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BERYLLIUM, CAESIUM, NIOBIUM (COLUMBIUM), GERMANIUM, HAFNIUM, THE RARE EARTHS, TANTALUM, TITANIUM, YTTRIUM, AND ZIRCONIUM

Production, Demand and Commercial Prospects

TABLE OF CONTENTS

PRODUCTION - DEMAND AND COMMERCIAL PROSPECTS*

BERYLLIUM

I. ORES AND DEPOSITS

There is a considerable number of beryllium-bearing minerals, the BeO content of which varies widely:

Barylite	BeO %	: 15 %
Bertrandite	"	: 40-43 %
Beryl	"	: 10-15 %
Beryllonite	"	: 19-20 %
Chrysoberyl	"	: 19-20 %
Euclase	"	: 17-18 %
Hambergite	"	: 53-55 %
Helvite	"	: 13-14 %
Herderite	"	: 15-16 %
Leucophanite	"	: 10-12 %
Meliphanite	"	: 10-14 %
Phenacite	"	: 44-46 %

Although its BeO content is not particularly high, beryl has always been - and still is - the basic raw material for the beryllium industry.

Beryl owes this position to its relative abundance and to the fact that it is easy to cob and sort by hand, thanks to the very large - even huge - size of its crystals in some of the pegmatites from which it is extracted.

Although considerably richer in BeO, bertrandite, phenacite, chrysoberyl, barylite and other beryllium minerals have not so far played a large part in the beryllium-mining industry. Their crystal structure, generally very fine, makes them unsuitable for cobbing. Their low concentration in the metalliferous matrices in which they occur make them low-grade ores, difficult to locate, the working of which presents very difficult problems. None the less, these ores have a great future before them, and it can be assumed that they will soon take the place of beryl.

1. <u>Conventional ores</u>: cobbable beryl

Cobbable beryl occurs in a particular type of pegmatite - the zonal pegmatites - found in certain metallogenic provinces.

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* By D. Soule de Lafont, Chief Geologist of the Pechiney-Saint-Gobain Chemical Company.

Although, by and large, it follows a fairly regular zoneographic pattern, the distribution of beryl in these pegmatites is capricious, accumulations varying greatly in size. Usually limited to a few tons, or tens of tons, reserves of beryl in mineralized zonal pegmatites may in some cases reach a hundred, or a few hundred, tons. 1/ In quite exceptional cases, they may amount to several thousand tons. A record must be held by the pegmatite at Villa Dolores, near Cordoba, in Argentina, from which some 4,000 tons of beryl have been extracted.

Some pegmatites are worked exclusively for their beryl. But in the majority of cases the working of a beryl-bearing pegmatite pays only if its quasi-precious constituents (feldspars, quartz, micas and other minerals) are exploited, the beryl thus becoming a by-product. The extraction methods used are often of the handicraft type; indeed, in many cases, any other way of working the deposit would be uneconomic.

Beryl also occurs, though only in small amounts, in unzoned pegmatites, especially in homogeneous, spodumenic varieties, but the grain size is always very fine. Although reserves of such pegmatites are large, their low beryl content, and the necessity to recover the mineral by flotation, deprive them of any immediate interest.

2. Deposits of the future: non-pegmatitic beryllium

Prospecting carried out in North America over the past ten years has brought to light the existence of large deposits of non-pegmatitic beryllium.

This paper is not the place for a detailed account of the metallogenesis of the different types of deposit discovered. It should however be mentioned that the beryllium occurs in the form of bertrandite, phenacite, chrysoberyl or barylite, as the case may be, in a rather varied range of geological surroundings.

Such deposits have been located in the United States of America, Alaska, Canada and Mexico, at the following sites:

SPOR MOUNTAIN (Utah),

where bertrandite, associated with fluor-spar, is irregularly distributed in rhyolitic tuffs.

WHITE PINE COUNTRY (Mount Wheeler, Nevada),

where phenacite, bertrandite and, as an accessory mineral, beryl are associated with scheelite, fluor-spar, pyrite, siderite and quartz in shear zones or in veins running through calcareous rocks, in the vicinity of greatly altered intrusive dykes.

1/ Except where explicitly stated otherwise, all tonnages in this paper relate to metric tons of 2,204 lb.

PARK COUNTY (Colorado),

where the greisens of a granitic contact are mineralized by beryl, bertrandite and fluor-spar.

SEWARD (Alaska),

where beryllium, in the form of chrysoberyl, occurs on the contact between calcareous rocks and porphyries or tin-bearing granites.

SEAL LAKE (Goose Bay, Labrador, Canada),

where beryllium, in the form of barylite, occurs in a differentiated alkaline complex.

AGUACHILE (Mexico),

where beryllium, in the form of bertrandite, is associated with fluoritic mineralization on the contact between calcareous rocks and rhyolites or microsyenites.

The reserves in some of these deposits are great. They generally involve large tonnages, sometimes of the order of several million tons, and usually assay between 0.5 per cent and 1 per cent.

If we are to believe the data given in the technical literature, reserves in these new deposits taken together may represent some 50,000 tons of Be metal, corresponding to 350,000 tons of conventional beryl. Their exploitation would therefore - at the level of demand prevailing over the last few years - keep the market supplied for another 30 to 40 years.

The exploitation of these non-pegmatitic beryllium minerals is a complicated matter. However, it appears that, in the most straightforward cases (e.g., Mount Wheeler), the problem could be solved by flotation.

The treatment of the Spor Mountain ores, on the other hand, will call for the use of hydro-metallurgical processes. This is not to say that the price of BeO produced in this way will not become competitive fairly quickly.

