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Andalusite in South Africa*

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SYNOPSIS

The occurrence, properties, and uses of andalusite, and its advantages over other refractory minerals and materials, are discussed. Ore reserves are given for the five producing areas, and statistics on production, export sales, and prices are included to illustrate the growth of the industry since the early 1960s.

The mining and beneficiation procedures are described, with special reference to new techniques in concentration and magnetic separation. As fines dumps represent a considerable source of andalusite, possible methods of recovery are discussed.

The outlook for the future appears favourable, and possible competition from other sources and substitute refractory minerals are mentioned. It is concluded that the industry is in a sound position to maintain South Africa's status as the world's foremost producer and supplier of andalusite.

SAMEVATTING

Die voorkoms, eienskappe en gebruike van andalusiet, en die voordele daarvan vergeleke met ander vuurvaste minerale en materiale word bespreek. Die ertsreserwes vir die vyf produserende gebiede en statistiek oor produksie, uitvoerverkope en pryse word ingesluit om die groei van die bedryf sedert die vroeë sestigerjare te illustreer.

Die mynbou- en veredelingsprosedures word beskryf met spesiale verwysing na nuwe tegnieke in konsentrasie en magnetiese skeiding. Aangesien hope fynmateriaal 'n aansienlike bron van andalusiet verteenwoordig, word moontlike herwinningsmetodes bespreek.

Die vooruitsigte vir die toekoms lyk gunstig en moontlike mededinging uit ander bronne en plaasvervangende vuurvaste minerale word genoem. Die gevolgtrekking is dat die bedryf in 'n gesonde posisie is om Suid-Afrika se status as die wêreld se belangrikste produsent en leweransie van andalusiet te handhaaf.

Introduction

Andalusite, sillimanite, and kyanite, generally referred to as the sillimanite-group minerals, constitute trimorphous forms of Al_2SiO_5 and are important raw materials for the production of superior-grade high-alumina refractories for both the ferrous and the non-ferrous industries. The relative proportions in which these sister minerals are used world-wide depends to a large degree on their availability. However, anadalusite has some important advantages that are associated with its low relative density, its related lower volume expansion on being heated, and the fact that it can be produced by a relatively simple mining and concentration procedure at its natural grain size.

The increasingly severe service to which refractories are now subjected in iron and steel plants has given rise to a change from fireclay materials to materials of higher alumina content. Low costs, energy-saving requirements, firebrick production techniques, and the ultimate chemical, physical, and dimensional characteristics of the brick combine to make andalusite the logical choice as a raw material to provide the additional alumina.

South Africa possesses by far the largest portion of the world's known deposits of andalusite, and the demonstrated economic reserves are given[1,2] at well over 50 Mt, which represent a reserve life of 250 years at the present rate of extraction.

It is interesting to note that andalusite is included in the list of minerals that are exempt from import restrictions by the USA. This fact is of great importance when it is realized that andalusite faces competition, not only from natural minerals that are produced elsewhere, but also from potential substitute materials, some of which are produced on a large scale. It is to the credit of the industry and to research organizations such as the Council for Mineral Technology (Mintek) that South Africa is today the foremost producer and exporter of andalusite, supplying countries as far afield as Japan, Italy, West Germany, Great Britain, Turkey, Spain, and the USA.

The Occurrence of Andalusite in South Africa

Andalusite occurs in the metamorphic aureole of the Bushveld Complex, particularly in the Marico and Thabazimbi areas of the western Transvaal[3] and in the Chuniespoort–Penge–Lydenburg area of the eastern Transvaal, where it occurs in hornfels and schists or as associated eluvial deposits[4,5]. These deposits were formed by the metamorphism of the aluminous sediments of the Pretoria Series as a result of regional and contact metamorphism. Fig. 1 shows the location of the major deposits that are being exploited, while Table I lists the major producing mines, togbether with relevant information on the holding companies and product specifications[6]. As can be seen from Fig. 1, there are five distinct areas in which andalusite is mined.

Groot Marico–Zeerust Area, Western Transvaal

The deposits in this area can be grouped into two types: the metamorphosed shales of the Daspoort Stage, and the alluvial sands of the rivers that drain these shales. This area is of minor importance at present since the andalusite with one exception is of low grade (less than 55 per cent

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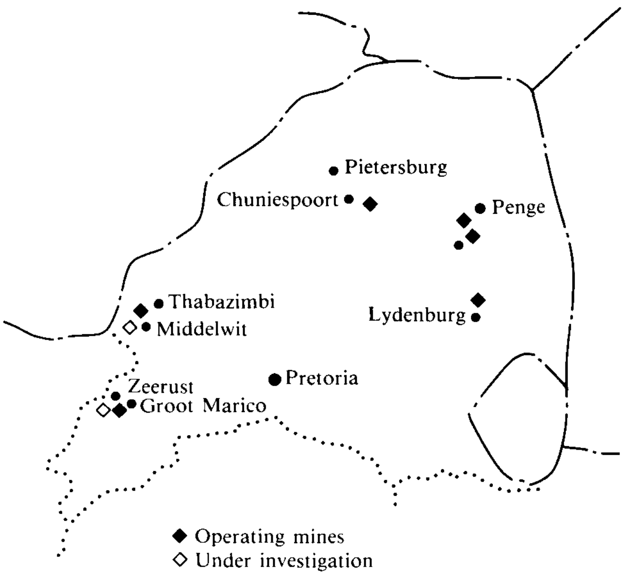


Fig. 1—Location of andalusite deposits in the Transvaal

Al_2O_3 and more than 1,5 per cent Fe_2O_3). No material of this grade is being produced at present. The exception is the shale deposit occurring on the farm Kleinfontein 260, where concentrates assaying more than 59 per cent Al_2O_3 and less than 1,0 per cent Fe_2O_3 are produced. Other high-grade shale deposits are likely to be exploited in the near future.

Thabazimbi Area, Northwestern Transvaal

Andalusite is well developed in the Timeball Hill shale near Thabazimbi, occurring in a soft, highly weathered mica hornfels[3]. This shale formation is the youngest part of a huge meta-sedimentary basin called the Transvaal system. The heat of the rocks in the middle of the sedimentary basin—known as the Bushveld Complex—was the major factor responsible for the alteration of the Pretoria shales to andalusite- and chiastolite-bearing hornfelses.

Weedon's Minerals (Pty) Limited operate the andalusite mine on the Timeball Hill shale, and four processing plants are currently in operation, with an annual production of close to 120 000 t. It is by far the largest andalusite mine in the world. The property runs along a strike in the Timeball Hill shales for about 6 km but the deposit extends much further. The andalusite is marketed under the trade name Purusite and contains 59 to 60 per cent Al_2O_3 and 0,65 to 0,75 per cent Fe_2O_3.

Chuniespoort–Penge–Lydenburg Area, Northeastern Transvaal

Before the discovery of the Thabazimbi andalusite, the deposits that occur in this area were considered to be the most important in South Africa.

Andalusite in the form of chiastolite is widely spread in metamorphosed shales of the Pretoria Series[5], and is recovered from both bedrock and surficial deposits. The deposit is characterized by its coarse crystal size compared with the Marico and Thabazimbi deposits, and by the presence of staurolite, an iron-bearing aluminium silicate. A remarkable feature of the andalusite from these areas (apart from its high alumina content and the coarse crystal size) is its consistent relationship between grade and density. The most important deposits in this area occur on the farm Annesley 109 KT, Streatham 100 KT, Havercroft 99 KT, Holfontein 126 KT, and Morgenzon 125 KT. The deposit has been proved over at least 16 km along strike in the Daspoort shales. The average andalusite content is 8 per cent.

Two mines are operating in the Penge area: Havercroft Andalusite Mine, owned by Vereeniging Refractories, and Annesley Andalusite Mine, owned in part by Annesley Andalusite (Pty) Limited. This mine was previously operated by Rand London Corporation, which purchased the mine from Zimro (Pty) Limited. The original owners, however, were Hudson Mining Co. Limited,

TABLE I
ANDALUSITE PRODUCERS IN SOUTH AFRICA

Location of mine and deposit	Administrative company	Trade name of concentrate	Grade, %		Annual production t/a × 10^3
			Al_2O_3	Fe_2O_3	
Annesley 109 KT* Penge	Annesley Andalusite (Pty) Ltd	Randalusite 59/12 60/09	59,5 60,0	0,92 0,86	75
Havercroft 99 KT* Penge	Verref Mining (Pty) Ltd	Standard Macle	58,8 61,6	1,30 0,60	36
Hoogenoeg 293 KS* Pietersburg	Hoogenoeg Andalusite (Pty) Ltd	Enrosit	59,0	1,00	15
Timeball Andalusite Grootfontein 352 KQ* Thabazimbi	Weedon's Minerals (Pty) Ltd	Purusite	59,5	0,70	120
Krugerspost Mine Klipfontein 400T* Lydenburg	Cullinan Minerals Ltd	K57 K53	57,2 54,0	0,90 1,20	50
Andafrax Kleinfontein 260 JP* Groot Marico	Purity Minerals (Pty) Ltd	Purity	59,5	0,70	12

* Identification of the farm on which the mine is situated

which started the mine in 1960. It was the first mine in the Free World to produce a coarse-crystal, high-alumina, low-iron andalusite, and it represents a good example of the co-operation that exists between industry and Mintek[7]. The first dense-medium separation plant in this area was installed at this mine.

