to have produced 10 kt of steel by melting scrap. A similar 20 MW furnace was installed at the Krugersdorp plant of Palmiet Chrome Corporation and brought into commission in the latter part of 1983. Severe operating problems were encountered during the first eight months of operation, one of which was sticking of the charge as it was fed to the furnace through the hollow electrode. Substantial improvements have been effected since then, and the furnace is believed to be producing about 45 t per day from a mixed charge of chromite ore and ferrochromium fines. Feeding of the fines through the hollow electrode must be the most effective way in which the charge can be introduced directly into the hot zone of the furnace, but obviously involves considerable practical difficulties.

### *Computer Control of Furnace Operation*

The application of computer control to furnace operations in South Africa has been based mainly on developmental work done during the past eleven years by the Measurement and Control Division of the Council for Mineral Technology (Mintek). Difficulties were experienced initially in the development of an analogue-based batching system for raw materials. This was replaced by a microcomputer-based system in which the

operator enters the required set points into the system using thumb-wheel switches. The set points are based on measurements supplied by load cells on the ore hoppers and by nuclear moisture meters that determine the moisture content of the reducing agents (mainly coke).

Stable furnace operation can be ensured to a great extent if the positions of the electrodes, which are immersed in the charge, are controlled. Ideally, such control should be based on the resistance, as measured under each electrode, but the voltage measurements required for the determination of the resistance are not accurate owing to induced voltages caused by the high magnetic fields. An alternative method, which is based on the measurement of electrode currents, may be seriously affected by the interaction effects caused by high reactance in the circuit. Repeated observations have shown that the relationship between the phase reactance in the equivalent circuit is almost constant over a wide variety of furnace conditions. Hence, if this relationship is assumed to be constant, the phase resistances can be calculated from accurate measurements, and erroneous measurements of voltage with respect to the bath of the furnace can be avoided. The system developed at Mintek for the control of electrode position is therefore based on the measurement of resistances and not of currents.

#### *Casting of the Molten Alloy*

The casting of molten ferrochromium is practised in several different ways. The simplest method is that in which the alloy is poured directly from the ladle into a concrete bed lined with fines. Use is also made of chill metal moulds and casting machines of the circular or belt type, but the latter are not being used on a large scale in South Africa. The method of casting used should be assessed in relation to the size range of products required by the market, and with particular reference to the production of as little unsalable fines as possible. Testwork on high-carbon ferromanganese has clearly demonstrated that a marked temperature gradient through the section of a slab of cast alloy is the major cause of fines production. Thin slabs can be cooled fairly rapidly, but thick slabs present problems unless they are cooled slowly, which is not done easily on a full-scale plant.

#### **Production of Stainless Steel**

The original techniques using the electric-arc furnace for the production of stainless steel, even the ferritic type of stainless steel with a low carbon content (e.g. a maximum of 0,15 per cent), presented considerable problems, the excessive oxidation of the chromium being the major problem. Even more problems arose in the production of austenitic steels, especially the 18/8 chromium-nickel type, which were required to have particularly low carbon contents. The quantities of stainless-steel scrap that could be incorporated in the charge were very limited, and the additions of chromium had to be made mainly in the form of expensive low-carbon ferrochromium. Until 1950, the world production of stainless steels was probably only about 1 Mt/a. Considerable expansion in production occurred in the next decade owing to the development of steelmaking techniques involving oxygen injection, which made it possible for the temperature of the steel bath to be raised rapidly to a level

at which the rate of chromium oxidation was greatly reduced.

A major advance in stainless-steel production was the development of the A.O.D. process by Union Carbide Corporation in the early 1960s. This involved the use of a mixture of oxygen and argon for decarburization, which resulted in a marked reduction in the partial pressure of carbon monoxide in the system and enabled the very low carbon contents specified for austenitic steels to be attained. Although A.O.D. is the most widely used process for the refining of stainless steel, a number of 150 t vessels having been installed, other methods have been developed that are also aimed at the reduction of the partial pressure of carbon monoxide during decarburization. A widely used adaptation of the A.O.D. process is the replacement of a proportion of the expensive argon by nitrogen, especially in the first stages. In the Creusot-Loire Uddeholm (C.L.U.) process, the argon is replaced by steam, the endothermic dissociation of which has the additional advantage that it offers a method for the control of temperature during refining. The process of oxygen injection can be carried out under vacuum by the vacuum oxygen decarburization (V.O.D.) process, and by several other techniques.