II. PRODUCTION

1. Consumption

The earliest figures for the consumption of beryllium date from 1936.

From a few hundred tons in that year, consumption shot up to 3,000 tons in 1943, only to fall back to 1,000 tons in 1946. It then rose, with a few reverses on the way, to 9,500 tons in 1961. The years 1962-1965 were not so good, demand falling to 4,435 tons in 1964 and to 5,845 tons in 1965.

The continued economic expansion in the United States of America in 1966 and the growing use of beryllium-copper alloys in the electronics industry, helped to keep demand firm during 1966. Figures showing how the market behaved in 1967 are not yet available, but the development of miniaturization in electronics suggests that the upward trend should not have been belied.

2. Producers

According to the US Bureau of Mines, the breakdown of world production of beryl and other beryllium ores over the period 1961-1965 was as shown in the table on the next page, in which all the figures are in <u>short tons</u>.

The tables show that there was a heavy fall in production between 1961 and 1965.

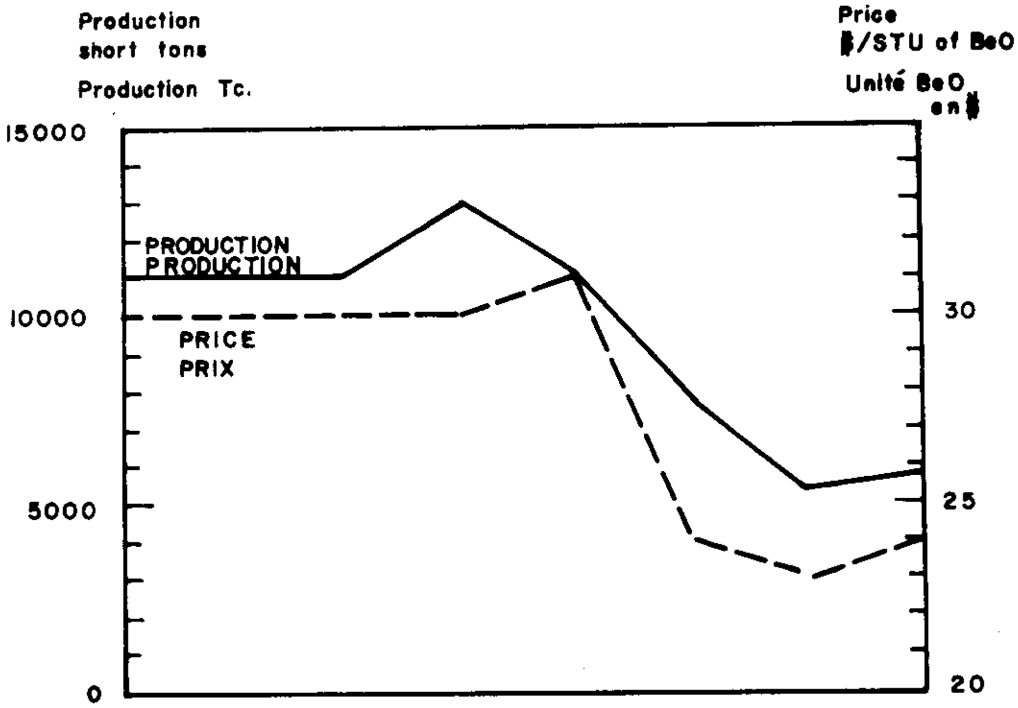
Ignoring production in the USSR, for which the statistics are not very precise, it will be seen that only in India and Rwanda was production greater in 1965 than in 1961, and that it fell steadily in all the other producing countries.

WORLD PRODUCTION OF BERYL

Producing country	1961	1962	1963	1964	1965	1966	1967
Australia	343	250	123	123	14		
Argentina	1,488	998	825	442	257		
Brazil	3,503	3,319	2,170	1,566	1,226		
Congo (Dem. Rep. of)	184	304	235	136	21		
India	885	150	—	—	1,507		
Kenya	1	—	—	1	1		
Republic of Korea	6	—	—	—	—		
Madagascar	836	743	453	34	22		
Mozambique	1,073	627	613	451	295		
Portugal	39	19	2	20	43		
Southern Rhodesia	396	559	249	182	90		
Rwanda	525	394	282	328	756		
South Africa	192	360	425	151	53		
South-west Africa	252	159	61	8	57		
Sweden	—	26	—	449	—		
Uganda	1,136	1,126	419	434	212		
USSR	900	1,000	1,100	1,100	1,100		
USA - Beryl	317	218	1	?	?		
Other ores	805	760	750	—	—		
Totals	12,900	11,000	7,700	5,200	5,700	4,700 ?	5,100 ?

WORLD PRODUCTION OF BERYL
(in short tons)
and
VARIATIONS IN F.O.B. PRICES OF ORES IMPORTED INTO THE USA
(per STU of BeO)

PRODUCTION MONDIALE DE BERYL
(en Tonnes Courtes)
ET EVOLUTION DES PRIX AUX PORTS D'EXPORTATION DES MINERAIS IMPORTES AUX USA (par unité de BeO)



SOURCE: Minerals Yearbook, 1965

India, Brazil and the USSR were the only countries where production exceeded 1,000 tons in 1965.

The table also shows that Africa, South America and India are the main potential producing countries.

In these several countries the tonnages marketed are the output of a multitude of small hand workings rather than that of large producers.

Moreover, the output is very often bought up by agents for a few middlemen, with the result that the origin of the parcels offered for sale is not always known.

III. PRICES

The price of beryl varies according to its BeO content. A "point" of BeO represents a "short-ton unit" (STU), or 20 lb. of BeO. The price of a short ton of beryl is worked out by multiplying the BeO content of the parcel by the value of the unit. Hence, for a price of \$25/STU, a parcel running 11 per cent will be worth (11 x 25) = \$275 per short ton.