The third mine to produce a coarse-crystal product is the Hoogenoeg Mine, which is owned and operated by Hoogenoeg Andalusite (Pty) Limited on the farm Uitkyk, some 30 km from Chuniespoort. The ore is exposed over a strike length of close to 10 km. The bedrock andalusite, which is the only source mined, occurs in a zone some 30 m thick. The degree of weathering is not constant, and there are some hard zones that make recovery difficult. The ore dips at about 30 degrees to the south, which increases the overburden as the face is developed. At present, development is along the strike, rather than into the dip. The orebody is unique in that it is high up on the side of a mountain, and hence has a large amount of overburden. A road 7 km in length had to be constructed up the side of the mountain from the village to give access to the deposit.

The andalusite content varies from 8 to 15 per cent, with an average of 10 per cent, and is characterized by the presence of large amounts of staurolite, which, when concentrated with the andalusite, can amount to over 20 per cent of the dense-medium concentrate.

Cullinan Minerals Limited operate the Krugerspost Andalusite Mine, which is situated about 10 km to the north of Lydenburg[8]. The ore at this mine differs from that at the other three mines in the area in that the crystal size is similar to that of the Marico–Thabazimbi deposits. The deposit is located at the eastern extremity of the Bushveld Complex, in which the invading lava of the Complex metamorphosed the highly aluminous shales of the Magaliesberg Stage of the Pretoria Series, resulting in the formation of andalusite. Erosion and weathering softened the hard metamorphic rocks, and no blasting is required in the mining operation. The mining method used is opencast bench mining on hill slopes with bench heights of about 4 m. The andalusite content of the shale is 8 to 12 per cent.

There are major differences in the physical properties of the andalusite and host rock from the various areas described above. These differences affect to a large degree the beneficiation procedures that are used to recover the andalusite, as will be shown later in this review.

Ore Reserves

Primary or *in situ* andalusite makes up the bulk of the ore reserves. The confirmed reserves and resources of recoverable andalusite from the various areas are given in Table II, which shows that some 30 Mt of high-grade andalusite are immediately available for recovery.

Production and Export

When the growth of the andalusite industry is assessed in terms of production, local consumption, and export sales, several factors are readily apparent as having influenced the beneficiation process, the rate of exportation, and the value of the material. Table III shows the production, exports, and export values for andalusite from 1960 to 1988, and Table IV gives the total exports of andalusite from South Africa to various world consumers.

As Table III shows, in 1966 there was a sharp increase in export tonnage, which was more than double the 1962 tonnage. This coincided with the coming into operation of the first mine in the eastern Transvaal, which is now the Annesley Andalusite Mine. This deposit, the first to exploit the coarse-crystal variety of andalusite, was characterized, not only by the coarse size of the crystals but, more importantly, by the substantial increase in grade compared with andalusite from other sources. The concentrate grades increased from 54 per cent Al_2O_3 and 1,5 per cent Fe_2O_3 to between 59 and 60 per cent Al_2O_3 and less than 1,0 per cent Fe_2O_3. Before 1965, andalusite

TABLE II
ANDALUSITE RESERVES AND RESOURCES IN SOUTH AFRICA*

Areas	Andalusite: Content %	Andalusite: Al_2O_3 %	Reserves, Mt: High grade	Reserves, Mt: Low grade	Reserves, Mt: Total	Identified resources† Mt	Inferred resources‡ Mt
Western Transvaal							
Shale	10	52–59	0,5	20,0	21	60,0	60,0
Alluvium	50	53		0,5			
Northwestern Transvaal							
Shale	10–15	58–60	0,5		0,5	2,5	2,5
Northeastern Transvaal							
Shale	8	56–59	28,5		29,0	29,0	44,0
Alluvium	10–15	58	0,5				
Total			30,0	20,5	50,5	91,5	106,5

* Source: Minerals Bureau

† Identified resources: that portion of a natural concentration of solid of which the location, quality, and extent are known to various levels of assurance, ranging from measured to inference from geological projection

‡ Inferred resources: That portion of the identified resource which is unexplored and estimates of quality and size are based mainly on geological projection

TABLE III
PRODUCTION AND EXPORT SALES*

Significant year	Total production t	Exports t	Export value† R f.o.b.	R/t
1960	9 320	3 701	82 880	23
1962	18 350	6 082	142 234	23
1966	21 530	12 632	334 565	26
1968	22 430	14 850	412 300	28
1970	42 530	21 500	642 150	30
1973	60 200	16 650	572 468	34
1975	77 150	23 800	1 241 187	52
1978	112 000	54 500	5 088 775	93
1980	189 909	116 180	11 435 247	98
1982	153 231	75 429	9 005 948	119
1983	116 576	69 264	7 875 964	114
1984	143 300	91 574	12 250 520	134
1985	194 693	142 143	25 002 746	176
1986	181 624	113 514	22 284 597	196
1987	194 373	117 622	26 503 981	225
Jan.-Oct.	262 358	79 064	20 605 046	255

* Source: Minerals Bureau
† Average value; high-grade concentrates can command prices of up to R320 per tonne

TABLE IV
DESTINATION OF ANDALUSITE EXPORTS (1987)*

Destination	Amount exported t	%
Western Europe	58 946	56
Asia	23 205	22
North America	18 574	18
Central and South America	2 792	2
Oceana	1 805	2

*Source: Minerals Bureau

was produced only in the Marico area, where the grades were low and the supplies inconsistent[9]. Although the export tonnages and the grade of the concentrate increased sharply, the increase initially had no significant effect on the monetary value per ton, which remained fairly constant up to 1975. However, the coming on-stream of the eastern Transvaal mine had the significant effect of assuring consistent supplies of a better-quality product.

The year 1978 showed another dramatic increase in production—77 000 tons in 1975 to 112 000 tons in 1978. More significant, however, was the virtual doubling in the export value of the concentrates. The total export value increased from R1,2 million to R5,1 million. This increase, which coincided with the opening of the Timeball Andalusite Mine in the Thabazimbi area, is indicative of the more responsible attitude that producers have adopted towards ensuring consistently high grades and regular supplies. This, together with the efforts of Mintek in providing technical advice and assistance, is the major reason for South Africa's prominent position as a reliable source of andalusite.

The production figures for 1987 were 194 373 t, of which 117 622 t were exported at a total value of R26,5 million. As can be seen from Table III, there were some fluctuations in the amount exported and the total value. The value per tonne showed a steady increase, however, and the present (1988) value per tonne is in the region of R300. Factors that affected exports, as well as local sales, are the world recession and the decrease in steel production world-wide. According to present indications, demand is exceeding supply, and several mines are enlarging their plants to cope with this increased demand.

Specifications of Andalusite

The name *andalusite* is derived from the Spanish province of Andalusia, where it was first noted. Andalusite is a refractory aluminium silicate with the chemical composition Al_2SiO_5 or $Al_2O_3SiO_2$. Ideally, andalusite should contain 62,9 per cent Al_2O_3 and 37,1 per cent SiO_2, but it hardly ever occurs in the pure form and contains a number of impurities that substantially reduce these values. The major variety of andalusite is chiastolite, which exhibits a regular arrangement of inclusions in the shape of a cross, as shown in Fig. 2. These inclusions are the major source of impurities that reduce the Al_2O_3 content, although other sources of impurities can also be present. Mineralogically, the impurities are as follows:

(i) hydrous iron oxides and carbon contained in the chiastolite cross,
(ii) micaceous impurities (sericite, biotite, and phlogopite) occurring mainly on crystal surfaces,
(iii) inclusions of ilmenite in the crystal lattice,
(iv) inclusions of FeO in the crystal lattice,
(v) quartz blebs intimately intergrown with the andalusite, and
(vi) extraneous impurities such as staurolite and shale.

Fig. 2—Andalusite crystals after concentration, eastern Transvaal

With the exception of the extraneous impurities, the impurities are not easily removed owing to their finely divided nature and intimate association with the andalusite. In spite of their apparent detrimental effects, they are absorbed into the glass phase when the material is fired. Phlogopite, which is present on the crystal surfaces, has a fluxing action that improves the body by aiding the bonding mechanism. Andalusite can be altered to sericite, a process that, in the case of chiastolite, begins along the lines of the carbonaceous inclusions or on the outer crystal surfaces.

Properties of Andalusite

Some of the relevant properties of pure andalusite are given below.

Chemical composition	$Al_2O_3SiO_3$ containing 62,9% Al_2O_3 and 37,1% SiO_2
Crystal system	Orthorhombic
Cleavage	Distinct on 1.1.0
Hardness (Moh)	6,5 to 7,5
Habit	Prismatic, often coarse, well-formed crystals
Colour	Grey to black, brown to reddish pink
Relative density	3,13 to 3,16
Volume expansion on being fired	3 to 6%
Decomposition	At 1300 to 1600°C, forming mullite and silica.

