J. S. Afr. Inst. Min. Metall., vol. 88, no. 3.
Mar. 1988. pp. 73-95.

Iron and steel in South Africa*

by D.J.C. TAYLOR†, D.C. PAGE‡, and P. GELDENHUYS§

SYNOPSIS

This paper gives a technical review of the history, occurrence, mining, and metallurgy of iron in South Africa. The reserves of iron ore worldwide and in South Africa are reviewed, and potential new developments in the iron-and-steel industry in South Africa are examined.

The paper concludes that the exploitation of lower-grade iron deposits will probably supplement the reserves of high-grade hematite ore in the distant future, and that, accepting this scenario, South Africa will be well placed to provide iron ore for its expected internal steel requirements, as well as supplying quality iron ore for the export market.

SAMEVATTING

Hierdie artikel gee 'n tegniese oorsig van die geskiedenis, voorkoms, myn en metallurgie van yster in Suid-Afrika. Die reserwes van ystererts wêreldwyd en in Suid-Afrika word hersien, en potensiële nuwe ontwikkelings in die ystererts- en staalbedryf in Suid-Afrika word ondersoek.

Die artikel sluit af met die stelling dat die ontginning van laegraadse ysterertsafsettings moontlik die reserwes van hoëgraadse hematietafsettings in die toekoms sal aanvul, en dat, indien hierdie veronderstelling aanvaar word, sal Suid-Afrika in die gunstige posisie wees om aan sy verwagte interne staalaanvraag en kwaliteit ystererts aan die uitvoermark te voorsien.

ANTIQUITY OF IRON[1-6]

Although iron is the second most-abundant metal in the earth, the character of its natural compounds prevented its use as early as some other metals.

An iron blade, probably 5000 years old, was found in one of the Egyptian pyramids. Even without this discovery, one could plausibly maintain that the ancient Egyptians must have had skilled steel workers in order to have built the great pyramids and other monumental architecture, to say nothing of the statuary and hieroglyphics cut into the hardest rocks.

Steel working and hardening, an advanced stage in the art that doubtless required centuries to reach, was common 3000 years ago in Greece, and is mentioned by Homer. It is more probable that iron was first found in the ashes of a large fire built near some red-paint rock, than that the first tools were made from meteorites.

By 1200 B.C. iron was manufactured but was still rare, and its industrial use did not start before 800 B.C., which dates the start of the Iron Age. Steel came into use about 800 years later, and the blastfurnace in the 14th century. During the 16th century, the forests of Great Britain were denuded to supply charcoal to smelt iron ore, but this waste became unnecessary when the great discovery was made about 1710 that coal could be used as a reductant in ironmaking. This was the beginning of the great industrial age of iron that culminated in the steel age, which was made possible by Bessemer's discovery of a steelmaking process in 1856.

Iron ore has been mined and smelted in South Africa since pre-historic times. Evidence of this is to be found in the remains of ancient workings, primitive furnaces, and accumulations of slag at locations scattered across South Africa with a concentration in the northern Transvaal.

These pre-European workings were mainly for the following purposes:

- the procurement of ochre and specularite for the making of a paint that was used on the body and a powder for dressing the hair;
- the mining of iron ore, which was used specifically for smelting.

Early man first worked iron ore in Southern Africa 14 000 years ago, as indicated by the carbon-14 dating of certain ancient workings at Bomvu Ridge, the site of the Swaziland Iron Ore Mining Company. This specular iron ore was not used for smelting to iron but purely for cosmetic purposes.

Slags found at Broederstroom in the Transvaal have been dated as from the 4th century A.D. This iron-smelting technology remained basically unchanged until it died out in the first decade of this century.

Fairly extensive pre-European iron ore mining was carried out in the vicinity of the Thabazimbi Iron Ore Mine. It is estimated that at least 400 tons were taken from there.

However, in all these mining activities the amount of iron ore handled could not have exceeded a few thousand tons in total, and it was left to the Europeans, who had the necessary technology, to initiate the development and full exploitation of the iron ore reserves of the country.

An interesting feature during this early history in ironmaking is that the metal, which was generally of high chemical purity, was not actually cast, but the products were forged to required shapes, similar to more recent wrought-iron practice.

* This is a further contribution to our Metal Review series of papers.

† Manager, Mining, Sishen Iron Ore Mine, Private Bag X506, Kathu, 8446 Cape Province.
‡ Consulting Geologist, Oxide Ores and Fluxes, Iscor Ltd, P.O. Box 450, Pretoria 0001.
§ Manager, Process Development, Pilot Plant, Iscor Ltd, P.O. Box 450, Pretoria 0001.

ISSN 0038-223X/$3.00 + 0.00. Paper received February, 1988.

OCCURRENCE OF IRON[1,5,7]

Iron is the fourth most-abundant element, composing approximately 5 per cent by mass of the earth's crust. The earth's core contains largely metallic iron, but in the crust the element has had an opportunity to react with other substances and the free metal is rarely found except in meteorites or disseminated as minute speculae in basaltic rocks. Iron is a constituent of hundreds of mineral species; small amounts are also found in water, plants, and blood.

The widespread distribution of iron is a result of the fact that it easily combines chemically with many other elements in a wide variety of physical and chemical environments. A large portion of the common ore- and rock-forming minerals contain appreciable amounts of iron, but only seven of the scores of iron-bearing minerals contain sufficient iron and are sufficiently abundant in large masses to be sources from which iron can be obtained economically at the current time or in the foreseeable future. These are listed below:

Hematite	Fe_2O_3	70% Fe	Economically the most important
Magnetite	$FeO.Fe_2O_3$	72% Fe	
Goethite	$FeO.OH$	61% Fe	
Siderite	$FeO.CO_2$	48% Fe	
Limonite	$Fe_2O_3.3H_2O$	59–63% Fe	
Lepidocrocite	$FeO.OH$	61% Fe	
Chamosite	$3FeO.Al_2O_3.2SiO_26H_2O$	± 35% Fe.	

Of the seven source minerals listed above, the three most important are hematite, magnetite, and goethite. Pyrite, FeS_2, is primarily a source of sulphur rather than of iron but, after the former has been driven off, the remaining cinder can be used for ironmaking.

Iron deposits can be regarded as abnormal concentrations in small restricted zones in the earth where geological processes have operated to concentrate iron into a useable mineral form, which can be separated relatively easily from undesirable minerals and chemical elements. The concentration of iron in the deposits being mined today is three to fourteen times the average iron content in the earth's crust.

The most common gangue minerals associated with iron ore deposits are quartz, feldspar, calcite, dolomite, clayey substances, and carbonaceous matter. The most important deleterious constituents of iron ores are phosphorus, potassium, aluminium, silica, titanium, sulphur, zinc, manganese, and arsenic.

PROPERTIES AND USES[5]

Iron is the most important of the metals and the most widely used; the tonnage of pig iron produced in the world is about fifty times as great as that of any other metal, and is probably ten to twenty times as great as the combined tonnage of all non-ferrous metals.

Iron is the backbone of modern civilization. Few are aware of the extent to which we have come to depend upon iron in homes, farms, cities, machines, automobiles, trains, and ships. Without it, we would spin our clothes by hand and travel in wooden carts over dusty roads. When iron, or steel, is not suitable for certain uses, it is alloyed with other substances to make it suitable. Apart from its use in the production of iron and steel, iron ore is used in relatively small tonnages by foundries and the paint industry, and as a catalyst (e.g. in the production of platinum), as a desulphurizing agent, for the production of roofing tiles, in heavy-medium separation and in concrete where high density is required. To enumerate the various uses of iron would be to compile a history of the innumerable creations of modern civilization and industry. Each of the main types of steel, cast iron, wrought iron, and iron alloys has its particular sphere of use; steel, of course, exceeds all others.

The outstanding position of iron is the result of several factors.

- There are large deposits of high- and low-grade iron ores that can be exploited cheaply by open-pit methods.
- Iron ores are comparatively easy to reduce to metal.
- As a result of the above two items, iron is the cheapest of all the metals.
- Iron has unique magnetic properties.
- Iron forms a remarkable series of useful alloys with carbon to form steel.
- Steel is easily malleable.

For most engineering uses, an iron alloy (steel, cast iron, alloy steel) is the first choice, and is often the only logical material to use. Great quantities of the non-ferrous metals are consumed in the iron and steel industry—manganese, aluminium, and titanium as deoxidizers; chromium, nickel, tungsten, vanadium, and many others as alloying elements; and zinc, cadmium, chromium, and others as protective coatings. Iron is not quite the universal metal, for there are some applications where the more expensive non-ferrous metals and alloys must be used.

Some of the outstanding disadvantages of iron are as follows.

- Iron has a relative density of 7,57, and its alloys are approximately as heavy as pure iron; for many uses where mass is important, aluminium, titanium, and magnesium are strongly competitive.
- Iron and its alloys rust, or corrode, when exposed to the atmosphere. Many other metals such as aluminium and titanium are much more active and oxidize more readily than iron, but they form a tightly adherent oxide coating that protects the metal from further attack. Iron rust normally forms a loose, flaky deposit that does not protect the underlying metal, but may even serve to accelerate further corrosion. There is little doubt that this is iron's most serious drawback. The highly-alloyed stainless steels and cast irons have much better resistance to corrosion, but they also contain large amounts of such expensive non-ferrous metals as chromium and nickel.
- For some specialized purposes, iron cannot be used because it is magnetic.
- Iron is a relatively poor conductor of electricity and heat and, for use in electrical conductors, aluminium and copper are far superior.

IRON ORE DEPOSITS IN SOUTH AFRICA[2,3,8,9]

The main types of iron ore deposits in South Africa can be classified as follows:

- banded cherty iron formation of the Algoma type, which occurs in the Archaean greenstone belts;
- banded cherty, oolitic, or massive iron ore of the Lake Superior type, which includes the high-grade deposits at Thabazimbi and Sishen;
- oolitic hematite iron silicate ore of the Clinton type, which includes large deposits in the Pretoria Group of the Transvaal Sequence;
- iron ore deposits of magmatic origin (in the Bushveld Complex and elsewhere); and
- small isolated 'blackband' deposits in the Karoo Sequence.

A brief outline of the deposits currently being exploited and the deposits that could possibly be developed in the future is given below (Figs. 1 and 2).

High-grade Deposits of Hematite

The largest reserves of high-grade (containing more than 60 per cent) iron ore in South Africa occurs in the Sishen–Postmasburg and Thabazimbi areas. These deposits were formed by secondary enrichment of the banded ironstones and ferruginous shales. The geology of these deposits is discussed in some detail under the individual mines in these areas.

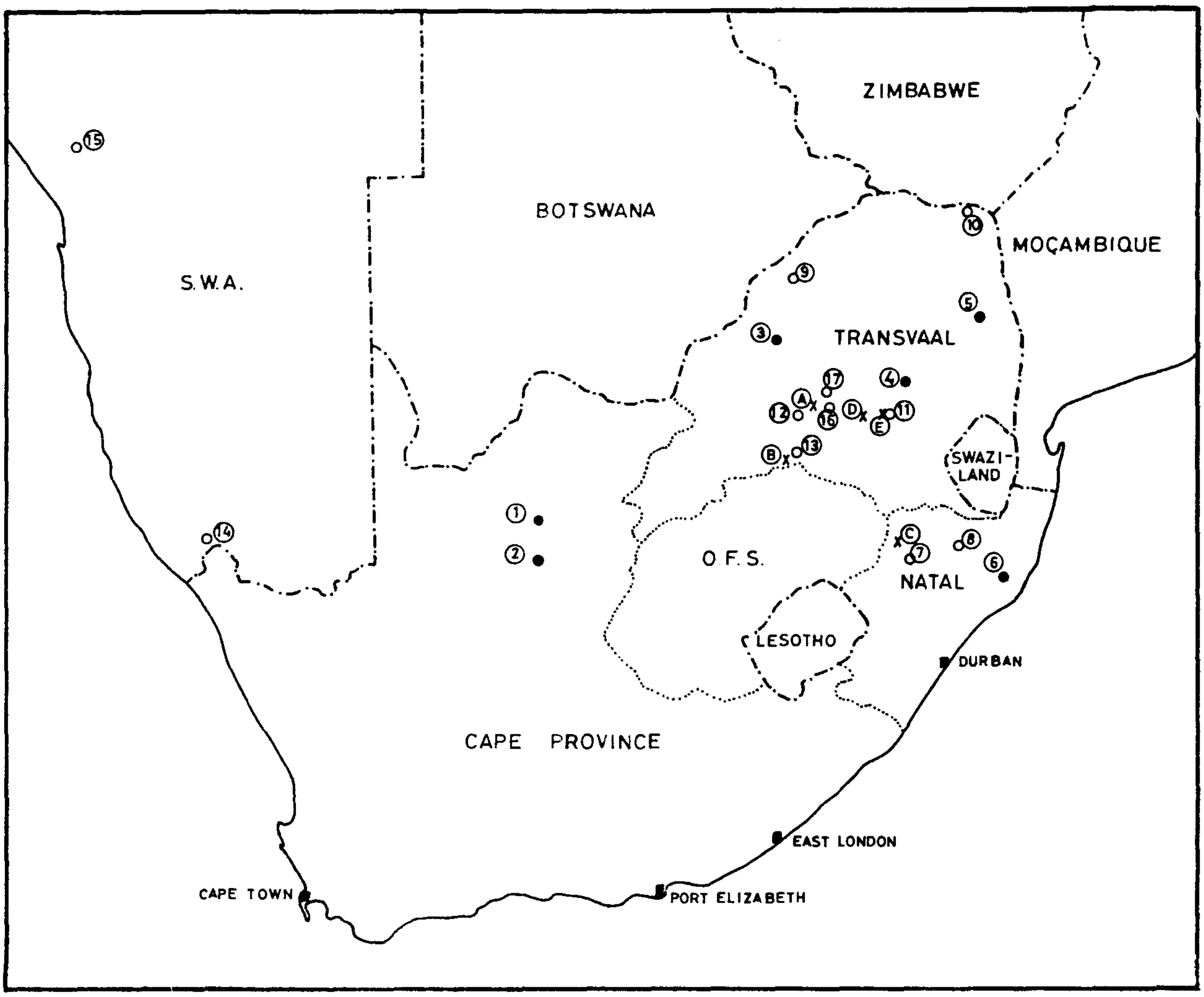


Fig. 1—Iron ore mines, steelworks, and captive mines to the steel industry in South Africa

Legend

●	Iron Ore Mines	○	Captive Mines		X	Steelworks
1	Sishen	7	Durnacol	Coal	A	Pretoria
2	Beeshoek	8	Hlobane	Coal	B	Vanderbijlpark
3	Thabazimbi	9	Grootegeluk	Coal	C	Newcastle
4	Mapochs	10	Tshikondeni	Coal	D	Highveld Steel
5	Palabora	11	Coastal Coal	Coal	E	Middelburg
6	Tisand	12	Mooiplaas	Dolomite		
		13	Glen Douglas	Dolomite		
		14	Rosh Pinah	Zinc		
		15	Uis	Tin		
		16	Donkerhoek	Quartzite		
		17	Fortsig	Sand		