When pure, beryl contains about 14 per cent of beryllium oxide, or 5 per cent of Be metal. Commercial beryl assays about 11 per cent of Be metal.

The graph on the next page shows the variations in the price of beryl per STU between 1936 and 1965.

The curve shows:

1. A fall in price from \$5 to \$2.5 from 1936 to 1940.
2. A steady rise from 1940 to 1953, with a peak of \$50.
3. A fairly steady decline, despite a few brief recoveries, from 1953 to 1963, bringing prices down to about \$30.

With a view to encouraging prospecting for and the production of beryl within its territory, the United States Government has granted a subsidy to home-produced beryl, paying \$ 46-48 for it against only \$ 28-39, according to the year, for the imported mineral.

IV. DEMAND

Having been relatively steady between 1959 and 1964, the annual turnover of the beryllium and beryllium-alloy industries in the USA rose to between 50 and 70 million dollars during 1965.

Although producers do not publish a breakdown of their sales, it is estimated that at least 80 per cent of these go into the production of beryllium alloys.

The jump in demand for Be-Cu alloys has thus more than offset the decline in the nuclear industries' requirements in beryllium metal.

The performance and remarkable reliability of Be-Cu alloys make them the ideal raw material for relays in the integrated circuits of computers. Again, despite their high cost, they are beginning to supersede phosphor-brorzes and brass for some of the purposes for which the latter are used. This replacement is already a fact in the case of highly sophisticated electronic equipment. The prospects of growth in the electronic and computer industries being what they are, demand for Be-Cu alloys cannot fail to expand.

Even though it has not entirely come up to expectations in the nuclear industry, beryllium metal seems to be sure of a bright future in the outer space field.

Its lightness ($\underline{d} = 1.87$, against 2.40 for aluminium), high melting point (1,300°C) and great mechanical strength (modulus of elasticity = 30,000 kg/mm^2) bestow on the metal exceptional properties which meet most of the requirements for space equipment.

The use of beryllium for space purposes began to expand in 1957 with its application as the anti-heating protective element for the Mercury capsules. Later, the metal was used for structural members of the Gemini capsules. This application has been further developed since 1964, the Agena rocket having 18 beryllium panels, making up 14.5 per cent of its outside surface.

Restricted in the first place to the outer space or military fields (brakes, rudders and inertia navigational systems), beryllium metal is now being extensively used for civilian purposes.

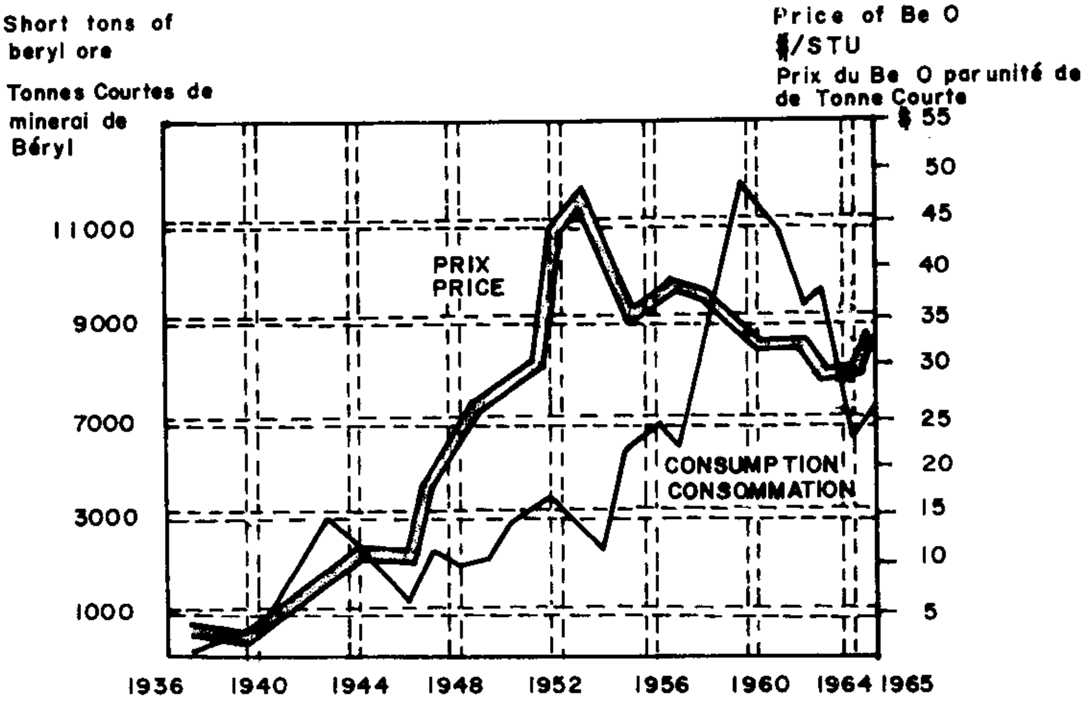
This is true, for instance, of the inertia navigational systems with which a number of commercial airlines are beginning to equip their aircraft. It is also to be expected that beryllium will find a variety of uses in the American supersonic commercial transport (the SST).

Although bound up with an increase in demand from the aeronautical and space industries, growth in the use of beryllium also depends on the possibilities of reducing its price.

As the cost of the ore accounts for only 10 per cent of the price of the metal, the latter can be brought down only through technological improvements in manufacture.

VARIATIONS IN THE CONSUMPTION AND PRICES OF BERYLE ORE IN THE USA

EVOLUTION DE LA CONSOMMATION ET DES PRIX DU BERYL MINERAI AUX U. S.A.