Weathering and alteration have a marked effect on the quality of the andalusite crystals and their relative density. Table V gives a typical chemical analysis of andalusite concentrates from three different mines. There are also large variations in the size of the crystals, and Table V gives the particle-size distributions of concentrates from the various areas. Table VI shows the relationship between the alumina and ferric oxide contents on the one hand, and the relative density on the other, resulting from weathering. It can thus be seen that the physical properties vary from deposit to deposit, and these properties to a large degree determine the precise nature of the best beneficiation process to be used.

TABLE V

TYPICAL CHEMICAL AND PHYSICAL ANALYSIS OF CONCENTRATES

Constituent	Analysis, % Purusite Weedon's	Randalusite Annesley	K57 Cullinan	K53 Cullinan
Al_2O_3	59,50	59,50	52,20	54,00
Fe_2O_3	0,70	0,90	0,91	1,20
SiO_2	39,00	39,20	40,78	41,80
TiO_2	0,20	0,14	0,26	0,33
CaO	0,20	0,06	0,06	0,06
MgO	0,10	0,12	0,11	0,20
Na_2O	0,10	0,10	0,10	0,15
K_2O	0,25	0,20	0,20	0,20
Loss on ignition*	0,40	0,50	0,47	0,55
Relative density, g/cm^3	3,10	3,10	–	–
Floats on TBE†, %	0,20	0,50	1,0	3,0
Particle size, %				
> 6.0 mm	0,00	27,00		0,0
> 3.3 mm	1,50	72,30		1,5
> 1.7 mm	75,00	0,70		47,0
> 0.6 mm	17,00	0,00		48,5
< 0.6 mm	6,50	0,00		3,0

* At 1000°C

† Tetra-bromo-ethane: relative density 2,96

TABLE VI

THE RELATIONSHIP BETWEEN ALUMINA AND FERRIC OXIDE CONTENTS AND RELATIVE DENSITY IN ANDALUSITE CONCENTRATES

	Marico, %			Thabazimbi, %			Lydenburg, %		
Relative density	Mass	Al_2O_3*	Fe_2O_3	Mass	Al_2O_3	Fe_2O_3	Mass	Al_2O_3†	Fe_2O_3
>3,10	3,7	58,4	1,27	15,4	61,2	0,30	43,6	59,9	0,60
3,05 to 3,10	60,0	55,2	1,31	67,0	59,0	0,60	47,2	56,3	0,90
3,00 to 3,05	20,6	50,5	1,94	15,0	58,4	0,80	5,4	42,5	1,15
2,95 to 3,00	11,5	47,3	2,16	2,6	57,6	1,20	0,9	47,8	1,48
<2,95	4,2	38,8	2,76	Nil	Nil	Nil	2,9	43,7	2,62
Average	100,0	52,8	1,60	100,0	59,7	0,59	100,0	57,2	0,84

* This type of material is not being produced at present but the higher-grade material shows similar tendencies

† Represents a fine-grained, high-grade andalusite; the coarse-grained crystals show little variation in density

Specifications for Andalusite Concentrates

Generally, specifications for andalusite concentrates are a matter of agreement between producer and consumer. In the early years up to 1965, concentrates assaying 54 per cent Al_2O_3 and more than 1,2 per cent Fe_2O_3 were accepted readily, but present demands are for high-alumina, low-iron material. The fine crystal size was also tolerated before, but present demands are for coarser crystals. Fine-grained concentrates are 'sweetened' by the introduction of coarser crystals from other sources. Some producers market separate grades according to their alumina and iron contents, and their crystal size. All the producers aim to provide concentrates containing the maximum amount of alumina possible and the minimum amount of impurities, notably iron oxides, and several producers are engaged in special retreatment processes, such as two-stage separations, multiple scrubbing, roasting and magnetic separation, and chemical treatment, to improve their grades.

The major requirements for andalusite concentrates can best be gauged from an examination of typical chemical analyses of the concentrates from various sources (Table V). This shows that there are major differences in the particle-size distribution of the concentrates. The Lydenburg material, for example, contains less alumina, and the lower-grade material is comparable with that produced in the Marico district in the early 1960s.

The nature of the impurities is apparent in both the beneficiation process used and the end-use of the concentrate. Iron that has replaced alumina within the crystal structure or that occurs in the chiastolite cross is not detrimental, the only effect being one of discoloration. However, iron present as relatively large discrete grains or adhesions to the crystal surfaces is very undesirable and must be removed by further beneficiation. Such iron shows up in fired bricks as black spots or blow-holes, which act as incipient fusion points when the bricks are in service.

Total alkalis in concentrations greater than 0,5 per cent lower the fusion temperature of the bricks, and weaken the strength under load, while the higher glass and silica levels due to alkalis make the refractory more prone to chemical attack. The grain size affects the strength under load and, for this reason, a certain proportion of coarse grains is required. Andalusite is recovered at its natural grain size and, although a maximum size is not generally specified, the ratio of particle sizes is analogous to that in concrete mixes. Sizes smaller than 0,5 mm are not accepted, which, conveniently, is also the lower size that can be treated effectively in the dense-medium separation process. Some fines, however, are added to the mixture when the brick is formed. Coarse crystals impart a higher physical strength under load and give a brick of higher apparent density. However, bricks made with material containing a large proportion of fines require several stages of compression in the mould if they are to match the apparent density of bricks made from coarser crystals. Fig. 3 compares grain sizes of South African andalusites with those of andalusites produced elsewhere[10]. Small grain sizes restrict the use of andalusite in the manufacture of firebricks, and fines below 0,5 mm are used mainly in monolithic applications.

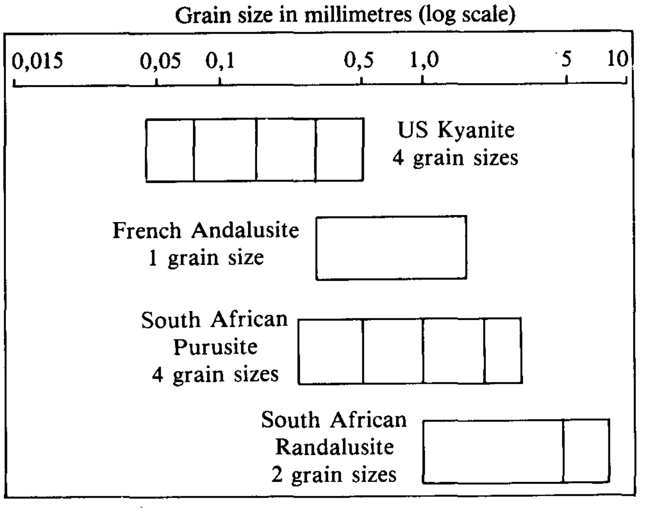


Fig. 3—Comparison of grain sizes in four andalusites

Advantages of Andalusite

Andalusite, together with its sister minerals kyanite and sillimanite, is consumed predominantly within the refractory industry because of its ability to form the refractory high-performance mullite phase ($3\ Al_2O_3 \cdot 2\ SiO_2$) at high temperatures. This phase confers a high, hot strength with high resistance to chemical and physical erosion—properties that are desirable at high temperatures and under chemically corrosive conditions.

Andalusite has several advantages over kyanite, sillimanite, and other high-alumina and fireclay materials. It differs from kyanite and sillimanite in that it can be used in the manufacture of fired refractory products without being calcined. This is possible because of its much lower volume expansion on being fired—1 to 1,5 per cent maximum at 1500°C.

Since andalusite needs no calcining, it offers significant economies in that it saves energy, an advantage that is certain to be of importance in the light of increased energy costs. Table VII compares the energy requirements for the calcining of various refractory materials.

TABLE VII

ENERGY REQUIREMENTS FOR THE CALCINING OF VARIOUS REFRACTORY MATERIALS

Material	Calcining temperature °C	Energy for calcination BTU × 10 per ton
Magnesite	1900–2000	6–52
Mullite	0	19
Bauxite (85–90%)	1700–1800	13
Bauxite (70%)	1700	9
Bauxite kadin	1650–1700	8
Kaolin	1500–1600	7
Fireclay	1350	4
Kyanite	1380–1380	4
Andalusite	0	0

Andalusite has excellent resistance to slag penetration and attack, especially by alkalis. This is due to its dense, homogeneous single-crystal structure, in which there are virtually no channels of weakness along which the slag can travel. Consequently, andalusite is superior in this respect to chamottes, bauxitic materials, and bauxite, in which even the smallest piece of material is still a compound of tiny crystals of kaolin and corundum between which the slag can penetrate. Fig. 4 illustrates the effect of slag attack on andalusite and a bauxitic material.

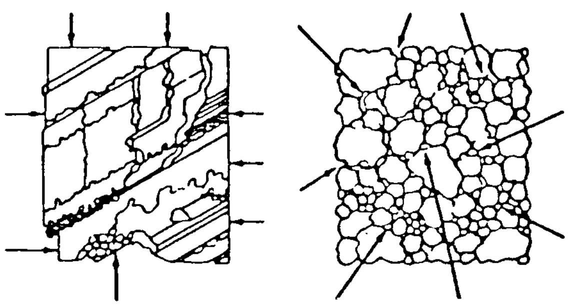


Fig. 4—Effect of slag penetration as shown through a petrographic microscope

In the manufacture of bricks, particularly of complicated shapes, andalusite has advantages over other alumina-bearing refractories. There are no large volume changes, and the changes during firing are slight, ensuring better dimensional tolerance and warpage characteristics. Andalusite is also the only mineral that can be used in its natural grain size as an aggregate in the manufacture of bricks.