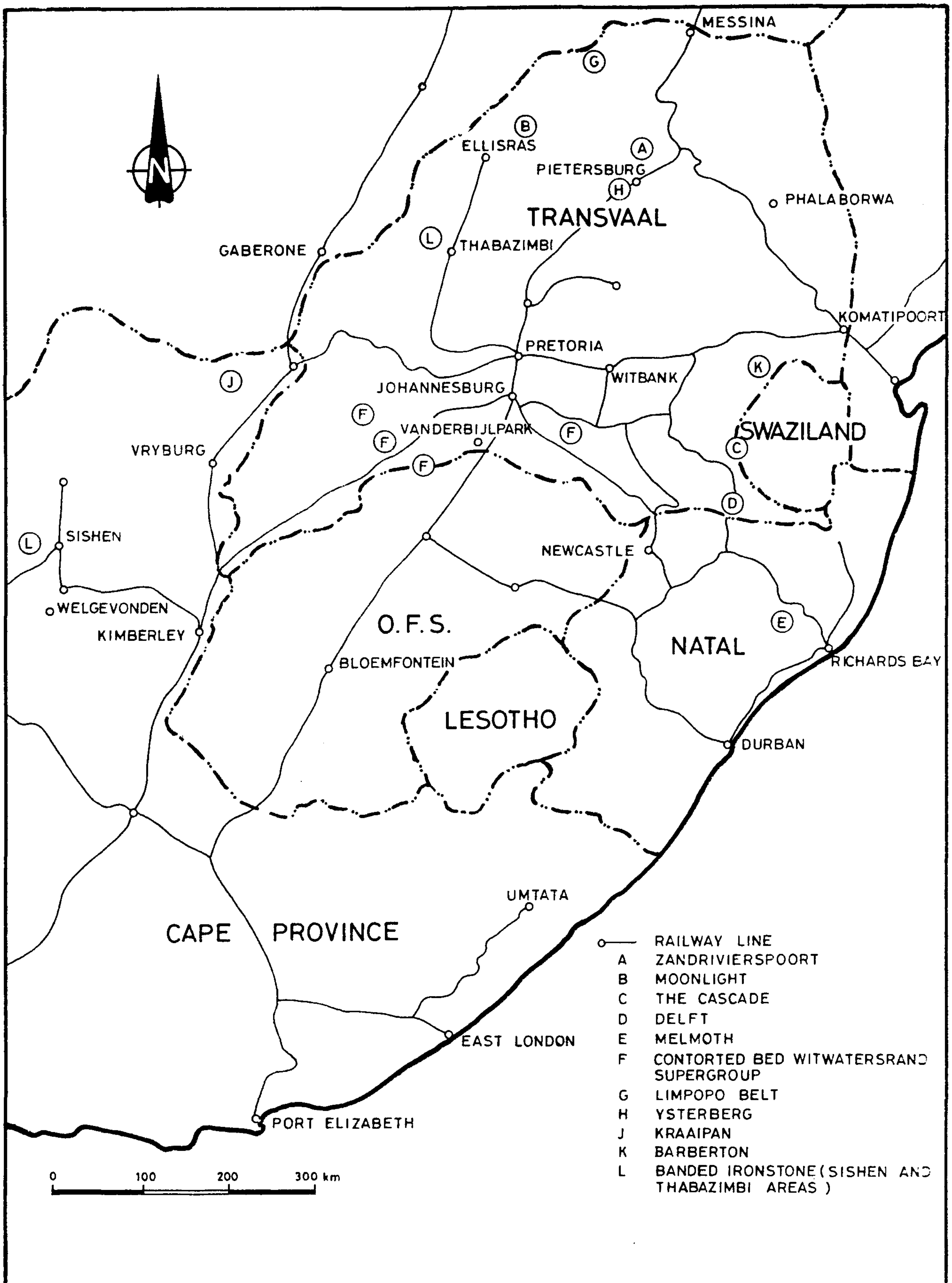


Fig. 2—Low-grade deposits of iron ore that are of possible importance in South Africa (the vanadium- and titanium-rich mines of the Bushveld Complex are not indicated since the ore is not suitable for conventional steelmaking processes)

Minor deposits of high-grade ore are also to be found at Assen (Brits district) and on the farms Seekoebaart and Welgevonden (Hay district, Cape). No other high-grade iron ore deposits of reasonable size and interest are known to occur—or according to present knowledge are likely to occur—on or near the surface in South Africa.

Deposits of the Bushveld Complex

The Bushveld Complex is a broad, shallow, saucer-shaped igneous deposit. It occurs in the Transvaal and covers an area stretching some 350 km east–west and 150 km north–south. This intrusive igneous assemblage forms one of the most remarkable geological occurrences in the world, and contains the world's largest reserves of platinum, chromium, and vanadium. The most striking feature of the deposit is the persistent layering or pseudo-stratification. Seams of chromite, magnetite, and platinum (Merensky Reef) have been found with a great persistence along strike and in depth.

The seams of chromium ore typically contain 20 to 26 per cent iron and, when this is smelted, the iron passes into the ferrochromium alloy from which stainless steel is made.

Seams of magnetite also occur in the Complex and extend for distances of over 120 km along strike. The magnetite contains 11 to 17 per cent titanium dioxide, part of which occurs in the crystal lattice of the magnetite and cannot thus be separated from the iron oxide by physical beneficiation methods. The high titanium content renders these magnetite seams quite unsuitable for smelting to iron by conventional (blastfurnace) methods because of the high melting point of titanium.

However, certain of the lower seams contain significant quantities of vanadium, up to about 1,8 per cent, and have been worked since 1957 as a source of this metal and for the recovery of the iron (Highveld Steel).

The Phalaborwa Complex

The Phalaborwa Complex is a carbonatite pipe deposit and is best known as the site of one of the largest copper mines in the world. This is worked by Palabora Mining Company and is a very large source of rock phosphate, which is mined by the Phosphate Development Corporation (Foskor).

Although essentially regarded as an ore for both copper and phosphate, the central carbonatite core contains varying amounts of magnetite, averaging about 20 per cent Fe_3O_4, while the surrounding foskorite contains an average of 30 per cent magnetite. This magnetite is removed as a concentrate during the beneficiation of the copper and the phosphate, and the Phalaborwa Complex can thus be regarded as a deposit of iron ore including copper, phosphate, and a host of minor minerals.

Deposits of Low-grade Iron Ore

Zandrivierspoort, Pietersburg District

The ore is fine-grained and occurs as a prominent layer of banded ironstone varying in thickness from 10 to 100 m. It contains approximately 37 per cent iron, and is made up of about 40 per cent magnetite and 10 per cent hematite, with quartz and other silicates. Tests have indicated that the ore can be upgraded to an acceptable feed for blastfurnace operations. Sufficient reserves have been delineated to warrant exploitation, and the orebody can be mined by open-pit mining methods at a low stripping ratio.

Moonlight, Potgietersrust District

The orebody is structurally complex. Three magnetite quartzite bands occur, but these split into a number of smaller bands, varying in thickness from a few metres to 90 m. The ore is coarse-grained. The grade and quality of the ore are similar to those found at Zandrivierspoort, and tests have indicated that the ore can be upgraded to an acceptable feed for blastfurnace operations. A large portion of the reserves can be mined by opencast operations at a reasonable stripping ratio.

Delft and Cascade Areas, Piet Retief District

Two magnetite-bearing banded ironstone layers (500 m apart) occur in the two areas, the top layer having an average thickness of 30 m, and the other an average thickness of 17 m. The ore occurs in synclines, and dips at 40 to 60 degrees in the Delft area and 10 to 30 degrees in the Cascade area.

The grade of the ore varies between 30 and 36 per cent iron. The ore is made up of very fine-grained magnetite, which will probably be difficult to upgrade. The open-pit reserves are significant at a low stripping ratio, but massive reserves could be exploited by underground mining methods if these proved feasible.

Banded Ironstone Deposits near Thabazimbi and Sishen

Important deposits of banded ironstone of the Lake Superior type occur in the Transvaal (Thabazimbi area) and in the northern Cape (Sishen–Postmasburg area) over a strike length of hundreds of kilometres. The banded ironstone contains from 25 to 45 per cent iron (averaging approximately 38 per cent iron) and 35 to 50 per cent silica, and the potential reserves are, to put it mildly, colossal. The ore is very fine-grained and is made up predominantly of hematite, which can be successfully upgraded to suit blastfurnace operations. Estimated reserves of banded ironstone ore on the Iscor properties that can be mined by open-pit mining methods amount to approximately 5700 Mt.

It is important to note that significant tonnages of low-grade ore were mined and stockpiled at Sishen during current mining operations—approximately 150 Mt ore at 50 to 60 per cent iron, and 250 Mt of ore at 35 to 50 per cent iron.

Other Low-grade Iron Ore Deposits

A number of other low-grade deposits occur in South Africa, most of limited extent and low economic potential. These include small 'black band' deposits in the Karoo Sequence in Natal, and occurrences of banded iron formation of Archaean age in Natal, the northern Cape, and the Transvaal. The bands of the latter are mostly thin, steeply dipping, and of limited strike length.

Magmatic magnetite ore, similar to that of the Bushveld Complex, occurs in Natal and the Transvaal, but the layers in which it occurs are much more irregular and disjointed. The vanadium content is also lower.

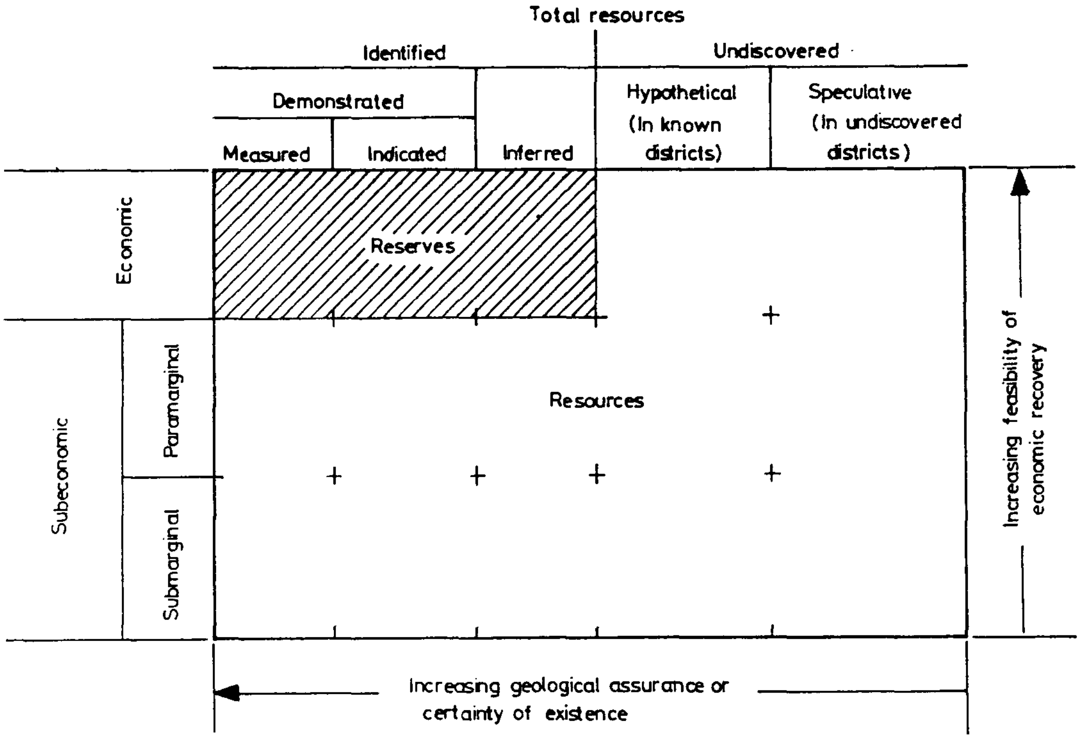


Fig. 3—Classification of mineral resources from the economic point of view (after McKelvey, and Brobst and Pratt)

RESERVES OF IRON ORE[3,7,8-11]

A widely recognized approach to the definition of ore reserves is illustrated in Fig. 3. The reserve figures quoted in this paper are confined to the category 'identified' resources of economic and possible economic (i.e. paramarginal) exploitability.

For the exploitation of iron ore reserves there are basically three types of iron that need to be defined.

- High-grade iron ore is an ore with an inherent iron content of 63 per cent or more that can be beneficiated simply and inexpensively via washing and screening, or washing, screening, and heavy-medium separation. Sishen and Beeshoek deliver this type of ore.
- Medium-grade iron ore is an ore with an inherent iron content of 55 to 63 per cent. Because of interbedded waste or disseminated gangue material, it is difficult to upgrade by washing and screening, or by washing, screening, and heavy-medium separation. This type of ore was especially used in the older steelworks, but the demand for it is on the decline. Thabazimbi ore is an example of the better type of medium-grade ore.
- Low-grade iron ore containing between approximately 20 and 47 per cent iron is the primary iron-bearing deposit from which the other types originated through enrichment. This ore must be milled in order to liberate the iron minerals from the host rock, and must undergo one or more beneficiation processes using magnetic, high-intensity magnetic, or flotation methods, or a combination of these (depending on the physical and chemical properties of the ore).

The world reserves of iron ore have been estimated as shown in Table I (1984 figures).

The reserves of high-grade ore are limited mainly to five countries, as can be seen in Table I. The reserves of high-grade ore are limited to approximately sixty years at the current world production of steel of 721 Mt per annum. The production from low-grade ore deposits can therefore be expected to increase in the future.

The present South African *in situ* reserves of high- and low-grade iron ore are estimated to be as shown in Tables II and III respectively.

In addition to the figures quoted in Table III, the possible reserves of low-grade banded ironstones in South Africa that can be mined by open-pit methods are vast

TABLE I

WORLD RESERVES OF IRON ORE[11]

Country	Iron ore reserves Mt	Estimated grade (%) Fe	Recoverable iron Mt
Predominantly High-grade Ore			
Australia	17 781	60,2	10 708
Brazil	34 546	56,7	19 601
India	13 500	61,5	8 306
Republic of South Africa	6 300	59,1	3 721
Sweden	3 353	59,5	1 996
Sub-total	75 480	57,6	44 332
Predominantly Low-grade Ore			
USSR	110 750	25,4	28 131
People's Republic of China	42 000	30,0	12 600
Canada	26 417	31,6	8 348
USA	25 401	20,7	5 263
France	4 064	40,2	1 633
Venezuela	2 337	54,4	1 270
Liberia	1 668	39,5	660
Other	2 235	28,4	635
Sub-total	214 872	27,2	58 540
World total	290 352	35,4	102 872

TABLE II

SOUTH AFRICAN RESERVES OF HIGH-GRADE IRON ORE[8,11]

Company	Area	Type of mining	Estimated reserve Mt	% Fe
Iscor	Sishen	Openpit	1180	> 65
		Underground	240	> 65
	Thabazimbi	Openpit	60	≈ 63
		Underground	40	≈ 63
	Other	Openpit	110	> 63
		Underground	1000	> 60
Sub-total			2630	> 63
Other	Sishen–Postmasburg	Openpit	400	> 63
		Underground	120	> 63
Sub-total			520	> 62
Total			3150	> 63

since the figures quoted are restricted largely to Iscor holdings.

Massive reserves of low-grade iron ore also occur at depth, but the exploitation of these deposits would require expensive underground mining methods. In the Bushveld Complex alone, the estimated reserves of magnetites high in titanium and vanadium (up to a depth of 1000 m) are in excess of 3500 Mt.