SOURCE: Engineering and Mining Journal, American metal and minerals market 1966

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V. COMMERCIAL PROSPECTS

The prospects of the beryllium-mining industry can be summed up as follows: (a) stagnation of demand for the metal, which must inevitably come about sooner or later; and (b) a very appreciable increase in the demand for Be-Cu alloys.

Reserves of cobbable beryl are hard to estimate. Provided demand does not greatly increase, production from this source could doubtless continue to satisfy the market for some time. Moreover, in 1966 the United States Government had a large stockpile (30,000 tons of beryl and 150 tons of beryllium metal), equivalent to several years' consumption.

Research on non-pegmatic ores is however likely to lead to new methods of producing the metal that will bring its price down.

If demand increases very substantially, or new technical methods work to the advantage of the non-pegmatitic beryllium ores, the latter, given the size of their reserves, will undoubtedly, sooner or later, oust cobbable beryl from the market.

As they are already known in the USA, and probably in the USSR too, it can hardly be doubted that new deposits of non-pegmatitic ores of beryllium will be discovered in various parts of the world in the near future.

Like that of niobium, the beryllium-mining industry has had the good fortune to be able to lay its hands on "second generation" ores ready to replace conventional deposits, themselves rich but scanty.

Hence the beryllium industries are faced with problems of the cost of the metal and of the promotion of new uses for it, rather than with those of raw-material supplies.

CAESIUM

I. ORES

Pollucite ($Cs_4Al_4Si_9O_{26}.H_2O$) is the only caesium ore of any importance; it assays 40.1 per cent of Cs, or 42.5 per cent of CsO_2.

Pollucite has always provided the raw material for the production of caesium, except during the period 1957-1960, when the element was extracted from "alkarb" - a mixture of alkali carbonates containing 2 per cent of caesium carbonate and 20-25 per cent of rubidium carbonate -, a by-product of the treatment of lepidolite.

II. DEPOSITS

Although pollucite is a rare mineral, several large deposits occur in zonal lithium pegmatites:

BERNIKE LAKE (Manitoba, Canada) -

The Bernike Lake deposit is the largest known at the present time. It has been estimated that it contains 300,000 tons of recoverable pollucite, assaying on average 20 per cent of Cs_2O_4.

During exploratory work carried out in 1959-1960, the ore mined was stockpiled and a few shipments made.

The deposit is worked by Chemalloy Minerals Ltd.

BIKITA (Southern Rhodesia) -

Reserves of pollucite at Bikita are estimated to amount to 150,000 tons, assaying 24 per cent of CsO_2.

The company concerned, Bikita Minerals, produced 100 long tons of ore in 1966.

KARABIB (South-West Africa) -

Reserves in this deposit are reported to be 50,000 tons. The ore assays from 25 per cent to 30 per cent of Cs_2O.

BERNIKE LAKE, BIKITA and KARABIB are exceptionally large deposits remarkable for their unusual concentrations of pollucite.

The mineral is also associated with the paragenesis of a number of pegmatites, in which it may occur in fairly large concentrations (USA, Mozambique, Sweden, Brazil and USSR).

Substantial tonnages of caesium could also be recovered from the tailings from the extraction of lithium from its ores or brines (USA, Africa and elsewhere). The process is economically sound, and part of the caesium produced in the USA was for a time recovered from such wastes.

III. PRODUCTION

No commercial uses of caesium salts calling for large tonnages of raw material have yet been reported.

In 1964, Mozambique exported 5.5 tons of pollucite to the USA.

In Southern Rhodesia, production at Bikita varied as follows over the period 1959-1966:

1959 : 2 tons
1960 : 5 "
1961 : 10 "
1962 : 20 "
1963 : nil
1964 : 26 tons
1965 : - ?
1966 :100 tons.

South Dakota is said to have produced 100 tons of pollucite in 1962.

IV. PRICES

Parcels of Rhodesian ore are reported to have changed hands at $255 per ton in 1962 and at $245 per ton in 1964.

South-West African Lithium Mines are reported to have offered pollucite at £100 per short ton, f.o.b. Walvis Bay, in 1966.

Prices of caesium metal have declined very considerably since 1960, falling from $452 per lb. for parcels of 1 lb. to $20 per lb. for parcels of 1 ton.

V. GROWTH OF DEMAND

In 1964, the USA consumed 8.5 short tons of caesium salts and 3,000 lb. of metal.

Research in the aeronautical and space industries has stimulated demand for caesium. The work is mainly focussed on ion propulsion. Small ion-propulsion motors have already been operated continusously for more than twelve months, and it is only a matter of time before larger ones are built. Space programmes scheduled for around 1975 may consume from 4,000 to 19,000 lb. of caesium per flight. Each lunar journey in the same period is likely to use 33,000 lb. of caesium.

According to some writers, passenger flights to Mars around the 1980s could burn from 80 to 300 tons of caesium per trip.

If the forecasts made by E. Stulhinger in 1963 are borne out, the demand for caesium metal and caesium salts will call for the treatment of the following quantities of pollucite over the next 12-13 years:

	1968	1971	1977	1980
		(short tons)		
For the production of caesium metal	40	70	?	?
For the production of caesium salts	75	120	350	550

VI. COMMERCIAL PROSPECTS

Experts foresee a moderate expansion of the use of caesium in conventional fields (multiplier photo-tubes, television pick-up tubes, infra-red lamps, spectophotometers, scintillation counters, X-ray aparatus etc.).

It seems, however, that caesium will not really get off the mark until thermo-electric generators and ion-propulsion motors have been perfected and developed.