Uses of Andalusite

Most of the andalusite that is produced is used in the manufacture of high-alumina refractories, a small proportion being used for ceramic purposes. Andalusite refractories are favoured under abrasive conditions where high loads and high temperatures are encountered. In hot-blast stoves, they are used as checker bricks in the upper zone, in the dome, and in the combustion shaft. In blast furnaces, andalusite refractories are used in the lining of the stack and bosh areas, in tilting and swivelling troughs, as linings for iron and slag runners, and as tap-hole muds. Andalusite also finds application in ladles that are used under a variety of conditions.

Other applications are as soaking-pot covers, nozzles for the blowing of argon gas, refractory shapes such as burner bodies and combustion chambers in cement kilns, linings for glass furnaces, kiln furniture for the firing of ceramic products, and in copper-roasting furnaces. It is also used in unshaped refractory applications, such as castable or gunning mixes, ramming mixes, foundry sand, roofs of reheat furnaces, and heat-treatment furnaces. Special-purpose products include sanitaryware and whiteware, and high-temperature applications such as spark-plug bodies, insulators, and pyrometer tubes.

Nature of Andalusite Deposits

As mentioned earlier, all the andalusite currently produced is derived from shale deposits. These deposits are basically hornfelses, consisting of a micaceous clayey matrix in which the andalusite crystals are distributed randomly, as shown in Fig. 5. Depending on locality, the shale is soft and highly weathered, and the crystals are readily liberated from the shale on processing. Then, again, the shales can be hard and compact, and more sophisticated methods are required to release the crystals from the host rock. The crystal sizes also vary and, since they are required to be recovered at their natural grain size, both the mining methods and the subsequent liberation and beneficiation procedures have to be adapted to ensure minimum breakage of the crystals and maximum recovery.

Fig. 5—Andalusite crystals in shale, showing random orientation and fracture

It can thus be seen that, although these procedures are generally standard throughout the industry, variations exist that allow for the inherent differences in ore characteristics that are found from deposit to deposit.

Mining of Andalusite Ore

All the deposits currently exploited are mined by opencast methods, using both face development and bench-mining procedures. Fig. 6 shows a typical opencast mine in the northwestern Transvaal.

Generally, mining consists in the removal of overburden, which is basically a bulldozer–loader–trucking operation. The overburden can range in thickness from a few metres to up to 60 m, as found at one of the mines in the northeastern Transvaal.

Once the ore has been exposed, the mining consists basically in an ore-loosening operation with the use of rippers, scrapers, or face-shovels but, as the mining proceeds and the ore becomes harder at depth, blasting has to be carried out to loosen the ore. All the mines treating the coarse-crystal variety are now resorting to controlled blasting to loosen the ore. At two of the mines, the depth

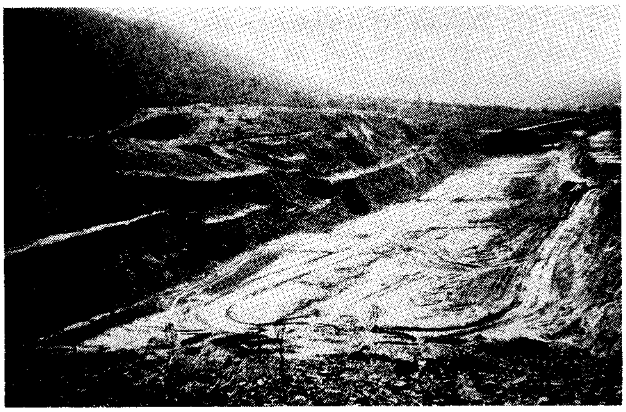


Fig. 6—An opencast andalusite mine in the Thabazimbi area

to which the ore extends and the thickness of the overburden make underground mining a distinct possibility.

In general, the deposits have strike lengths of between 2 and 8 km, and ore depths or thicknesses of up to 100 m. The andalusite content of the shales is not consistent, but can vary from 8 to 20 per cent with an average content of 10 per cent. Mining costs constitute only a small portion of the overall costs, and mining and transport can generally be carried out at a cost of R2 to R3 per tonne. *In situ* values of ore vary according to head grade and recovery, but usually amount to about R18 per tonne (1988), based on a recovery rate of 65 per cent.

In contrast to the South African situation is the mining procedure used at Glomel, France, which is at present the only andalusite producer of significance outside South Africa. The ore is loosened by vertical blasting, and is further broken by hydraulic-percussion lump breakers. Several stages of jaw and gyratory crushing are followed by semi-autogenous milling using steel balls. By the time liberation has been achieved, the andalusite crystals are very much finer than in the South African product. For South African producers to follow this procedure would seriously affect their viability, and it is fortunate that most of the deposits are amenable to relatively simple and inexpensive mining and liberation procedures.

Beneficiation

The beneficiation process generally relies on three physical characteristics of the ore:

(i) the friable nature of the shales and the natural cleavage between crystal and shale,
(ii) the differences in relative density between the andalusite and the shale, and
(iii) differences in magnetic susceptibility between the andalusite (non-magnetic) and the iron-bearing impurities, which are usually only feebly magnetic.

Impure andalusite has a relative density of 3,05 to 3,10, compared with a relative density of 2,70 to 2,85 for the shale component. This difference in relative density allows separation by gravity means, but is not sufficiently great for simple procedures such as jigging, tabling, or spiralling to be effective. Shape is also a negative factor when jigs are considered, and the crystal size rules out the use of tabling of other forms of thin-film concentration.

Dense-medium separation has been found to be a very efficient means of concentration, and is the only method of concentration currently used in the production of andalusite[11]. Before dense-medium separation can be applied, however, the material has to be properly prepared, and it is in the preparation of the feed to this separation that variations are found.

A standard beneficiation procedure consists of the stages shown in Fig. 7. Since no two ores behave similarly when treated by the standard procedure, producers have incorporated variations in these procedures. These variations are indicative of differences in approach to the problems of beneficiation by producers, which is a healthy sign since it shows that they are not satisfied with the standard procedure but are looking for ways and means to improve recovery, reduce costs, and provide still higher-grade products.

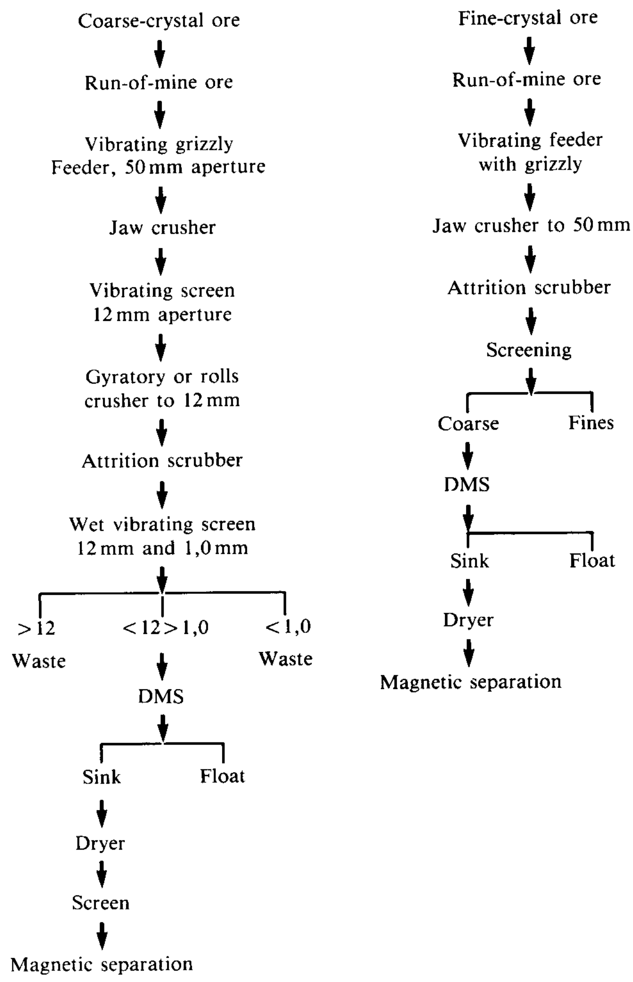


Fig. 7—Schematic flowsheets for plants operating on coarse- and fine-crystal andalusite

In the application of the various unit operations shown in Fig. 7, it must be borne in mind that the object is, firstly, to release the andalusite crystal with minimum breakage and, secondly, to clean the liberated crystal from the adhering impurities while at the same time dispersing the particles of soft shale that can adversely affect the subsequent concentration processes. The final object is the production of a pure concentrate that will conform to the specifications.

Primary Crushing

Run-of-mine ores usually have a maximum size of 350 to 400 mm, and will, because of their friable nature, contain a considerable amount of fines. It has been shown that up to 20 per cent of the andalusite content of an ore can be lost as fines smaller than 1,0 mm and, for this reason, it is advisable to remove the fines prior to crushing.