Of prime importance is the fact that the reserves quoted in Table III (apart from the reserves in the Bushveld Complex) can be mined by relatively cheap open-pit methods, and can be concentrated to an acceptable feed grade for blastfurnace operations—although expensive in relation to the beneficiation of high-grade ores.

IRON ORE MINES OF SOUTH AFRICA[2,3,6,9,12,13]

The locations of operating iron ore mines in South Africa are given in Fig. 1. The geological setting and operations at the major mines are briefly discussed below.

Sishen Iron Ore Mine[6,13]

Sishen is by far the largest iron mine in South Africa and is among the world's largest open-pit mines. The plant capacity is 22,5 Mt of run-of-mine ore and 18 Mt of product per year, of which 10 Mt is planned for export and 8 Mt for internal use. The planned stripping ratio at present is 2,5 (waste) to 1 (ore). The total ore and overburden production at Sishen since start-up is illustrated in Fig. 4. The total shipments of the product in the 10-year period 1975 to 1985 were 104 Mt to the export market and 58 Mt to the internal market. Iron ore is supplied to Iscor's Vanderbijlpark Works (690 km by rail) and Newcastle Works (1000 km by rail). Iron ore is also exported via Saldanha Bay (860 km by rail). The Sishen–Saldanha railway system, as well as the harbour, was specifically designed and equipped for this purpose, and can handle up to 27 Mt per annum. The shiploading system can load vessels at an average rate of 7000 t/h and can handle vessels of up to 260 000 t.

The first ore-handling plant at Sishen was a dry-crushing and screening plant, which was commissioned in 1953. In 1961 this plant was replaced by a wet-screening plant with a capacity of 500 t/h since geological surveys had shown that some form of upgrading of the raw ore would be necessary if the vast ore deposit were to be utilized to its maximum. This would make it possible to exploit the high-grade laminated ore with interbedded shales.

In 1973, this plant, known as the South Plant, was modified and extended to obtain a final annual capacity of 9 Mt at a rated throughput of 2250 t/h.

The construction of the North Plant, which was designed for the production of iron ore for export, also started in 1973, and was commissioned during 1976. The final annual capacity of this plant is 18 Mt at a rated throughput of 4500 t/h.

In 1984, it was decided to rationalize production as a result of an international decline in the demand for iron ore. Both plants were producing on a two-shift basis and utilization was low. This resulted in the closure of the South Plant, while production at the North Plant was stepped up to its full annual capacity of 18 Mt.

Geology

High-grade hematite deposits are found in two geological units, namely in the Gamagara Formation and minor deposits in the banded ironstone of the Lower Griquatown Stage, both formations belonging to the Griqualand West Sequence. The ore in the banded ironstone (Thaba-type ore) had been formed by secondary enrichment in a manner similar to the formation of the ore deposits of the Lake Superior Region in the USA. The ore in the Gamagara Formation consists of reworked and redeposited secondary enriched ore (conglomeratic and gritty ore), primary deposited and precipitated ore (lamellated and massive ore), and secondary enriched ore (part of lamellated and massive ore). Limited deposits of detrital ore also occur in places on the surface. To the west, the ore deposits are covered by volcanic rock of the Middle Griquatown Stage. These formations all date from the pre-Cambrian period. The Kalahari beds, which date from the Recent to the Tertiary period, cover the above formations over large areas.

The general strike of the ore deposit is north to south, with a regional inclination of approximately 10 degrees to the west. A generalized section illustrating the rock types and the sequence in which they occur is given in Fig. 5.

The Sishen ore is classified chemically as follows:

High-grade	Fe 66,0% and higher
Medium-grade	Fe 63,0% to less than 66,0%
Low-grade	Fe 60,0% to less than 63,0%.

The ratio of high- to medium- to low-grade iron ore over the total openpit area as planned is 64:27:9.

The *average* chemical composition of the iron ore (which contains more than 60 per cent iron), as calculated from all the available borehole information, is as follows:

Fe	65,74%	S	0,01%
SiO_2	3,07%	K_2O	0,20%
Al_2O_3	1,25%	Na_2O	0,03%
P	0,07%	Mn	0,04%.

Large reserves of groundwater occur in the Sishen area, and the water is of necessity pumped from the pit area

TABLE III
SOUTH AFRICAN RESERVES OF LOW-GRADE IRON ORE[3,8,11]

Area	Estimated openpit reserve Mt	Fe, %	Type of ore	Comments
Ores of sedimentary origin:				
Zandrivierspoort	480	37	Magnetite	Medium-grained ore that can be upgraded to >66% Fe. Reasonably positioned regarding infrastructure
Moonlight	280	31,5	90% magnetite, 10% hematite	Coarse-grained ore that can be upgraded to >67% Fe. Close to coal and electricity (70 km from Ellisras)
Cascade	450	32,5	Magnetite	Fine-grained ore. Will probably require flotation in addition to magnetic processing. Can be upgraded to >66%. Close to water and Newcastle (130 km). Similar to ore at Empire, USA. High potential of underground reserves
Delft	290			As for Cascade
Sishen	130 >1300	50–60 35–50	Hematite Hematite	Very fine-grained. Will be expensive to process via high-intensity magnetic separation or flotation. 400 Mt also mined and stockpiled. Existing infrastructure.
Sishen–Postmasburg and surrounding areas	>400	35–60	Hematite	Similar to Sishen. Estimated reserve based on the assumption that ratio of high- to low-grade deposits at Sishen applies here as well
Thabazimbi	3900	≈35	Hematite	Very fine-grained, expensive to process. Existing infrastructure and relatively close to Pretoria
Sub-total	>7230	35–60		
Ores of magmatic origin:				
Phalaborwa	100	60	Magnetite	Byproduct of copper and phosphate mining. Reserves that can be utilized in conventional smelting operations
Bushveld Complex: Lower Magnetite Zone	200	53–37	Magnetite	Highveld Steel mining and processing ore from Mapochs for vanadium and steel. Deposit high in vanadium and titanium. Not suitable for blastfurnace operation
Upper Magnetite Zone	>500	50–55	Magnetite	Lower concentration of vanadium, but still high titanium concentration, 12 to 20% TiO_2, 0,3 to 0,5% V_2O_5. Not suitable for blastfurnace operations
Sub-total	>800	50–55		
Sum total	>8030	35–50		

to ensure that the water table is below the pit floor at all times. The water pumped for pit dewatering, 1500 m^3 per hour, suffices for the total water requirements. The reserves of water available on the mine will last at least to the year 2000 at present pumping rates.

Ore Reserves

The estimated *in situ* reserves of iron ore (higher than 60 per cent iron) at Sishen at present is 1410 Mt, of which 1180 Mt can be mined by openpit methods. It is of interest to note that in 1970 the estimated *in situ* ore reserves at Sishen were 1200 Mt. The tendency to replace ore reserves mined by ongoing exploration is expected to continue for at least the next five years.

Mining

Conventional methods of openpit mining are used at Sishen. Material is drilled (310 mm and 380 mm holes, using Bucyrus 60 and 61 R and GD 120 rotary drills) and blasted (with Anfo, Heavy Anfo, and emulsions) in 12,5 m benches, shovel loaded (with P & H 2100 and 2300 shovels), and hauled (with 150 t trucks) to the primary

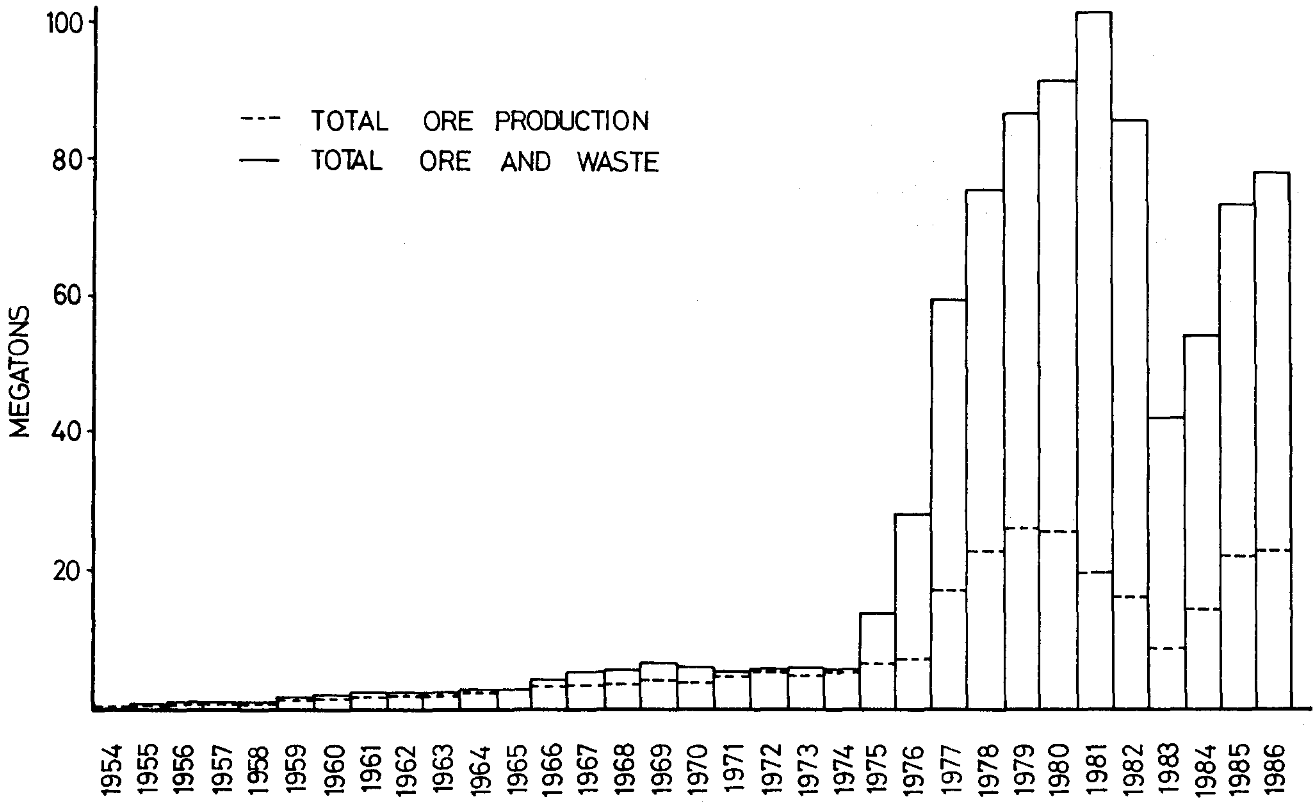


Fig. 4—Production from Sishen Mine for the years 1954–1986

GEOLOGICAL CODE	ROCK TYPES	THICKNESS (m) TO	THICKNESS (m) NORMAL
KK	Calcrete	50	30
KL	Clay	80	20
S1	Shale, black, green	150	40
T	Tillite	150	50
L	Lava	>10000	
S2	Shale, black, red	50	10
KW	Quartzite	60	30
S3	Shale, red	20	5
P	Flagstone	40	20
S4	Shale, white, red, brown	200	30
KE	Ore - conglomeratic	50	10
E	Ore - laminated to massive	100	30
S5	Shale, brown	50	10
LY	Banded ironstone, Jaspilite	150	10-20
S6	Shale	50	10
TE	"Thaba" - iron ore	70	10
C	Chert, Manganese Marker	150	10-20
DO	Dolomite	Unknown > 1000	
DI	Diabase	do	

Fig. 5—Generalized geological section through Sishen Mine

ore crusher or in-pit overburden crusher, or is dumped on the overburden dump or low-grade stockpiles.

The hardness of the rock formations varies widely. In some areas, very hard conglomeratic ore occurs, which results in exceptionally high drilling costs. The rate of penetration in hard iron ore varies between 3 and 8 m per hour, and the average life of drill-bits in this material is 120 m. However, the drilling costs in calcrete and shale formations are relatively low, and penetration rates in excess of 16 m per hour and an average drill-bit life of 2000 m are obtained.

The average blasting block contains roughly 250 kt of material.

Recent Developments

Explosives. The introduction of competitiveness in explosives at Sishen and the technological development of explosives have enabled the mine to lower the drilling and blasting costs over the past four years. A new technological development was recently tested successfully at Sishen and involves the use of limestone ammonium nitrate (LAN) instead of ammonium nitrate in certain explosives. This has resulted in a significant saving in blasting costs as a result of the lower cost of LAN, as well as savings in railage costs for LAN since it is classed as non-explosive.

Computerized Truck (Dispatch) Allocation. Transportation constitutes a large proportion of the total mining costs, and optimal utilization of the trucks is of prime importance. To ensure this, a controlled system of truck allocation (known as CTA) was developed and implemented with success in 1975.

Trolley-assist System. A trolley-assist system was introduced at Sishen in 1980. Overhead 1200 V direct-current power lines were erected on the main uphill routes, and the trucks were equipped with pantographs and the required control systems. The diesel consumption of each truck on uphill grades was reduced from 328 l/h to less than 80 l/h, with the additional advantage of an increased speed of 17 km/h on uphill grades as opposed to the previous 10 km/h.

Semi-mobile In-pit Crusher. Sishen was the first large openpit operation in South Africa to install a semi-mobile in-pit crusher. The crusher has a belt-conveyor system to the waste dump, where the waste rock is stacked by a stacker. The system has a rated capacity of 5 kt/h, with a peak capacity of 6 kt/h, and was commissioned during 1982. The feasibility study that preceded the project indicated a saving in transportation costs of approximately 11,3 per cent and a fuel saving of 100 Ml within nine years at full capacity.

Fig. 6 illustrates the comparison in terms of average fuel consumption between the conventional, trolley-assisted, and semi-mobile in-pit crusher for a typical haulage distance.

The Need for Beneficiation at Sishen

The hematite ore at Sishen occurs in beds of varying thicknesses and grades. Interbedded impurities, such as shales, occur in bands in the laminated ores. In order to supply a product of acceptable and constant quality to blastfurnaces, either selective mining methods have to be used, or the ore has to be upgraded. By the use of heavy-medium separation, the ore reserves can be increased considerably through better utilization of the medium- and lower-grade ores. A mixture of high-, medium-, and lower-grade ores is therefore fed to the plant, where the waste material is effectively separated from the ore.

Blastfurnace performance is adversely influenced by fluctuations in the iron content of the ore. Without beneficiation and the associated blending processes, the fluctuations in the iron content would be very difficult to control.

