Mineral Resources
Consultative Committee

Mineral Dossier No. 20

Bauxite, Alumina and Aluminium

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Preface

The Mineral Resources Consultative Committee consisted of representatives of interested Government Departments, and specialist advisers. It was set up in 1967 to keep present and future requirements for minerals under review and to identify problems associated with the availability, exploitation and use of mineral resources, both inland and offshore, having regard to competing demands on land use and other relevant factors.

Widespread and increasing interest in the mineral resources of the United Kingdom led the Committee to undertake the collation of the factual information available about those minerals (other than fossil fuels) which were being worked or which might be worked in this country. The Committee produced a series of dossiers, each of which was circulated in draft to the relevant sectors of the minerals industry. They bring together in a convenient form, in respect of each of the minerals, data which had previously been scattered and not always readily available. These dossiers in updated form are now being published for general information.

Acknowledgements

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Metric units are employed throughout this document except where otherwise stated. In most cases this has necessitated the conversion of originally non-metric data. The units and conversion factors used are as follows:

millimetres (mm) = inches x 25.4
metres (m) = feet x 0.3048
kilometres (km) = miles x 1.609344
hectares (ha) = acres x 0.404686
kilogrammes (kg) = pounds x 0.45359237
tonnes (1000 kg) = long tons x 1.01605

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SUMMARY

The term bauxite is applied to certain consolidated or semi-consolidated rocks in which hydrated oxides of aluminium are the most important constituents in an aggregate which also contains a variety of impurities. Although bauxite has a number of industrial uses, the development of a large mining industry and extensive world trade in the commodity reflects the fact that it has proved to be the raw material from which it is possible to produce alumina at lowest cost. *Alumina* is the name commonly applied to the pure anhydrous oxide of aluminium. The conversion of bauxite to alumina on an industrial scale involves solution, recrystallisation and calcination. In turn, although alumina also has a number of uses in its own right, its main industrial importance is as the raw material from which *aluminium* metal is produced in electrolytic smelters.

Bauxite was formerly mined in Northern Ireland but the production of aluminium in the United Kingdom is now entirely based on imported alumina. In 1976 total United Kingdom production of aluminium metal exceeded 0.5M tonnes.

Bauxite - Nature and Mode of Occurrence

Bauxite is not a clearly defined 'mineral' in the scientifically acceptable sense but is a composite substance consisting primarily of minute crystals of one or more of three hydrated aluminium oxides, namely *gibbsite* ($\gamma Al_2O_3.3H_2O$), *boehmite* ($\gamma Al_2O_3.H_2O$) and *diaspore* ($\alpha Al_2O_3.H_2O$). In addition an amorphous form of hydrated aluminium oxide known as *cliachite* may be present. The commoner impurities in bauxite include kaolinite, quartz and goethite. A high-grade bauxite, low in impurities, might contain about 60 per cent Al_2O_3, equivalent to about 40 per cent aluminium by weight. Some typical analyses of bauxites are given in Table 1.

Table 1 Chemical analyses of typical bauxites.

	1.	2.	3.	4.
Al_2O_3	59.8	62.44	62.96	60.53
SiO_2	5.3	2.79	.40	1.42
Fe_2O_3	1.9	2.05	.63	9.75
FeO	....	....	Trace	....
MgO	....	.14	.19	.73
CaO	....	....	Trace	....
Na_2O	....	....	.55	....
K_2O	....	....	Trace	....
TiO_2	2.0	.45	3.89	2.21
ZrO_2	....	....	....	....
P_2O_5	....	....	.34	.11
SO_3	....	....	....	....
Cl	....	....	....	....
MnO	....	....	Trace	.42
H_2O-	....	....	.74	....
H_2O+	....	31.96	30.12	25.59
Loss on ignition	30.6	....	....	....
Insolubles	....	....	....	....
Total	99.6	99.83	99.82	....

1. 'Granitic-textured' bauxite derived from nepheline syenite, Saline County, Ark, U.S.A. Average of 3 samples.

2. Surficial bauxite above hornblende schist, Guyana,

3. Yellowish-white pisolitic bauxite above hornblende basalt, Surinam.

4. Average of 17 lateritic bauxites formed over Voltaian System shales, Ghana.

Source: U.S. Geological Survey.

By virtue of its mixed and inhomogeneous character bauxite is difficult to define. To the aluminium industry the term implies merely commercial or semi-commercial ore and the distinction between these two categories depends upon the silica and iron content of the material as well as that of *available alumina* (q v). Bauxite is also classified according to trade use into alumina, refractory, abrasive and chemical grades.

True bauxites grade into aluminous clay when the content of hydrated aluminium oxides decreases relative to aluminosilicates such as kaolinite. The intermediate category of *bauxitic clay* refers to material which, although not commercially acceptable as bauxite, contains a slight excess of alumina over silica in its chemical constitution which will result in the presence of some hydrated aluminium oxides as well as kaolinite in its mineral composition. Bauxitic clay is considered briefly in this dossier in order to complete the account of British resources of bauxitic material but it belongs properly to the separate subject of refractory clays. With increasing proportions of hydrated oxides of iron, bauxite may also grade into laterite. A high proportion of iron, although not directly affecting the Bayer process (see p. 15), acts as a diluent and may also preclude the commercial exploitation of certain bauxites.

Bauxite is extremely variable in gross appearance. Although usually an amorphous earthy substance, it may sometimes be hard enough to fracture conchoidally. Unlike clays, to which it may bear a superficial resemblance, bauxite does not possess a plastic consistency. Its colour varies greatly between deposits and sometimes within them; some varieties with a low iron content are almost white but increasing proportions of iron give rise to the commoner yellow, red and brown bauxites.

A broad geological classification of bauxite deposits, based upon their morphology, has been suggested by S H Patterson.

Blanket deposits occur at or near the present day land surface and consist of flat-laying bauxite layers varying in thickness and lateral extent. Most blanket deposits have a largely residual origin, having been derived from the degradation of aluminosilicate minerals present in the underlying rocks, but some may contain a certain amount of material transported from elsewhere. Blanket deposits are typically associated with plateaux or denuded plains in which geomorphological and climatic conditions have been stable for long periods; the stability of these environmental factors is as important to the genesis of bauxites as the nature of the underlying rocks from which they are derived. This is demonstrated by the existence of blanket bauxites over many kinds of igeneous, sedimentary and metamorphic bedrocks. Some of the very largest bauxite deposits in the world, notably those in northern Australia and in the Republic of Guinea, are of the blanket type.

Interlayered deposits are found as discontinuous beds and lenses intercalated in sedimentary or volcanic rocks or along the contact between igneous or metamorphic rocks and younger sedimentary strata. In most cases such bauxites are merely the remnants of blanket deposits that have been partially eroded and subsequently buried under younger rocks. The important deposits of Guyana and Surinam are examples of this type as are also the small occurences in Northern Ireland. A few bauxites of interlayered type appear to be entirely of transported origin. Examples of these are found in Arkansas, USA., where bauxitic material originating as the weathering products of a number of upstanding stocks of nepheline syenite has been buried, along with the stocks themselves, under younger sedimentary rocks.

In Patterson's classification *pocket deposits* are the third important category of bauxite occurrence. These most commonly occur as fillings of depressions formed in the topographic surface of massive beds of limestone or dolomite.

Considerable controversy has centred on their origin and three distinct hypotheses have been put forward. These are, firstly, that the deposits result from intensive concentration, followed by bauxitisation, of the minute quantities of aluminous materials already present in the associated limestone; secondly, that they represent a fortuitous concentration of material transported from elsewhere or, finally, that they result from the weathering of a younger clay or volcanic ash band originally deposited on top of the limestone. Evidence from different areas is often conflicting and the problem remains unresolved. Some pocket deposits are continuous at higher levels and therefore grade into blanket-type deposits; others have been buried and are thus interlayered pocket deposits. Pocket deposits associated with limestone are especially characteristic of the medium-sized bauxite mining areas of Jamaica, Haiti and the Dominican Republic. They are also present in several countries of southern and central Europe where, within the Alpine orogenic belt, bauxites, ranging in age from Triassic to Eocene, are found which have been folded, faulted and subsequently re-exposed after erosion. The area around Les Baux in southern France, from which bauxite derives its name, shows deposits of this kind.

The Nature of the Bauxitisation Process

The geochemistry of aluminium and the nature of its concentration in bauxite are features that set it apart from many other important industrial metals. Elements such as copper, zinc, lead, uranium, tungsten, gold and platinum form a very minor component of most crustal rocks and occur in economic quantities where relatively rare geological events have led to their concentration. In contrast, aluminium is the most abundant metallic element in the terrestrial crust and, after oxygen and silicon, is the third most abundant of all elements.

Aluminium is part of the crystal structure of many rock-forming minerals of which the feldspars are the most important. Most common rock types in the crust, irrespective of whether they are igneous, metamorphic or sedimentary in origin, contain a high proportion of aluminium-bearing minerals. The only important exceptions to this generalisation are limestones and most sandstones together with their respective metamorphic derivatives.

In feldspars and other aluminous rock-forming minerals aluminium exists in strong chemical bonding with silicon and oxygen in aluminosilicate lattices. *Bauxitisation* is the process whereby these strong aluminosilicate lattices are broken down by the removal of silicon and the alkaline elements, potassium, sodium and calcium, leaving aluminium in chemical compounds which are more amenable to industrial treatment.

Bauxitisation takes place under critical conditions of temperature, annual rainfall, soil pH and Eh, and soil drainage in rocks subjected to weathering in the zone above the permanent water table. Following removal of silicon and alkaline elements a mixture of hydrated aluminium oxides and other residual impurities is left. If the residuum is rich in iron, laterite is formed; in ideal cases, however, the iron content is low and true bauxites form. Bauxitisation (or laterisation) of the original minerals may take place *in situ* or such minerals may be partially weathered and transported to a site where they undergo subsequent bauxitisation or, thirdly, bauxite itself may be eroded, transported and re-deposited elsewhere. In all three cases, however, the critical climate and soil conditions necessary for the conversion of aluminosilicate to hydrated aluminium oxide appear to be similar.

A hot and humid climate appears to be an essential pre-requisite for the deep and intense weathering of a variety of primary rocks which leads to their bauxitisation. There is some evidence that bauxitisation is encouraged by a well-marked seasonal variation of monsoonal type. For the formation of thick bauxite deposits such climatic conditions would have to persist for prolonged periods and, for the bauxites to develop over a wide area, the land surface on which they are forming would have to remain undisturbed by tectonic movements for a corresponding period.

Many bauxites are known, and some are mined, in areas where the climate is not now conducive to bauxitisation or where tectonic movements subsequent to bauxitisation have brought the process to a halt and, perhaps, caused the erosion of much of the bauxite already formed. Therefore, for a variety of reasons, older bauxites tend to be preserved in relatively small bodies. The giant bauxite deposits of, for example, Guinea and Australia are of fairly recent origin, being less than about 65 million years in age, and, in some cases, may still be in the process of formation. Within this relatively short time the effects of continental drift have been limited and the distribution of the Earth's climatic belts has not changed greatly. Consequently all the large deposits of Tertiary to Recent age fall within present tropical limits and it can be inferred that future discoveries of major importance will be confined to these regions.

The physical and chemical constraints on the formation of gibbsite, boehmite and diaspore are also not fully understood. It is a possibility that a broad correlation with age exists. Thus, for example, the geologically young Cainozoic bauxites of northern Australia are gibbsitic. Older Cainozoic and Mezozoic bauxites are mainly boehmitic. In very old bauxites such as the Palaeozoic deposits of Pennsylvania and Missouri boehmite and gibbsite are almost entirely replaced by diaspore.

Bauxite - Domestic Resources

Within the United Kingdom there are no bauxite deposits sufficiently large or of grade high enough to encourage mining at the present time.

In Scotland, the Ayrshire bauxitic clay, a weathering horizon developed on basaltic rocks of mid-Carboniferous age, has a main outcrop in northern Ayrshire extending from the coast at Saltcoats eastwards for 20 km to Kilmarnock. Clays of similar character occur at about the same horizon in central Ayrshire, in the Sanquhar basin of Dumfriesshire, near Stranraer, in the Machrihanish coalfield of Kintyre and in Arran. Except in Ayrshire and, possibly, the Stranraer occurrence, these clays have an excess of silica and cannot be termed bauxitic. Even within the main outcrop in northern Ayrshire, only the western portion contains significant amounts of alumina hydrates. In the eastern part the clay is of poor quality and has a high iron content. These bauxitic clays have been extensively worked in several areas in the past for the manufacture of alluminium sulphate and of refractory bricks. The only recent clay production has been from three small opencast pits in the Stevenston and Kilwinning areas.

In Northern Ireland bauxites are recorded from a number of places, mainly located in the northern and eastern parts of Co. Antrim, but also in the adjacent part of Co. Londonderry near Coleraine. In Antrim small-scale mining commenced about 1870 and continued until 1934; during this period the production of bauxite was associated with a much larger iron ore mining industry. Bauxite mining was briefly resumed as a war-time measure in 1941-1945.

The bauxites of Northern Ireland are a part of lateritic horizons interbedded with the Tertiary basalt lavas of the Antrim Plateau. Such horizons represent a pause in volcanic activity during which time the underlying basalts were subjected to deep atmospheric weathering under tropical conditions.

In the north of Antrim and near Coleraine there are two such persistent interbasaltic beds occurring above and below an intermediate group of tholeiitic basalts; in southern and eastern Antrim there is only one major interbasaltic bed intervening between the Lower and Upper Basalts which are both mainly olivine-basalts in composition. Some rhyolites occur in association with the predominant basalts of the Antrim Plateau and in places the interbasaltic rocks themselves include rhyolite or rhyolitic debris. Ideally, however, the interbasaltic beds consist of clay or lithomarge formed of decomposed basalt overlain by bauxite which is, in turn, followed by a thin layer of iron ore at the top. A lignite layer occasionally overlies the bauxite and this also has sometimes been mined.

The basalts form an essentially flat-laying series of lavas so that bauxite occurs as a horizontal or gently-dipping sheet often cropping out around the flanks of plateaux and outlying hills formed of the Upper Basalts. In some cases the outcrop of the interbasaltic beds can be traced continuously for many kilometres and on a regional scale the altitude of the main bed varies from about 60 to over 450 m above sea level. The interbasaltic horizons are not invariably present. In places they are known to be very thin or absent, although they may be obscured by superficial deposits in some areas. Local absence or thinning of both the bauxite and the iron ore within the interbasaltic beds are common; the bauxite especially tending to occur in lenticular seams separated by barren areas.

Two contrasting types of bauxitic rocks are found in Northern Ireland. Ferruginous bauxites, derived from basalt, are typically red in colour and are iron-rich (20-30 per cent Fe_2O_3) but contain less than 10 per cent silica. This type has been used for alumina production. The second type is grey argillaceous bauxite or bauxitic clay. These are poor in iron but contain 20-40 per cent silica. They are often associated with lignite and some of them are clearly derived from rhyolitic material..Although not suitable for the production of alumina, the grey bauxites have been mined for alum manufacture and the possibility of using them for ferro-silicon-aluminium production was considered during the Second World War.

Although limited tonnages of bauxite have been removed by opencast working along the outcrop of the interbasaltic beds, most of the mining was by adit. Operations have generally been simple because of the gently-dipping nature of the seams and the safe roof normally provided by the basalt. During the most recent phase of bauxite mining it was found necessary to extract the overlying iron ore to provide a sound roof of basalt. In the old iron ore mines, much more extensive than the bauxite mines, haulage ways were commonly cut into bauxitic material or lithomarge beneath the iron ore.