These processes revolutionized the methods used for the manufacture of stainless steel, and reduced the processing costs because they permitted the use of high-carbon ferrochromium alloys instead of the far more expensive low-carbon product that had been used previously. Processing costs were further reduced by the widespread application of continuous casting techniques in place of the old established ingot-casting method, in that an increased charge of molten steel yields more rolled product: a yield of 80 to 85 per cent as against the previous yield of 60 to 70 per cent. These two factors unquestionably made a substantial contribution to the marked increase in stainless-steel production from 1,5 to 7 Mt/a in twenty-five years.

#### *Ferritic and Austenitic Stainless Steels*

Over 60 per cent of all the chromium produced is absorbed in the production of stainless steel and the closely related heat-resistant steels. Conventional stainless steels fall into two broad categories: the ferritic steels containing little or no nickel, and the austenitic steels, the commonest of which is the 18/8 chromium-nickel type. The total stainless-steel production rose to over 7 Mt/a in the mid 1970s, but fluctuated between 6 and 7 Mt up to 1983, when it again reached an output of 7 Mt.

Smelting is typically a two-stage process: the first stage involves the smelting of ferrochromium and scrap (mild as well as stainless steel); and the second stage involves the transfer of the molten charge to the A.O.D. vessel, where the carbon is removed to the levels specified and the final concentration of alloying elements is adjusted.

Although the food and chemical industries, including petroleum refining, will absorb hot- and cold-rolled austenitic steels, there may be an increase in the demand for ferritic stainless steels. These steels typically contain about 12 per cent chromium, and the AISI 400 series usually permit up to 0,15 per cent carbon, which makes welding of these steels rather difficult. However, the A.O.D. process can be used to produce 12 per cent

chromium ferritic steels with much lower carbon contents (maximum 0,03 per cent), one of which is the 3CR12 steel produced in South Africa. Under present conditions, this steel costs about three times as much as mild steel, and possibly slightly less than half as much as 18/8 austenitic stainless steel. There is a possibility that the 12 per cent chromium ferritic steel with a low carbon content may replace mild steel in applications where its greater resistance to moderately corrosive conditions makes it more attractive economically. The low carbon content of this steel permits welding to be done relatively easily, and facilitates its use in construction.

The growth of the austenitic stainless-steel market is attended by many uncertain factors, particularly the growth in the chemical industry and in oil refining, which absorb a large proportion of rolled flat products, tubular products, and valve castings. Cold-rolled flat products account for 55 to 60 per cent of the stainless steel used in the industrialized world, where the demand is approaching saturation market levels and consequently exhibits cyclical behaviour. In Latin America and the Far East (excluding Japan), the market is not at saturation levels, and a steadier and higher growth rate is expected.

### *Stainless and Heat-resisting Steels*

Chromium is the main effective agent in producing a protective or passive film on the surface of steel of this type. At elevated temperatures, this film becomes a thin scale that is relatively impermeable to oxygen. As oxygen gradually diffuses through the scale and chromium oxidizes preferentially to iron, the metal adjacent to the scale becomes depleted in chromium and the remaining iron oxidizes to form a more porous type of scale. This gradual breakdown in resistance to corrosion and oxidation depends upon the chromium content, temperature, time of exposure to temperature, and the effects of allied alloying elements like nickel, molybdenum, and aluminium.

The stainless steels most commonly used are the 18/8 chromium-nickel austenitic steels belonging to the AISI 300 grades, of which 304 is frequently referred to as a 'work-horse' steel, particularly at temperatures not exceeding 100°C. Two points are of concern mainly in relation to the weldability of the steels: the carbon content, and the alloying elements added, particularly molybdenum, titanium, niobium, and tantalum. The main difficulty encountered during welding is the intergranular corrosion of the parent metal in the heat-affected zone. When plain 18/8 chromium-nickel austenitic steels are heated to temperatures within the range 480 to 820°C, either locally (as in welding) or in bulk form (as in stress relieving), chromium carbide may precipitate at the grain boundaries. On subsequent exposure of the steel to corrosive conditions, the metal adjacent to the grain boundaries will be subject to chemical attack, and intergranular cracking may develop. The two most feasible methods by which the danger of 'weld decay' can be reduced are

- (a) reduction of the carbon content of the steels (hence the importance of the 'L' symbol attached to types 403L and 316L, which have a maximum carbon content of 0,03 per cent); and
- (b) the addition of strong carbide-forming elements like niobium, titanium, or tantalum to the steels as is done

in the making of types 321, 347, and 348; the very stable complex carbides formed by the 'stabilizing' elements diffuse much less easily through the steel, which greatly minimizes the danger of intergranular corrosion.

Molybdenum is added to the 316, 316L, and 317 types of austenitic stainless steel, conferring much-improved resistance to corrosion and enhanced creep resistance at temperatures in the range 480 to 820°C.