The Sishen plant is designed to process 22,5 Mt of raw ore per annum into three products: lumpy ore between 25 and 8 mm, lumpy ore between 11 and 5 mm (direct-reduction ore), and fine ore less than 5 mm, at a mass recovery of approximately 80 per cent. The raw-ore feed,

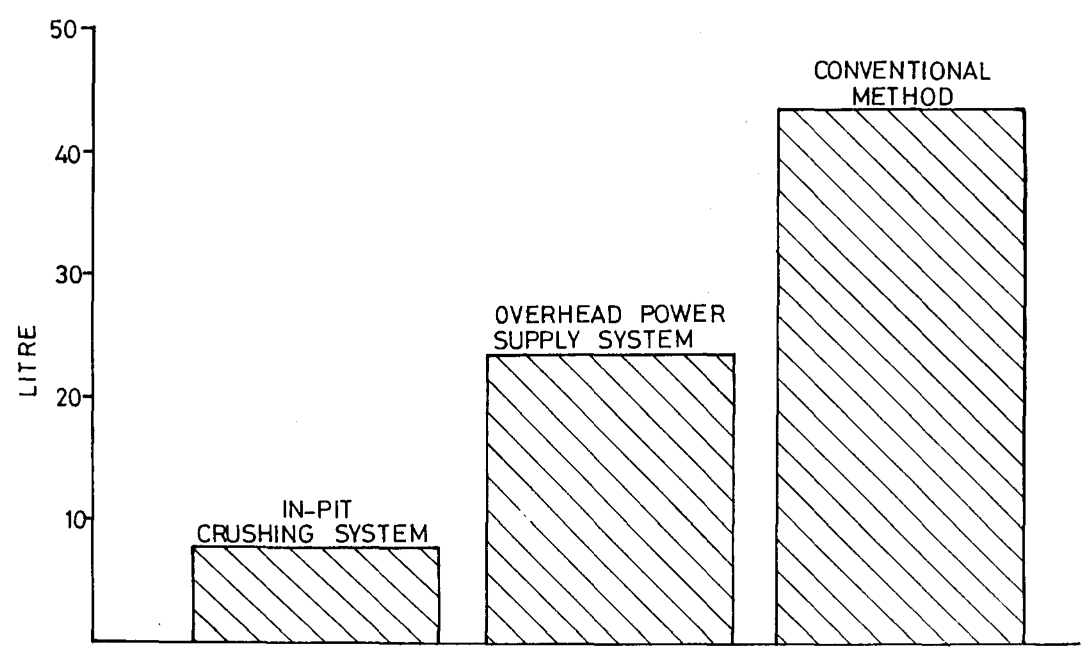


Fig. 6—Comparison of diesel-fuel consumption per 150 t truck for a typical haulage distance

57 to 60 per cent iron, is upgraded to more than 66 per cent iron in the lumpy ore and more than 65 per cent iron in the fine ore.

The plant operates for 24 hours a day, six days a week, and is designed for a throughput of 4,5 kt/h. Sections of the plant are stopped on a scheduled basis for preventive maintenance.

The final products are obtained by different stages of crushing, wet and dry screening, heavy-medium separation, and blending. The beneficiation process is illustrated in the flow diagram of Fig. 7.

The ore is deposited longitudinally on beds using stackers and a drum type of reclaimer to recover the ore transversally. This method of stacking and reclaiming ensures that any variation in ore quality of the beds is eliminated and that a product of uniform quality is despatched. The typical product qualities at Sishen are given in Table IV.

TABLE IV
TYPICAL PRODUCT QUALITIES AT SISHEN

Ore fraction	Size mm	Fe %	SiO_2 %	Al_2O_3 %	K_2O %	P %	S %
Lump	<25>8	66,38	3,03	1,12	0,14	0,043	0,015
Lump	<11>5	66,29	3,07	1,12	0,15	0,043	0,015
Fines	<5	65,42	3,54	1,53	0,23	0,047	0,020

New Plant Development

Originally the plant was designed for two products: lumpy ore (between 25 and 8 mm) and fines (smaller than 5 mm). To make the Sishen Mine more flexible to fluctuations in product demand, a third product of between 11 and 5 mm has been introduced, and stacking, blending, and reclaiming facilities have been installed. This enables the mine to produce a concentrate of between 11 and 5 mm that is up to 15 per cent of total output.

Thabazimbi Iron Ore Mine[14,15]

Thabazimbi Iron Ore Mine is situated in the north-western Transvaal (Fig. 1) and produces iron ore for Iscor's steelworks. The mine was established in 1931, and started production in 1933. Since then, some 96,3 Mt of high-grade ore have been produced, of which some 55,4 Mt were produced from the underground section. At present, the underground production rate is 1,15 Mt run-of-mine ore per annum, while 1,8 Mt are produced from an open-pit section.

Geology

A number of large and small, secondary, enriched hematite orebodies occur within the mountain ranges in the vicinity of Thabazimbi. Two of these are being mined at present, namely the Donkerpoort Open Pit Mine and the East Mine, an underground operation. Fig. 8 is a schematic cross-section through an orebody.

The orebodies occur within the basal portion of the Penge Formation, a rock sequence consisting mainly of banded ironstone that is a subdivision of the Transvaal Sequence. The orebodies dip southwards at an average of about 50 degrees, approximately concordant with the footwall and hangingwall rocks, and vary in thickness from 5 to 60 m. The ore varies from a hard, competent rock to a totally soft, sandy mass.

The ore is overlain by a large thickness of very hard banded ironstone. This tends to break into relatively small blocks, and readily caves into areas from which ore has been extracted on a large scale. It is generally competent from a tunnelling point of view, except for some areas close to the orebody. The footwall rocks consist of massive, competent dolomite that is separated from the orebody by a layer of very weak shale from 1 to 40 m thick.

The *in situ* high-grade ore reserves at Thabazimbi are estimated at 100 Mt, of which 60 Mt are mineable by open-pit methods. The average iron grade of these reserves is approximately 63 per cent.

Underground Mining Method

The mining method employed in the underground section is sub-level caving. At present, the workings are some 400 m below the mountain crest, and from 150 to 250 m below the surface of caved material in the mined-out areas. Fig. 8 shows a schematic section between two main levels.

Access to the orebody is via adits from the side of the mountain and along footwall drives developed in the dolomite. These main levels are 100 m apart vertically. Spiral ramps connect the main levels and sub-levels, which are developed 10 m apart.

Trackless equipment is used for all the mining operations, except for the conveyance of rock on the hauling level. Rock from the sub-levels is fed down rock passes into trains. Electric trolley locos haul the waste trains to the waste dumps on the side of the mountain and ore trains to an underground crusher, from where a conveyor belt transports the ore to the plant.

Open-pit Mining

The open-pit mine is a conventional operation having bench heights of 15 m. Blast-holes of 250 mm diameter are drilled, and the rock is blasted using ammonium nitrate. The ore and overburden are loaded onto 50 and 100 t trucks with 1600 and 2100 P and H shovels respectively, and are hauled to the ore crusher or dumped along the side of the mountain respectively. The average haulage distance is 1 km.

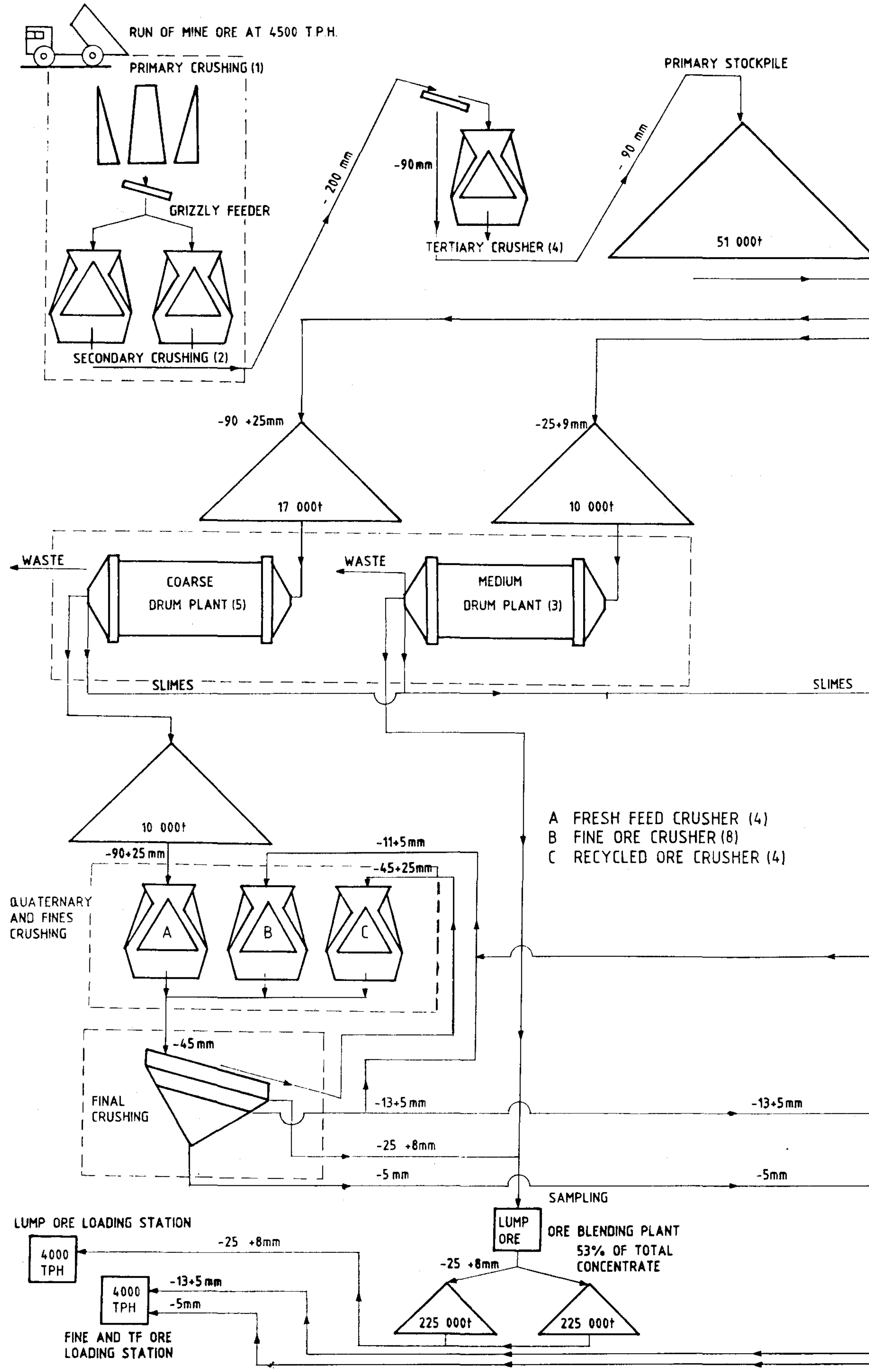
Ore-beneficiation Plant

The plant consists of washing and screening, heavy-medium separation by scoop-wheel separators for the medium and coarse fractions, heavy-medium separation by cyclones for the finer fractions, and gravity separators by spirals for the very fine (smaller than 1 mm) fractions.

The typical product qualities at Thabazimbi are given in Table V. Sinter ore constitutes about 50 per cent of the total ore produced.

Recent Developments

Shotcrete Support System Underground. The introduction at Thabazimbi in 1984 of wire meshing and shotcreting underground, instead of timber support, has led to significant cost reductions (from R1,18 per ton mined to R0,47 per ton mined) and to the following additional


RUN OF MINE ORE AT 4500 T.P.H.
PRIMARY CRUSHING (1)
GRIZZLY FEEDER
SECONDARY CRUSHING (2)
- 200 mm
-90mm
TERTIARY CRUSHER (4)
- 90 mm
PRIMARY STOCKPILE
51 000t
-90 +25mm
17 000t
-25+9mm
10 000t
WASTE
COARSE
DRUM PLANT (5)
WASTE
MEDIUM
DRUM PLANT (3)
SLIMES
SLIMES
10 000t
-90+25 mm
-11+5mm
-45+25mm
A FRESH FEED CRUSHER (4)
B FINE ORE CRUSHER (8)
C RECYCLED ORE CRUSHER (4)
QUATERNARY
AND FINES
CRUSHING
A
B
C
-45mm
FINAL
CRUSHING
-13+5 mm
-13+5mm
-25 +8mm
-5 mm
-5mm
SAMPLING
LUMP ORE LOADING STATION
4000
TPH
-25 +8mm
LUMP
ORE
ORE BLENDING PLANT
53% OF TOTAL
CONCENTRATE
-25 +8mm
4000
TPH
-13+5 mm
-5mm
FINE AND TF ORE
LOADING STATION
225 000t
225 000t