Primary crushing is done in jaw crushers, although a rolls crusher is the only stage of crushing used at the Krugerspost Mine owing to the friable nature of the ore. The size to which the ore is crushed depends largely on the nature of the ore and its subsequent treatment. For fine-grained andalusite (smaller than 4,0 mm), a single stage of jaw crushing provides feed to the attrition scrubbers (usually smaller than 50 mm), which is the major method of liberation for crystals of this size.

At mines treating shales with coarse crystals (smaller than 10,0 mm), jaw crushing serves to prepare the ore for subsequent secondary crushing. In these examples, the practice is to screen out material of the correct size from the run-of-mine ore by means of a vibrating grizzly feeder. The fines and the crushed product are then combined to form the feed to the secondary stage.

Secondary Crushing

Secondary crushing is generally used only for ores that have coarse crystals and are generally not as friable, i.e. shales that will not readily disperse in an attrition mill. Secondary crushing is thus the major means of achieving the liberation of the coarse crystals from the shale. It has been shown that a shale particle that has been crushed to below 12,0 mm will, in the case of ores with coarse crystals, be virtually barren of andalusite, whereas a similarly sized particle of shale, in the case of ores with fine-grained crystals, can contain up to 5 per cent andalusite. These particles will then need to be crushed to below 6,0 mm for complete release of the andalusite crystals. Crushing to this size in conventional crushers such as gyratory crushers or rolls will result in the crystals being broken to sizes too fine to be recovered; hence, the difference in procedure for ores containing coarse and fine crystals. Secondary crushing can be done in a gyratory or cone crusher or in a rolls crusher.

Horizontal-impact crushers are also coming into prominence, and are now being used at the Andafrax Mine in the Marico district. Rolls crushers are used at Havercroft and Annesley in the northeastern Transvaal, while the Hoogenoeg Mine uses a gyratory crusher.

Screening

Screening is used at various stages in the process, as shown in Fig. 7, and serves to scalp out the fines and remove the slimes. For the efficient removal of slimes, wet screening is used.

Vibrating screens are favoured, and the use of polyurethane panels to minimize wear is now standard on most mines. Trommels are still used, particularly where they form an integral part of the scrubbing mill. Probability screens, such as the Morgenson Sizer, are used on some mines where sticky ores are encountered and blinding could be a problem.

Screening is also used further down the beneficiation procedure. In dense-medium separation, it is used to dewater the ore prior to concentration and to drain and recover the medium from the ore particles. Magnetic separation is more efficient on sized material, and the dense-medium concentrate after being dried is screened by means of double-deck vibrating screens or trommels into several sizes for processing on a magnet.

Attrition Scrubbing

The process of attrition scrubbing is usually the stage in the beneficiation process that is subject to more variations than any of the other unit operations. Attrition scrubbing fulfils several functions, depending on the type of ore that is being treated. Its major function is in the cleaning of adhering surface coatings from the andalusite crystals. This is important since crystals that are inadequately scrubbed not only have a lower alumina and a higher iron content, but surface coatings can lower the fusion temperature and weaken the strength of the brick. An equally important function of the attrition scrubber is the dispersal of particles of soft shale, which, if not dispersed, can disintegrate in the dense-medium separation stage and contaminate the medium.

As mentioned previously, the attrition scrubber can also serve to liberate the andalusite from the shale and, for mines treating fine-grained andalusite shales, this is the only effective method of liberation.

Attrition scrubbers operating on fine-grained crystals thus serve the treble purpose of crystal liberation, crystal cleaning, and shale dispersal. They also substantially increase the concentration of andalusite and, from a run-of-mine ore with an andalusite content of 10 per cent, scrubbing can provide a feed material containing up to 50 per cent andalusite, with a commensurate reduction in the mass to be treated in the subsequent stages.

Multiple stages of attrition scrubbing are often necessary when harder shales are treated, and a producer in the northwestern Transvaal has included a cyclone desliming stage between the primary and the secondary attrition milling. This avoids the use of an additional screening stage, and removes light particles of shale together with the slimes.

The deficiencies of attrition milling are often overcome by the use of varied operations or even alternative procedures. In France, semi-autogenous milling with steel balls is practised, whereas a local producer resorts to hard rubber lugs in the second stage of milling as a means of obtaining good disintegration of the shale and cleaning of the crystal surfaces. Mintek developed a procedure that involved pre-screening of the feed to the scrubber for the removal of liberated crystals. The screen oversize was then fed to a modified attrition mill (shown in Fig. 8) fitted with discharge grates in the mill shell. Hollow steel pipes in the mill break down the harder particles of shale to a size that will pass through the grate. Liberated andalusite crystals also passes through the grate, thus minimizing further breakage as would have happened in a conventional mill. This procedure increased the andalusite recovery by as much as 30 per cent[12]. However, this mill was not as effective with shales containing coarse crystals, in which the mechanism of liberation is different from that of fine-crystal shales.

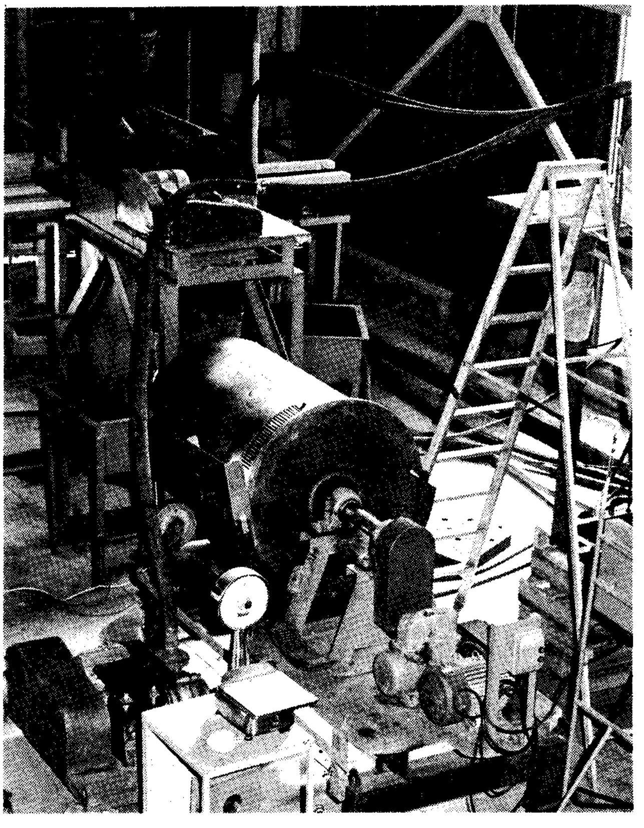


Fig. 8—Mintek-modified mill, with discharge grates in the shell and a prescreening trommel

Diamond pans have been found to be an effective means of attrition scrubbing in addition to acting as a concentrator, and are used exclusively at the Havercroft Mine. The ore is prepared by two-stage crushing in jaw-and-rolls crushers. No fines removal is carried out (the fines acting as a dense medium analogous to puddle in diamond treatment), and the ore passes direct into the pans. Slimes and light particles of shale discharge over the central weir, while the heavier andalusite crystals migrate to the bottom of the pan, where the raking action creates sufficient attrition to clean the surfaces of the andalusite crystals and to disperse the softer particles of shale. The water required is claimed to be much less than for drum-type scrubbers. The enriched underflow passes to screw classifiers, where the slimes are removed by the use of additional wash water.

Attrition scrubbers are now being used further down the process route on finished and semi-finished concentrates to further improve the quality of the final product. These scrubbers are smaller versions of the primary scrubbers, and are probably more effective in reducing the surface impurities since there is a more intimate contact between the andalusite particles than would be the case in primary scrubbers, where particles of shale and slimes can dampen or inhibit the contact between the andalusite particles.

Dense-medium Separation

As mentioned previously, the differences in relative density between andalusite and the other constituents of the ore were thought to be sufficiently high for the application of conventional gravity-concentration procedures such as jigging, pneumatic (dry-air) tabling, and water-film concentrators[9], and in the early years, when production was confined to the Zeerust–Groot Marico area, there were several examples of plants using these types of concentrators. However, these methods were very inefficient because of the shape factor and the fact that the differences in relative density were not sufficient for good separation. This was particularly so with andalusites that had been subjected to extensive weathering or that had a large range of densities (Table VI). Furthermore, these methods were not able to treat the high tonnages required to make the deposit economically viable.

Dense-medium separation eventually proved to be the only effective method of concentration to attain the grades of andalusite required by the consumer. This method is capable of separating particles with differences in relative density that are as little as 0,1 density unit at high-tonnage throughputs and at a large range of particle sizes.

The major factor influencing efficient separation in dense-medium separators is the quality of the medium. Ferrosilicon is the only medium used in the concentration of andalusite, and various grades are available to provide suspensions with relative densities of up to 3,8 without seriously affecting the viscosity[13]. The properties, advantages, and uses of ferrosilicon powders are described by Collins *et al.*[14], which is an excellent guide to the selection of the correct medium.

Various types of separating vessels are used in dense-medium separation, and Fig. 9 shows details of three of the separators most commonly used in the andalusite industry.