Resources of caesium are relatively abundant:

Reserves of pollucite alone exceed 500,000 tons, equivalent to some 100,000 tons of Cs_2O; and

Caesium is a by-product of the treatment of lithium ores and brines. No inventory of these has yet been drawn up, but they certainly constitute substantial reserves.

The development of the market for caesium is a question of technological progress and practical applications. It does not seem that there will be a raw-material problem for a long time to come.

NIOBIUM (COLUMBIUM)

I. ORES

The principal ores of niobium are:

Columbite : containing from 60 per cent to 70 per cent of Nb_2O_5;

Columbite-tantalite, a mixed ore, of variable composition, containing from 33 per cent to 67 per cent of Nb_2O_5; and

Pyrochlore: containing from 50 per cent to 68 per cent of Nb_2O_5.

Tin smelter slags: containing up to 20 per cent of $Nb_2O_5 + Ta_2O_5$.

For a long time, columbite and columbite-tantalite, together with tin slags, were the only raw materials used by the niobium industry. Production matched demand in normal times, but was unable to satisfy the market at times of international crisis. Prices then rocketed, possibly soaring to 6 or 7 times the original figure in the course of a few years.

The appearance on the market, around 1960, of pyrochlore concentrates changed this unhealthy state of affairs, and it can be taken that the excessive speculation that marked the years 1950-1955 is a thing of the past.

Reserves of pyrochlore are very large. Two deposits that together satisfy two thirds of the industry's needs are already being worked. Other occurrences are being surveyed or opened up, and the mining industry is now in a position to meet consumers' growing needs.

Although there is a large number of small producers, the niobium-mining industry is at the present time highly concentrated. Three countries - Nigeria (columbite), and Brazil and Canada (pyrochlore) - alone supply more than 90 per cent of the concentrates used as raw material by industry.

Tin slags have also been an important source of raw material for the niobium and tantalum industries, as they may contain as much as 20 per cent of the combined pentoxides of the two metals. Although slags have lost none of their interest as a source of tantalum, the arrival of pyrochlore on the market will gradually whittle down their importance as a source of niobium.

1. Columbite and columbite-tantalite ores

The primary deposits of columbite and columbite-tantalite occur in certain pegmatites and in highly differentiated granites.

This "massive" type of occurrence, within the matrix, is however workable only very rarely. Mineralization that can be exploited economically is, as a general rule, found in the eluvial and alluvial secondary deposits of the primary lodes.

The Nb/Ta ratio differs from deposit to deposit. It is low for columbite tantalites and high for columbites.

A few such ratios are given in the following table.

Source of concentrates	% Nb_2O_5	% Ta_2O_5	Nb_2O_5/Ta_2O_5 ratio
Malaysia	44	15	2.9:1
Mozambique	46	19	2.4:1
Nigeria	67	7	9.6:1
Portugal	37	27	1.4:1
Uganda	33	10	3.3:1

Producers

Columbite and columbite-tantalite are mined in many countries: Guyana, Brazil, Rwanda, Congo (Kinshasa), Mozambique, Madagascar, South-west Africa, Uganda, Malaysia and Australia.

Although there are many producing countries, their relative importance is very unequal. Nigeria, which by itself accounts for 80-90 per cent of world production, is by far the largest source of supply.

1.1. Nigeria

Until the 1960s, the greater part of the world output of niobium ores came from the columbite granites of Nigeria. Between 1946 and 1948 the country produced 84 per cent of total world production; it was still providing 75 per cent in 1960.

With an output of 5.5 million lb. of concentrates - amounting to rather more than one third of the cumulative world production of columbite and pyrochlore - Nigeria is still very favourably placed.

Nigerian columbite is a by-product of tin-mining operations on the Jos plateau. The principal producers are:

	1966 output (long tons)
Amalgamated Tin Mines	559
Jantar Nigeria	551
Tin and Associated Minerals (a subsidiary of Kennecott)	373.75
Bisichi Tin Co.	447.5

1.2. Other producers of columbite and columbite-tantalite

The output of the other producing countries is very much lower than that of Nigeria. The available statistics give the following figures for 1965:

	lb. of concentrates
French Guyana[1]	837
Brazil 2/	675,168
Rwanda 2/	34,412
Congo (Dem. Rep. of)	45,125
Mozambique 2/	32,187
Madagascar 1/	4,410
South-west Africa	1,080
Uganda 1/	8,960
Malaysia	103,040
Australia	10,830
Total	916,049
Production from Nigeria	5,707,520
Total world production	6,623,569

2. Pyrochlore ores

Whereas in the columbites and columbite-tantalites used as ores of niobium the Nb/Ta ratio varies from 10:1 to 1.4:1, it is of the order of 20:1 to 100-200:1 in the case of pyrochlores.

Hence pyrochlore is a true niobium ore, and not a mixed ore (of niobium and tantalum) as is the case with the columbite-tantalites.

Pyrochlore is an accessory mineral of carbonatites (intrusive calcareous rocks) and associated alkaline complexes.

Of the hundred or so complexes already logged, some 15 are sufficiently mineralized to constitute potential deposits. The concentrations nearly always occur in the carbonatites proper so-called or in their alteration products. The range of niobium content of known possible deposits extends from 0.2 per cent to 4 per cent.

The degree of alteration and the fine grain-size of the pyrochlore make some deposits unworkable at the present stage of technological progress.

1/ Production of columbite-tantalite taken as half the total.

2/ Imports into the USA.

The known deposits of pyrochlore are found in Scandinavia, North America, Brazil, Central Africa and East Africa.