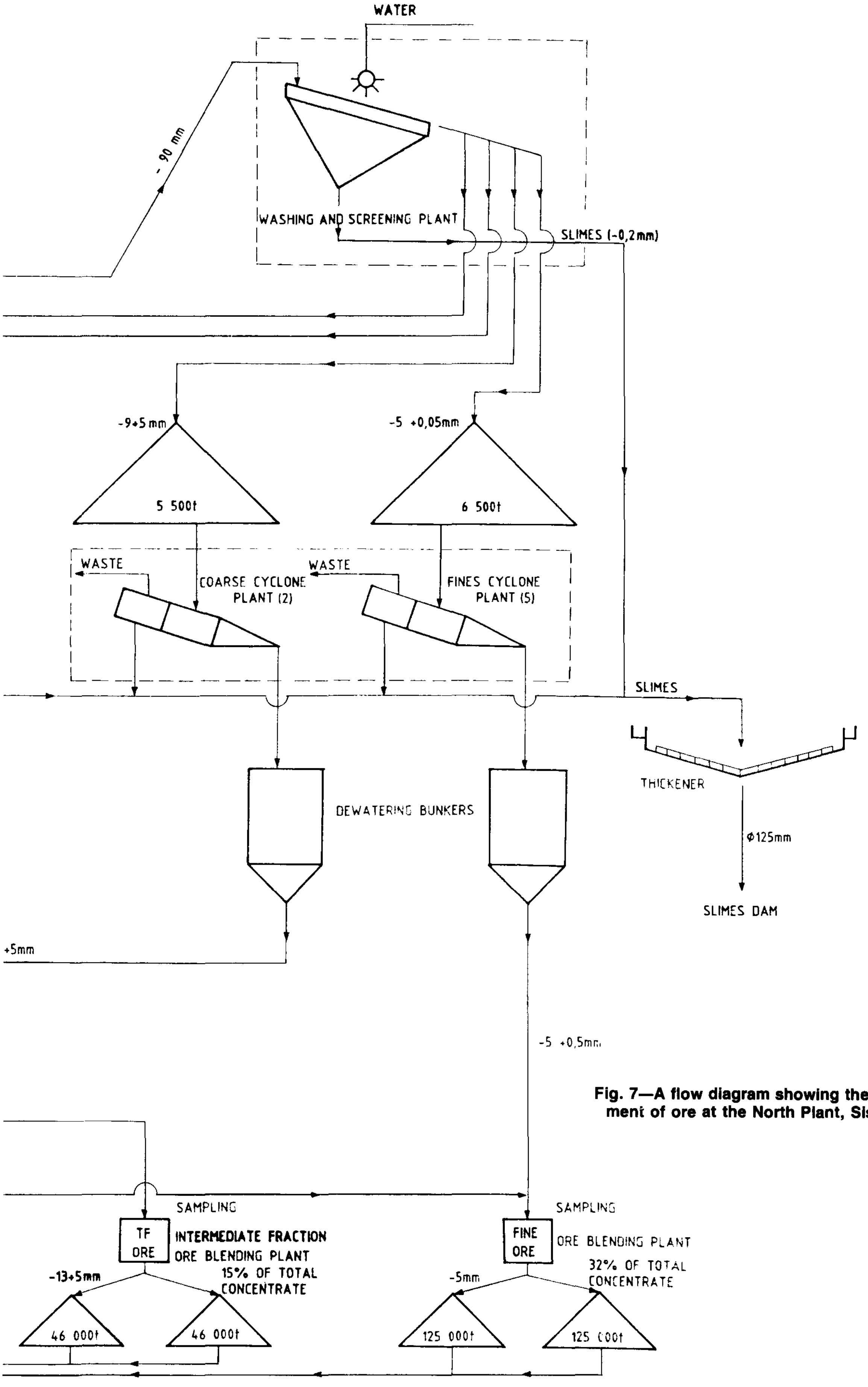


Fig. 7—A flow diagram showing the treatment of ore at the North Plant, Sishen

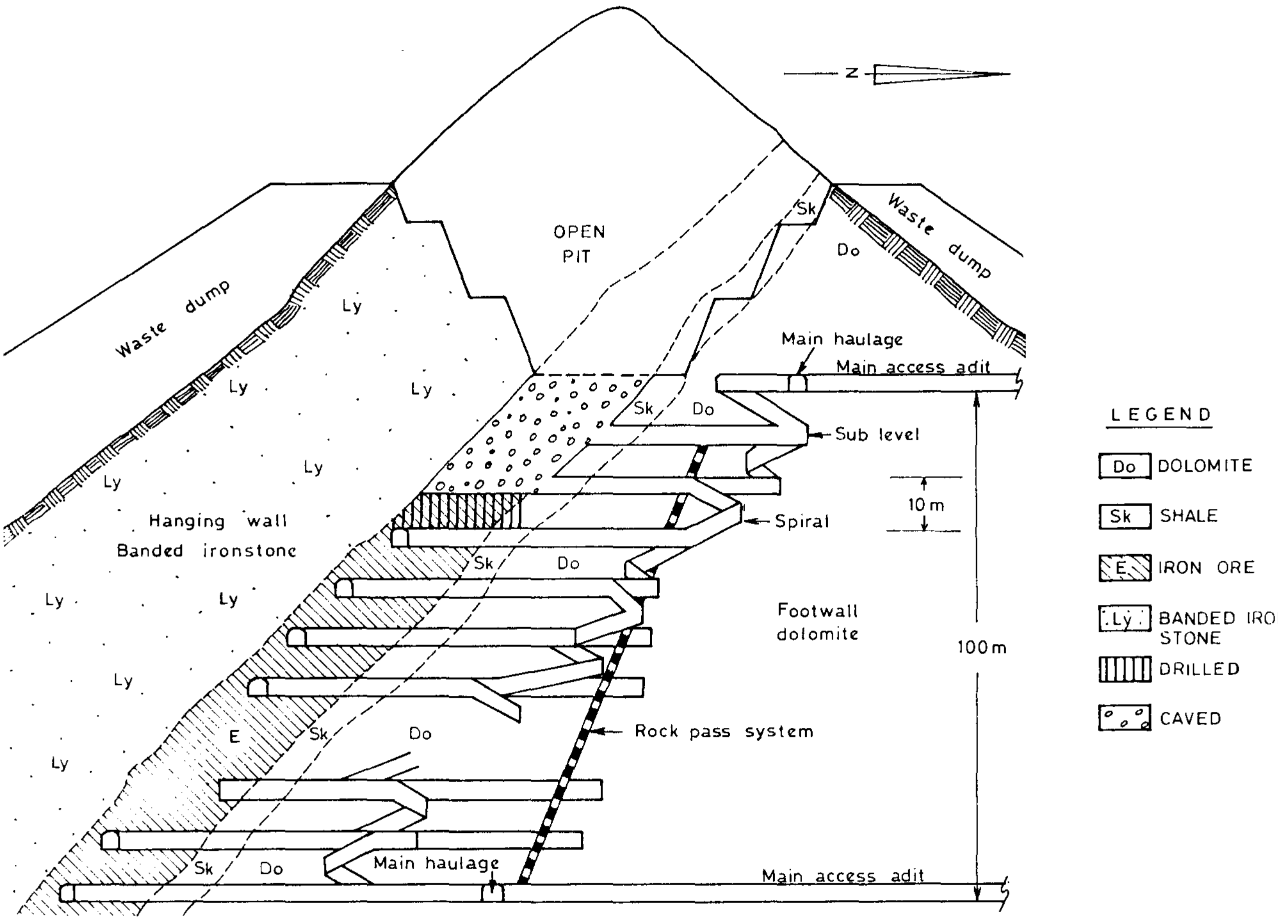


Fig. 8—Schematic underground layout at Thabazimbi Iron Ore Mine

TABLE V
TYPICAL PRODUCT QUALITIES AT THABAZIMBI

Ore fraction	Size, mm	Fe, %	SiO_2, %	Al_2O_3, %	P, %	MnO, %	K_2O, %	CaO, %	MgO, %
Lumpy ore	<30>12	64,0	6,0	1,0	0,03	0,4	0,09	0,5	0,4
Lumpy ore	<12>6	64,0	6,0	1,0	0,03	0,4	0,09	0,5	0,4
Sinter ore	<6>0,07	63,0	6,5	1,3	0,03	0,5	0,09	0,5	0,4

advantages.

- The extraction ratio has increased markedly since it is now possible to keep the production tunnels open until the end of the caving process.
- The tunnels previously lost owing to the collapse of timber support were reclaimed using shotcrete support, thus extending the life of the mine.
- Less re-support work is necessary. The very high cost of the timber support was due largely to the re-support required to maintain the tunnels after the failure of the initial support.
- Ring drilling is more accurate, and closure of the ring boreholes occurs less frequently. Blasting is thus more effective, resulting in better extraction. It was also difficult to drill accurately through the timber, and the timber was a nuisance during the caving process since it had to be removed prior to blasting.
- The brow stability at drawpoints has improved.
- The total amount of development has been reduced by some 30 per cent since access tunnels can now be developed in the orebody instead of in the hangingwall. This also favours the production since the hauling distances are shorter.
- The support occupies less of the excavated space than timber, and offers no obstruction to the equipment. This is reflected in better production rates for the load–haul–dump trucks.
- The fire hazard has been virtually eliminated.
- A safer and cleaner working environment has been created, with an overall improvement in mining conditions and standards. This has improved the productivity and safety of the mine as the underground accident statistics (Table VI) indicate.

Wall Control Blasting in the Open Pit. Wall-control blasting at the Donkerpoort iron ore operation involves pre-splitting, buffer blasting, and staggered-hole depth

TABLE VI
UNDERGROUND ACCIDENT STATISTICS*

	1982	1983	1984	1985	1986
No. of injuries resulting in lost time	18	19	16	1	7
Reportable injuries associated with ground conditions	2	3	5	0	0

* Shotcreting started replacing timber during 1984 and got into full stride during 1985

blasting in banded ironstone, weathered material, and dolomite respectively. After extensive trials, theoretical drilling patterns and charges were developed into a successful drilling-and-blasting system, utilizing the different rock properties. The steepening of pit slopes resulting from the protection of final faces by controlled blasting techniques yielded a reduction of the stripping ratio, as well as the overall mining costs.

Beeshoek Mine[2,11]

The Beeshoek Iron Ore Mine belongs to and is run by Associated Manganese of South Africa, and is situated 6 km to the west of the town of Postmasburg.

The production of iron ore started at Beeshoek during 1959. The capacity of the crushing, screening, and washing plant at Beeshoek is 5 Mt of run-of-mine ore per annum. The present production is of the order of 1 Mt of ore per annum. Iron ore produced at Beeshoek is transported 70 km by rail to Sishen, where the trucks are transferred to the Sishen–Saldanha railway line for export.

The iron ore deposits belonging to Associated Manganese occur at Beeshoek and at Bruce, Mokaning, and McCarthy farms, the latter three farms being situated close to the Sishen Iron Ore Mine.

The geological setting and environment of the high-grade hematite ore at Beeshoek is similar to that described for Sishen. As at Sishen, four different types of ore occur at the Beeshoek open-cast mine: Thaba-ore, laminated ore, conglomeratic ore, and detrital ore. The bulk of the Beeshoek ore is of the conglomeratic type. Although not linked with each other in the outcrop area, the orebodies are stratiform and of varying thickness, with a great lateral extent displaying a regional dip of approximately 10 degrees to the west.

The high-grade ore reserves at Beeshoek and in the surrounding areas belonging to Associated Manganese have been estimated at some 400 Mt at an average grade of 63 to 66 per cent iron. The average analysis of the iron ore at Beeshoek is as follows:

Fe	65,3 %	Al_2O_3	3,51 %
Mn	0,26 %	Na_2O	0,017%
SiO_2	4,04 %	K_2O	0,19 %
CaO	0,01 %	P	0,029%
MgO	0,01 %	S	0,004%.

Beeshoek open-pit mine is a conventional operation with bench heights of 10 m. Holes of 215 mm diameter are drilled, and the rock is blasted with ammonium nitrate. All the blast-holes are over drilled by 2 m, and the drilling grid is 5 × 6 m. Primary loading equipment at Beeshoek comprises 6 diesel power shovels (3,5 m^3) and 3 electrically driven (1 × 3,5 m^3 and 2 × 6 m^3) power shovels. These are supplemented by two front-end loaders for secondary cleaning. The ore and waste rock is hauled by 5 diesel rear-dump trucks of 55 t capacity and 6 of 50 t capacity. At present, the stripping ratio at Beeshoek is of the order of 1 ton of waste to 1 ton of ore, but gradually improves with increasing depth of the individual pits.

The run-of-mine product of the Mine is beneficiated by a washing and screening plant. Selective mining practices are applied together with primary blending of the ore at the primary crusher. By washing and screening of the run-of-mine product, the ore is upgraded by 0,5 to 1 per cent iron.

Mapochs Mine[12,16]

The mining and processing of the vanadium-rich magnetites of the Bushveld Complex was recently described in detail by Rohrmann[12], and the present paper will therefore give only a brief outline of the mining activities.

The open-cast Mapochs Mine of Highveld Steel & Vanadium Corporation Limited was commissioned in 1967, and is situated to the north of the village of Roossenekal, in the eastern Transvaal. In this region, the main magnetite seams dip westwards at approximately 13 degrees, and can be traced for hundreds of kilometres around the elliptical rim of the complex. The grade of the ore is remarkably constant. A generalized section of the titaniferous–vanadiferous magnetite seams in the Bushveld Complex is given in Fig. 9.

The proven ore to openpit limits is in excess of 130 Mt. The grade and quality of the magnetite ore are as follows:

Fe	53–57%	Cr_2O_3	0,15–0,6%
TiO_2	12–15%	SiO_2	1,0–1,8%
V_2O_5	1,4–1,9%	Al_2O_3	2,5–3,5%.

The titanium in the ore is present as a solid solution in the magnetite phase (ulvospinel Fe_2TiO) and to a lesser degree as ilmenite. The vanadium occurs in the ore as a solid solution within the magnetite–ulvospinel, where V^{3+} has replaced Fe^{3+}. Where exposed to weathering, the magnetite has been oxidized to vanadomaghemite, $(Fe,Ti,V)_2O_3$, and to small concentrations of hematite without any alteration in the texture or the ore. The titanomagnetite is highly magnetic.

The overburden and unconsolidated ore are mined by bulldozers without blasting, while the unweathered main seam is drilled (holes of 64 mm diameter) and blasted (with dynamite and Anfex). The ore and overburden are loaded with front-end loaders onto 35 t trucks, and conveyed to the plant and waste dump respectively.

The products from the ore-treatment plant are lumpy ore 4,5 to 25 mm in size, and magnetically upgraded ore fines smaller than 4,5 mm. The lumpy ore is railed to the iron and steel works, and the ore fines to the Vantra Roast–Leach Plant. The plant capacity is 3,5 Mt per annum, and approximately 1,8 Mt of lumpy ore is produced per annum.

Palabora Mine[2,9]

Palabora is a large conventional open-pit mine producing as a primary product copper from a low-grade (0,5

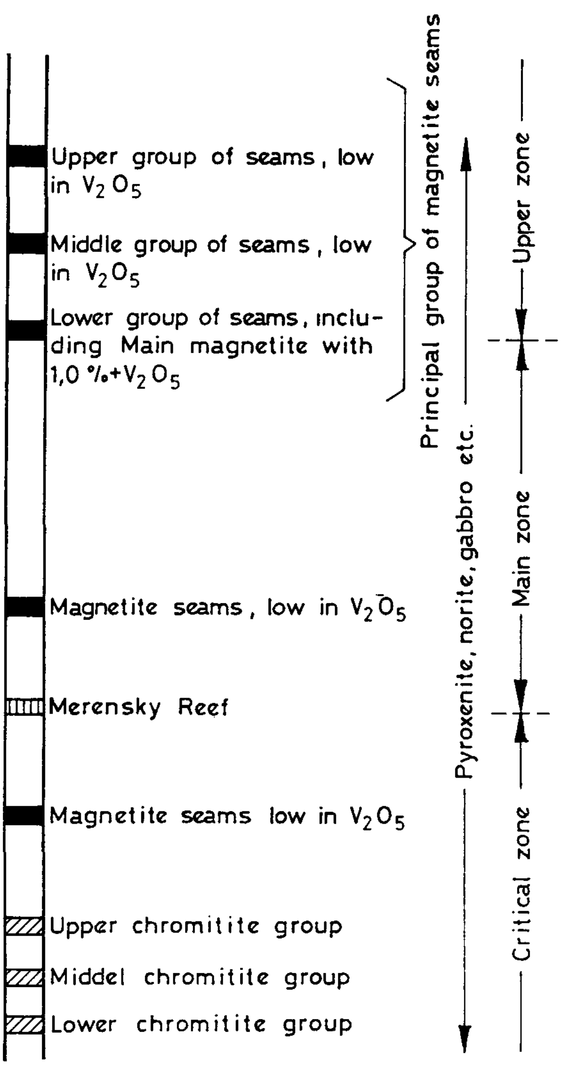


Fig. 9—A generalized section of the titaniferous-vanadiferous magnetite seams in the Bushveld Complex

per cent copper) orebody, which occurs as a pipe-like carbonatite intrusion. It is regarded as one of the most efficient and cost-effective open-pit mines in the world.

A trolley-assist system was introduced at the mine with great success. Palabora is currently in the process of installing an in-pit crusher, which will further reduce fuel costs and the number of operating haulage trucks.

Magnetite is a major constituent in the various rock types of this intrusion, and is produced as a byproduct to the winning of copper ores.

On average, the orebody contains approximately 27 per cent magnetite; the distribution conforms to the annular ring structure of the pipe, but its correlation with the main rock types is less clearly defined than is the case with copper. In general, however, the highest concentration, up to 50 per cent magnetite by mass, is found in the foskorite, while the carbonatites forming the central part of the orebody carry 15 to 30 per cent magnetite. The surrounding pyroxenite is virtually barren.

The concentration of titanium in the magnetite is clearly demarcated; in the central parts of the pipe, i.e. in the carbonatite, the magnetite contains essentially less than 1 per cent TiO_2, but this amount increases outwards to about 5 per cent in the foskorite.

The annual production of magnetite at Palabora Mining Company is 5 Mt, of which approximately 1 Mt carry less than 1 per cent titanium. The latter is reground, cleaned of apatite, copper impurities, and gangue, and exported to Japan. The remaining production is stockpiled. The reserves of magnetite present in the Palabora Complex are estimated at 100 Mt.

The possibility of establishing a steelworks based on the magnetite from Phalaborwa has been considered by several people, but no formal plans have yet been announced. Schemes have also been considered for the slurrying of this magnetite and its transportation either to the port of Maputo, or even as far as Richards Bay, by pipeline.

The typical specification for the material is as shown in Table VII.