These austenitic steels are marketed in several forms: bars, wire, hot-rolled flat products, cold-rolled flat products, and strip. Cold-rolled flat products constitute the largest proportion in all the producing centres.

Other types of stainless steel are the high-chromium ferritic types containing 25 to 30 per cent chromium and 1 to 4 per cent molybdenum. Originally, the major advantage of these steels was their high resistance to stress-corrosion cracking, but their low impact resistance and difficulty in welding presented serious problems. Additions of nickel of up to 5 per cent have been found to give adequate toughness and substantially reduced resistance to stress-corrosion cracking. The ferritic-austenitic groups contain 5 to 6 per cent nickel, 3 to 4 per cent molybdenum, and 20 to 22 per cent chromium, the advantage claimed being the combination of the good mechanical properties of the austenitic component and the good resistance to stress-corrosion cracking of the ferritic component. Apparently neither type of steel has yet been produced or marketed on a large scale.

Heat-resisting steels, which are required to exhibit high-temperature strength and resistance to oxidation and corrosion, find applications in high-temperature bolts and compressors, turbine discs, rings, and bands for jet engines, and in valve parts. The 12 per cent chromium super-alloys are essentially steels of the AISI 400 series, but contain significant amounts of other alloying elements like molybdenum, tungsten, vanadium, or niobium to improve their high-temperature strength. The creep resistance of these steels is critically dependent on the formation of the mixed carbide  $M_{23}C_6$ , rather than  $M_7C_3$ . As the  $M_{23}C_6$  carbides do not dissolve until temperatures of 1095°C are reached, they confer greatly enhanced creep resistance compared with the less complex  $M_7C_3$  carbides, which dissolve at about 950°C. Nickel is used as a component of these steels to inhibit the formation of delta ferrite, which may result in badly segregated carbides and reduced creep resistance. Such steels are available as forged billets, hot- and cold-rolled bars, wire, sheet, strip, plates, and special shapes. However, the forging of these steels can present difficulties since a relatively high finishing temperature is necessary. All steels of this type must be heat-treated by austenitizing at 950 to 1095°C and tempering at not more than 705°C.

A comparatively small modification of the type described above gives the martensitic precipitation-hardening grades, which are characterized by nickel contents of 5 to 10 per cent, but have significantly lower carbon contents. The particular advantage of these steels is their amenability to cold-forming after rapid cooling from solution-annealing temperatures. Subsequent heat treatment at temperatures about 480°C develops strengths equal to those of carbon and low-alloy steels at ambient temperatures. Because of the low carbon contents, they

can be welded without preheating or post-annealing treatment, and their corrosion resistance is equal to that of the 18/8 types. These steels are widely used in structural and skin applications in aircraft.

Further modification of this type of steel yields a product containing about 1 per cent carbon and 3 to 5 per cent molybdenum. The major application of such steels is in aerospace bearings for use at temperatures from 425 to 480°C. After heat treatment, their hardness values are above 60R<sub>c</sub>. These values are reduced at 480°C, but are usually not lower than 50R<sub>c</sub>.

The heat-resistant or austenitic iron-base super-alloys are based essentially on the AISI 300 series of stainless steels, and 316 can be regarded as the parent. For these steels, the basic 18/8 composition has been modified so that they have increased strength, particularly at high temperatures, while retaining good formability and corrosion resistance. In addition to containing the basic alloying elements (iron, chromium, nickel, and molybdenum), the austenitic super-alloys may contain cobalt, tungsten, and niobium. All these elements effectively raise the recrystallization temperature of the super-alloys and therefore enable them to retain the strengthening effects of prior cold working while subjected to service at elevated temperatures. As these additional elements are normally ferrite stabilizers, the amount of nickel required to maintain the austenitic structure is frequently higher than in the 316-type steels, being in the range 24 to 27 per cent in some cases.

Austenitic iron-base super-alloys can be strengthened by strain hardening or precipitation hardening. The strain-hardening types are normally worked at temperatures within the range 650 to 900°C, which are still below recrystallization temperatures (above 925°C). This 'warm-working' strain hardens the steels, and confers optimum properties for service in the range 650 to 735°C. The precipitation-hardening types are of two groups: low-carbon grades, which are hardened by the precipitation of intermetallic compounds usually containing titanium, and medium-carbon grades, which are hardened by the precipitation of carbides and carbonitrides. The steels are subjected to solution treatment at high temperatures and subsequently to 'aging' in the range 650 to 815°C to effect precipitation. Cold drawing and forming can be carried out between the solution treatment and the aging. Problems in heat treatment may occur in the control of grain size, and slightly more difficulty is experienced in the welding of these steels than in the welding of the 300 series austenitics.