The size of remaining bauxite resources in Northern Ireland is difficult to estimate. The intermittent and lenticular nature of bauxitic occurrences along the outcrop of the interbasaltic beds is probably representative of the nature of occurrences obscured by the 380 km^2 outcrop of the Upper Basalts. The Upper Basalts are likely, therefore, to conceal potential resources amounting to many millions of tons. During the period of mining, bauxite occurring away from the outcrop zone was regarded as inaccessible, but since the thickness of the overlying basalts rarely exceeds 150 m and is frequently much less, mining of such concealed deposits might be feasible if a way could be found to locate them.

Estimates of reserves in certain limited areas were made during war-time investigations. The main locality at which significant reserves were shown to exist and which were not subsequently exploited is at Ballylig near Broughshane where it is estimated that 500,000 tonnes of bauxite averaging over 37 per cent recoverable alumina are in place.

The accompanying map (Fig. 1) shows the distribution of the main bauxite deposits and mining operations in Northern Ireland. Near the north coast of Antrim between Coleraine and Ballycastle three major subdivisions of the basalts are separated by interbasaltic weathering horizons. The lower or main interbasaltic bed crops out in the cliffs near the Giant's Causeway but bauxite is not apparently present. Inland grey bauxitic clay extends for over 3 km along the outcrop near *Ballintoy*. This clay is overlain by lignite which was formerly worked at Ballintoy. Just to the west of the Ballintoy mine, some bauxite was produced from adits at *Glengnagh* and *Lamnaghmore*. The latter mine closed in 1913 after having produced over 6000 tonnes during the final two years of its existence.

Further to the west, in the district south of Portrush, there were other bauxite and iron ore mines developed in the main interbasaltic bed at *Urbalreagh* and *Craigahulliar*.

South of Craigahulliar bauxite occurs in the upper interbasaltic bed at *Ballylagan* and *Killygreen* and some production was recorded at the latter locality around 1915. Except here, in the extreme west of its outcrop, the upper interbasaltic bed does not appear to contain significant amounts of bauxite.

Apart from some very small outliers, all the other occurrences of the Upper Basalts in Northern Ireland are concentrated in a fairly compact area of eastern Antrim extending west and northwest from the Larne district. In this region bauxite and iron ore are confined to the one major interbasaltic horizon between the Lower and Upper Basalts.

Northeast of Newtown Crommelin an isolated plateau of Upper Basalts is separated from the main area of these basalts in eastern Antrim by the Glenravel and Glenariff valleys. This plateau extends for 8 km and culminates in Trostan Hill (554m). On the northwestern flank of the Trostan plateau no economic concentrations of bauxite or iron ore are known but intensive mining has taken place on the opposite side above Glenravel and Glenariff. Although iron ore was the main product of the Trostan plateau mines, some bauxite was produced from workings near *Essathohon Burn, Evishacrow, Salmon's Drift* and *Skerry Water.* In the same general vicinity some bauxite

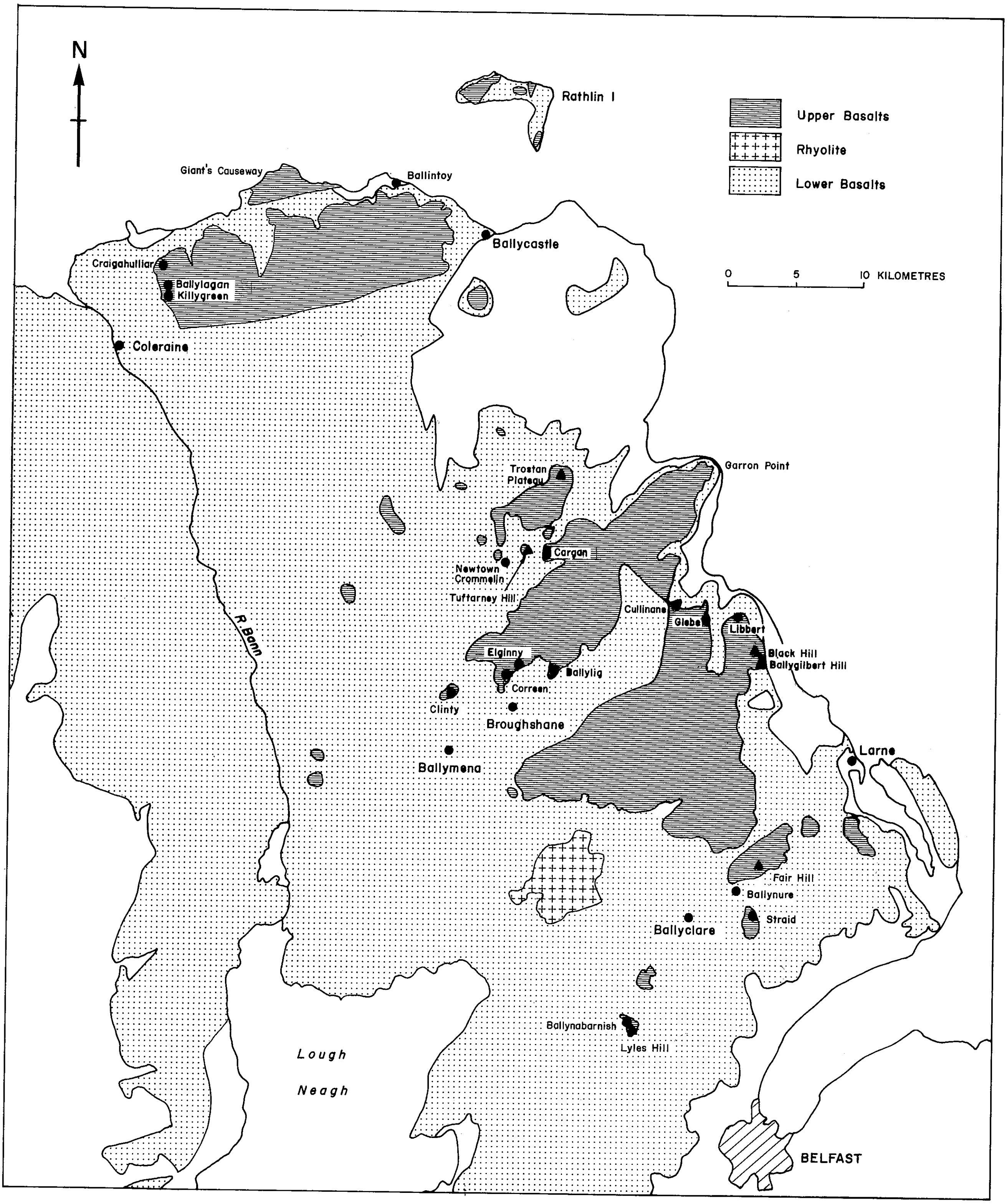

Fig 1 Bauxite occurrences in Northern Ireland

clay was produced from workings below an outlier of Upper Basalt on *Tuftarney Hill.* Of these the most recent production appears to have been from Skerry Water when over 60,000 tonnes of bauxite were produced during 1942-43.

To the southeast, and falling within the main area of Upper Basalts in eastern Antrim, the interbasaltic horizon can be traced almost continuously around the upland tract for about 22 km extending northeastwards from near Broughshane to the coast of Garron Point. Iron ore has been mined at intervals along the northwestern facing part of the outcrop but some bauxite production has only been recorded at *Cargan.* Immediately north of Broughshane the interbasaltic bed crops out along an east-west trending escarpment and here bauxite is known for several localities. Production is recorded at *Correen,* 3.2 km north of Broughshane and just to the east of this about 27,000 tonnes were produced at *Elginny* in 1942. East of Elginny a spur of Upper Basalts extends southwards towards the Braid River and here, at *Ballylig,* the relatively large reserves mentioned in a previous paragraph were located in 1943.

North of Ballymena some bauxite was produced at *Clinty* situated on the edge of the Berk Hill outlier of Upper Basalts. East of Ballymena a large tract of Upper Basalts is known to be underlain by interbasaltic beds in only a few localities and mining has been confined to the coastward edge in the region of the Glenarm Valley. Minor production of bauxite has been recorded at the *Glebe Mine, Libbert Mine* and on *Ballygilbert Hill.*

Further south, in the country extending towards the Belfast Lough, bauxite has been recorded at a number of localities, but the only production appears to have been from the eastern side of the *Straid Hill* outlier near Ballynure and from the most southerly known outcrops associated with another Upper Basalt outlier at *Lyles Hill* and *Ballynabarnish* about 13 km northwest of Belfast. At Lyles Hill the interbasaltic bed crops out around the base of a small hill of Upper Basalt. A NW-SE fault separates this from the larger Ballynabarnish mass to the north in which the ore zone is known along the eastern edge. Bauxite was first produced in 1942 although much earlier a number of adits had been driven into the seam at Lyles Hill. This area was the main wartime source of bauxite in Northern Ireland and up to 1945 more than 200,000 tonnes were produced. The bauxite averages about 1m thick but shows rapid variations in thickness and quality. The Lyles Hill part of the deposit is now worked out and resources at Ballynabarnish are restricted owing to faulting.

Since the bauxite mining ceased in 1945, the only major resurvey of the Antrim deposits has been undertaken by Rio Tinto-Finance and Exploration Ltd. This company withdrew in 1973 having concluded that there was little possibility of discovering extensive new resources of metallurgical-grade bauxite.

In the early 1970's Dorking Minerals Ltd removed material from Ballylig for testing as a road aggregate. Although this company subsequently withdrew, Mining Permission was granted to the Department of the Environment of Northern Ireland in April 1976 to take bauxite from Ballylig for further evaluation as a source of aggregate and for use in water purification.

A further Mining Permission was sought in April 1978 in respect of the Clinty quarry, near Ballymena, where it was proposed to remove bauxite also for tests by the local Department of the Environment.

Bauxite - World Resources

In 1978 the United States Bureau of Mines estimated world bauxite reserves, that is to say material that has been proven to be mineable in prevailing economic circumstances, as 24,500 million tonnes (Table 2). Bauxite resources (reserves plus subeconomic and undiscovered deposits) may amount to as much as 35,000 to 40,000 million tonnes. A continuous transfer of bauxites into the reserves category can be expected as exploration and evaluation continues and, possibly, along with advances in methods of treating low-grade deposits.

Table 2 Bauxite - World Mine Production and Reserves

	Million tonnes		
	Mine Production		Reserves
	1976	1977 (e)	
Australia	24.2	25.3	4,500
Guinea	10.9	11.5	8,200 *(a)*
Jamaica	10.3	11.4	2,000
Surinam	4.6 *(e)*	4.6	490 *(a)*
Greece	2.7	3.1	750
Guyana	2.6 *(e)*	3.1	1,000 *(a)*
France	2.3	2.2	40
United States	2.0	2.0	40
Other Market Economy Countries	6.7	7.2	6,700
Central Economy Countries	11.4	12.1	950
	77.7	82.5	24,500

(e) Estimate

(a) Data published by International Bauxite Association

Source: United States Bureau of Mines

Australia and Guinea are shown in Table 2 as possessing the largest reserves of bauxite. Of countries not specifically shown in Table 2, Brazil, Cameroun and India probably offer the best prospects for the location of extensive new reserves.

Twelve other countries, namely Yugoslavia, Hungary, Greece, Ghana, Sierra Leone, Dominican Republic, Haiti, Jamaica, Guyana, Surinam, Indonesia and Malaysia, export significantly more bauxite, or alumina derived from indigenous bauxite, than is consumed by their domestic aluminium industries. Some of these countries possess only limited reserves and, in general, their relative contribution to world trade in bauxite and alumina is declining.

Although possessing large reserves of bauxite, India has until recently consumed virtually all her domestic production; this, however, is likely to change following agreements with countries like Iran and the Soviet Union who will accept payment in alumina in return for assistance in the construction of refineries.

Of seven countries with aluminium smelting capacity in excess of 400 million tonnes per year, namely, USA, USSR, Japan, Canada, Federal Republic of Germany, France and Norway, only France is approximately self-sufficient in bauxite. The United States and the Soviet Union obtain only a proportion of their bauxite and alumina requirements from local sources. Yugoslavia and Hungary have long been the principal source of bauxite imported by the Soviet Union but it is evident that this country is now seeking material from entirely new areas, for example Greece, Guinea and India. Aluminium production in Japan, Canada, Norway and the Federal Republic of Germany is entirely sustained by imported alumina or bauxite. With a somewhat smaller aluminium smelting capacity, the United Kingdom is now also wholly dependent on imported alumina for metallurgical purposes.

Bauxite - Mining and Beneficiation

Bauxite deposits are most often situated at no great depth and, consequently, the majority are worked opencast. Many operations are on a large scale and are highly mechanised; draglines and bucket wheel excavators being used to remove overburden. The bauxite itself may require blasting prior to mechanical excavation. In many deposits some selective working of the higher grade material is carried out on the basis of appearance or detailed analysis; in others blending of various grades of bauxite may be undertaken. The economic overburden ratio varies considerably from one deposit to another; the maximum thickness of overburden removed appears to be 75 m at the East Montgomery mine in Guyana where there is also up to 12 m of bauxite. Some underground mining, in addition to conventional opencast operations, is undertaken in Arkansas, France, Hungary and Yugoslavia.

Run-of-mine bauxite is usually crushed, washed and screened to remove coarse sand although at some operations, for example in Western Australia, dry screening methods are employed. At some mines it was common practice to dry the ore in kilns to bring the moisture content down to as little as one per cent but with the need to control dust arising from handling bauxite, the shipping of wet ore is increasingly practised. Partial drying may still be undertaken to remove excessive moisture; in Jamaica, for example, the moisture content is reduced from 22 to 15 per cent, below which extreme dusting occurs.

Bauxite - Uses

About 90 per cent of the total world production of bauxite is consumed in the manufacture of alumina which, in turn, is principally used in the production of aluminium metal. Both bauxite and alumina have also important non-metallurgical uses for which they are to some extent interchangeable. Alumina, being more expensive, is preferred only where high purity is specified.

The design of an alumina refinery is specific to a certain type of bauxite, whether gibbsitic, boehmitic or a mixture of the two. Diasporic bauxites are not normally suitable for conversion to alumina by conventional means. In general terms, alumina refineries handle dried bauxites with an Al_2O_3 content in the range 55-62 per cent and with maxima for impurities as follows: SiO_2, 2-7 per cent; Fe_2O_3, 3-8 per cent and TiO_2, 2-4 per cent. Some plants in the USA are designed to treat bauxites containing as little as 48 per cent Al_2O_3 and as much as 15 per cent SiO_2. Moreover, as the presence of Fe_2O_3 has no chemical effect upon the refining of alumina but acts merely as a diluent, some US companies have experimented with high-iron bauxites of domestic origin.

A more precise index of the commercial value of a bauxite is its content of soda-soluble or *available alumina* and the complementary content of *reactive silica.* Any such reactive silica in the ore combines with alumina and sodium hydroxide to form insoluble hydrous sodium aluminosilicates from which alumina can be recovered only by a costly lime soda sintering process. Some of the silica shown in the analysis of a bauxite will be free quartz or chalcedony which, at least at lower temperatures, is unreactive and will not reduce the available alumina content of the ore. In Bayer plants designed to treat boehmitic ores at temperatures above 180° C a certain proportion of the quartz content of the ore does, however, become reactive.

Most of the bauxite which is utilised directly, rather than converted first to alumina, is simply calcined. Calcined bauxite is produced by heating to temperatures of 1,100 to 1,600° C in rotary kilns. This results in the volatilisation of chemically combined water and leaves an impure form of anhydrous alumina. Approximately two tonnes of crude wet ore are required to produce one tonne of calcined bauxite.

There are no recognised specifications for calcining-grade bauxites but the requirements of the refractory and abrasives industries, which are the main consumers of the product, considerably limit the number of bauxite deposits from which high value calcining-grade material can be produced. The refractory industry places a premium upon a low-iron bauxite and manufacture of fused aluminous abrasives demand a low silica content. Bauxites combining properties acceptable to both the refractory and abrasive industries are readily available in large quantities only from Guyana and Surinam although some calcining-grade material for the abrasive industry is produced elsewhere, for instance in France and Australia.