Whereas, everywhere else, the niobium content is usually less than 1 per cent, the Brazilian deposits have a conspicuously high average content: 3 per cent at Araxa and 4 per cent at Tapira. These two deposits are no less remarkable for their size, reserves at each being reported to exceed 5 million tons of Nb_2O_5, whereas those at other sites are rarely greater than 200-300 thousand tons.

Total possible reserves at all known deposits of pyrochlore may be estimated at 20-30 million tons of Nb_2O_5, of which 80-85 per cent is to be found at Araxa and Tapira in Brazil.

These figures bring out the major importance of the carbonatitic type of deposit and show clearly that these will constitute the future source of niobium.

Producers

The first attempt to exploit carbonatitic pryochlore dates from 1953. It was made at the [illegible] lode in Norway. The low niobium content and limited reserves did not make for success, and production was stopped in 1965.

Only with the start of mining operations at Araxa, in Brazil, and at Oka, in Canada, in 1961-1962, did pyrochlore really break into the market.

By 1963, Oka pyrochlore was already accounting for 50 per cent of United States supplies of niobium concentrates.

A change of policy on the part of the Brazilian Atomic Energy Commission enabled that country to start exporting pyrochlore in 1965, in which year it won 11 per cent of the US market, increasing its share to 50 per cent in 1966.

2.1. Canadian producers

(a) St. Lawrence Columbian and Metals Co.

This company works the Oka deposit, 200 miles west of Montreal.

Reserves at this mine are about 3.25 million tons of ore assaying 0.45 per cent of Nb_2O_5. Four hundred tons of run-of-mine ore have to be milled to yield 1 ton of Nb_2O_5.

The concentrates assay on average 52 per cent of Nb_2O_5 and output rose to 5 million lb. in 1966 (equal to 2.6 million lb. of Nb_2O_5.

(b) Columbian Mining Products

This company, which also operates in the Oka area, intends to open up a property at the end of 1968 capable of producing 2.6 million lb. of concentrates. The deposit contains 100 million tons of 0.25 per cent ore, and the company is believed already to have concluded a 10-year sales contract with a large consumer.

(c) A third company, in which Imperial Oil, Consolidated Morrison, Goldray Mine and Argor Exploration are partners, is also expected shortly to open up a new deposit of pyrochlore in the James Bay Lowlands area of Northern Ontario.

2.2. Brazilian producers

DEMA MINE, or CBMM.

Dema Mine, which works the Araxa deposit in the State of Minas Geraes, is controlled fifty-fifty by Brazilian interests and by the American Molycorp company. Dema Mine - whose business name has been changed to CBMM (Companhia Brazilia de Metalurgia e Mineração - doubled its production capacity and improved its flotation methods in 1966. As a result of the latter improvements, the Nb_2O_5 content of the concentrates rose from 54 per cent to 57-58 per cent.

The Araxa deposit is extremely large. According to the technical literature, reserves are estimated at between 5 and 12 million tons of Nb_2O_5. The Nb_2O_5 content of the ore is very high at 3 per cent.

According to present plans, output at Dema should have reached 13 million lb. in 1967.

The size of the deposit and the richness of the ore puts Dema in a very strong, almost predominant, position in the niobium-mining industry.

3. Tin slags

Tin slags may assay up to 20 per cent of $Nb_2O_5 + Ta_2O_5$. They are of special interest as a source of tantalum. However, their past interest as a source of supply of niobium has to some extent been eroded by the advent of pyrochlore concentrates on the market.

Such statistics as are available refer to US imports for the years 1963-1965, and are expressed in lb.

	1963	1964	1965
Stanniferous slags	30,968,743	2,516,153	8,822,135
Nb_2O_5 content	1,627,641	280,459	563,886
Ta_2O_5 "	1,410,778	140,538	428,911

Source: US Bureau of Mines.

II. MARKET FEATURES

1. Growth

Statistics on the production of niobium and tantalum began to be compiled regularly around 1935, in which year world production amounted to 500 tons of concentrates.

Since that time, Nigeria has remained the chief producer of columbite. At first, its production rose but slowly: 800 tons in 1940 and 1,200 tons in 1943, it shot up to 2,700 tons the following year. Thereafter, it varied between 1,200 and 1,800 tons a year until 1952.

The Korean war and its after-effects led to a recovery with a maximum output of 4,700 tons in 1955, followed by another steep drop in 1958, after which production fluctuated until 1961.

Since 1961, output of columbite concentrates has been more or less steady around 5,500,000 lb. (2,750 short tons) a year.

In 1962, pyrochlore concentrates appeared on the market, and were able to meet a fresh boom which set in in 1964 and pushed up demand again to the high levels of 1954.

World production of niobium-tantalum concentrates has risen as follows over the past ten years or so:

6,744,000 lb.	(3,372 short tons)	on average for the years	1956-1960
9,530,000 "	(4,765 " ")	in	1963
11,745,000 "	(5,872.5 " ")	in	1964
14,880,000 "	(7,440 " ")	in	1965.

Nigeria, with an output of 5,707,520 lb. (c 2,854 short tons), headed the list of producing countries in 1965, followed by Canada (4,510,182 lb., c. 2,255 short tons) and Brazil (2,636,702 lb., c. 1,318 short tons).

We do not have the official figures for 1966. However, it seems that with an output of the order of 9,500,000 lb. Brazil has replaced

Nigeria as the main producer. Nigerian production fell off but very little, and was still running at around 5,500,000 lb.

2. Trade channels

The USA is the largest importer and the biggest processor of niobium concentrates.