TABLE VII
SPECIFICATION OF PHALABORWA MAGNETITE

	Specification %	Weighted average, 1975 %
Fe	64 min.	66,05
SiO_2 + Al_2O_3	2 max.	0,58
Cu	0,06	0,041
P	0,08	0,063
TiO_2	1,30	1,047
Ni	0,04	0,027
Cr	0,04	0,020
MgO	–	2,5
S	–	0,045
Sizing	>44 um	29,9
	<44 um	71,1

PROCESSING OF IRON

Steelmaking Processes[11,17]

The steelmaking routes available at present are shown in Fig. 10.

The steelmaking process from raw materials to a saleable product can be divided into two major steps: the production of raw steel from raw materials, and the processing of this raw steel into the final quality, form, and shape required by the customer. The present processes for the making of raw steel are basically the route using the coke oven, blastfurnace, and basic oxygen furnace (BOF) with coking coal and iron ore as raw materials, and the electric-arc furnace using steel scrap. There is also the relatively new direct reduction–electric-arc furnace process using coal and iron ore as raw materials.

The major cost inputs in the production of raw steel are for capital, energy (coal and electricity), and iron ore or scrap.

Blastfurnace

The blastfurnace is at the moment still the most energy-efficient smelter of iron ore as is manifested by its continued use worldwide. Iron ore, sinter, coke, dolomite, and limestone are charged from the top into the blastfurnace in alternating layers (Fig. 11). Heated (blast) air is blown in through nozzles (tuyères) in the bottom of the furnace. The blast air burns a portion of the coke

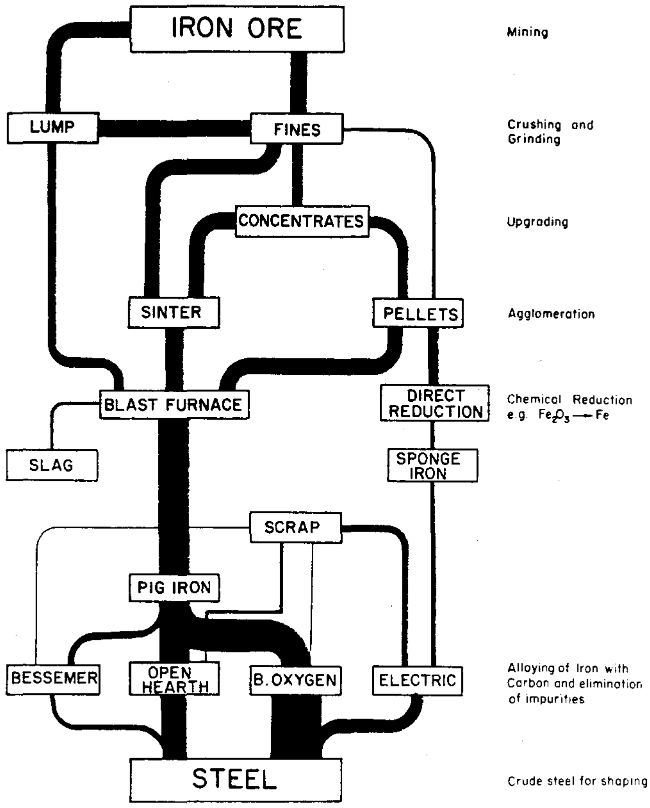


Fig. 10—Main steelmaking routes

to produce heat for the chemical reactions and to smelt the ore. The rest of the coke and carbon monoxide formed during the burning of the coke combine with the oxygen in the ore, and thus release the metal from the ore. The process by which the ore is reduced to metal and the metal is melted is called smelting.

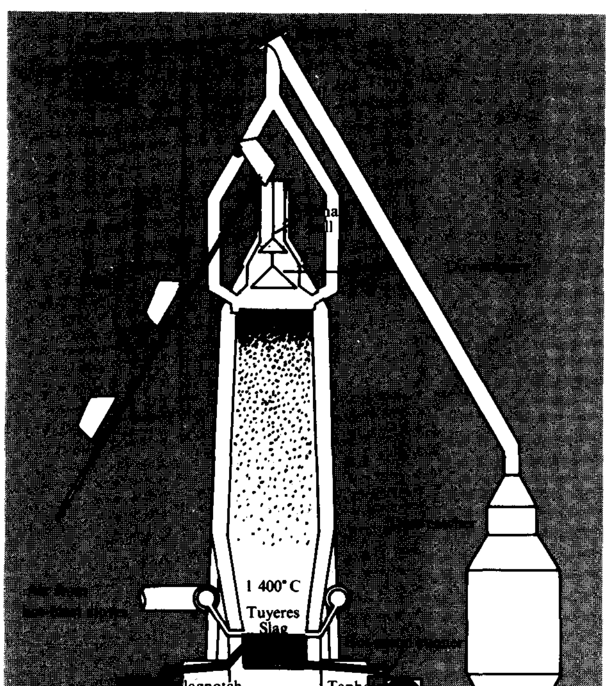


Fig. 11—A conventional blastfurnace

The dolomite and limestone serve as fluxes to form a slag together with the impurities, such as alumina and silica, in the ore and the ash, which arises from the combustion of the coke. Because the liquid slag floats on the molten iron, it can easily be separated from the liquid iron when the furnace is tapped. The temperature of the molten iron is about 1400°C.

The blastfurnace slag, consisting of compounds of calcium and magnesium silicates and aluminates, is granulated in a stream of water to form granulated slag, which is used in the manufacture of slag cement.

To produce 1 t of iron requires approximately 1,5 t of iron ore, 550 kg of coke, and 200 kg of fluxes.

Although most of the iron produced by a blastfurnace passes to the steel-smelting plant in liquid form for refining into steel, a portion of the output is cast. The molten iron, also known as hot metal, is poured from a ladle into a slowly moving conveyor line of moulds, forming part of what is known as a pig-casting machine. The pieces of iron obtained in this way are called pigs. The molten iron can also be cast into a shallow pool, hence the term *pool iron*. The pool iron is broken into pieces by a steel ball dropped from a crane to make it suitable for use.

Pig iron is hard and brittle, mainly on account of its high carbon content of between 3,5 and 4,5 per cent and the presence of elements such as sulphur and phosphorus. It therefore does not have the strength, malleability, or shock resistance of steel. The two major applications of pig iron are as a feedstock in the foundry industry for the casting of such products as engine blocks, machine parts, sanitary ware, coal stoves, and baths and, secondly, as a supplementary source of iron for steelmakers who do not have their own blastfurnaces.

Direct Reduction of Ore

This process, known as DR, is reminiscent of the ancient smelting method to bring the ore into physical contact with carboniferous material, with the application of heat at a relatively low temperature—considerably below the melting point of pure iron (about 1530°C). The product obtained in this way was processed into useful tools by hammering.

The direct reduction of iron ore is effected with a reducing gas in a shaft furnace or with coal in a rotary kiln. In South Africa, where coal is the main source of energy, rotary kilns are preferred.

The rotary kiln is an elongated, inclined rotating drum in which the charge gravitates from the input to the discharge end (Fig. 12). Coal and dolomite are charged into the kiln together with iron ore. Usually, a portion of the coal is also blown in from the discharge end to obtain, *inter alia*, a uniform distribution of the reducing agent over the length of the rotary kiln.

The heat for the process is obtained by burning of the volatile matter in the coal and the carbon monoxide leaving the bed in the kiln. The air supply is controlled by the blowing of air over the length of the rotary kiln with the aid of fans. The reduction of the ore is accomplished by the carbon in the bed, which generates carbon monoxide.

It is important that the temperature in the rotary kiln should remain below the melting point of any component

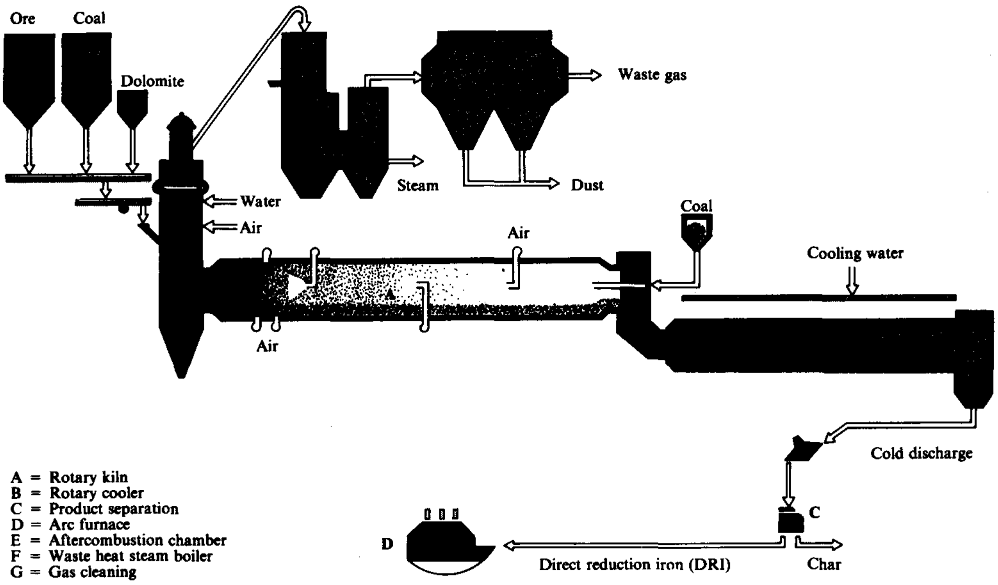


Fig. 12—A schematic representation of the DR process

in the charge. In this case, the dolomite does not act as a flux as in the blastfurnace. However, it plays a major role by combining with the sulphur in the input raw materials, thus preventing the sulphur from being absorbed in the sponge iron.

The direct-reduced iron, or sponge iron, is a dark grey, porous solid that has retained the shape of the original lump of ore. It is melted with steel scrap mainly in arc furnaces. The DR–arc furnace route therefore offers an alternative to the blastfurnace–BOF route for the production of steel from ore. The main advantage of the DR–arc furnace route is that it eliminates the use of coking coal, which is available in limited quantities in South Africa at a cost that is rapidly increasing.

KR or Corex Process

A new process is curently being developed in which liquid iron can be produced by the direct use of coal. The process is appropriately referred to as the KR process, which is derived from the German *Kohle Reduktion* (coal reduction). The raw materials are the same as for the coke oven–blastfurnace route, except that the KR process can use a non-coking coal, which is found abundantly in South Africa.

A KR plant consists of a melter–gasifier and a reduction shaft. It can be regarded as a blastfurnace in which the shaft and hearth portions are separated physically. The same metallurgical reactions as in the blastfurnace occur in the KR process (Fig. 13).

Coal is charged through the dome of the melter-gasifier, where it is dried and volatilized to form coke (cinder). The cinder is burnt (gasified) into carbon monoxide by oxygen blown in through the tuyères above the hearth of the melter–gasifier. The reducing gas leaving the melter–gasifier is purified, and then cooled to the desired temperature before it flows through the reduction shaft. As in the case of a blastfurnace, the ore is top-charged into the reduction shaft. In the shaft, the iron ore (Fe_2O_3) is reduced to sponge iron by the carbon monoxide. The sponge iron is withdrawn from the bottom of the shaft by means of screw feeders, from where it drops onto the melter–gasifier. In the melter–gasifier the cinder 'floats' in a fluidized bed; in other words, the particles float in the stream of gas that arises above the hearth as a result of the blowing-in of oxygen. The sponge iron, which is much heavier than the cinder, descends and melts when it reaches the tuyère zone. The liquid iron and slag that collect in the hearth are tapped at regular intervals as in a blastfurnace.

To control the basicity of the slag for efficient desulphurization, limestone and dolomite are charged

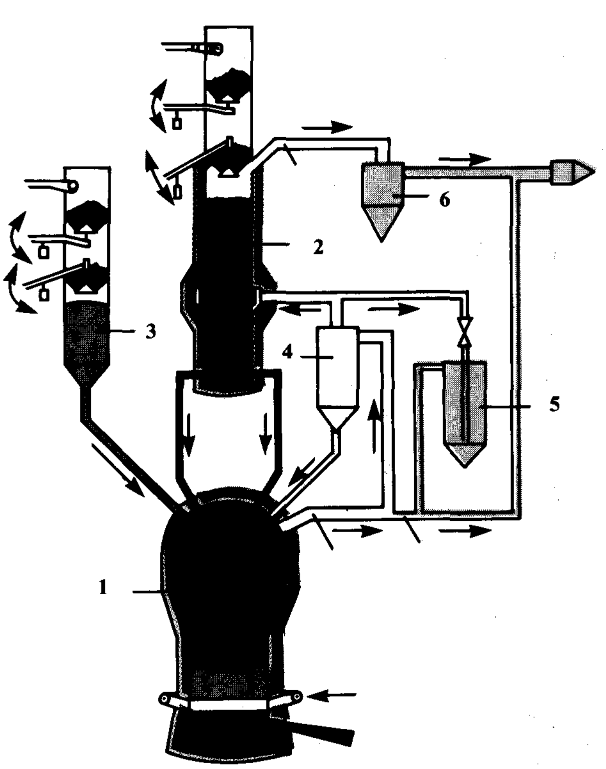


Fig. 13—A schematic representation of the KR process
1 Melter–gasifier 2 Reduction shaft furnace
3 Coal feed bin 4 Hot-dust cyclone
5 Gas cooler 6 Top-gas cooler

together with the coal or ore.

The KR process produces more gas than is needed for ore reduction. Some of the surplus gas can be utilized advantageously elsewhere in the steelworks, for instance to reheat steel and for heating the ladles.

IRON AND STEELMAKING IN SOUTH AFRICA[18]

History and Development

The modern conversion of ore to metal started when initial proposals were made in 1860 for the exploitation of the coal and ore fields in Natal, leading to the production of pig iron with a primitive blastfurnace near Pietermaritzburg on a small and temporary scale in 1901. The emphasis then changed from ore to electric smelting of scrap, mainly railway scrap, leading in 1911 to the founding of Union Steel Corporation. During 1917 and 1918, Marks and Lewis (USCO) and Neame (Dunswart) operated a blastfurnace at Vereeniging, producing 650 t of liquid iron.

The first industrial-scale smelting of iron ores was initiated by Cornelis Delfos, who obtained a concession in 1916 to mine iron ore in the Pretoria area. A blastfurnace was constructed and blown in during 1918. Some good foundry iron was subsequently produced from this furnace, and Delfos's efforts eventually resulted in the founding of the South African Iron & Steel Industrial Corporation in 1928 and the construction of the Pretoria integrated iron-and-steel works with an initial annual capacity of 160 kt.

J.K. Eaton constructed a 120 to 140 t/d blastfurnace at Newcastle in Natal that came into operation during 1926 as the first commercial-scale smelting of iron ores in South Africa. Control of the plant at that stage had passed to USCO, later to be taken over by Samancor, and eventually to become Iscor's Newcastle South Works. The North Works was started during 1974.

On 4th April, 1934, the first South African steel produced from ore, rather than scrap, was tapped in Pretoria via the coke oven–blastfurnace–open-hearth route using Thabazimbi iron ore. Bessemer open-hearth duplex steelmaking was initiated during 1941, and the blastfurnace–open-hearth steelmaking route at Vanderbijlpark in 1950 using Sishen iron ore. Oxygen steelmaking in Pretoria started with the rotor process during 1959, to be eventually followed by the current BOF process at Vanderbijlpark and Newcastle, and electric steelmaking at Vanderbijlpark. Pretoria also introduced electric steelmaking during 1985.