Fused calcined bauxite can be used for abrasives where the purer but more costly calcined alumina is not essential. Such abrasives are used, for example, in grinding wheels and polishing powders for which fused bauxite has largely replaced corundum, the naturally-occurring form of anhydrous alumina, and other abrasives.

Pure alumina has a melting point of 2,050° C. That of bauxite is somewhat lower in the approximate range 1,740° C to 1,820° C according to its composition. Calcined bauxites, as well as other high-alumina clays, can therefore be used for refractory purposes where furnace conditions are not exacting enough to demand the use of pure calcined alumina. Bauxite is chemically inactive and its firing characteristics compare favourably with those of other refractories. Material containing the alumina monohydrates, boehmite and diaspore, offers certain advantages over that containing the trihydrate gibbsite in that it is denser and is subject to less shrinkage. Diasporic clays have been extensively used for this purpose and, although diasporic bauxites could also be used, they do not appear to have been exploited to any degree.

Two main forms of refractory are manufactured from bauxite. Aluminous fire bricks can be made by mixing ground calcined bauxite with about 10 per cent of bonding material and then drying and baking the mixture. Fused aluminous refractories are made by fusing calcined bauxite or alumina in electric arc furnaces and casting the product into moulds.

Interest has been expressed intermittently in the possibility of using calcined bauxite as a skid-resistant aggregate for road surfacings. In 1973 the Transport and Road Research Laboratory of the Department of the Environment reported that refractory-grade bauxite from Guyana appeared to provide the highest resistance to polishing and abrasion among a number of bauxites tested. The high cost of this material however is likely to limit its use to particularly hazardous sectors of highway surfaces, for example, the approaches to traffic signals and pedestrian crossings (see Mineral Dossier No 19 in this series). More recently the Department of the Environment of Northern Ireland has commissioned research into the use of local bauxites as road aggregates.

Only a small proportion of the bauxite which is not calcined is used for purposes other than conversion to alumina. Some uncalcined bauxite is utilised directly in the manufacture of various alums and aluminium salts. The most important of these products is aluminium sulphate used in the manufacture of paper, for water purification and for the decolourisation of mineral oils. Other chemicals made from bauxite include aluminium chloride, used in the refining of mineral oils, the carbonising of wool and the manufacture of certain compounds, and also aluminium fluoride which is used as a flux in ceramic glasses and enamels.

The manufacture of *activated bauxite* involves partial calcination of gibbsitic or boehmitic bauxite. The temperature at which the activated material is produced depends upon the composition of the original bauxite. A commercially pure boehmite sample does not begin to decompose until a temperature of over 400° C is reached.

In contrast, gibbsite will give a highly active material at temperatures between 300° and 400° C. The effect of heating is to drive off most chemically combined water and to leave an impure form of alumina which has a high absorptive capacity for water varour and which can be used for the dehydration of gases, organic liquids and powders, and the clarification, desulphurisation and decolourisation of all varieties of oil. For all these applications activated bauxite is used when the purity of the product is of only marginal importance. Where high purity is specified, activated alumina is used at the penalty of higher cost.

Uncalcined bauxite can also be used in the manufacture of 'high alumina' cement or, as it is sometimes termed, *ciment fondu.* Such cement is manufactured from a crushed mixture of bauxite and limestone. High alumina cement contains over 30 per cent Al_2O_3 as compared with the 4 to 8 per cent present in ordinary Portland cement. It is characterised by ultra-rapid hardening and good chemical and temperature resistance. Recently some well-publicised failures in concrete structural components made with high alumina cement have encouraged a closer degree of control over its use.

Potential Non-Bauxitic Sources of Alumina and Aluminium

Outside the Soviet Union the world aluminium industry is at present almost entirely dependent upon bauxite but considerable research into the possibility of using different raw materials is being carried out. These investigations fall into two groups. Firstly, interest has been expressed in alternative raw materials and methods for the production of alumina from which aluminium would be manufactured by the conventional electrolytic method. More recently, however, interest has centered upon the possibility of direct reduction of bauxite or non-bauxitic materials to aluminium. The economic and engineering problems entailed in a radical change from bauxite to non-bauxitic materials as ores of aluminium are discussed in a later section of this dossier.

A wide variety of naturally-occurring aluminous minerals and rocks might attain future importance as sources of alumina or aluminium if the major problems in industrial technology are resolved. Such materials include igneous rocks like anorthosite, nepheline syenite, and leucite-bearing lavas; metamorphic rocks rich in minerals like muscovite, andalusite, kyanite and sillimanite and, among sedimentary rocks, many aluminous clays and shales. Other potential sources include the mineral dawsonite, which is found in association with certain oil shales; the mineral alunite and aluminium phosphate 'rock' both of which arise as the result of the secondary alterations of other rocks and, finally, laterite which is a ferruginous surface weathering product closely related to bauxite.

During the Second World War, when some countries, notably Germany and Japan, were cut off from normal supplies of bauxite, some partially successful attempts were made to obtain alumina from clay and shale.

Only in the Soviet Union is there currently any extensive use of non-bauxitic raw material. Here, in addition to a number of conventional refineries, alumina is also produced from nepheline syenite as well as from nepheline concentrates left after the benefication of apatite ores. It is believed that some use is also made of alunite.

Outside the Soviet Union, effort directed towards the identification of non-bauxitic resources, as opposed to research into ways of processing them, has been largely confined to the United States. Considerable work in this direction was done by the US Bureau of Mines during the Second World War and more recently research has been carried out by the major aluminium companies. In 1972 it was announced that Alcoa intended to purchase considerable areas of land in Wyoming underlain by anorthosite; the company appears to regard this as a hedge against a future shortfall in imported bauxite supplies rather than a source of raw material for immediate exploitation. In March 1974 the Reynolds company announced that in the event of a serious interruption of bauxite supplies it anticipated that the company's existing plant in the USA could be adapted to produce alumina from domestic resources of laterite at the cost of a considerable reduction in alumina output. The possibility of using alunite ore from Utah was also under consideration in 1974.

The United Kingdom is not particularly well endowed with naturally occuring, potential alternatives to bauxite as a source of alumina. The two most interesting possible sources of indigenous material are the Harris and Laxford anorthosites in northwestern Scotland and the vast amounts of colliery waste shale and fireclay present in tips in several regions.

Alumina - Manufacture

In all countries the *Bayer Process* is the exclusive industrial-scale method by which metallurgical grade bauxite is converted to alumina. The production of alumina from non-bauxitic material by methods other than the Bayer process is only undertaken industrially in the Soviet Union although pilot-scale plants exist in a number of countries notably USA, Poland and France.

To produce one tonne of anhydrous alumina the Bayer process treats between two and three tonnes of bauxite according to type and grade and requires replacement of between 30 and 100 kg of caustic soda. Total energy requirements range from 2.5 Mwh to 6 Mwh per tonne of alumina according to the type of bauxite used, the method of processing and the size of the plant. In comparison the electrolytic production of aluminium from alumina requires as much as 13 to 18 Mwh of electrical energy per tonne of molten metal produced.

The following description of the Bayer process is based upon information provided by the British Aluminium Company but is typical of procedures adopted in alumina refineries throughout the world. Twelve stages in the process can be distinguished and the numbering of these is duplicated on the accompanying flow chart (Fig. 2).

1. *Preparation of Bauxite* Crushing, washing and screening of the bauxite is usually undertaken at the mine. In certain circumstances, however, this preliminary treatment may be carried out at the refinery. Ores of different compositions may also be blended prior to milling.

2. *Milling* Crushed ore lumps up to 20 mm in size are fed to grinding mills for further reduction. Milling takes place in the presence of sodium hydroxide liquor. Further liquor is then added to the mill slurry, the quantity being metered carefully in order to obtain optimum extraction in the autoclaves.

3. *Extraction in autoclaves* The mixture of ore and liquor is pumped into a series of steam heated autoclaves and retained there under pressure for times varying between a few minutes to eight hours.

The following chemical reactions take place:

$$Al_2O_3.3H_2O + \text{Impurities} + 2NaOH = 2NaAlO_2 + 4H_2O + \text{'Red Mud'}$$

$$Al_2O_3.H_2O + \text{Impurities} + 2NaOH = 2NaAlO_2 + 2H_2O + \text{'Red Mud'}$$

That is; the alumina content of the bauxite is taken into solution in the form of sodium aluminate. Bauxites of the trihydrate type (gibbsite) are more soluble in hot sodium hydroxide solutions than those of the monohydrate (boehmite) type and can be extracted effectively in a low strength solution at boiling point.

Monohydrate ores require temperatures between 180° C and 250° C. Digestion conditions have therefore to be adjusted to the ore, or ore mixture, being processed. At the British Aluminium Company refinery at Burntisland, Fife, which uses mainly Ghanaian ore, a low temperature extraction at 140° C first removes trihydrate and is followed by digestion at temperatures above 180° C to remove monohydrate.

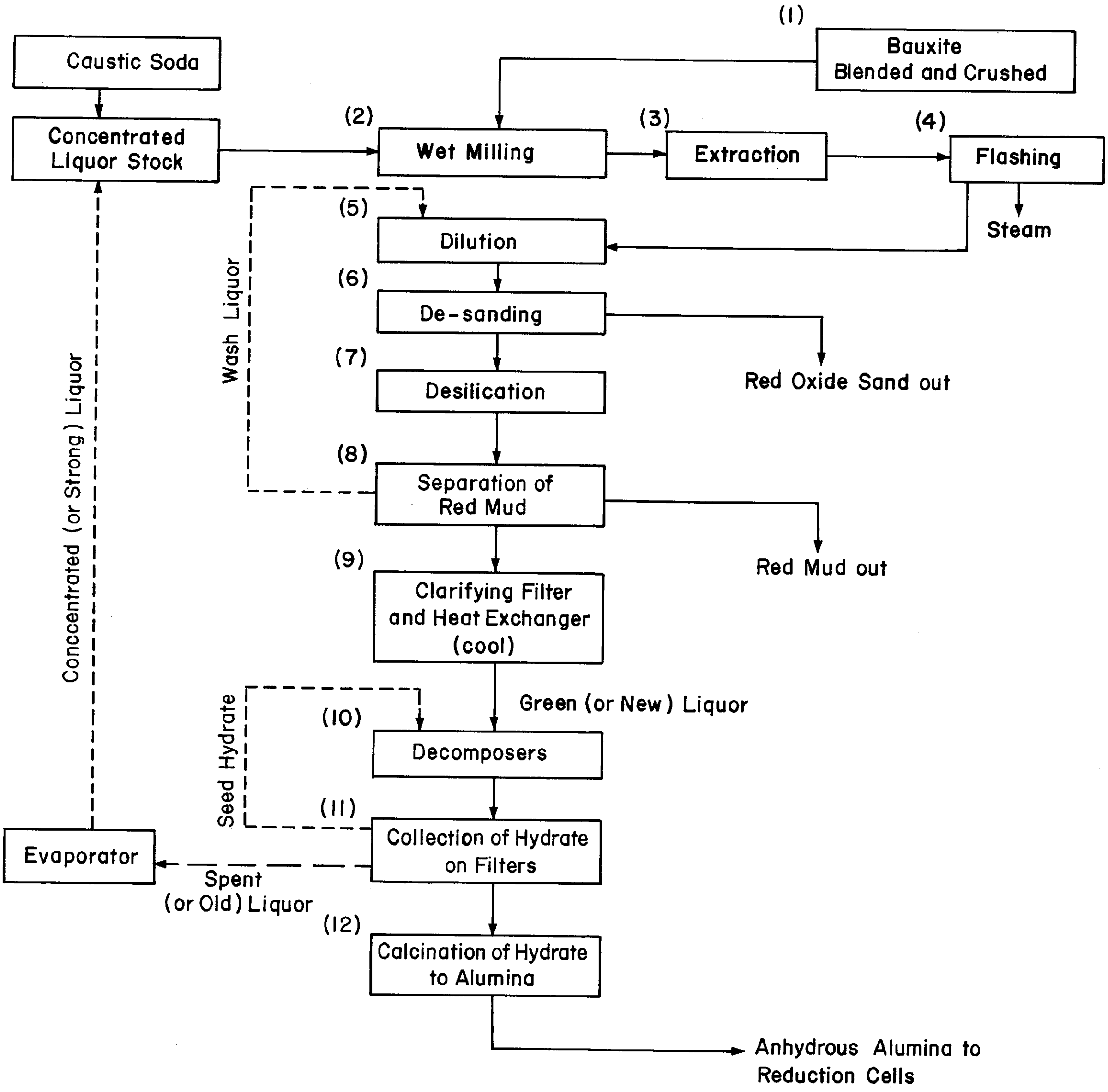

Fig 2 Simplified flow chart of the Bayer Process
(Courtesy: British Aluminium Company)

4. *'Flashing'* Following extraction the reacted autoclave slurry is blown under its own steam pressure into a series of 'flash vessels' within which steam is recovered for heating caustic liquor (stage 2). Residual heat is trapped through heat exchangers or condensers in wash water from elsewhere in the process.

5. *Dilution* In preparation for removal of suspended insoluble matter, the slurry from the 'flash vessels' is mixed with controlled amounts of heated wash water and also 'old liquor' from a later stage in the process. 'Old liquor' has the effect of preventing dissolved sodium aluminate ($NaAlO_2$) from precipitating as alumina hydrate between this stage and the heat exchangers.

6. *De-sanding* The diluted slurry from the 'flash' vessels is fed into a bowl and rake classifier. All coarse residues from the bauxite settle out at the base of this tank to be washed either for sale as a source of iron oxide or for disposal along with the red mud from Stage 8. The product is termed 'sand' or 'red oxide sand' and consists mainly of iron oxide (Fe_2O_3) with about 10 per cent of alumina and lesser quantities of silica and titanium oxides.

7. *Disilicification* After de-sanding the slurry is held at the boiling point to allow for the complete precipitation of 'digested silica', that is to say that part of the silica content of the bauxite that is reactive. This silica is removed in the form of insoluble sodium aluminium silicate.

8. *Separation of red mud residue* Insoluble residues are next removed from the diluted and stabilised slurry by passage through thickeners. The concentrated residual sludge, known as 'red mud', is discharged after several stages of counter-current wash thickening and filtration on rotary vacuum filters to recover as much caustic liquor as possible.

9. *Clarification of liquor* Liquor leaving the rotary filters is a saturated solution of sodium aluminate ($NaAlO_2$) carrying a few fine particles of red mud which are removed by passage through leaf filters. The solution, known as 'new' or 'green' liquor, is cooled in heat exchangers to reduce its stability and is then pumped to the decomposer vessels.

10. *Decomposition of sodium aluminate* The most important technical characteristic of the Bayer process is the means by which the clarified sodium aluminate liquor is induced to yield a dense crystalline precipitate of alumina trihydrate. The normal habit of precipitation from an unstable aluminate solution gives a gelatinous suspension which cannot be washed or handled on an industrial basis. This can be avoided by the addition of residual slurry or filter cake obtained from the previous decomposition charge. This contains a large number of crystalline particles of alumina trihydrate which act as nuclei for the growth of more crystalline alumina trihydrate formed by the decomposition of sodium aluminate in solution.

The decomposer charge of clarified liquor and 'seed' hydrate is stirred for up to three days while the hydrate crystals grow and the caustic soda is regenerated according to the following chemical reaction:

$$2NaAlO_2 + 4H_2O = Al_2O_3.3H_2O + 2NaOH$$

This is the reverse of the reaction causing solution of impure alumina trihydrate in Stage 3 above.

Decomposition is conducted in vessels of capacities between 150 - 3000 cubic metres each provided with an agitator and feed and draw-off pipe lines. After completion of the reaction the slurry is drawn off from the base of the vessel.