Cone Separators. This type of separator was initially favoured because of its simplicity of operation and because a relative density of 2,95 for the medium ensured a gangue-free andalusite concentrate. The major disadvantages of cone separators are the low throughput in terms of the size of the vessel and the large amount of medium in circulation. Also, the viscosity of the medium affects the efficiency of the method and limits its use to particles above 2 mm in size. There is only one example of a cone separator at present in use in the processing of andalusite. In this example, the cone is used as a secondary concentrator to up-grade a low-grade concentrate from a cyclone separator.

Cylindrical Separators. A typical example of a cylindrical separator is the Dyna-Whirlpool and, at the Krugerspost Mine near Lydenburg, Dyna-Whirlpool separators are used to treat a fine-grained andalusite ore[8]. A newer version of the Dyna-Whirlpool is the Tri-Flo separator, which is a two-stage separator that can produce two separate concentrates and a tailing or, alternatively, a middling product that can be recycled[15]. Although this type of separator is not being used at present, the increasing tendency towards two-stage separations warrants an investigation of its use.

Cyclone Separators. With one exception, all the andalusite mines in South Africa use the dense-medium cyclone as the means of separating andalusite from gangue, and it has been shown to be a highly efficient separator when operated correctly[16]. Cyclones with an included cone angle of 20 degrees are standard in mineral separations.

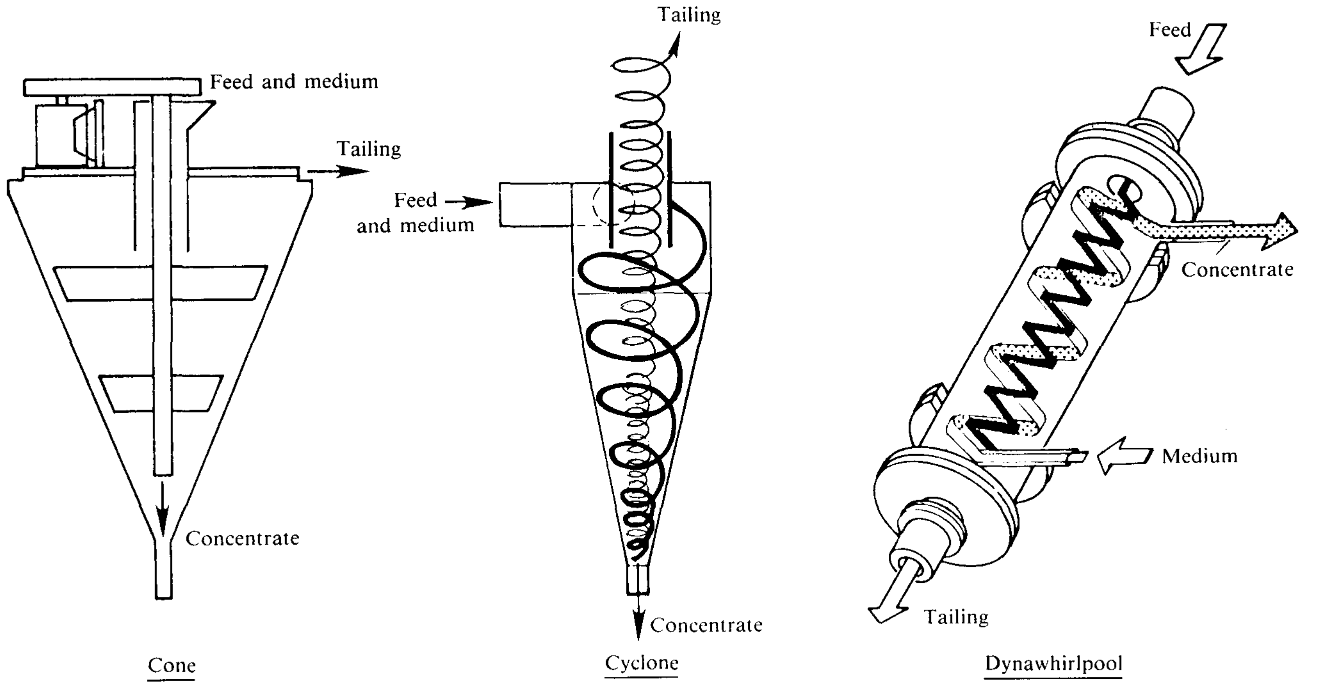


Fig. 9—Examples of heavy-medium separators

At the Timeball Hill Mine, a cyclone with an included cone angle of 10 degrees has proved highly effective. Cyclones with larger cone angles (40 to 60 degrees) have a tendency to reject coarse, heavy particles and are not favoured.

Operation of a Dense-medium Separation Plant

The major factors that influence the efficient operation of a dense-medium separation plant are, firstly, the preparation of the feed to the cyclone and, secondly, the choice of the correct medium. Poor feed preparation will affect the quality of the medium, leading to inefficient separations, while incorrect grade or poor quality of the medium will negate the effect of a properly prepared feed.

Other factors that affect the efficiency are variations in feed pressure, the ratio of medium to ore, and the recovery, cleaning, and densification of the medium[9,17,18]. Modern practice in medium recovery, cleaning, and densification involves the use of cylindrical densifiers, two-stage magnetic separation, and automatic density control. The cost of ferrosilicon is at present close to R800 per ton, and an efficient recovery and cleaning system is of paramount importance in reducing operating costs. An efficiently operated plant will have a ferrosilicon loss of between 100 and 200 g/t of feed to the dense-medium plant. Fig. 10 show the principle of operation of dense-medium separation and the various components of the plant.

Determination of Efficiency

Since there are no practical methods of analysing an ore for its andalusite content (the host rock and other gangue minerals also contain alumina and iron), the determination of the head grade of ores or other andalusite-bearing materials other than concentrates requires the use of physical methods. Heavy-liquid separation is the method most commonly used, and the results are reproducible. The heavy liquid most frequently used is tetrabromo-ethane (TBE), which has a relative density of 2,96. The determination of the andalusite content of ores requires careful crushing to liberate the crystals from the host rock. A relatively simple test of the efficiency of the separation is thus the treatment of the products of dense-medium separation by heavy-liquid separation, which indicates the amount of misplaced particles. Chemical analysis is then used to determine the quality of the concentrates, as shown in Table V.

A more reliable method of determining efficiency, which allows a comparison of the effect of changes in operating conditions, is the use of the Tromp Efficiency Curve[19]. From this curve, both the density of separation (D_s or D_{50}) and the efficiency or Probable Error (E_p) can be obtained. A typical Tromp Curve is shown in Fig. 11.

Allied to the use of the Tromp Curve is the washability curve, which is used extensively in the coal industry. The washability curve shows the amenability of the ore to dense-medium separation and, when used in conjunction with the Tromp Curve, gives an accurate prediction of the performance of the concentrator.

Two-stage Concentration

Currently, there is a tendency for producers to use multiple concentration stages as they strive, not only to improve the quality of their product, but also to obtain higher recoveries. Recoveries at the various mines are generally low, and over half of the andalusite content of the ore is lost as fines and as misplaced particles in the various stages of concentration.

At the Annesley Mine, a low-grade concentrate produced in the primary cyclone is further scrubbed and then subjected to a second stage of dense-medium separation. At the Andafrax Mine, a cone separator is used to upgrade the cyclone concentrate. At the Hoogenoeg Mine, the dense-medium concentrate is screened at 6,0 mm, and