The blastfurnace originally used only screened ore, and in 1948–1949 the first sinter plant using fine ore was commissioned at Pretoria Works. This was followed by sinter plant No. 2 at Pretoria Works in 1958. Sinter plants Nos. 1 and 2 were commissioned at Vanderbijlpark Works in 1964 and 1971, and the sinter plant at Newcastle in 1976.

Latest Developments

The present conventional coke oven–blastfurnace–BOF route is highly capital-intensive and uses coking coal, which, owing to its special characteristics, is in limited supply and, owing to the narrow coal seams, is expensive to mine in South Africa. The direct-reduction process is less capital-intensive, and uses a cheaper coal with characteristics less restrictive than those of coking coal.

The first coal-based rotary-kiln plant in South Africa for a directly reduced iron (DRI) product was constructed by Krupp for the Dunswart Iron & Steel Works in Benoni and commissioned in 1973 with a nominal design capacity of 150 kt of DRI per annum.

Iscor, in particular, investigated the possibility of producing DRI in order to alleviate the shortages of coking coal, especially high-grade, straight coking coal, and also as a substitute for steel scrap. The cheapest way of making steel is from steel scrap, but a shortage of recycled scrap in South Africa and an appreciable price rise were forecast. The initial DRI processes were based on reformed natural gas but, as natural gas was not commercially available in South Africa, a completely coal-based operation was required.

An international search for coal-based DRI technology produced many promising routes. The alternatives included processes based on coal gasification combined with shaft reduction and rotary-kiln reduction using non-coking coals. The outcome of a detailed techno-economic investigation completed during 1980 favoured a coal-based rotary-kiln process. Iscor opted for the SL/RN design, while Scaw Metals favoured a DRC plant. The Scaw Metals plant for 75 kt/a was commissioned in 1983, and the SL/RN four-kiln plant of Iscor, designed for a nominal 720 kt of DRI per year, went into operation during 1984–1985 at the Vanderbijlpark Works.

Although the new DRI routes provided iron units to compensate for scrap shortages without using expensive coking coals, they still required electrical energy for melting. In an effort to move away from the constraints of both the scarce coking coals and electrical energy with escalating cost, Iscor began to examine the new 'reduction smelting processes' for liquid-iron production where, in some cases, the total energy requirement can be supplied from a coal feed.

The KR, Kohle-Reduktion process of Korff Eng. (Fig. 13) and also now Voest-Alpine, was identified as having potential as a viable commercial process. After extensive pilot-plant trials in Germany and a full techno-economic investigation, Iscor decided to construct the first KR plant in the world to be used on an industrial scale. This 300 kt/a plant at Pretoria Works will come on stream in 1988.

This type of plant is capable of being accommodated in the existing integrated steelworks configuration, and produces an acceptable process gas. If proved viable, it could replace the present blastfurnace process for the future production of liquid iron.

The BOF steelmaking units are being improved by the addition of bottom bubbling facilities, and conventional casting is being replaced by continuous casting.

At present, 54 per cent of Iscor's steel production is continuously cast and, with the new caster being built at Vanderbijlpark, this will increase to 71 per cent. Plans are being investigated to increase this still further. In Japan, over 95 per cent of the steel is continuously cast.

As elsewhere in the developed countries, secondary manufacturing industry in South Africa is demanding steel that complies with more stringent quality specifications. Active research-and-development is being done on a continuing basis to develop improved types of steel with improved strength, wear-resistance, and anti-corrosion characteristics. These developments are also required for survival in the highly competitive world of substitute materials, and involve the steel industry in substantial capital investment to produce such steels.

SUPPLY/DEMAND AND FORECASTS FOR IRON ORE AND STEEL[10,11,17,19-22]

The change in location of the world's steel production is given in Fig. 14. For instance, US production dropped from 40 to 10 per cent of the world's total during the period 1955 to 1985. Its steel-production capacity also dropped, from a peak of 160 Mt in 1977 to 133 Mt in 1985, and its production of steel in 1985 was 87 Mt or 65 per cent of capacity. In a matter of ten years, over 600 steelmaking facilities in the USA were closed. As a contrast, the developing nations have more than doubled their capacity in the past fifteen years. Korea, for example, was an insignificant steel producer a decade ago. Today, that country is producing over 9 Mt of steel annually and is expanding this to 15 Mt.

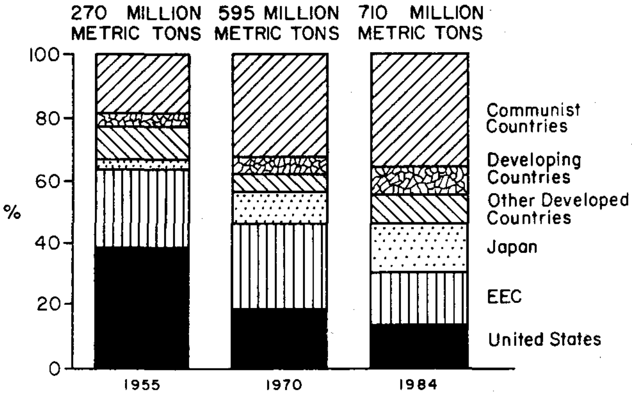


Fig. 14—Shifting world production of steel (in percentage shares)

The International Iron and Steel Institute estimated the world's steelmaking capacity in 1985 at 936 Mt, the actual steel production being 723 Mt (77 per cent of capacity). The forecast for 1990 is 910 Mt capacity and 730 Mt of actual steel production (80 per cent of capacity). The world's steel consumption for 1986 was 721 Mt. It is expected that this level of production will be maintained in 1987, with an increased steel consumption in the developing and Communist Bloc countries being offset by a corresponding drop in the Western industrialized countries (including Japan).

The shifting world production of iron ore by region is given in Fig. 15. The production of iron ore declined from 883 Mt in 1974 to 785 Mt in 1984. This decline can be attributed to the following factors.

- The gradual increase in the production of crude steel by the electric arc-furnace route, which uses mainly scrap and requires only limited tonnages of iron ore. This situation results in a steady decrease in the production of crude steel by the blastfurnace route.
- The reduced total demand for crude steel as a result of
  - (a) quality and productivity improvements in the steel industry;
  - (b) requirements for lighter, stronger, higher-quality steels;
  - (c) substitution by alternative materials, e.g. aluminium, plastics, etc.
  - (d) saturation of demand in the developed countries.

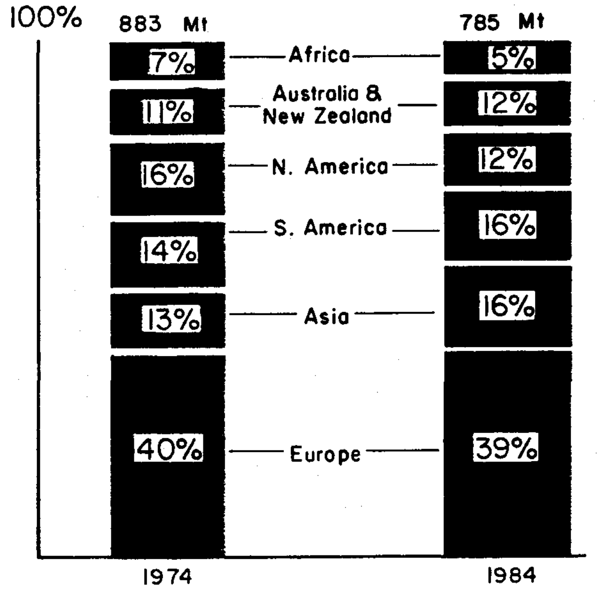


Fig. 15—Shifting world production of iron ore

This reduced demand aggravates the over-capacity in supply (Fig. 16).

In 1984, the combined total iron ore production capacities of the Free World exceeded the demand by 210 Mt of iron content (Mt of iron ore × average percentage iron (Fe) content), resulting in a capacity utilization of only 69 per cent (Fig. 16), and the position has deteriorated, with the Brazilian Carajas ore coming onto the market at an annual rate of 35 Mt.

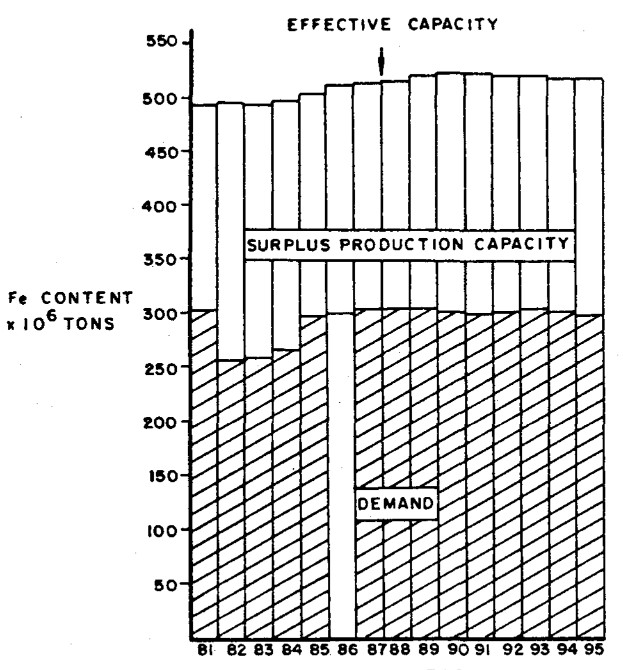


Fig. 16—Estimated iron ore production capacity and demand in the Free World

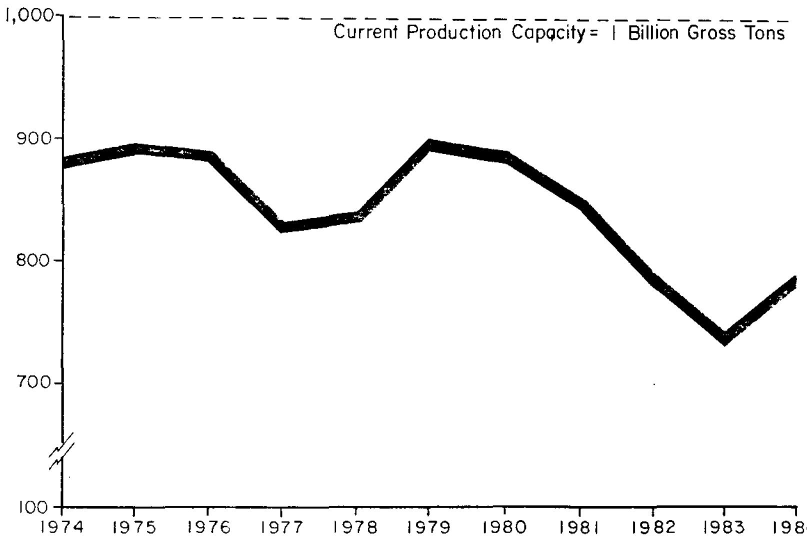


Fig. 17—World iron ore production versus current capacity (in millions of gross tons)

The world's total production capacity is estimated at 1000 Mt, and the total world production of iron ore during the past ten years is given in Figure 17.

The forecast for the consumption of iron ore in the foreseeable future is discouraging—analysts are of the opinion that zero growth can be expected in the consumption from 1986 to 1995.

Steel consumption in South Africa during the past twenty years is given in Fig. 18. The consumption dropped from a peak of 5,4 Mt in 1975 to 4,2 Mt in 1986.

Iscor produces some 75 per cent of all South Africa's iron and steel from iron ore, sponge iron, or scrap, with Highveld Steel & Vanadium contributing 10 to 15 per cent and a large number of smaller producers accounting for the remainder of the total output.

The total sales of Iscor steel products from 1972 to 1986 is given in Fig. 19. During that period, the sales increased from 2,7 to 5,7 Mt, which is some 76 per cent of Iscor's installed capacity (Vanderbijlpark 4 Mt, Newcastle 1,9 Mt, Pretoria 1,4 Mt, Dunswart 0,2 Mt, total approximately 7,5 Mt). This performance was made possible by a concerted export drive. In 1986, some 45 per cent of the steel produced was exported.

It has been forecast that the consumption of steel in South Africa will grow at a rate of 3 per cent per annum (4,2 Mt in 1986) for the next decade (5,5 Mt in 1995). The forecast production in 1995 of 5,5 Mt is therefore well below production capacity.

The shipments of iron ore from Sishen for the past ten years are given in Table VIII.

THE FUTURE OF THE SOUTH AFRICAN IRON ORE AND STEEL INDUSTRY

The installed steelmaking capacity far exceeds the domestic demand in South Africa at present, and the existing capacity is expected to suffice for at least twenty-five years at the expected growth in domestic demand (2 to 3 per cent per annum).

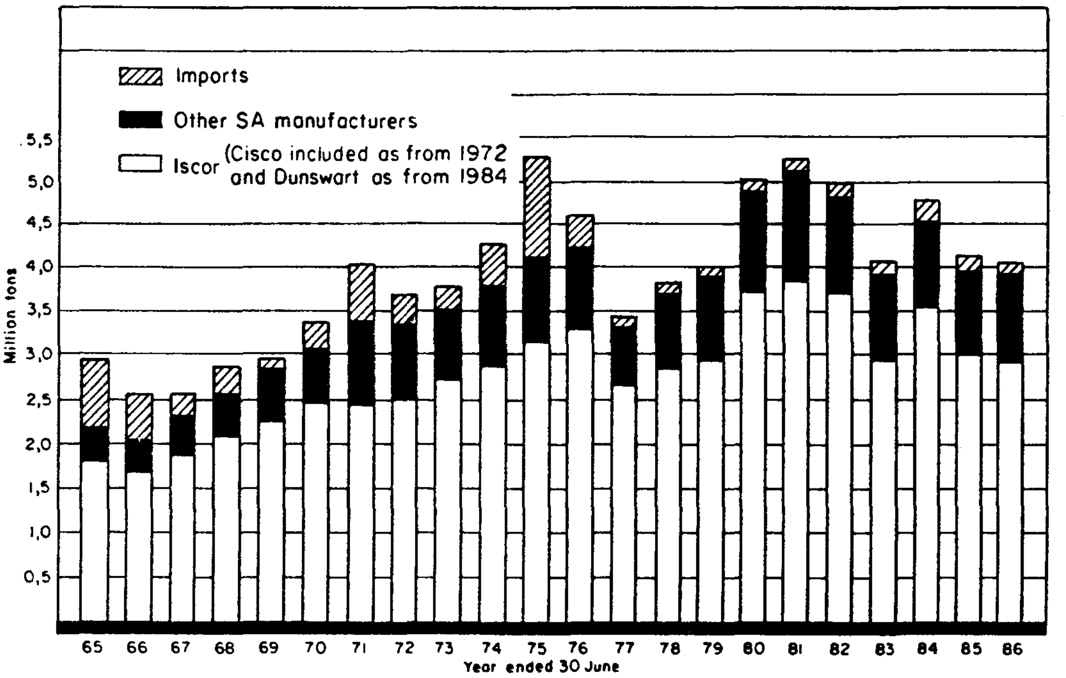


Fig. 18—Rolled, drawn, and forged steel products supplied to the local market

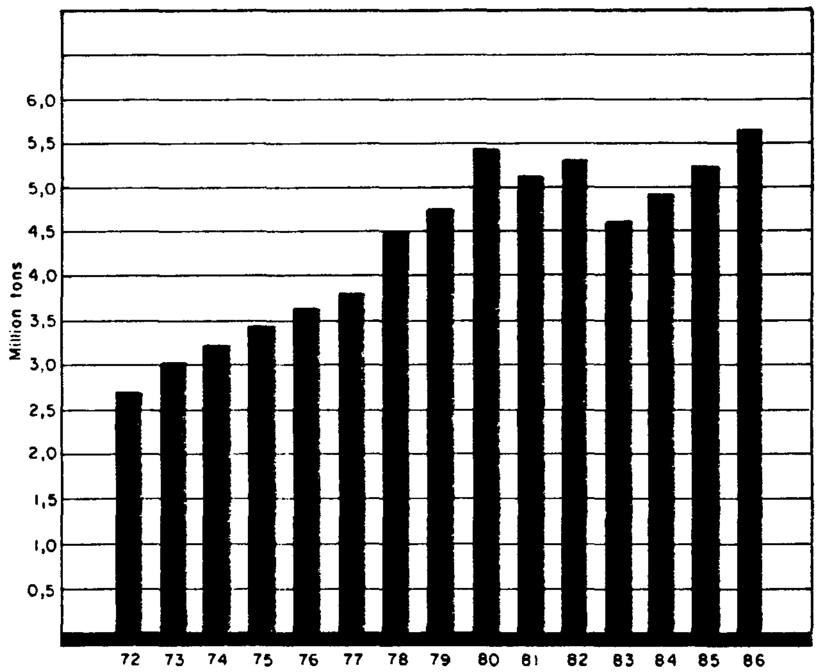


Fig. 19—Sales of Iscor's steel products (including Cisco throughout and Dunswart from 1984)