11. *Collection of hydrate* The slurry of crystals is filtered on disc filters, part of the product cake being mixed with new liquor to form the 'seed' of the next cycle of decomposition. The remainder of the cake is mixed again with filtrate to form a new slurry and pumped to the final filters. The precipitate retained by these filters is given a final washing and scraped on to a conveyor. The filtrate is partly evaporated in order to increase the soda concentration before being returned for further treatment of a new bauxite charge.

12. *Calcination of hydrate to alumina* All grades of anhydrous alumina are obtained by calcining the trihydrate made by the Bayer process. This is usually undertaken in rotary kilns at controlled temperatures between 1200 and 1500° C but also sometimes in fluidised bed calciners. For the production of industrial calcined aluminas, particularly careful control of hydrate particle size, structure and purity, as well as of the calcination cycle itself, are required.

Alumina - Properties and Uses

Alumina, Al_2O_3, is the only known stable oxide of aluminium and contains 52.9 per cent of that element by weight. However, it has a number of different crystalline and textural forms, each possessing distinct physical properties.

Corundum, the only naturally occurring form of unhydrated alumina, is occasionally found in certain aluminous igneous and metamorphic rocks. The mineral may occur in the form of barrel-shaped hexagonal crystals or in compact granular and lamellar masses. Ruby and sapphire are rare transparent crystalline varieties of corundum with distinctive colouration. Corundum, after diamond, is the hardest mineral known and is classified as 9 on the Moh scale.

Emery is the name given to naturally-occurring mixtures of corundum and iron oxides (Fe_2O_3 or Fe_3O_4) which, in some cases, are believed to result from the metamorphism of bauxites. The hardness of emery varies from 7 to near 9 depending upon the proportion of corundum present.

Crystallographically, corundum is the naturally occurring form of α alumina which can be made artifically by heating the hydrated aluminium oxides, boehmite, diaspore and gibbsite, and other aluminous compounds to around 1300° C. It can also be synthesised by solidification of molten alumina and, in certain circumstances, by heating aluminium in oxygen.

Commercial production of α alumina is undertaken by calcining the refined alumina trihydrate crystals produced in Bayer process refineries. This product is therefore often marketed under the name *calcined alumina* to distinguish it from uncalcined material sold as hydrated alumina (q v). References simply to 'alumina' in trade literature can usually be taken to imply calcined alumina produced in Bayer process refineries.

Calcined alumina is a non-hygroscopic powder with a melting point of 2050° C and a hardness of 9.

The main demand for calcined alumina is as feedstock for electrolytic aluminium smelters. For use in the production of primary aluminium it is desirable that the alumina should be free of titanium and phosphorus and should contain not more than 0.05 per cent $Si0_2$, 0.02 per cent Fe_20_3 and 0.5 per cent Na_20. Potash is also undesirable because of its effect on the carbon cathodes of the electrolytic cell.

Calcined alumina is in demand for a number of industrial uses other than the production of aluminium, often as a purer, but more expensive, substitute for calcined bauxite.

Calcined alumina may be used alone in a pure sintered form, or it may be mixed with up to 15 per cent $Si0_2$, Mg0 or Ca0 for many ceramic uses. Such ceramics are used, for example, in capacitor and resistor cores, spark plug bodies and grinding balls and rods.

In the abrasives industry fused material produced from calcined alumina has largely replaced natural corundum. Typical uses include grinding wheels, coated abrasives and polishing compounds.

Calcined alumina is consumed in the manufacture of refractories. The refractoriness of the product increases in proportion to the amount used. The presence of alumina also increased the load-bearing capacity, resistance to heat shock and spall resistance.

Some alumina is also used during the manufacture of glass, whiteware and certain catalysts.

Low soda alumina is a variety of calcined alumina in which a maximum Na_20 content of 0.1 per cent is specified. Low soda alumina possesses particularly good dielectric properties and can be used in high-grade electrical insulators in certain electronic applications.

Although ordinary calcined alumina finds many ceramic and refractory application, limitations upon its use for these purposes can be met by a denser form of α alumina marked under the name *tabular alumina.* Tabular alumina is produced from high purity calcined alumina. The manufacturing process alters the way of the crystals of α alumina are aggregated together. Ordinary calcined alumina is constituted of small crystals associated with relatively large voids and this porous structure is subject to a certain degree of shrinkage at elevated temperatures. By heating calcined alumina to 2000° C, which just falls short of its melting point, the pore structure of the calcined material is collapsed and a much denser inert material is obtained to which the name tabular alumina is given. The dense crystalline structure results in enhanced resistance to thermal shock which coupled with a high electrical resistance makes it suitable for specialised refractory and electrical applications.

When gibbsite and boehmite are heated to about 450° C they lose most of their chemically combined water and are converted to a crystallographically distinct form, sometimes loosely termed γ alumina although other crystal forms are in fact present. This special grade of alumina is very porous and has a high affinity for water vapour and other gases. The product is marketed under the name *activated alumina.* Its uses are similar to those already given for activated bauxite.

The commodity marketed under the name *hydrated alumina,* and appearing as such in the trade returns of some countries, is pure gibbsite, $Al_2O_3.3H_2O$, and represents the uncalcined product of the Bayer Process. Hydrated alum alumina is used as a source of the pure aluminous chemicals required by the paper, petroleum and paint industries among others.

Aluminium - Historical

The name *aluminium* is derived from *alumine,* a term suggested by L B G Morveau during the eighteenth century for the earthy base of *alum,* a naturally occurring double sulphate of potassium and aluminium long used in dyeing, tanning, papermaking and other applications. The word alumine subsequently became anglicised to *alumina.* A L Lavoisier in 1782 suggested that alumina was probably the oxide of a metal with an affinity for oxygen so strong that neither carbon nor any of the reducing agents then known was able to overcome it. Sir Humphry Davy, who had unsuccessfully attempted to isolate the metal by electrolysis, suggested that the name *alumium* should be applied to it, but later agreed that it might be changed to *aluminium.* Elsewhere in Europe the spelling aluminium was adopted and gradually this version came to be applied almost universally. The same spelling was also originally used in the United States of America but in 1925 *aluminum* was adopted by the American Chemical Society and has since been used in that country.

H C Oersted may have been the first to isolate an impure form of elementary aluminium in 1825 by heating aluminium chloride with potassium amalgam. A purer form of the metal was obtained two years later by Friedrich Wöhler who treated aluminium chloride with metallic potassium. Wöhler's method gave the metal only in a finely divided form. However, by 1845 he had succeeded in isolating a sufficient quantity to permit determination of the metal's melting point and some other properties. Nine years later Henri Sainte-Claire Delville obtained the metal by reducing aluminium chloride with sodium and using sodium aluminium chloride as a flux; in this process Delville was able to obtain aluminium in the form of small ingots with a purity of 97 per cent.

With financial backing from the government of Napoleon III, Delville established a large scale experimental plant for the production of aluminium at the Favel Chemical Works near Paris. Here he was able to produce various objects made from the metal and these were shown at the Paris Exhibition of 1855. Commercial production followed a year later.

In Britain aluminium was first made by Allan Dick and Richard Smith who used a modification of Deville's method in which the natural form of sodium aluminium fluoride, cryolite, was used in place of sodium aluminium chloride. Specimens produced by this method were exhibited by Michael Faraday at the Royal Institute in March 1855.

Commercial production of aluminium grew slowly during the latter half of the nineteenth century but output remained small and the product expensive. In 1891, for example, the Oldbury plant of the Aluminium Company Ltd was producing 230 kg of metal a day and this was selling at the then considerable price of 7s 3d (£0.36) per kg.

The development of the Castner process for the production of metallic sodium had led to a corresponding drop in the cost of producing aluminium by chemical means. Nonetheless investigations continued into the possibility of reducing costs even further.

During the first half of the nineteenth century abortive efforts had been made to produce aluminium by the electrolysis of fused alumina and aluminum salts. However, in 1854 both W Bunsen and Deville did succeed in producing the metal by the electrolysis of fused sodium aluminium chloride. In the following decades electrolytic methods began to hold more commercial promise with the introduction of cheap dynamo-generated electric power.

The major technical innovation that was needed to launch the modern aluminium industry finally came in 1886. Almost simultaneously the American C M Hall and the Frenchman P L T Héroult discovered that fused *cryolite,* a double fluoride of sodium and aluminium ($AlF_3.3NaF$) would act as a solvent for alumina which could then be decomposed electrolytically. Named the Hall-Héroult process after its originators, this technique rapidly became the exclusive industrial method for the mass production of aluminium.

Aluminium - Manufacture

Production of Primary Aluminium - General Description

At 1000° C molten cryolite will dissolve up to 15 per cent alumina by weight. The solvent action depends upon the near equality in size of oxygen and fluorine atoms resulting in a practical replacement of fluorine by oxygen within aluminium fluoride ions present in molten cryolite. The presence of sodium ions also contributes to the electrical conductivity of the melt.

Owing to the corrosive nature of molten cryolite both the anodes and cathode of the electrolytic cell have to be made of carbon or graphite. Essentially, therefore, the cell consists of a steel box with a carbon lining forming the cathode. The anodes must be made of exceptionally high purity carbon and are suspended in the molten electrolyte. With the passage of electricity molten aluminium forms in a pool on the cell floor whilst oxygen is liberated at the anodes with which it reacts to give carbon dioxide. There is, in consequence, a progressive consumption of the anodes which have to be replaced. The cathode linings are more durable and need replacement only at comparatively long intervals. The optimum current density is about 1 ampere/cm^2 and as aluminium has an equivalent weight of 9 it follows that, with an anode area of 2.9m^2, 2982 ampere-hours are theoretically required to produce 1 kg of metal every hour.

A modern aluminium smelter consists of long cell rooms each containing one or more rows or electrolytic cells. The individual cells are referred to as 'pots' and up to about 180 pots are electrically connected in series in a 'potline'. A high current, in the range 40 to 200 KA, with a potential drop of 4 to 5 volts for each cell, is passed through the potline. Each cell continuously produces molten aluminium - about one tonne per day in a 140 KA cell - which is tapped daily by suction.

An aluminium smelter has a high capital cost to set against its production capacity. In 1976 the British Aluminium Co estimated that the cost of a smelter was in the region of £700 to £1000 per annual tonne. Although formerly much smaller, the minimum size for new smelters is now in the region of 50,000 to 100,000 tonnes per annum. Some plants have capacities of as much as 400,000 tonnes per annum.

Cell Design

Each cell consists of a rigidly braced steel box lined with carbon in the base and sides (see Fig 3). The base is formed of pre-baked carbon blocks within which are embedded steel conductor bars. This acts as the cathode.

A rammed carbon mixture may be used for the side linings. This consists of partially graphitised anthracite bonded with a coal tar pitch. Thermally insulating refractory material such as packed alumina or firebricks can be provided beneath the carbon cathode and also between the carbon sides and the steel box to minimise thermal losses.

Construction techniques and materials have been progressively improved over the years to meet the more exacting requirements for larger cells. A cell (about 3 x 8m for a 140 kA cell) must be deep enough to hold the bath of molten electrolyte 10 to 25cm deep (density 2.1 g/cm^3) and beneath it a pool of molten aluminium 20-40cm deep (density 2.3 gm/cm^3).

Carbon anodes are suspended in the electrolyte and spaced about 5cm from the surface of the liquid metal. Two types of anode are commonly in use. One type consists of a number of pre-baked carbon blocks made from a mixture of petroleum coke and pitch, which are replaced in rotation after a life of about 18 days. The other type of anode is the continuous self-baking Soderberg electrode, of which there is only one per cell, consisting of a thin aluminium casing through which is fed periodically a mixture of ground coke aggregate and pitch binder. The mixture bakes as it gradually descends forming a hard dense column which is consumed at the bottom. With both types of anode current is led into the carbon through steel contact rods or studs which also act as supports. The steel studs are connected by aluminium hangers to the anode beam or bus bar. With the Soderberg type the steel studs have to be disconnected in turn and replaced at a higher level to bake into the soft paste at the top.

Early reduction cells utilised pre-baked anodes but the Soderberg electrode which proved to be cheaper to operate, was introduced in many smelters built in the 1950's. In the 1960's pre-baked anodes returned to favour because of better power performance and the greater ease with which the cells can be hooded to give efficient fume protection.

Most cells are now in the 60 to 150 kA range, although some 200 kA cells are operating. Large cells have presented a number of design problems but it is uncertain whether the upper limit on cell size has yet been reached.

The position of the anodes is an important consideration in cell design since the heavy currents set up strong magnetic fields. As a result the molten electrolyte and metal in the cell circulates within the magnetic fields during the passage of the electric current. Problems arising from circulation, which can lead to both inefficiency of metal production and to side wall erosion, tend to become more acute as the size or amperage of cells is increased.

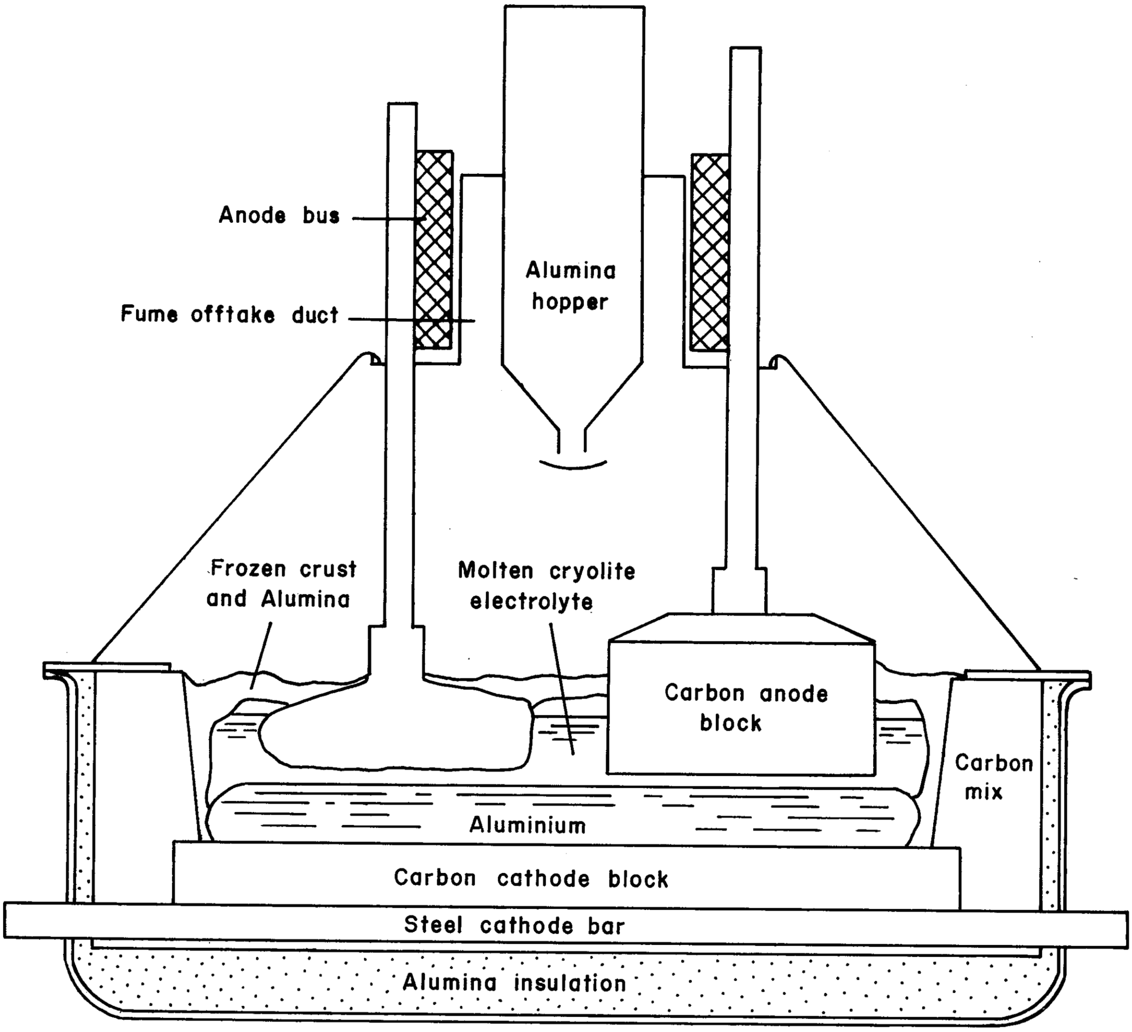

Fig 3 Cross section of reduction cell
(Courtesey: British Aluminium Company)

Cell Operation and Performance

As electrolysis proceeds a film of solidified electrolyte and alumina forms both along the cell sides and on top of the molten bath; this acts as a thermal blanket and has the beneficial effect of cutting down heat losses from the cell.