Its imports in 1965 and 1966 can be broken down as follows:

	1965		1966	
	lb. x 10^3	%	lb. x 10^3	%
Canada	1,861	38.0	1,728	18.0
Brazil	675	13.8	4,800	51.0
Nigeria	2,112	43.2	2,592	27.0
Other producing countries	244	5.0	480	4.0
Totals	4,892	100.0	9,600	100.0

The above table brings out clearly a number of trends, namely:

- US imports have regained the high levels that prevailed from 1952 to 1955 (the Korean war and building up of stockpile).
- Demand practically doubled between 1965 and 1966.
- Brazil has become the primary supplier of the USA, providing 51 per cent of the latter's imports against 13.8 per cent in 1965.
- Imports from Nigeria have declined on a percentage basis (from 43.2 per cent to 27 per cent) despite a slight increase in tonnage (from 2,112 to 2,592 tons).
- Exports from Canada to the USA have not changed much in quantity but have fallen from 38 per cent to 18 per cent on a percentage basis.

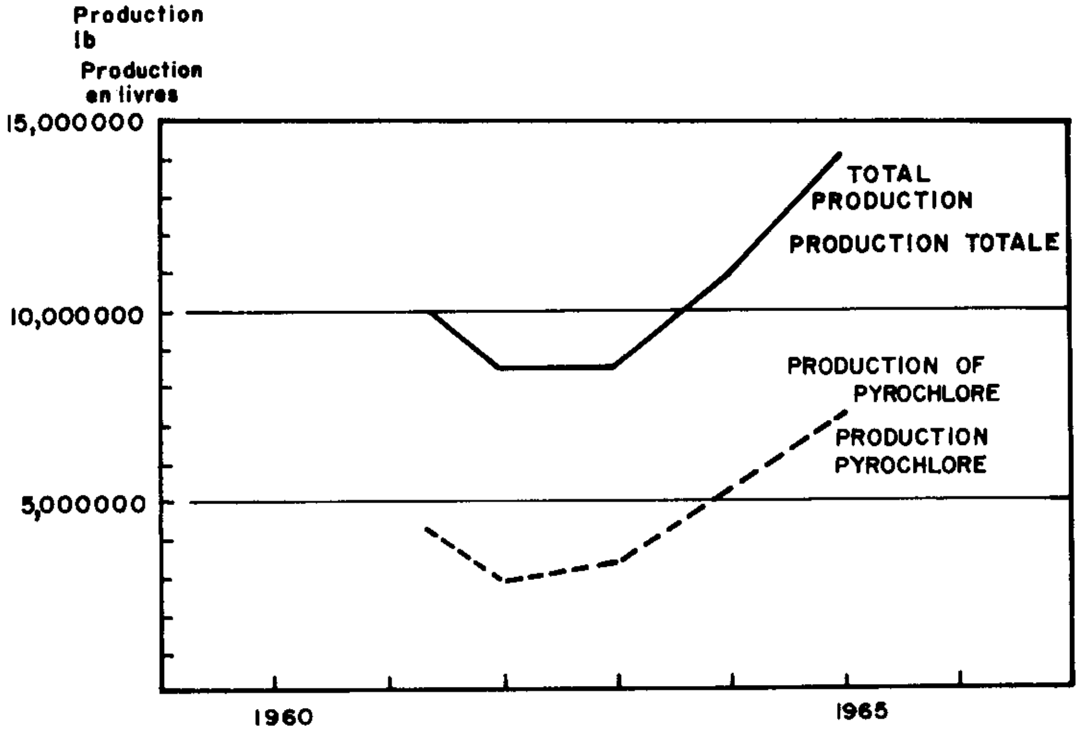
III. PRICES

1. Columbite

The graph on the next page shows the way in which the price of columbite per lb. of combined Nb and Ta pentoxides varied since 1940.

WESTERN PRODUCTION OF CONCENTRATES of COLUMBITE-TANTALITE AND PYROCHLORE in CANADA, BRAZIL AND NORWAY

PRODUCTION OCCIDENTALE de CONCENTRES de COLUMBITE TANTALITE et de PYROCHLORE du CANADA, BRESIL, NORVEGE



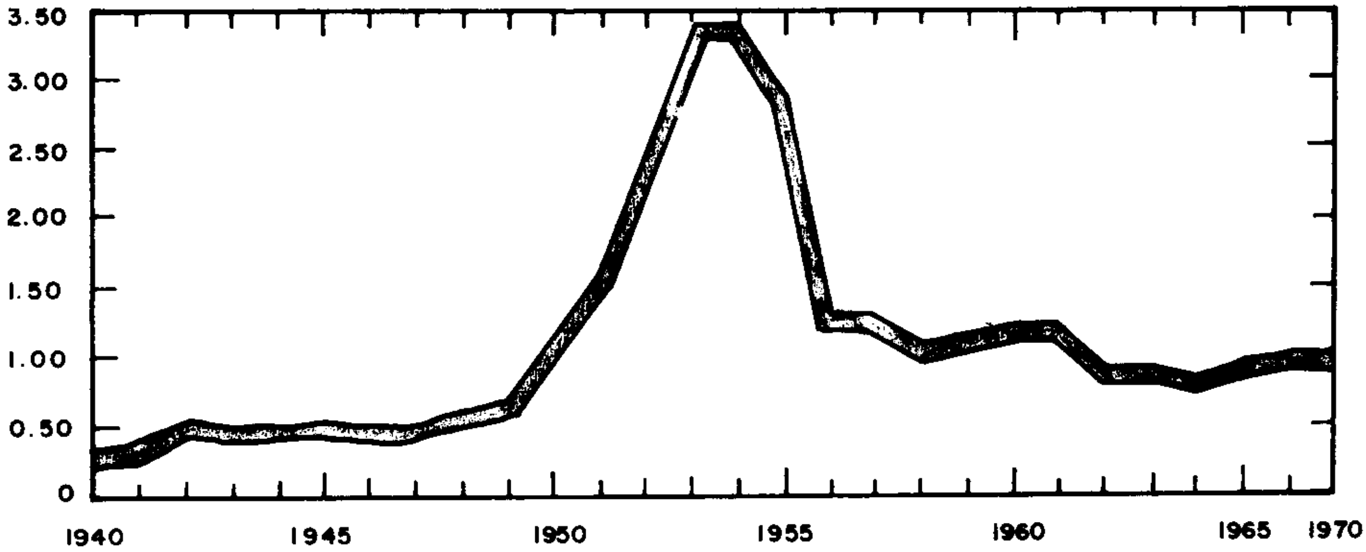
NB. In the case of certain countries, production has been arbitrarily split as to 50% of columbite and 50% of columbite-tantalite.