Sales of finished steel products

	Tons	
	1985/86	**1984/85**
Vanderbijlpark	**3 541 500**	**3 317 000**
Newcastle	**1 242 100**	**1 091 400**
Pretoria	**566 700**	**604 100**
Dunswart	**187 400**	**155 500**
Cisco	**136 300**	**112 300**
	5 674 000	**5 280 300**

TABLE VIII
SHIPMENTS OF IRON ORE FROM SISHEN FOR THE PAST 10 YEARS

Year	Shipments, kt		
	Export	Iscor	Total
1976	66	4 423	4 489
1977	8 146	5 615	13 761
1978	12 902	5 238	18 140
1979	13 409	5 934	19 343
1980	15 683	7 229	22 912
1981	12 662	7 424	20 086
1982	12 883	7 009	19 892
1983	7 301	4 319	11 620
1984	11 165	5 290	16 455
1985	10 068	5 896	15 964
1986	8 043	5 845	13 888

It can be expected that the reserves of high-grade ore, which can be mined by open-pit methods, will be supplemented by the vast reserves of low-grade ore reserves in future. However, this is not expected to materialize in the next 40 years.

The limited reserves of high-grade hematite ore at Thabazimbi could be replaced by an increased production of high-grade ore at Sishen, but this would have a negative influence on railage costs. (The cost of railage as a percentage of total cost of iron ore delivered from Sishen to the Vanderbijlpark Works is approximately 64 per cent.)

In conclusion, it can be stated that South Africa, with its vast reserve base of both high- and medium- to low-grade iron ore, is well placed to provide the necessary ore for the internal steel industry, as well as providing for the export market, well into the 21st century.

ACKNOWLEDGEMENTS

The authors thank Iscor for permission to publish this paper.

REFERENCES

1. Bateman, A.M. *Economic mineral deposits.* Second Edition, Mar. 1965. pp. 561–563.
2. Duke, V.W.A., and Williams, D.H. The South African iron ore industry: Past, present and future. Metal Bulletin's Second International Iron Ore Symposium, Frankfurt, Mar. 1983.
3. Hammerbeck, E.C.I., Fourie, G.P., and Snyman, A.A. Iron. *Mineral resources of the Republic of South Africa.* Fifth Edition, 1976.
4. Encyclopedia Britannica. Iron. Vol. 12, 1962.
5. Newton, J. *Extractive metallurgy.* Third Edition, 1966. pp. 9–12.
6. Alberts, B.C., and Ortlepp, J.A.L. Iron ore mining in South Africa. *Transactions of the Seventh Commonwealth Mining and Metallurgical Congress,* vol. 2, 1961.
7. Gross, G.A. Nature and occurrence of iron ore deposits. *Survey of world iron ore resources.* New York, United Nations, 1970.
8. Page, D.C. Langtermynysterertsvoorsiening, agtergrond gegewens ten opsigte van ysterafsettings in Suid-Afrika, 1986. Internal report, Iscor, not published.
9. Hammerbeck, E.C.I., and Schoeman, J.J. Copper. *Mineral resources of the Republic of South Africa.* Fifth Edition, 1976.
10. Olivier, P.A. Steel demand and marketing. Iscor presentation to parliamentarians and members of the President's Council.
11. Commodities Research Unit. World iron ore: The steel crises and after, vols. 1 to 4, 1984.
12. Rohrmann, B. Vanadium in South Africa. *J.S. Afr. Inst. Min. Metall.,* vol. 85, no. 5. May 1985. pp. 141–150.
13. Iscor Limited. Sishen Iron Ore Mine. *Technical Report,* 1986.
14. Jordaan, A.J., and Graham, H.L. Wall control blasting at Donkerpoort. *The planning and operation of open-pit and strip mines.* Johannesburg, The South African Institute of Mining and Metallurgy, Symposium Series S7, 1984.
15. Lourens, M.J., and Lindsay, J.R.W. The implementation of a Shotcrete support system in the underground section at Thabazimbi Iron Ore Mine. Association of Mine Managers of South Africa, Jun. 1987.
16. Luyt, J.F.M. Vanadium. *Mineral resources of the Republic of South Africa.* Fifth Edition, 1976.
17. Prince, K. Iscor's approach to the future. Iscor presentation to parliamentarians and members of the President's Council.
18. Wagner, P.A. The iron deposits of the Union of South Africa. *Geological Survey Memoir* no. 26. 1928.
19. Anderson, R.F. North American iron ore. Is there a future? 59th Annual meeting of the Minnesota Section, AIME 47th Annual Mining Symposium, Duluth, 1986.
20. Iscor Limited. *Annual report,* 1986.

21. ALBERTS, B.C. Mining at Iscor. Iscor Presentation to parliamentarians and members of the President's Council.
22. HIGHVELD STEEL & VANADIUM LIMITED. *Annual report*, 1986.

BIBLIOGRAPHY

ALBERTS, B.C., and NAUDE, R.T. Mineral potential of the Republic of South Africa with special reference to raw materials for the iron and steel industry. Thirteenth Annual Mining Symposium and Forty-second Annual Meeting of the Minnesota Section, AIME, Jan. 1969.
ANON. Iscor reshaping for a new world. *S.A. Financial Mail*, 13th Apr., 1974.
ISCOR LIMITED. From ore to steel. Technical brochure, 1987.
JOHNSTON, T.G., and SARGENT, R.E. Steelmakers' rationalization impact on iron ore producers. Proceedings of Metal Bulletin's Third International Iron Ore Symposium, Athens, Mar. 1982.
LAAKSO, L.J. The competitive position of Mesabi Range taconite pellets. Fifty-ninth Annual Meeting of the Minnesota Section, AIME 47th Annual Mining Symposium, Duluth, 1986.
MOORE, J.J. An examination of the new direct smelting processes for iron and steelmaking. *J. Metals*, Jun. 1982. pp. 39–48.
SERBENT, *et al.* State and future prospects for direct reduction and smelting reduction processes. 5th Lurgi Kiln Operators Conference, Vanderbijlpark, Apr. 1985.

New President of AS&TS*

Mr Douglas Hazelton Mills took office as President of the Associated Scientific and Technical Societies of South Africa on 25th November, 1987. Mr Mills was born in Johannesburg in October 1926, and was educated at Marist Brothers College in Observatory, Johannesburg, and the University of the Witwatersrand, where he graduated in 1946 with a B.Sc. degree in Electrical Engineering.

In 1950 he joined the South African Broadcasting Corporation. The last position he held at the SABC before his retirement in September 1985 was that of Deputy Director General:Technical. He remains professionally active through part-time consulting work and service on numerous boards and committees.

Mr Mills has served on the Council of the South African Institute of Electrical Engineers since 1969, and was President of that Institute in 1980. He has also served on the Council of the South African Council for Professional Engineers, and on advisory committees of the Council for Scientific and Industrial Research. He was President of the Federation of Societies of Professional Engineers in 1985/1986.

Mr Mills has represented the SABC and been a South African delegate at various international conferences. He has read papers at international conventions in Hamburg, Brussels, Montreaux, London, and Sydney, and has chaired sessions at the International Broadcasting Convention in London on several occasions. His influence both internationally and within the Republic has been of inestimable value to the engineering professions.

Mr Douglas Hazelton Mills

* Released by The Associated Scientific and Technical Societies of South Africa, Kelvin House, 2 Hollard Street, Johannesburg 2001.

Minerals and energy

Minerals and Energy Bulletin is the newsletter of the CSIRO Institute of Energy and Earth Resources. That Institute ceased to exist on 31st December, 1987.

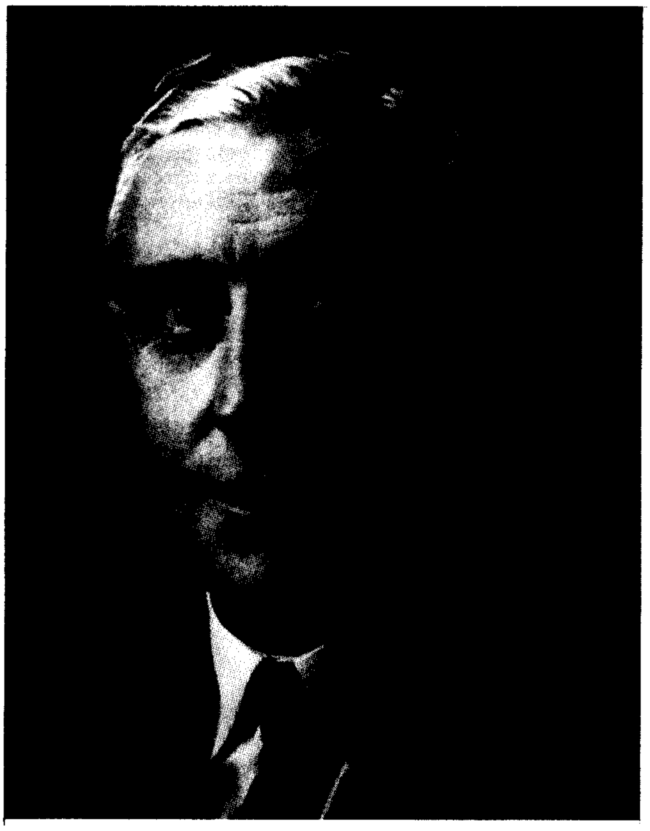
The minerals and energy research divisions were reorganized and transferred to a new Institute of Minerals, Energy and Construction on 1st January, 1988. The publication of *Minerals and Energy Bulletin* was suspended from issue 26, pending a review of the communication plans and needs of the new Institute.

In the meantime, the Institute would welcome views and opinions of readers on the usefulness of the *Bulletin*, whether it should continue, what changes they would like to see in content and format, etc. Readers' opinions will be most helpful in making plans for the future.

Please write to

Ms J. North, Editor
Minerals and Energy Bulletin
CSIRO
P.O. Box 225
Dickson, ACT 2602
Australia.

Professor Leonard Taverner: 1893–1987



The news of the death of Professor Leonard Taverner will recall for many his work during two important periods of South Africa's history—the years of the Second World War and those during which the country's uranium industry was established.

Taverner matriculated in England and continued his education at the École de Commerce at Neuchatel in Switzerland. Among the benefits of his broad education on the Continent was a proficiency in technical French, and his précis of *Metallography*, a translation from the French of Guillet and Porterin, which was one of his early publications; another benefit was the forging of new friendships, among which was that with the famous Russian singer with the deep bass voice, Feodor Chaliapin.

Taverner studied metallurgy at the Royal School of Mines, and held technical posts in the Royal Navy Air Service and the Royal Air Force during the First World War. Subsequently, he worked in industry as a research metallurgist, and then joined the staff of the University College of Swansea. He was head of the metallurgy department there when he accepted the offer from the University of the Witwatersrand of the Professorship of Metallurgy and Assaying, which carried with it the position of Director of the Minerals Research Laboratory. This laboratory had been established in 1934 by the University and the Department of Mines, and was the progenitor of the now well-known Council for Mineral Technology (Mintek).

Taverner started his duties at the University of the Witwatersrand and the Minerals Research Laboratory in January 1940, shortly after the outbreak of the Second World War and South Africa's entry into that war. In addition to his duties as Professor of Metallurgy and Assaying, Taverner had the responsibility of adapting the work of the Minerals Research Laboratory to many wartime problems such as the search for substitutes for materials previously imported—of which rubber was an unexpected example—and assisting in the production of minerals of strategic importance. Additional duties assumed by Taverner were in connection with his appointment as Metallurgical Consultant to the South African Air Force and to the South African Mint, whose facilities had been converted into a munitions factory. As part of his work for the Air Force, Taverner established a research group at the University, staffed by personnel seconded from the armed forces.

The work of the Minerals Research Laboratory in the war years provided convincing evidence of the importance to South Africa of minerals research, and gave Taverner the opportunity for the first step in the development of the Minerals Research Laboratory. In 1944 its name was changed to Government Metallurgical Laboratory, and the construction began of what was considered in those days extensive laboratory buildings at Yale Road, opposite the University. Taverner later described the Government Metallurgical Laboratory and its functions in a paper presented to The South African Institute of Mining and Metallurgy (*J. S. Afr. Inst. Min. Metall.*, vol. 52, pp. 235–236).

The second period in which Taverner played an important role began somewhat before the end of the Second World War, when he received the first intimations of the Western World's intensive and secret search for sources of uranium. By the time the war ended, Taverner and the Minerals Research Laboratory were committed to the Government's undertaking to extract uranium from Witwatersrand gold ores, and to cooperation with both the South African mining industry and the relevant organizations in the USA, Canada, and Great Britain for this purpose. Taverner's role in the intensive and clandestine activities of the next six years was a prominent one and constituted a major contribution to the establishment of South Africa's uranium-extraction industry, which was marked by the opening of the first full-scale plant at the West Rand Consolidated Mine in October 1952. This date is a milestone in the history of uranium production in South Africa, but research on many still-unsolved problems continued under Taverner until his retirement in 1958.

Indications of Taverner's role in the development of the uranium-extraction process come through in his paper to The South African Institute for Mining and Metallurgy (*J. S. Afr. Inst. Min. Metall.*, vol. 57, no. 4, Nov. 1956).

Taverner was a colourful character, somewhat wilful, somewhat autocractic, with a dislike for rigid rules and a delight in circumventing, wherever possible, bureaucratic red tape. He was a raconteur with a fund of stories based on a wide variety of experiences from which there was usually something to be learnt.

The University of the Witwatersrand accorded Taverner the honour of Emeritus Professor on his retirement, which was spent, together with his wife Peggy, at Hermanus in the Cape. He died on 24th July, 1987.