Whilst the electrolyte consists principally of molten cryolite, small proportions of various additives such as aluminium fluoride, calcium fluoride, magnesium fluoride, lithium cryolite and sodium chloride are often used. These have the effect of lowering the bath temperature and thereby increasing the current efficiency. However, temperature reduction and dilution of the cryolite also reduce the solubility of alumina. Calcium fluoride also increases the density of the electrolyte and, in consequence, the density difference between the electrolyte and the metal layer is reduced leading to greater instability of the latter. The use of additives is therefore a matter of judgment and experience in operation, but generally their total does not exceed 12 per cent. A typical electrolyte might consist of:

4 - 6 per cent excess AlF_3
4 - 6 per cent CaF_2
2 - 6 per cent Al_2O_3
82 - 90 per cent cryolite

and have a melting point in the range 960 to 985° C.

As the alumina is consumed the cell has to be fed with fresh material. At intervals of perhaps two to four hours a portion of the crust is broken into the bath to dissolve the solid alumina it contains and a standard weight of alumina is added to form a new crust. Normally the alumina concentration is kept at about 3½ to 4 per cent. Constant monitoring of the cells is necessary to ensure that the concentration of alumina does not drop too low. Immediately prior to a feed the concentration may drop to as low as 2½ per cent. Below this a polarisation or 'anode effect', due to the build up of a film of carbon tetrafluoride gas on the anodes, may cause the normal operating cell voltage of 4 to 5 volts to increase rapidly to as much as 40 to 60 volts. A single operator can detect anode effects in individual cells on a central console and can react by feeding alumina and stirring the electrolyte. In some smelters this monitoring can be carried out automatically with a computer-based control system.

Primary Smelters - Material and Energy Requirements

A large expenditure of energy is required to reduce alumina to aluminium. About 13000 to 18000 kWh of electric power are consumed per tonne of aluminium produced. In practice it is found that about 2.0 kW of installed generating capacity is required for each tonne per year of aluminium production capacity. For the production of one tonne of metal by the Hall-Héroult process raw material requirements are estimated to be 1.9 tonnes alumina, 0.5 tonne carbon electrode, 0.023 tonne cryolite and 0.029 tonne aluminium fluoride.

Super-Purity Aluminium

Metal produced by the conventional Hall-Héroult electrolytic process is normally 99.00 to 99.90 per cent pure aluminium. A specialised electrolytic process is used to refine smelter metal to super-purity grades averaging 99.99 per cent aluminium. Refining depends upon the use of an electrolyte possessing a specific gravity between that of molten aluminium (2.3) and that of a molten alloy of aluminium with copper or some other metal (2.8 to 3.15). The bath consists of three layers; the lowermost is the molten alloy which constitutes the anode. Floating on this is the molten electrolyte, the composition of which varies from refinery to refinery but may typically possess a specific gravity of 2.7 and be composed of a mixture of cryolite and fluorides of barium and aluminium. Above the electrolyte an accumulating layer of molten high purity metal serves as the cathode. The cell operates at a temperature of around 700° to 800° C depending upon the electrolyte used, 6 to 7 volts and a current of 20 to 40 kA. Carbon is used as the base of the cell to introduce the current into the anode. Magnesite is used as a cell lining. When the three layer cell is in operation pure aluminium is periodically ladled from the cathode layer. As the aluminium content of the anode alloy diminishes it is replenished by adding unrefined aluminium through a forewell.

Secondary Aluminium

This term is applied to metal recovered by the re-melting of scrap, fabricating waste, skimmings or dross and is therefore distinguished from primary or 'new' metal produced from alumina in electrolytic smelters.

Scrap is melted in furnaces of standard design. Dross and skimmings are first treated to increase the proportion of metals and then melted in rotary furnaces below a cover of molten salt. As a rule aluminium clippings are melted in induction furnaces. Hot metal from rotary salt and induction furnaces is usually fed directly into larger hearth furnaces where all the metal is treated by chloride fluxes at a temperature of about 750° C and then cast into foundry ingots. Primary aluminium may be incorporated into the secondary metal to bring it to the desired composition.

Aluminium and alloys – properties and uses

General

The versatile use of aluminium in many applications is based upon an unique combination of desirable physical and chemical properties. The element is low in the periodic table (Atomic Number 13; Atomic Weight 26.98) and possesses a specific gravity of 2.7, about one third that of steel. Its great ductility permits it to be rolled to very thin gauges or extruded into many different shapes. Aluminium foil for example, is a widely used product which exploits the ductility of the metal to the full.

As aluminium possesses a considerably lower melting point than steel, the production of castings and the handling of molten metal are relatively uncomplicated. The pure metal has a melting point of 659° although that of some aluminium alloys may be as low as 550° C.

The thermal conductivity of aluminium is less than that of copper but greater than that of cast iron, wrought iron or steel and it is suitable for the manufacture of cooking utensils.

Aluminium is a good electrical conductor. A copper bar will have the same resistance to an electric current as an aluminium bar of 1.6 times its cross-sectional area, but the weight of the aluminium conductor will be only half that of the copper. Round bars of aluminium also offer an advantage over copper conductors in showing less 'corona loss'.

Although aluminium is a chemically reactive element and a strong reducing agent, it is far more resistant to corrosion than most other industrial metals. A freshly exposed surface of aluminium metal, either solid or molten, immediately oxidises upon exposure to the air or other oxidising agent and the thin film of aluminium oxide so formed prevents further electron transfer from the metal and hence stops the process of corrosion. The natural oxide layer can be thickened by the process of anodising or anodic oxidation which will be described at a later stage.

Both the metal and its salts are non-toxic and can be ingested without harm. Through surface treatment processes of various kinds aluminium can be used to give a wide variety of decorative effects and in this respect it is superior to other metals.

Aluminium Alloys

The properties of super-purity aluminium (Al 99.98 per cent and over), high-purity aluminium (Al 99.80 per cent and over) and pure aluminium (Al 99.00 to 99.80 per cent) can, for specific purposes, be improved or modified by alloying with other elements.

Aluminium alloys can be classified in various ways. One of the most important distinctions is that between *non-heat treatable alloys* and *heat treatable alloys.*

The non-heat treatable alloys obtain their strength as a result of being subjected to cold working processes known as work or strain hardening and which include stretching, drawing or rolling. Owing to the progressive loss of ductility during cold working it may be necessary to re-soften the metal by annealing at various stages during the cold working sequence.

The term 'heat treatment' used in connection with heat treatable alloys refers to a strengthening process and is therefore distinct from the annealing process that may be required during the cold working of non-heat treatable alloys.

The strengthening process normally consists of:-

1. Solution treatment at about 500°C
2. Quenching
3. Ageing either a) spontaneously at room temperature *(natural ageing)*
   or b) by heating at temperatures up to 200°C *(artificial ageing)*

Solution treatment followed by quenching and natural ageing is referred to as *single heat treatment*. The term *full* or *double heat treatment* is applied when artificial ageing is involved. Age-hardening of the metal involves a decrease in ductility and an increase in brittleness.

Solution treatment is usually carried out in a salt bath containing a fused mixture of sodium nitrite and sodium or potassium nitrate. The temperature of the bath is held between 490° and 535°C for a length of time which depends upon the size of material being heated. The same effect that is gained by a salt bath may also be obtained by heating the alloy in a forced circulatory furnace. Rapid quenching is achieved by building quenching tanks immediately alongside the salt bath or furnace. The quenching medium is generally oil or water but quenching can also be carried out in a stream of compressed air. Any working that is required on naturally ageing alloys must be done within about two hours of quenching, although age-hardening can be delayed by refrigeration.

The other major basis for classifying aluminium alloys is the distinction between those used for *casting* and the *wrought alloys* which are suitable for mechanical working. Both groups contain heat treatable and non-heat treatable types. Casting alloys may contain up to 15 per cent of alloying elements but wrought alloys always contain less than 6 per cent. One of the main uses of secondary metal is in the manufacture of casting alloys.

A summary of the various categories of alloy and their usage is given in Table 3. Proprietary names are not given; each alloy may be produced by several companies under different trade names. It should be noticed that grades of aluminium from 'pure' upwards can be classified with non-heat treatable wrought alloys.

Casting

The casting alloys most widely used contain silicon or copper as alloying elements. Silicon alloys have excellent fluidity and good casting properties. They have a good resistance to corrosion but are difficult to machine. Owing to their low coefficient of expansion they are preferred for many components of internal combustion engines.

Copper and magnesium alloys are heat treatable and are preferred for use in sand castings and for products in which high strength and ductility are required. They have good machining qualities and finishing characteristics. The magnesium alloys are particularly resistant to corrosion by salt water.

Casting of aluminium alloys is carried out in foundries which may be controlled by the major producers of primary aluminium or by smaller independent firms. A great deal of secondary aluminium is used in the production of castings.

Pure aluminium contracts in volume by about 7 per cent on solidification and in order to avoid the development of cavities, it is desirable that molten metal should be fed into the casting during solidification. This is accomplished by the provision of 'risers', vertical columns of metal attached to the casting from which more metal can be supplied under hydrostatic head to make up for the shrinkage as the metal in the centre of the casting gradually solidifies. Because of its sharp freezing point it is difficult to cast pure aluminium successfully except in large ingots where the rate and manner of solidification can be controlled. Smaller cast products are usually made from alloys in which there is a longer solidification range.

Table 3 Classification and Uses of Aluminium Alloys

GROUP A NON-HEAT TREATABLE WROUGHT ALLOYS

Alloy Composition	*Uses*
Al 99.99 per cent	The highest purity aluminium with applications in the chemical industry, foils for electrolytic capacitators.
Al 99.0 to 99.8 per cent	Cooking utensils, containers, chemical apparatus, electrical equipment, foils.
Al-Mn	Roofing, containers, packaging.
Al-Mg (Mn)	Work-hardening structural material, containers, apparatus, ship building, rail and road vehicles, architecture, materials handling equipment.
Al-CuPbBi	Free machining alloys.

GROUP B HEAT TREATABLE WROUGHT ALLOYS

Alloy Composition	*Uses*
Al-MgSi	Decorative anodising, ship building, road and rail vehicles, structural engineering, electrical applications, the main architectural alloy, electrical conductors.
Al-CuMgZn	Very high strength structural materials.
Al-CuMg	High strength structural materials.
Al-MgZn	Medium strength structural materials.

GROUP C NON-HEAT TREATABLE CASTING ALLOYS

Alloy Composition	*Uses*
Al-Si	Medium strength with good casting properties.
Al-Mg	Moderately good castability, easily worked and suitable for anodising. Resistant to sea water.

GROUP D HEAT TREATABLE CASTING ALLOYS

Alloy Composition	*Uses*
Al-SiMg	Alloys used for components that are difficult to produce and require high strength.
Al-CuTi	Alloys of the highest strength suitable for components subjected to impact or repeated stress. Poor chemical resistance.
Al-ZnMg	Naturally ageing alloys of medium strength, specially suitable for sand casting and decorative anodising.

Casting operations using sand moulds are suitable for small series castings of all types, especially for difficult and complicated pieces with intricate hollow shapes. The main disadvantages of sand casting is that each mould is one-off and has to be destroyed when the casting is removed.

Although all castings made in re-usable metal moulds tend to be described as *die-castings*, it is preferable to refer to those made by pouring molten metal under gravity into permanent moulds by some such term as chill-casting. This is the best casting process for large numbers of components. Permanent mould castings also show good and consistent mechanical properties and constant dimensional accuracy.

True die-casting or *pressure die-casting*, as it is frequently termed, is carried out using charges of molten metal subjected to dies mounted on a hydraulically operated press. The dies for this process are made from heat-treated alloy steel to very close limits. Pressure die-castings demand only minimal final machining.

Mechanical Working

Wrought alloys used without heat treatment mainly include those containing manganese and magnesium. A greater variety of metals is used in heat-treatable alloys and includes copper, manganese, magnesium, silicon and zinc. Those containing copper, magnesium and manganese have particularly good mechanical properties and are in common use for structural purposes. Aluminium-magnesium-silicon alloys have slightly poorer mechanical properties than the copper alloys but are more easily workable and are more resistant to corrosion. The magnesium-zinc alloys also have particularly good mechanical properties.

Much of the world output of primary aluminium and aluminium alloys is subjected to various mechanical working processes. Such processes are somewhat arbitrarily divided into those which produce *semi-fabricated* forms and other, more specialised, techniques for the production of fully-fabricated metal components. In general, semi-fabrication implies mechanical working undertaken by the primary smelting companies themselves and many include the manufacture of plate, sheet, foil, strip, circles and slugs by rolling; bars, rods and sections by extrusion; wire, rod and tubes by drawing; forgings and stampings; powder and paste. Semi-fabricated metal is then sold to specialist manufactures who treat it according to their own needs by techniques such as spinning, stamping, stretching, impact intrusion, bending and by using various joining methods and surface treatments.

Rolling is usually undertaken, at the semi-fabricating stage, on rectangular slabs produced by a continuous casting process. Such slabs, subsequent to cooling, have first to be scalped to remove the casting skin and then annealed for six to eight hours depending upon the alloy in use. The pre-heated slabs are then hot rolled to plate of thickness between 6 and 10 mm, cooled and either cut to length or further rolled fown to sheet or cold rolled to strip of 0.2 to 3 mm thickness. In addition the material may be passed through several smaller rolls in order to flatten it. Since the metal will become progressively more work hardened during cold rolling it may be necessary to apply one or more intermediate anneals between passes. This will depend upon the alloy being used and the desired final thickness.

Foil rolling is a process additional to the normal rolling technique. The starting material for foil production is rolled strip of 0.6 to 0.8 mm thickness. By repetitive passes through the same mill, or through a number of mills arranged in series, foil thicknesses in the range 0.009 to 0.15 mm can be achieved. Still thinner foils, down to about 0.004 mm thick, may be produced by rolling two thicknesses of coarse foil placed one on top of the other. As a consequence of this treatment surfaces in contact with the rollers are bright while the inner surfaces in contact with each other are matt.

Metallic aluminium posesses good plastic formability and therefore the shapes of profiles that can be produced by aluminium *extrusion* is very wide. For the extrusion process a cylindrical continuously cast billet is pre-heated to a temperature between 400 and 500°C according to alloy. It is then placed in the heated container of the extrusion press and forced under pressure through a die with the required profile.

For the production of *wire* cast rod is drawn through multi-die drawing machines. Electrical conductivity may be improved by subsequent heat treatment which alters the character of the silicon content. In contrast excessive cold work may impair conductivity.

Aluminium *forgings* are produced by the die forging process. The forging blank or billet may be either cast or extruded. Forging is done in two stages. In the first the blank is kneaded in every direction using either a power hammer or a hydraulic press so as to achieve an isotropic crystalline structure. The 'dummy' thereby produced is re-heated prior to the second stage of forming which is performed by hammering or pressing in a die of appropriate shape. Two or three successive operations may be required to form the forging into the final shape required. The finished forging has a dense, fine-grained, wrought structure.