Austenitic iron-base super-alloys find their main application in components for gas turbines and turbo-superchargers, and are used for high-pressure and high-temperature steam piping.

#### *Low-alloy Steels Containing Chromium*

For very many years, chromium-molybdenum steels have been used extensively for high-temperature equipment, particularly in the electric-energy industry and petroleum-refining and other chemical plants. Steels of this type, which contain from 0,5 to 10 per cent chromium and 0,4 to 1,5 per cent molybdenum, are ferritic in structure, and are used mainly in the hot-rolled, annealed, or normalized conditions. Of the alloying elements common-

ly used in these ferritic steels, molybdenum is the most effective in increasing the resistance to creep-rupture stress. The carbon-molybdenum steels generally have about twice the creep-rupture strength of equivalent plain carbon steels, mainly because of the strong carbide-forming tendency of molybdenum. These carbides are precipitated very slowly in finely divided form throughout the ferrite when the steels are exposed to elevated temperatures, and greatly reduce the softening processes. These steels may suffer from graphitization if they are exposed to temperatures above 468°C. This phenomenon is particularly dangerous in relation to welded joints in heavy sections, where the precipitation of graphite may occur in the form of 'eyebrows' that are linked together in almost continuous chains across the section. The graphite flakes act as stress concentrators and reduce fatigue resistance. Other elements can also significantly affect graphitization in these steels, silicon and aluminium having adverse effects, so that aluminium deoxidation of the steels is not desirable. Chromium, as a strong carbide former, resists graphitization. The initial additions of 0,5 to 1,5 per cent chromium are made primarily for this purpose, but also improve the resistance of the steel to oxidation and corrosion. For this reason, a steel containing 0,5 to 0,8 per cent chromium, 0,5 per cent molybdenum, and 0,15 to 0,2 per cent carbon has been used extensively for many years for pipes and tubes for boilers, superheaters, heat exchangers, and cracking stills in oil refining. The welding of these steels presents some difficulties, and preheating and post-heating are recommended. Cast valves, flanges, and fittings may contain about 1 per cent nickel and 0,3 per cent vanadium as well.

Higher additions of chromium further increase the resistance to oxidation and corrosion, and there are two main groups of these steels: those containing about 3 per cent chromium, and those containing 5 per cent chromium. Although the steels that contain 3 per cent chromium and 0,5 per cent molybdenum have very good creep-rupture strength up to 620°C, their usefulness is limited by their lack of resistance to corrosion and oxidation, and, for use in this temperature range, the 12 per cent chromium steels are more valuable. The 5 per cent chromium steels in the form of seamless tubing are used extensively in petroleum refining because of their high strength and corrosion resistance in the presence of hydrogen sulphide and other corrosive agents. Except for the 18/8 austenitic types, these steels are the most useful for service at temperatures up to 650°C under severely corrosive or oxidizing conditions.

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## Record number of millionaires

The South African mining industry has achieved another significant safety milestone by setting a new record for the number of mines achieving a million fatality-free underground shifts in one year. This follows the achievement of the lowest-ever rates for fatalities and reportable injuries in the first half of 1985.

The new record was established when Wildebееstfontein South platinum mine became the 18th 'millionaire' of 1985, eclipsing the previous best of 17 in one year, which was set in 1981. The final total for 1985 could be higher, since two mines still had a chance of reaching the million mark before the end of the year.

The Chamber of Mines' millionaire shield is one of the most-sought-after safety awards in the South African mining industry.

Among the mines to achieve millions was one of South

Africa's youngest gold producers, Beatrix Mines in the Orange Free State, which gained the added distinction of notching up more than two million consecutive fatality-free shifts.

Two other gold mines achieved a million on two separate occasions in 1985, Deelkraal and Western Areas. The other gold mines that achieved millions were Free State Geduld, Free State Geduld North Division, Stilfontein, Blyvooruitzicht, Loraine, and Bracken.

Seven of the eight platinum mines in the competition became millionaires in 1985: Bafokeng South, Bafokeng North, Wildebееstfontein North and Wildebееstfontein South of Impala Platinum Mines, Union Section and Rustenburg Section of Rustenburg Platinum Mines, and Western Platinum.



Proud employees of Wildebееstfontein South platinum mine show their delight at winning the Chamber of Mines' Millionaire Shield for the third time. Holding the Shield are (left) Mr Alan Germond, Acting Mine Manager Underground, and Mr Dave van Niekerk, Mine Overseer. Behind the Shield is the General Manager of the Mine, Mr James Cockburn