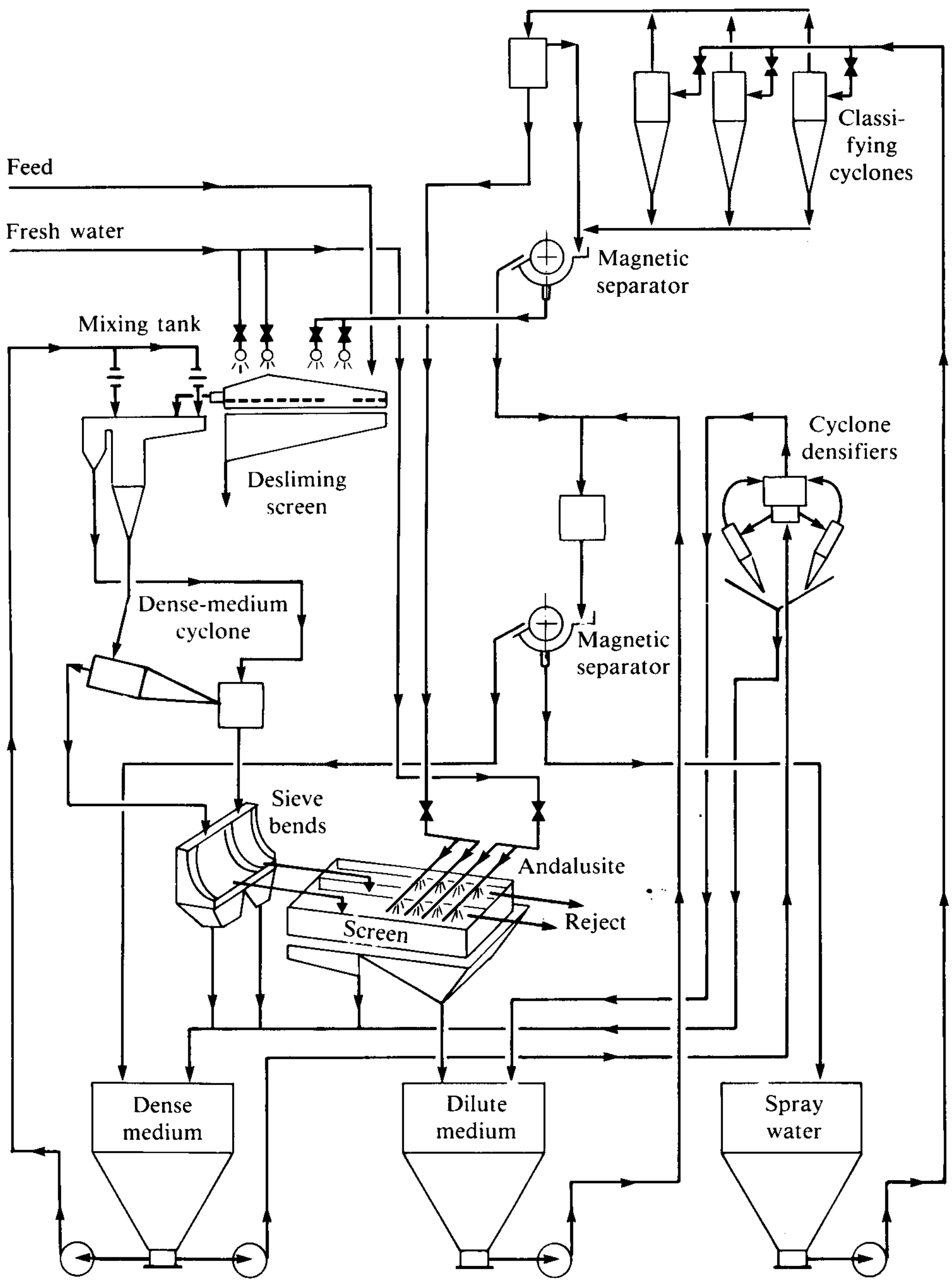


Fig. 10—Details of a dense-medium cyclone plant

the particles above 6,0 mm in size are carefully crushed to below 6,0 mm and are then recycled to the scrubbing stage. Since the particles break preferentially along the lines of the chiastolite cross, liberation of the impurities present in the cross results in a product of higher grade.

Magnetic Separation

The final stage in the concentration procedure is magnetic separation. Specifications for andalusite concentrates require the Fe_2O_3 content to be not greater than 1,0 per cent. Concentrates with lower values will command a premium price while penalties are imposed for every 0,1 per cent that the Fe_2O_3 content exceeds the specified value.

Since most of the iron-bearing impurities are only feebly magnetic, high-intensity magnetic separation is required to reduce the Fe_2O_3 content to acceptable levels. Mintek initially used a four-pole Crossbelt separator when evaluating ores. Induced roll (IR) separators were used with success at the various mines, but these machines had the disadvantage that the rolls were subject to high wear as a result of particles rubbing between the roll and the pole piece. The need for maximum field strength requires that the air gap be kept as small as possible[20]. This is shown graphically in Fig. 12, which also illustrates the principle of the IR separator. Other disadvantages of IR separators are the high power requirements and the high mass in relation to size.

A new development in dry high-intensity magnetic separation is the Permroll separator, and at present five of the six mines use Permrolls in their circuits. Timeball Andalusite uses both IR and Permroll separators, and the Krugerspost Mine uses only IR separators. Permroll-type separators are claimed to have achieved markedly lower

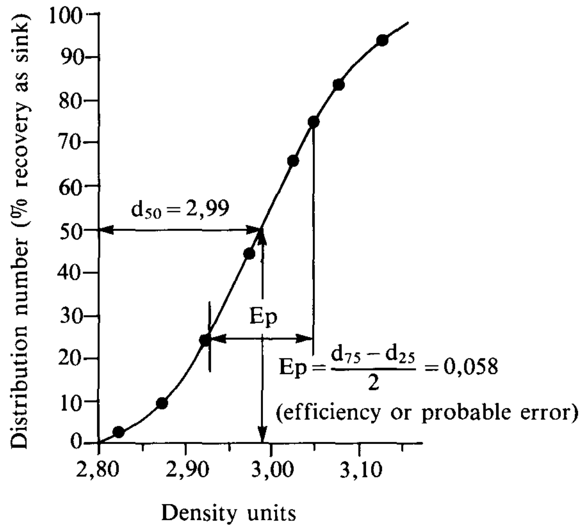


Fig. 11—The Tromp efficiency curve for a dense-medium cyclone

iron values in andalusite concentrates than other types of separator. The Permroll separator, details of which are given in Fig. 13, has the advantage of minimal power requirements, low mass, light construction, the absence of an air gap, and no direct contact between particle and roll, which completely eliminates roll wear. Fig. 14 shows a single-stage Permroll separator in operation.

Table VIII compares the operation of Permroll, IR, and Crossbelt separators. A new magnetic alloy neodymium–iron–boron will soon be available, which will increase the magnetic induction by a substantial amount.

The Havercroft Mine has introduced a roasting stage prior to magnetic separation. Roasting under controlled conditions increases the magnetic susceptibility of feebly magnetic particles, and gives a superior-grade product with an Fe_2O_3 content of less than 0,6 per cent.

Recovery of Fine Andalusite

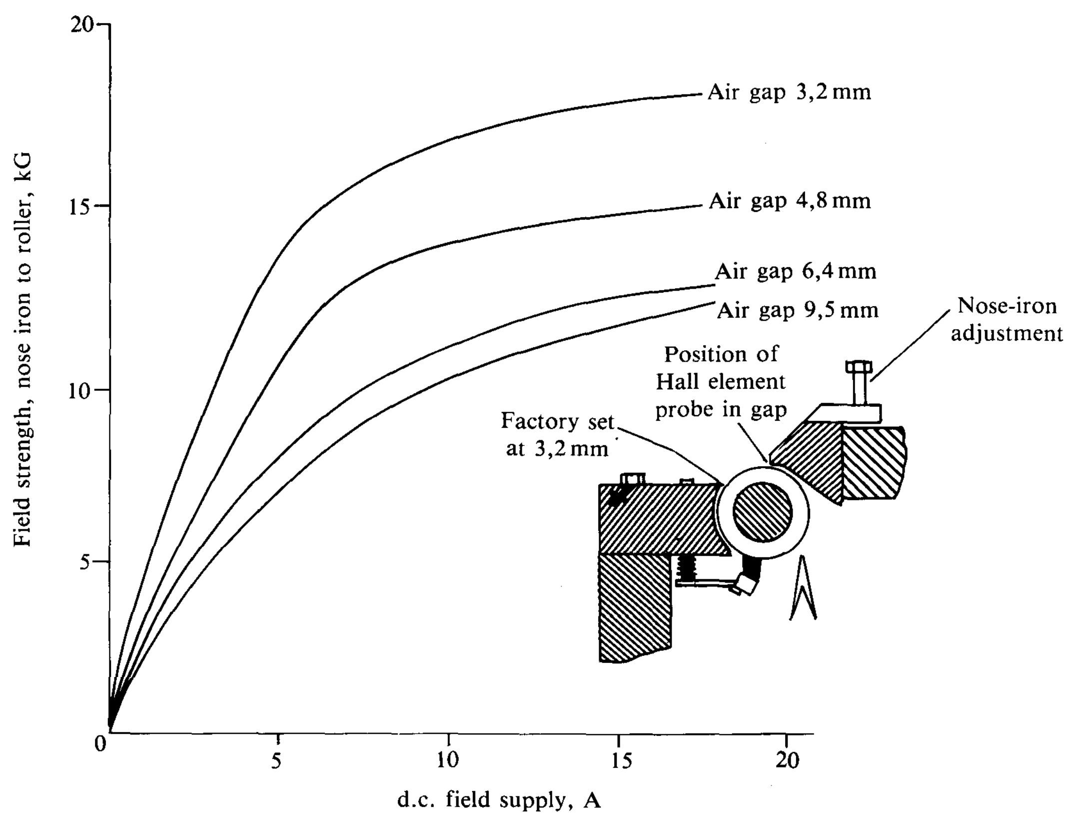
Andalusite particles below 0,6 mm are not recovered by dense-medium separation, the major reason being that, at sizes below 0,6 mm, recovery of the medium by screening becomes very inefficient and excessive screen areas are required in addition to the huge quantities of water that are needed to wash particles of this size free from the adhering medium. In the early days of the industry, specifications for andalusite concentrates required a minimum of fines below 0,6 mm, and this requirement is still adhered to at present.

The demand for fine andalusite down to 0,1 mm is increasing, and several producers are investigating the recovery of andalusite from their slimes dams, which represents a vast source of high-grade material if it can be recovered.

Several methods of concentration are available in theory. Dense-medium separation is the obvious choice since it has been proved on fine materials such as coal and cassiterite. The plant required for fine material differs in several respects from that required for coarse material. The major difference is in the recovery of the medium from the separation products and, since screens cannot be used for this purpose, wet-drum magnetic separators are the obvious alternative. This technology is well established in coal mines treating fines down to 0,1 mm.