Aluminium can be *shaped* by both hot and cold forming processes. The degree of formability depends on the alloy and its condition. With heat treatable materials it is necessary to carry out forming directly after solution treatment and quenching. As increasing amounts of cold working cause hardening, further stages of annealing may be required.

The forming processes used most frequently for aluminium are bending, pressing, press brake forming, hammering, spinning, stretch forming, deep drawing and impact extrusion.

Because aluminium offers a much lower resistance to *machining* than steel, higher cutting speeds and lower machining times are achieved. Moreover, the high thermal conductivity of aluminium relative to that of steel permits rapid removal of the heat during cutting. The lower hardness of aluminium demands a lower cutting force than that required for steel, so that the cutting efficiency of machine tools is higher for a given amount of electrical power. The ideal alloys for machining purposes are those which form small chips rather than long shavings which may be difficult to remove in the course of fast production.

Surface Treatment Methods

The process of *anodising* is utilised to thicken and therefore reinforce the natural oxide film which forms on the metal surface. The component is suspended as the anode in an electrolyte, usually sulphuric acid but sometimes oxalic or chromic acids. The thickness of the additional oxide film produced depends upon various factors but, for external architectural use for example, a film around 25 microns thick is added. This is sufficient to avoid an unsightly pitted appearance resulting from the irregular growth of the natural oxide film which develops after a time on normal mill-finish aluminium subjected to the weather.

For many internal applications, anodising is complemented by the process of *sealing*. This has the effect of rendering the oxide film completely impermeable and non-absorptive. The film on the surface of the anodised metal is shown microscopically to be composed of flat tabular crystals of aluminium oxide arranged at right angles to the metallic surface. The voids, or 'pores', between the crystals can be sealed simply by boiling in water or by treatment in superheated steam. Such treatment results in hydration, swelling and fusion of the distal ends of the oxide crystals.

Anodising, followed by sealing, makes possible a number of surface treatments which, in general, cannot be applied to other metals. Perhaps the most familiar is the production of anodised coloured metal ware. If a dye is added prior to sealing it will be held tenaciously on the metal surface following treatment. An extension of the technique of colouring anodised surfaces allow the use of the screen printing methods whereby dye is introduced only into that part of the anodised metal not masked by the screen. In this way lettering, for example, can be firmly imprinted on the metal surface. The pores of the anodised surface can also act as a key for paint. *Hard colour anodising* is a refinement of the normal colouring process which gives light-fast shades ranging from pale bronze to black. In addition, there are a series of self-colouring alloys in which certain alloying elements produce the desired colour during treatment in the anodising electrolyte; again such tints are light-fast and hence weather resistant.

Very reflective metal surfaces, competitive with chrome plate, can be produced by anodising aluminium alloyed with one per cent of magnesium. In order to retain maximum reflectivity the amount of cold working applied to the metal surface must be limited.

A special type of surface treatment is the coating of aluminium sheet with plastics for which special plastic foils are mainly used. Coated or lined sheets can be worked by all the normal manufacturing processes such as cutting, drilling, folding or deep drawing without damage to the surface.

Aluminium can be electroplated on various other metals but the technique has not been widely applied in recent years.

Electrolytic brightening of aluminium is achieved by anodic treatment in an electrolyte under conditions so controlled that the anodic oxide is dissolved by the electrolyte almost as quickly as it is formed thus removing any unevenness of the uniformly bright surface. In this fashion the total reflectivity of the pure aluminium can be increased from about 72 per cent to 85 per cent. The electrolyte used may consist of a dilute solution of sodium and trisodium phosphate. After brightening the work is rinsed and anodised in an electrolyte of sodium bisulphate to give it a transparent protective film. Electrolytically brightened super-purity aluminium finds an increasing use in reflectors.

Various mechanical methods of surface treatment are also widely applied to aluminium. Such methods include grinding and polishing, burnishing and satin-finishing by conventional methods, and the production of embossed or patterned sheets by patterned rollers.

Joining Processes

Joining of aluminium components by conventional welding or soldering methods is difficult owing to the protective effect of the surface oxide film. However, specialised techniques to remove this film have been developed and have some limited application. More recently adhesive bonding processes have come to be used widely.

Riveting is used particularly to join highly stressed aluminium components. Aluminium rivets can be driven cold.

Specialised Uses of Aluminium

In addition to its main uses in the construction, architectural, transport, domestic, engineering and electrical fields, aluminium also finds use in a number of specialised miscellaneous applications.

Aluminium is a component of certain iron alloys used for a number of electrical purposes. Iron-nickel alloys containing some aluminium are used for permanent magnets. Nitrided steels are produced by heating steel containing about one per cent aluminium in ammonia. The aluminium in the outer portion of the steel forms a hard nitride, the depth of which depends upon the length of time the alloy is immersed in ammonia. The high surface hardness of nitrided steels provides improved water resistance and fatigue strength.

Steels coated with aluminium are used particularly in marine or industrial applications where resistance to corrosion is essential.

The addition of aluminium to magnesium, up to a maximum of around 11 per cent, results in improved hardness and strength.

About four per cent aluminium is added to zinc to increase the hardness of zinc die casting alloys and reduce the rate of corrosion of the die-casting equipment by the alloy. Zinc alloys used in sand castings frequently also contain aluminium. Brass containing about two per cent aluminium is employed in marine condenser tubes.

Anhydrous aluminium chloride is produced as vapour by passing dry chlorine gas through a charge of molten aluminium and then collected in air-cooled iron condensers. The major use for anhydrous aluminium chloride is as a catalyst in the manufacture of ethyl benzene, dyestuffs, detergent alkylates, ethyl chloride and pharmaceuticals. To a lesser extent it is utilised in the manufacture of titanium dioxide, hydrocarbon resins and in oil refining.

Powdered aluminium is consumed in the manufacture of explosives and pyrotechnics. Aluminium granules are added to ammonium nitrate to form a slurry containing 20 to 30 per cent aluminium. The aluminium functions as a sensitiser which enables the ammonium nitrate to explode when ignited by a fuse. This slurry replaces dynamite in certain mining and quarrying applications and its particular advantages are safe handling and the ability to work under water.

Prices

Because the large quantities used by the vertically-integrated aluminium industry are usually obtained from affiliated companies or are purchased under long-term contracts, it is not generally possible to quote accurate prices for metal-grade bauxite and alumina.

In recent years difficulties have arisen between multi-national aluminium companies and certain developing countries which are among the main producers of bauxite. The host countries dissatisfaction rested on the fact that tax revenue from bauxite mining was based only upon the tonnage of bauxite shipped or refined locally into alumina and bore no relation to the selling prices of aluminium ingot produced by the company. The companies argued that only a small part of the final cost of the metal is related to bauxite mining and shipping costs, and that the greatest proportion of the value added lies in smelting, the rapid rise in the costs of which is beyond the direct control of the companies. Despite this the Jamaican government in 1974 introduced a levy on bauxite and alumina shipped from the island the level of which was, in part, determined by the price of primary metal ingot published regularly in *American Metal Market.* Other bauxite-producing nations have subsequently followed Jamaica's lead with schemes of their own.

It is possible to estimate a notional price for metal-grade bauxite imports based upon mining and transport costs and tax payments, which can be used as a basis for comparing bauxite prices over a period of time. Such figures cannot be provided for the United Kingdom which does not import bauxite for metal production. However, in 1976 H.M. Treasury provided figures applicable to Jamaican bauxite imported into the USA. In terms of 1973 constant dollars the price of Jamaican bauxite was estimated at $18.1 per tonne – before the new Jamaican legislation of 1974. In 1975, after introduction of the producer's levy, this had risen to $24.4 per tonne. On the assumption that the Jamaican tax structure remains unaltered it was estimated that the 1985 figure would be $21.3 per tonne, again in constant 1973 dollars.

In contrast to metal-grade bauxite and alumina, market prices are available for certain grades of calcined material. The journal *Industrial Minerals* of London publishes monthly figures for four categories. (Table 4).

The particularly steep rise in price of refractory grade bauxite may be attributable to the long-standing Guyanan monopoly of this commodity. The recent increase of exports from China may ultimately affect world prices.

The trend in world prices of primary aluminium can be found in the published international selling price of Alcan Aluminum Ltd for exports from Canada since Alcan is the largest trader in primary ingot in the greatest number of countries. Another useful index is the published United States domestic price of ingot as the market in that country is the largest in the world. Discounts may be obtained depending upon the prevailing supply and demand situation. In some countries domestic taxes may be added.

In the United Kingdom prices for primary aluminium ingot are normally sensitive to variations in the basic North American levels but recently the effects of price restraint and exchange rate variations have complicated this relationship. In April 1978 the ingot price in the United Kingdom was £680 per tonne. In the earlier years of the decade, during a period of over-supply, the price had remained fairly constant in the £220 to £250 range but from early 1974 onwards it steadily moved up to its current (1978) level. Historic fluctuations in the price of aluminium metal are illustrated on the front cover of this dossier.

Table 4 Prices of Calcined Bauxite and Alumina 1972 - 1977 (a)

Pounds sterling

	1972	1973	1974	1975	1976	1977
Alumina, calcined, 98½ to 99½% Al_2O_3. bags included, 20 tonne lots delivered UK	n.a.	64.9	64.9	93.1	117.6-122.5	160-165
Alumina, calcined, medium soda content, 50 tonne lots	78.5	80.4	80.4	102.9-107.8	126.4-137.2	175-180
Bauxite, abrasive grade, min. 86% Al_2O_3. c.i.f. (per tonne)	19.2	19.6-21.6	23.6-25.5	35.3-37.2	41.2-48.0	160-165
Bauxite, refractory grade, min. 86% Al_2O_3. c.i.f. (per tonne)	25.4	25.4	39.2	49.0	60.8	82

n.a. No comparable figure available

(a) Prices are approximate and, for figures prior to 1977, a recalculation from long tons to metric tonnes is employed. Prices are those prevailing in September of the year specified.

Source: Industrial Minerals

British and foreign prices for primary aluminium ingot are published twice-weekly in *Metal Bulletin* of London. This periodical also publishes regular details of the price of foundry ingots, secondary aluminium and certain semi-fabricated forms.

Production

Bauxite

Bauxite is no longer mined in the United Kingdom. The brown aluminous iron ores of Antrim were worked in the mid-nineteenth century but bauxite production was not recorded before 1873. From 1877 to 1934, when output ceased, some 414,000 tonnes was produced. Mining operations were resumed in Northern Ireland as a war measure and a further 301,500 tonnes were produced between 1941 and 1945. The annual production of bauxite in Northern Ireland is summarised in Table 5.

Table 5 United Kingdom (Northern Ireland) : Production of Bauxite 1877 - 1945

Year	*Tonnes*	*Year*	*Tonnes*	*Year*	*Tonnes*	*Year*	*Tonnes*
1877	2,807	1894	8,108	1911	6,103	1929	2,359
1878	3,481	1895	10,575	1912	5,883	1930	2,070
1879	3,716	1896	7,765	1913	6,152		
1880	3,526	1897	13,541	1914	8,419	1931	3,394
		1898	12,601	1915	11,911	1932	1,497
1881	7,856	1899	8,138	1916	10,495	1933	709
1882	8,524	1900	5,872	1917	14,960	1934	58
1883	13,694			1918	9,743		
1884	8,697	1901	10,355	1919	9,369	1935-1940	–
1885	9,175	1902	9,192	1920			
1886	8,395	1903	6,226			1941	13,090
1887	4,236	1904	8,804	1921	2,305	1942	97,260
1888	9,821	1905	7,417	1922	5,953	1943	109,656
1889	9,297	1906	6,761	1923	3,504	1944	44,502
1890	11,712	1907	7,658	1924	5,241	1945	36,981
		1908	11,904	1925	5,121		
1891	10,936	1909	9,652	1926			
1892	7,440	1910	3,853	1927			
1893	8,880			1928			

Sources: 1877 - 1881 Mineral Statistics, Memoirs of the Geological Survey.
1882 - 1896 Mineral Statistics, Home Office.
1897 - 1919 Mines and Quarries; General Report with Statistics, Home Office.
1920 Mines and Quarries; General Report with Statistics, Mines Department, Board of Trade.
1921 Annual Report of the Secretary of Mines, Mines Dept. Board of Trade.
1922 - 1945 Northern Ireland Ministry of Commerce.

Alumina

The production of alumina in the United Kingdom began in 1894 at a plant at Larne in Northern Ireland which at first used local bauxite. Other alumina plants were later built at Burntisland, Fife (1917) and Newport, Gwent (1939) using imported ores but the Newport plant closed in the early seventies and at present Burntisland is the only plant producing alumina in the UK. There are no official production statistics but figures derived from a number of sources are given in Table 6.

Table 6 United Kingdom – Production of Alumina 1966 - 1976

Thousand tonnes

Year	*Production*	*Year*	*Production*	*Year*	*Production*
1966	119.0	1970	107.1	1974	94.7
1967	135.3	1971	99.1	1975	82.5
1968	117.4	1972	116.1	1976	96.0
1969	105.7	1973	96.9		

Source: Institute of Geological Sciences.

Aluminium

Aluminium metal was first produced commercially in the United Kingdom in 1896 at the British Aluminium Co plant at Foyers in Invernesshire and later from two other smelters in the same area. Initially production was 200 tonnes a year but by 1904 had risen to about 1,000 tonnes a year. With increased demand in the First World War United Kingdom production rose to nearly 10,000 tonnes per year and afterwards continued to rise steadily to over 20,000 tonnes in 1930. The Second World War again stimulated demand and in 1943 over 56,000 tonnes were produced. Output fell back to around 20,000 to 25,000 tonnes on the post-war period but rose again sharply in the seventies when large new smelters at Holyhead, Lynemouth and Invergordon came on stream. The annual production of both primary and secondary metal is shown in Table 7.

Table 7 United Kingdom : Production of Aluminium Metal 1950 - 1976

Thousand Tonnes

Year	Primary (1)	Secondary (2)	Primary metal added to secondary (3)	Total (1+2-3)	Year	Primary (1)	Secondary (2)	Primary metal added to secondary (3)	Total (1+2-3)
1950	30.0	81.2	n.a.	n.a.	1965	36.2	188.8	10.8	214.2
1951	28.1	72.5	n.a.	n.a.	1966	37.1	198.3	14.7	220.7
1952	28.5	94.8	20.5	102.8	1967	39.0	191.2	12.6	217.6
1953	31.4	91.8	9.6	113.2	1968	38.2	200.4	12.4	226.2
1954	32.1	105.0	19.6	117.5	1969	33.8	227.1	17.5	243.4
1955	24.8	129.1	32.0	121.9	1970	39.6	214.4	13.0	241.0
1956	28.0	119.5	21.8	125.7					
1957	29.9	110.2	11.4	128.7	1971	119.0	189.1	7.5	300.6
1958	26.8	111.5	10.9	127.4	1972	171.4	197.4	12.6	356.2
1959	24.9	123.3	14.3	133.9	1973	251.6	209.6	20.3	440.9
1960	29.4	131.9	20.5	140.8	1974	293.1	206.6	17.7	482.0
					1975	308.3	176.2	9.0	475.0
1961	32.8	133.2	14.1	151.9	1976	334.5	205.8	18.0	522.3
1962	34.6	143.5	11.7	166.4					
1963	31.1	163.7	14.7	180.1					
1964	32.2	186.1	14.4	203.9					

n.a. Not available

Source: World Bureau of Metal Statistics

The production of secondary metal is based largely on recovery from domestic waste, arisings from the fabrication of aluminium and imported scrap, details of which are shown in Table 8.

It should be noted that production of secondary metal by smelters given in Table 7 does not tally with despatches of scrap to secondary smelters indicated by Table 8. This is attributable to some process loss in the secondary smelters and variations in stock held by them.

Table 8 United Kingdom: Aluminium Scrap Arisings, Imports and Consumption 1965 - 1976 *(a)*

Thousand Tonnes

Year	Scrap Arisings	Imports Waste & Scrap	Consumption of scrap		
			By secondary smelters	By other uses	Total
1965	213.3	23.9	206.8	11.5	218.3
1966	221.5	16.2	211.7	15.9	227.6
1967	221.2	14.1	205.8	14.3	220.1
1968	243.8	13.0	227.7	16.1	243.8
1969	261.0	13.2	244.5	15.1	256.6
1970	249.7	15.5	232.4	19.5	251.9
1971	240.2	11.9	221.2	24.5	245.7
1972	252.4	13.9	215.5	31.0	246.5
1973	253.0	20.7	225.7	23.2	248.9
1974	247.1	22.2	224.2	26.7	250.9
1975	227.7	13.7	199.2	31.2	230.5
1976	249.4	16.7	213.3	32.5	245.8

(a) All figures are gross weight of aluminium metal and alloys.

Source: World Bureau of Metal Statistics.

Consumption

Bauxite

The United Kingdom has been wholly dependent on imported bauxite since 1945 so that apparent consumption can be approximately equated to imports less the relatively small amounts of re-exported material (Table 9).

Table 9 United Kingdom : Apparent Consumption of Bauxite 1965 - 1976

Thousand tonnes

Year	Imports	Exports	Apparent Consumption	Year	Imports	Exports	Apparent Consumption	Year	Imports	Exports	Apparent Consumption
1965	553.2	0.0	553.2	1970	528.3	0.2	528.1	1975	436.5	1.4	435.1
1966	567.6	0.0	567.6	1971	594.1	0.1	594.0	1976	458.1	1.5	456.6
1967	536.1	0.0	536.1	1972	435.0	0.4	434.6				
1968	532.8	0.0	532.8	1973	396.3	0.5	395.8				
1969	588.0	0.0	588.0	1974	476.8	3.0	473.8				

Source: Institute of Geological Sciences

For recent years total apparent consumption of bauxite was distributed between grades as shown in Table 10. It should be noted, however, that alumina for metallurgical use has not been produced from bauxite at Burntisland for some years.

Table 10 United Kingdom: Apparent Consumption of Bauxite by Grade 1970 - 1976

Thousand tonnes

Year	Metallurgical & abrasive grades								
	Calcined			Uncalcined			Calcined - refractory grade		
	Imp.	Exp.	App. C	Imp.	Exp.	App. C	Imp.	Exp.	App. C
1970	28.3	0.1	28.2	391.7	0.1	391.6	108.4	n.a.	n.a.
1971	35.2	0.0	35.2	411.1	0.1	411.0	147.8	n.a.	n.a.
1972	20.3	0.4	19.9	297.3	0.0	297.3	117.3	n.a.	n.a.
1973	24.4	0.5	23.9	274.6	0.0	274.6	97.3	n.a.	n.a.
1974	29.4	0.1	29.3	294.4	0.1	294.3	153.0	2.7	150.3
1975	31.0	0.2	30.8	264.8	0.2	264.6	140.7	1.0	139.7
1976	23.2	0.1	23.1	273.1	0.0	273.1	161.8	1.4	160.4

Imp. Imports
Exp. Exports
App.C Apparent consumption

Source: Institute of Geological Sciences

Alumina

As with bauxite there are no official statistics relating to consumption of alumina, but approximate figures for apparent consumption can be estimated from production and trade information (See Table 11).

Table 11 United Kingdom : Apparent Consumption of Alumina 1965 - 1976

Thousand tonnes

Year	Production	Imports *(a)*	Exports *(a)*	Apparent consumption
1965	n.a.	9.8	21.3	
1966	119.0	7.0	13.9	112.1
1967	135.3	6.1	22.2	119.2
1968	117.4	5.9	17.1	106.2
1969	105.7	8.7	10.2	104.2
1970	107.1	54.3	3.4	158.0
1971	99.1	272.1	18.8	352.4
1972	116.1	314.5	19.4	411.2
1973	96.9	546.0	33.3	609.6
1974	94.7	602.0	114.2	582.5
1975	82.5	672.8	24.7	730.6
1976	96.0	525.6	43.0	578.6

Source: Institute of Geological Sciences

(a) Imports and exports of aluminium oxide, metallurgical and other aluminium oxide and aluminium hydroxide.

n.a. Not available

Aluminium

Statistics of the consumption (despatches to consumers) for aluminium metal, both primary and secondary, are compiled by the Aluminium Federation and published by the World Bureau of Metal Statistics. Data on secondary aluminium (Table 12) refer to consumption by end-user of aluminium metal produced by the secondary smelters and do not therefore correspond to data given previously in Table 8 which covers the consumption of aluminium scrap by the secondary smelters themselves.

Table 12 United Kingdom Consumption of Aluminium 1951 - 1976

Thousand tonnes

Year	Primary	Secondary *(a)*	Total *(a)*
1951	206.3	175.4	321.7
1952	325.5	90.2	415.7
1953	183.5	74.7	258.2
1954	228.8	82.8	311.6
1955	290.8	91.6	382.4
1956	280.6	84.6	365.2
1957	216.7	93.9	310.6
1958	236.2	98.5	334.7
1959	293.6	108.2	401.8
1960	359.6	105.4	465.0
1961	284.1	111.6	395.7
1962	286.6	127.2	413.8
1963	318.5	142.2	460.7
1964	359.0	168.3	527.3
1965	363.6	165.8	529.4
1966	369.4	154.1	523.5
1967	360.5	154.9	515.4
1968	394.9	166.9	561.8
1969	396.0	182.0	578.0
1970	404.2	166.2	570.4
1971	334.5	155.7	490.2
1972	418.0	156.2	574.2
1973	487.0	156.3	643.3
1974	491.2	143.2	634.4
1975	392.7	132.2	524.9
1976	444.5	122.7	567.2

Source: World Metal Statistics 1970 - 1976

Central Statistical Office 1951 - 1969

(a) In order to avoid double-counting, the small amount of primary metal used in the production of secondary aluminium has been subtracted from the figure for total despatches to end-users from the secondary smelters.

Overseas Trade

Bauxite

Since the Second World War the United Kingdom has relied entirely on imported supplies of bauxite. Imports for the period 1970 to 1976 are shown in Table 13 under the three headings on which they are classified in the United Kingdom Tariff and Overseas Trade Classification. In 1976 these were:

Aluminium ores and concentrates –

Calcined bauxite (metallurgical & abrasive grades)	2601	7334
Other	2601	7366
Calcined bauxite (refractory grade)	3819	5241

These three categories have been separately shown in the trade information compiled by H M Customs since 1965; although descriptions and code numbers have been changed from time to time, data are broadly comparable over the whole period.

Table 13 United Kingdom : Imports of Bauxite 1970 - 1976

	METALLURGICAL/ABRASIVE GRADE				REFRACTORY GRADE		TOTAL	
	Uncalcined		Calcined		Calcined			
	Tonnes	*£ cif*	*Tonnes*	*£ cif*	*Tonnes*	*£ cif*	*Tonnes*	*£ cif*
1970	391,680	2,202,696	28,278	417,008	108,359	2,123,567	528,317	4,743,271
1971	411,113	2,472,186	35,213	595,551	147,762	3,436,644	594,088	6,504,381
1972	297,348	2,043,614	20,299	364,938	117,305	3,051,857	434,952	5,460,409
1973	274,570	1,899,162	24,428	472,934	97,297	2,525,301	396,295	4,897,397
1974	294,359	2,404,792	29,448	734,355	152,969	5,556,018	476,776	8,695,165
1975	264,788	2,657,427	31,043	947,666	140,689	6,299,163	436,520	9,904,256
1976	273,106	3,621,731	23,207	1,029,651	161,804	9,749,574	458,117	14,400,956

Source: H M Customs & Excise

Details of imports by country of consignment are shown in Tables 14 and 15.

Table 14 United Kingdom : Imports of Bauxite by countries 1973 - 1976

Country of consignment	1973		1974		1975		1976		1976
	Tonnes	*£ cif*	*Tonnes*	*£ cif*	*Tonnes*	*£ cif*	*Tonnes*	*£ cif*	*Av. value £1/tonne*
Ghana	225,046	1,538,569	223,215	1,694,594	224,481	2,205,937	195,590	2,583,236	13.21
Guyana	88,791	2,302,887	112,687	4,359,552	119,866	5,585,825	110,411	7,549,713	68.38
Australia	11,778	207,443	260	21,658	5,196	134,652	12,314	463,027	37.60
Greece	48,374	326,133	55,031	594,915	40,307	451,490	53,127	706,054	13.29
China	6,163	146,872	22,012	549,255	15,137	526,137	37,800	1,647,848	43.59
Netherlands	1,102	28,305	27,662	759,947	25,477	779,725	10,467	380,354	36.34
Surinam	9,800	192,099	3,909	110,597	4,608	168,087	9,723	491,934	50.59
Switzerland	12	600	17,858	165,245	1,020	42,353	2,570	113,300	44.09
Trinidad & Tobago	4,536	121,743	–	–	–	–	–	–	–
Saudi Arabia	–	–	5,964	190,927	–	–	–	–	–
Cyprus	–	–	4,692	156,617	–	–	–	–	–
Italy	–	–	–	–	–	–	19	1,253	65.95
Belg/Lux.	–	–	2,550	60,948	–	–	–	–	
Fed. Germany	502	14,692	518	18,791	95	9,640	5	211	42.20
U.S.A.	171	16,332	318	12,119	11	410	1,624	121,618	74.89
Guinea	–	–	–	–	–	–	478	24,586	51.44
Brazil	–	–	–	–	–	–	100	6,794	67.94
Sierra Leone	–	–	–	–	–	–	23,889	311,028	13.02
Austria	20	1,722	–	–	–	–			
TOTAL	396,295	4,897,397	476,776	8,695,165	436,520	9,904,256	458,117	14,400,956	31.44

Source: HM Customs & Excise

Table 15 United Kingdom : Imports of Bauxite by Countries and by Grades 1974 - 1976

	METALLURGICAL/ABRASIVE GRADE						REFRACTORY GRADE		
	Calcined			Uncalcined			Calcined		
	Tonnes	*£ cif*	*Average value £/tonne*	*Tonnes*	*£ cif*	*Average value £/tonne*	*Tonnes*	*£ cif*	*Average value £/tonne*
1974									
Ghana	–	–	–	223,215	1,694,594	7.59	–	–	–
Guyana	–	–		–	–	–	112,687	4,359,552	38.69
Greece China	6,000	134,954	22.49	10	150	15.0	16,102	414,151	25.72
Australia	260	21,658	8.33	–	–		–	–	
Surinam	3,909	110,597	28.29	–	–		–	–	
Netherlands	15,960	379,864	23.80	–	–		11,702	380,083	32.48
Switzerland	5	148	29.60	16,103	115,133	7.15	1,750	49,964	28.55
Saudi Arabia	–	–	–	–	–		5,964	190,927	32.01
Cyprus	–	–		–	–		4,692	156,617	33.38
Belg/Lux.	2,546	60,693	23.84	–	–		4	255	63.75
Fed. Germany	450	14,433	32.07				68	4,358	64.09
U.S.A.	318	12,008	37.76	–	–		...	111	
1975									
Ghana	–	–	–	224,481	2,205,937	9.83	–	–	–
Guyana	6,601	216,078	32.73	–	–	–	113,265	5,369,747	47.41
Greece	–	–	–	40,307	451,490	11.20	–	–	–
China	3,000	107,188	35.73	–	–	–	12,459	418,949	33.63
Australia	5,196	134,652	25.91	–	–	–	–	–	–
Surinam	4,608	168,087	36.48	–	–	–	–	–	–
Netherlands	10,627	280,498							
Switzerland	10,627	280,498	26.39	–	–	–	14,850	499,227	33.62
Others	11	410	37.27				95	9,640	101.47
1976									
Ghana	–	–	–	195,590	2,583,236	13.21	–	–	–
Guyana	–	–	–	–	–	–	110,411	7,549,713	68.38
Greece	–	–	–	53,127	706,054	13.29	–	–	–
China	–	–	–	500	21,413	42.83	37,300	1,626,435	
Australia	12,314	463,027	37.60	–	–	–	–	–	–
Surinam	9,723	491,934	50.59	–	–	–	–	–	–
Netherlands	–	–	–	–	–	–	10,467	380,354	36.34
Switzerland	–	–	–	–	–	–	2,570	113,300	44.09
Sierra Leone	–	–	–	23,889	311,028	13.02	–	–	–
Guinea	478	24,586	51.44	–	–	–	–	–	–
U.S.A.	592	43,310	73.16	–	–	–	1,032	78,308	65.88
Others	100	6,794	67.94	–	–	–	24	1,464	61.00

Source: HM Customs & Excise

Until quite recently Ghana, Guyana and Greece have been the major sources of supply of bauxite to the United Kingdom accounting for over 90 per cent of all imports. However, by 1976 the proportion originating from these countries had dropped to 80 per cent. China, Australia and Surinam have become significant sources, and in 1976 as much as 5 per cent of United Kingdom bauxite imports came from Sierra Leone. Imports from Ghana consist entirely of uncalcined metallurgical and abrasive grade bauxite. Guyana is the major supplier of calcined refractory bauxite accounting for about 70 per cent of imports into the United Kingdom in 1976 with China, supplying about 23 per cent, also an important source.

Alumina

Alumina is listed in the 1976 United Kingdom Trade and Tariff Classification as follows:-

28.20	Aluminium oxide and hydroxide; artificial corundum
	Aluminium oxide
2820 1137	Metallurgical
2820 1176	Other
2820 1557	Aluminium hydroxide
	Artificial Corundum
2820 3017	Ground and graded
2820 3056	Other

The term aluminium hydroxide used in this trade classification refers to various commercial grades of alumina that have not been calcined and chemically are therefore hydrated oxides. Artificial corundum is a collective name given to material prepared by fusion of either calcined bauxite or alumina for use as an abrasive.

Imports of alumina into the United Kingdom, shown on Table 16, show a marked increase from 1971 onwards coinciding with the inauguration of three large new aluminium smelters. All the alumina consumed by these, and by the smaller smelters of western Scotland, is now imported.

Table 16 United Kingdom : Imports of Alumina 1970 - 1976

Tonnes

Description	1970	1971	1972	1973	1974	1975	1976
Alumina							
Metallurgical grade	50,246	269,965	305,112	532,892	448,918	533,263	346,953
Others			8,534	11,765	151,031	137,571	175,538
Aluminium hydroxide	4,024	2,162	850	1,311	2,081	1,947	3,139
Total	54,270	272,127	314,496	545,968	602,030	672,781	525,630
Total cif value £	2,602,474	10,085,981	11,520,799	20,013,241	27,869,711	39,074,991	40,705,755

Source: HM Customs & Excise

Further details of alumina imports by country of consignment are given in Table 17.