Tests at Mintek on fines below 0,6 mm showed dense-medium separation to be successful, and concentrates assaying 61,0 per cent Al_2O_3 and 0,5 per cent Fe_2O_3 were

Fig. 12—Variation of field strength with air gap in an induced-roll magnetic separator



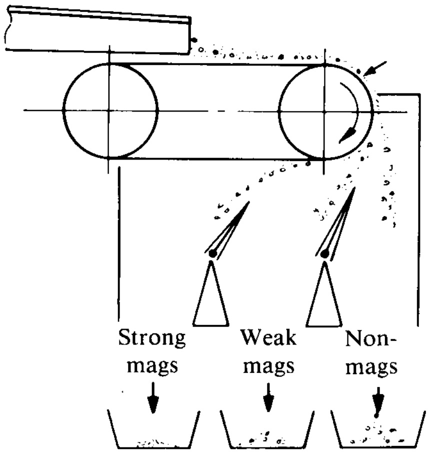


Fig. 13—The product split in a single-stage Permroll separator

Fig. 14—A Permroll separator treating andalusite concentrate

TABLE VIII
PERFORMANCE OF MAGNETIC SEPARATORS IN THE TREATMENT OF ANDALUSITE CONCENTRATE

Separator	Product	Grade, % Al_2O_3	Grade, % Fe_2O_3	Non-magnetics %
Crossbelt	Feed	56,3	2,58	
	Non-magnetics	57,4	1,03	91,0
Induced roll	Feed	56,2	2,58	
	Non-magnetics	58,6	0,95	87,0
Permroll	Feed	56,2	2,58	
	Non-magnetics	59,6	0,71	83,0

Note: In all cases four passes over the separator were required

produced. The low Fe_2O_3 value was obtained in a wet high-intensity magnetic separator. However, no attempts have been made to establish whether a dense-medium plant using magnetic separation to recover the medium and clean the andalusite crystals of adhering medium is economically viable.

Flotation is an optional method for the recovery of fine andalusite. However, it is limited at present to a maximum particle size of 0,3 mm, although new techniques such as column flotation can treat coarser sizes. Some success has been achieved at Mintek with flotation, but the recoveries have been very low and the grades are not yet comparable with those obtained by dense-medium separation. Gravity concentration by spirals or tables is possible provided closely sized feeds are used, but insufficient work has been done on the evaluation of this technique. The water requirements are obviously a serious factor and must be considered in the evaluation of these procedures.

The Role of Mintek

A review of the andalusite industry would not be complete without an acknowledgement of the role that Mintek and its predecessors have played in the processing of andalusite[21]. In fact, the first work on andalusite was done about 50 years ago in the Minerals Research Laboratory, which eventually became Mintek[22]. Since that time there has been a close association between the industry and Mintek, and many of the developments and improvements that have been introduced are a direct result of research carried out at Mintek. This included work on dense-medium separation, washability, the use of the Tromp Curve in the prediction of results and the determination of efficiencies, and improvements in attrition-scrubbing techniques, as well as extensive tests on various types of magnetic separators.

This close co-operation with the industry has resulted in the successive implementation of more efficient methods in South African andalusite plants. Mintek's service continues, not only in improving mineral-processing methods, but also in developing analytical techniques and certified analytical reference materials.

Future Outlook

The present demand for andalusite is strong and is likely to continue so for the foreseeable future. At present, producers are hard-pushed to fulfil the demands from consumers world-wide, and all the plants are operating at full capacity. Several producers are increasing their plants to cope with the demand, and it is likely that one or two new producers will be in operation soon.

The major reasons for the increased demand lie, firstly, in the improved economic conditions world-wide allied to a shortage of zircon and, secondly, in the high prices being asked for bauxite. The South African producers have improved considerably both in their consistency of supply and in the quality of their products, and premium quality concentrates are being sold at between R320 and R330 per tonne f.o.b. Richards Bay. Material of lower quality commands a price of R250 to R260 per tonne.

The demand for fine andalusite (smaller than 0,6 mm) is also increasing. It is unfortunate that natural fines are not being produced at present, but dump material represents a vast source of fine andalusite if it can be recovered. At present, coarse concentrates are being milled to supply the demand.

Future competition is most likely to come from new sources located in other countries and from substitute materials. Extensive andalusite deposits in China are under investigation, and both Australia and Brazil are reported to have andalusite deposits that can be exploited. However, for the foreseeable future, it is evident that

South Africa will be the major supplier of this vital commodity. It is to the credit of the industry in general that much effort is being put into improving, not only the efficiency of the plants, but also the quality of the products, by the application of new technology, and that South Africa's dominant position in this particular area is being maintained.

Acknowledgements

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21. The production of andalusite and other refractory minerals. Randburg, Council for Mineral Technology, *Application Report* no. 5, 1988.
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Reference works on advanced materials

Each of the following seven studies is a comprehensive state-of-the-art reference work with executive summary and conclusions. Alumina, the general workhorse ceramic, has been used commercially since the 1930s. The various forms of boron nitride find specialist uses. Aluminium nitride is of particular current interest as an electronic substrate and packaging material for VLSIs. Titania is no longer a minor appendage of the pigment business but now constitutes a major range of advanced materials. Rapid development of the silicon ceramics and zirconia has been spurred by the ultimate goal of the all-ceramic engine that will run unlubricated and uncooled, and will save energy. This goal has not been realized but has resulted in the development of new, stronger, tougher, and more temperature- and corrosion-resistant forms of the materials—and also fibres, whiskers, and composites. These materials are all being used by industry to save fuel, time, and money. The sections include: The different forms of the materials; Methods of production; World production in the major countries; World trade; World consumption; End-uses; Prices; Activities by companies and research organizations; Exchange rates and terms used. All seven of the reports, which are world-wide in scope, were prepared by MMR (Mitchell Market Reports) of Harrow, England.

- *Zirconia.* 285 pp. (2 vols.) 06/88 \$1050 (£600)
- *Alumina.* 389 pp. (2 vols.) 05/87 \$1315 (£750)
- *Silicon carbide.* 300 pp. 09/88 \$1050 (£600)
- *Boron carbide and boron nitride.* 163 pp. 12/87 \$875 (£500)
- *Silicon nitride and the sialons.* 230 pp. (New edition). 07/89 \$1050 (£600)
- *Aluminium nitride.* 150 pp. 05/89 \$875 (£500)
- *Titania and the inorganic titanates.* 150 pp. 06/89 \$1050 (£600).

Safety at Genmin mines

Seven out of the ten gold mines that had the lowest fatality rates in 1988 were in the Genmin group. According to statistics released by the Chamber of Mines, the Winkelhaak Gold Mine, situated close to Evander in the eastern Transvaal, was at the top of the list, with the lowest fatality rate of 0,198 per thousand workers. This figure compares favourably with the average fatality rate of 1,1 per 1000 workers of the 39 gold mines that are members of the Chamber of Mines.

Besides the Winkelhaak Mine, which received the Lynne van den Bosch Award for the lowest fatality rate in the Chamber of Mines Gold Division, the following mines turned in low fatality figures per thousand workers: West Rand Cons. (0,410), situated near Krugersdorp; Grootvlei (0,411), near Springs; Leslie (0,440) and Kinross (0,680), both in the Evander area; and Stilfontein (0,716) and Buffelsfontein (0,720) in the Stilfontein area of the western Transvaal. The average fatality figures for these mines were more than 50 per cent better than the average of the 39 mines for which the Chamber kept statistics.

Two of the collieries in the Genmin stable, Trans Natal's Kilbarchan Mine, near Newcastle, and the Delmas Colliery, near Delmas, had the third- and sixth-lowest fatality figures out of the 31 coal mines that are members of the Chamber of Mines. These two mines were also awarded the C.S. McLean Shield for the lowest reportable accident figures per 1000 workers over a three-year period.

On top of this, Winkelhaak, Kilbarchan, and Bafokeng South (a platinum mine near Rustenburg) also achieved double-millionaire status for working two million shifts without any fatal accidents.

Three other mines managed by Genmin are currently millionaires. They are Delmas, Samancor's Wessels–Hotazel Mine, and Barberton Gold Mines, which were also awarded the St Barbara trophy. Another member of the group, Impala's platinum refinery at Springs has also become a millionaire.

Genmin's success in the field of mine safety can largely be attributed to the work done by the highly specialized mine-safety unit that was created about two years ago. Genmin's Senior Consultant, Health and Safety, Mr George Krafft, says the unit has done intensive research that has, in turn, led to improved and updated safety procedures and better training programmes. These steps, as well as the attitude of the employees and management towards safety, have led to higher safety standards and lower accident figures.

The photograph, which was taken at the launching of General Mining Metals & Minerals (Genmin), shows the Chairman of Genmin, the General Managers of five of the mines, and the General Manager of the Platinum Refinery at Springs, who received awards for the low fatality and accident rates during 1988. Left to right: Derrick Parfitt (Barberton Gold Mines), Humphrey O'Keefe (Impala Platinum Refineries), Steve Ellis (Chairman of Genmin), John Smithies (Bafokeng South), Cyril Warburton (Winkelhaak), Harry Kruger (Wessels-Hotazel), and Dutch Botes (Delmas Colliery)