Table 17 United Kingdom : Imports of Alumina by Countries 1974 - 1976

Country of Consignment	1974		1975		1976	
	Tonnes	*£ cif*	*Tonnes*	*£ cif*	*Tonnes*	*£ cif*
Alumina-metallurgical						
Jamaica	368,162	15,263,866	438,320	24,991,596	167,142	11,345,962
Surinam	23,173	843,736	–	–	85,783	6,068,863
Trinidad/Tobago	–	–	–	–	26,140	1,732,757
Guyana	55,054	1,744,523	68,886	3,285,979	20,988	1,303,809
Italy	–	–	25,470	1,315,447	45,987	3,306,549
France	1,511	446,411	415	129,891	490	253,719
Fed. Rep Germany	200	36,697	46	10,375	150	61,659
Netherlands	730	62,043	44	5,070	–	–
Others	88	34,165	82	22,650	273	65,365
TOTAL	448,918	18,431,441	533,263	29,711,008	346,953	24,138,683
Alumina - other						
Jamaica	83,649	4,424,895	125,935	6,673,993	115,457	8,378,220
Australia	52,097	2,386,404	1,674	26,999	33,357	2,941,578
Surinam	–	–	–	–	9,873	760,568
Fed. Rep Germany	4,493	586,257	2,860	442,924	7,030	1,015,716
USA	5,701	665,224	3,420	722,724	5,023	1,346,060
Austria	3,061	601,358	1,371	322,671	2,795	766,557
France	298	162,392	402	373,101	809	308,162
Canada	233	22,555	1,189	145,625	751	113,083
Netherlands	1,349	130,397	715	139,925	298	72,650
Others	150	33,889	5	6,236	6,236	35,719
TOTAL	151,031	9,013,371	137,571	8,854,198	175,538	15,738,313
Aluminium hydroxide						
Fed. Rep Germany	753	91,143	1,030	194,930	1,845	389,328
France	428	95,228	281	99,809	437	128,792
Irish Republic	242	98,586	180	76,401	244	84,821
USA	554	117,740	411	114,468	541	183,067
Others	104	22,142	45	24,175	72	42,751
TOTAL	2,081	424,899	1,947	509,783	3,139	828,759

Source: HM Customs & Excise

Table 18 gives details of imports of artificial corundum, a commodity manufactured by fusion of alumina or high-purity bauxite and which must be distinguished from abrasive grade bauxite already dealt with in Tables 13 and 15.

Table 18 United Kingdom : Imports of Artificial Corundum 1974 - 1976

Country of consignment	1974		1975		1976	
	tonnes	*£ cif*	*tonnes*	*£ cif*	*tonnes*	*£ cif*
Surinam	–	–	–	–	116,969	8,733,370
Jamaica	–	–	–	–	10,492	778,898
Canada	11,379	909,925	11,351	1,226,023	8,586	1,329,130
Netherlands	3,442	459,411	4,525	598,146	3,962	1,052,098
Fed. Rep. Germany	1,678	296,063	2,164	298,793	2,824	655,803
France	889	155,431	3,448	94,435	818	261,227
USA	2,587	746,418	1,298	445,392	810	507,554
Others	352	43,517	104	30,092	2,244	507,554
TOTAL	20,327	2,610,765	22,890	2,692,881	146,705	13,727,400

Source: HM Customs & Excise

Aluminium metal, unlike bauxite and alumina, is exported from the United Kingdom in considerable amounts. Tables 19 and 20 deal with trade in unwrought aluminium ingot and Table 21 covers waste and scrap.

Table 19 United Kingdom : Imports of Unwrought Aluminium by Countries *(a)* 1972 - 1976

Tonnes

Country of destination	1972	1973	1974	1975	1976
Norway	127,367	136,413	130,785	80,176	109,833
Canada	73,778	62,565	66,634	13,114	17,229
Ghana	14,513	20,974	18,289	11,018	18,891
Iceland	13,865	18,904	16,751	16,686	31,359
Soviet Union	6,913	13,739	8,278	15,330	5,955
Poland	6,035	4,851	1,216	1,630	–
France	501	568	9,980	8,596	12,541
Germany F.R.	2,511	2,895	3,981	411	4,937
USA	1,226	2,885	1,252	377	608
Others	20,154	23,523	13,571	12,308	16,548
TOTAL	266,863	287,317	280,715	159,644	217,901

(a) Virgin aluminium and alloy ingots and notch bars, secondary aluminium and alloy ingots and notch bars, other shapes of aluminium and alloys.

Source: HM Customs & Excise

Table 20 United Kingdom : Exports of Unwrought Aluminium by Countries *(a)* 1972 - 1976

Tonnes

Country of destination	1972	1973	1974	1975	1976
Netherlands	8,382	18,026	16,640	16,904	68,096
Belgium	2,768	3,625	9,512	3,788	20,788
Germany F.R.	13,701	12,237	14,587	8,950	19,102
USA	18,279	5,008	3,812	5,799	8,741
Canada	10,174	11,283	6,694	3,705	6,191
Sweden	1,808	1,199	2,119	4,554	3,193
Finland	180	3,762	603	202	2,999
Irish Rep.	1,139	1,768	1,059	2,694	4,923
China	–	–	1,051	23,163	2,576
France	870	4,418	1,944	982	2,258
Denmark	756	1,200	1,793	651	1,266
Others	26,905	22,802	27,616	16,303	21,952
TOTAL	84,962	85,328	87,430	87,695	162,085

(a) Virgin aluminium and alloy ingots and notch bars, secondary aluminium and alloy ingots and notch bars, other shapes of aluminium and alloys.

Source: HM Customs & Excise.

Table 21 Imports and Exports of Aluminium Waste and Scrap 1973 - 1976

Tonnes

Country of Consignment/destination	1972	1973	1974	1975	1976
IMPORTS					
Soviet Bloc	9,657	13,398	15,224	10,415	7,969
Netherlands	–	900	998	301	1,890
Norway	403	953	314	183	1,358
Germany F.R.	1,477	655	700	1,112	1,300
Irish Rep.	370	409	923	796	873
Belg/Lux.	2	271	374	242	810
Canada	–	834	1,411	154	556
USA	1,090	2,789	1,300	188	273
Yugoslavia	641	–	240	–	–
Others	288	499	732	259	1,700
TOTAL	13,928	20,708	22,216	13,650	16,729
EXPORTS					
Germany	908	1,291	5,980	8,811	3,132
Netherlands	143	122	876	2,922	1,667
France	799	1,061	1,714	1,325	610
Other EEC	443	772	2,235	2,048	892
Others	305	209	889	312	568
TOTAL	2,598	3,455	11,737	15,477	6,869

Source: HM Customs & Excise

Alumina and Aluminium – alternative technology

Background

At an early stage of its history the world aluminium industry became heavily committed to the Bayer process, which, in turn, is dependent upon a steady supply of bauxite conforming to relatively tight specifications. This was because the bauxite and alumina route to aluminium production proved to be far more economic than any feasible alternatives. Any future shortfall in bauxite supplies could not, therefore, be met by simply switching to an alternative raw material but is also likely to require very considerable re-investment in new industrial plant.

Although known reserves of bauxite suitable for use in Bayer process plants presently amount to 24.5 x 10^9 tonnes and could perhaps be doubled, production from them is increasing nearly exponentially. In 1940, 1950, 1960 and 1970 world annual production figures were, respectively, 4.3 million, 8.5 million, 26.5 million and 57.0 million tonnes. At the current annual rate of increase of about 7 per cent, world production is likely to exceed 100 million tonnes in 1980 and, if energy costs for smelting aluminium remain competitive, could be as much as 370 million tonnes per year by 2000. The latter figure implies a cumulative production of about 4.5 x 10^9 tonnes for the remainder of the century and therefore suggests that no overall shortage of bauxite will develop in that time.

There is, nonetheless, a tendency for bauxite production to be concentrated among a decreasing number of major producing nations. For example, in 1965 two countries, Australia and Guinea, possessing 48 per cent of world reserves of bauxite (at the 1977 figure) contributed only 3 per cent to world production. By 1970 their contribution had increased to 23 per cent and in 1977, in a share coinciding roughly with their reserves position, they provided about 45 per cent of world production. Further extrapolation to the end of the century of contributions made by individual countries is subject to a number of uncertainties but, if, by that time, national production capacities are roughly proportional to reserves, it is likely that about 70 per cent of world production will originate from five or six countries who will occupy a position of considerable influence.

Along with the steadily increasing concentration of bauxite production from a relatively few countries, several of the producing nations have recently taken steps to maximise returns on their bauxite resources, particularly where these are their only significant source of foreign exchange. Guyana moved to outright nationalisation of the largest foreign-owned mining and refining operation in that country as early as 1971 and several other countries have subsequently negotiated participation agreements giving them an increased share in the control of local industries. In 1974 a producer cartel, the International Bauxite Agency, was established with an initial membership including Australia, Jamaica, Surinam, Guyana, Guinea, Sierra Leone and Yugoslavia. The IBA has already had some influence upon the course of negotiations between certain producer countries and the international aluminium companies.

In response to the formation of the IBA and other developments in their relations with producer countries, several multinational aluminium companies have now announced plans to examine possible alternatives to bauxite.

As the existing Bayer process technology is completely dependent upon high quality bauxite as a raw material, the successful introduction of an alternative to bauxite would entail a very high degree of technical innovation, although some of the alternative routes to alumina or aluminium production might permit the use of bauxite of grade too low to be treated by the Bayer process.

Research into methods of extracting aluminium from non-bauxitic materials involves both investigations into the possibility of replacing the bauxite-based Bayer process as a source of alumina and also the prospect of producing aluminium directly from such materials. A third line of enquiry has been aimed towards radical improvement of the economics of the conversion of alumina to aluminium. Although this latter does not relate directly to the possible introduction of non-bauxite raw materials, it is of significance in the possible improvement of the economic performance of the smelting industry which would become desirable in the context of increasing energy and bauxite costs.

Alternative Methods of Producing Alumina

Many different processes for the production of alumina have been proposed and a few have been tried out on a semi-industrial scale. The various processes can be classified into three main groups.

1. Alkaline processes in which the aluminium is dissolved as the aluminate ion $Al0_2^-$. This is the basis of the Bayer process but, in order to treat ores with a high proportion of silica, some way has to be found to avoid the formation of insoluble aluminosilicates. Either very intensive leaching conditions are applied or, alternatively, the aluminosilicate is decomposed by sintering, for example with limestone mixed with soda ash, after which the alumina can be readily leached from the resulting clinker. At the present time a lime-soda sinter technique is used on an industrial scale in the Soviet Union for the production of alumina from nepheline residues left after the mining of apatite in the Kola peninsula and also from nepheline syenite mined at a number of localities. In Poland a lime sinter process utilising colliery shale is being evaluated. In both countries cement is an important by-product of the operations.

2. Acid leach routes in which the aluminium is taken into aqueous solution as Al^{3+} tons. The aluminium salt of the acid is then usually crystallised to yield an alumina product and acids driven off for re-use. Unfortunately the leaching is not selective for aluminium, and iron, in particular, also dissolves and can contaminate the final product. Methods for removing the iron form the basic differences between many of the proposed processes. The Pechiney-Ugine-Kuhlmann company is currently conducting pilot plant tests in France on an acid leaching process designed principally to produce alumina from colliery shales.

3. Combined acid and salt leaching processes in which the aluminium is dissolved as potassium or ammonium alum. Iron also dissolves but if it is reduced to the ferrous state, for example by addition of sulphur dioxide, an iron-free alum can be crystallised. Alumina can then be recovered by calcination of the alum.

Direct Routes to Aluminium Metal

Theoretically aluminium oxide can be reduced using carbon at temperatures around 2000°C but the recovery of metallic aluminium is difficult because it vapourises above 1800°C. Aluminium alloys with copper, iron or silicon have lower vapour pressures and can be successfully made by carbothermic reduction of metal oxide mixtures. This, however, has not been attempted on a commercial scale since the 1920's.

More recently research into direct methods of producing aluminium from various ores has centred on the possibility of vapourising halide or sub-halide compounds of aluminium and decomposing them to obtain the metal. Three methods, the Alcan sub-halide process, the Toth process and the Clarion Research-Levi process have received considerable attention. The main difficulties common to all these processes appear to be the handling of corrosive vapour at high temperatures and the removal of impurities from aluminium. No detailed costs are available for these processes but it is possible that the cost of producing metal would be comparable with the existing bauxite-based technology. Development costs, however, are likely to be very high.

Improved Aluminium Smelting Techniques

Considerable publicity has been given to the 'Alcoa smelting process' for which the Aluminum Company of America applied for patents in early 1973. The company suggested that the process would consume as much as 30 per cent less electricity than the conventional Hall-Heroult process. In addition to requiring less energy, it was stated that the process is more tolerant of power reductions during periods of peak demand or even of total interruptions. Although full details have not been published the Alcoa process is known to involve conversion of alumina to aluminium chloride by reaction with chlorine. Molten chloride is then electrolysed to give aluminium and chlorine, the latter of which is re-cycled. In this process there is no need to use expensive cryolite and no provision has to be made to combat fluoride emissions.

A full economic assessment of the alternative routes for aluminium production utilising bauxitic or non-bauxite ores is beyond the scope of this dossier. It would appear, however, that in the changing political and economic circumstances of recent years some of these processes may now be potentially viable alternatives to the conventional Bayer-Hall-Héroult route.

Industry

Outside the communist countries the world aluminium industry is in the hands of a number of large multinational companies and exhibits a high degree of vertical integration; in general, company interests extend from bauxite mining to the production of semi-fabricated metal components. The seven largest companies include three based in the United States, namely Aluminum Company of America (Alcoa), Reynolds Metal Company and Kaiser Aluminum and Chemical Corporation. The largest of all the companies is the Canadian concern Alcan Aluminum Ltd. In Europe important companies are the French combine Pechiney Ugine Kuhlmann (PUK), Swiss Aluminium Ltd (Alusuisse) and, in Germany, Vereinigte Aluminium Werke Aktiengesellschaft (VAW). In the United Kingdom the British Aluminium Company (Baco), although having some overseas interests in its own right, is now a jointly owned subsidiary of Reynolds Metals and Tube Investments Ltd.

Within the United Kingdom the British Aluminium Company owns the only active alumina refinery at Burntisland, Fife, with a capacity of about 110,000 tonnes per year. The first British reduction plant for the production of aluminium metal was built at Foyers, Invernessshire in 1896. This was supplemented by two other small smelters at Lochaber, Invernessshire, opened in 1908 with a capacity of 32,000 tonnes per year and Kinlochleven, Argyll, opened in 1929 with a capacity of 11,000 tonnes per year. The Foyers smelter, after serving for a period as a superpurity refinery, finally closed in 1967. All three West Highland smelters were designed to depend upon locally generated hydroelectric power and thus their capacity for expansion was limited.

In the late 1960's HM Government offered attractive incentives through regional grants and subsidised power costs for the construction of much larger smelters, three of which were eventually commissioned. The largest, with a capacity of 132,000 tonnes per year is owned by Alcan and is situated at Lynemouth, Northumberland. Two other smelters, each of 112,000 tonnes per year capacity were built at Holyhead, Anglesey by Anglesey Aluminium Ltd and at Invergordon, Ross and Cromarty, by British Aluminium. 67 per cent of the equity of Anglesey Aluminium Ltd is owned by Kaiser and 33 per cent by Rio Tinto Zinc Corporation.

Of other major multinational companies, both Alcoa and Alusuisse have interests in semi-fabricating plants in the United Kingdom but are not involved in primary smelting. This also applies to the Norwegian smelting company Norsk Hydro A/S.

A much larger number of companies are engaged in recovery of aluminium from scrap. Domestically Britain is well served by this industry and it is estimated that more than 90 per cent of old aluminium scrap finds its way back to secondary smelters.

Apart from the major international companies which usually have interests in both the secondary refining and semi-fabricating fields, approximately 25 to 30 other British-registered companies have their major interests in one or other of these areas.

Two important trade associations concerned with aluminium are based in the United Kingdom. The International Primary Aluminium Institute, founded in 1972, has its headquarters located in London and is an international association of companies engaged in the production of primary aluminium. Its aims include 'the promotion of understanding of the world's aluminium industry and broader use of its products, the collection and publication of statistical information relating to the international industry, the study of environmental problems affecting the industry and the provision of a forum for discussion of developments affecting the industry'.

The interests of the aluminium industry within the United Kingdom are the concern of the Aluminium Federation, based in Birmingham, and founded in 1962 by a merger of the Aluminium Development Association and the Aluminium Industry Council. Included under the general federal umbrella are several associations covering specialised fields such as primary production, extrusion, rolled products, powder and paste, and forgings. Major companies which are concerned with all or most sectors of the industry are also members of the Federation in their own right.

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