N.B. La production de certains pays est arbitrairement divisée en 50% Columbite et 50% Tantalite.

Sourse, Minerals Yearbook 1965

VARIATIONS IN THE PRICE OF COLUMBITE
US $ per lb. of $(Nb,Ta)_2O_5$)

EVOLUTION DES PRIX DE LA COLUMBITE
en dollars par livre de $(Cb,Ta)_2O_5$)



Source: US Bureau of Mines

NB. Columbite content as follows: 1940-1942 = 65% of combined pentoxides
1943-1944 = 50% " " "
1945-1950 = 50-55% " "
1952-1955 = 50 % " "
1956-1967 = 65% " "
with Nb/Ta ratio = 10:1.

Source: US Bureau of Mines

Note: Les teneurs de la columbite sont les suivantes: 1940-1942 = 65% de pentoxydes combinés
1943-1944 = 50% " "
1945-1950 = 50 à 55% " "
1952-1955 = 50% " "
1956-1967 = 65% " "
Pour Cb/Ta = 10

Reproduced from: Engineering and Mining Journal,
American Metal and Minerals Market 1967

Starting from $0.3 in 1940, prices rose to a peak of $3.3 during the Korean war; between 1955 and 1964 the general trend was slightly downhill, with a minimum of about $0.8, reached in 1964. Since then, there has been a slight upward tendency, quotations having been very close to $1.0 in 1965.

It should be pointed out that specifications have varied slightly during the different periods under review, prices having been related to the composition of the concentrates in the following way:

1940-1942 = 65% of combined pentoxides (Nb_2O_5 + Ta_2O_5).
1943-1944 = 50% " " " " "
1945-1951 = 50-55% " " " " "
1952-1955 = 50% " " " " "
1956-1967 = 65% " " " " ", with Nb/Ta ratio = 10:1.

Growth of demand

	Average 1956-1960	1961	1962	1963	1964	1965	1966
Niobium metal produced	—	252,000	128,000	104,000	94,609	—	90,000
Imports of niobium concentrates	4,010,363	2,777,700	5,050,888	5,909,512	4,600,800	4,891,786	9,600,000
Consumption of ferro-niobium & ferro-niobium-tantalum (Nb + Ta content)	533,375	1,052,181	1,397,638	1,345,789	1,478,770	2,198,785	2,800,000

2. Pyrochlore

In 1955, Canadian pyrochlore was quoted at $1.15 to $1.18 per lb., f.o.b. mine, for spot sales, and at $1.12 to $1.15 per lb. under long-term contracts. These prices experienced some sporadic increases in 1965 and 1966.

Brazilian pyrochlore is cheaper than the Canadian product.

In 1966, it was quoted at 95 cents per lb. of Nb_2O_5 content, f.o.b. Rio de Janeiro, and at $1 per lb. c.i.f. European ports. Three-year contracts have apparently been concluded on the basis of slightly lower prices.

IV. GROWTH OF DEMAND

The USA is the largest importer and the biggest processor.

The table on page 19 traces the growth of demand in that country. But it is difficult to assess the effect on the figures of the war in Viet-Nam.

No attempt will be made in this paper to give a detailed account of the various uses to which niobium is put. It can be quite simply stated that its practical applications lie in the field of ferro-alloys for which purpose the consumption of niobium metal rose by 27 per cent in the year 1966 alone.

It may however be of interest to recall that the influence of niobium on steel was discovered as long as thirty years ago. But it was not until 1958 that a metallurgist began to add niobium to carbon steels. Since that date, the steel industry has provided the largest market for the metal.

V. COMMERCIAL PROSPECTS

Before the deposits of carbonatitic pyrochlore were opened up, the niobium market was highly speculative, prices rocketing during times of international crisis or in war time.

The niobium industry now enjoys a variety of sources of supply. An increase in the output from deposits already being worked, or the opening up of new deposits, will make it possible to meet any additional demand, whether this arises from the normal growth of market requirements or from the discovery of new uses for the metal. There may, of course, be tight periods, but these should be short-lived, as national stockpiles will to some extent serve as buffer stocks regulating market conditions.

Moreover, the production of niobium will have to be adjusted not only to boom conditions, but also to slumps in the steel industry. But this danger is, perhaps, not immediate.

As a result of the steadily increasing use of niobium in the iron and steel industry, consumption of the metal is bound to undergo further considerable expansion.

Although it is still on the upward path, and seems to have a brilliant future, the niobium market should no longer, thanks to the arrival on the market of carbonatitic pyrochlores, be prey to the violent bouts of feverish speculation to which it was heir in the past.

GERMANIUM

I. ORES

Although it has its own specific minerals, such as:

Argyrodite	(Ag_8GeS_6)	containing	6.7 per cent	germanium,	
Germanite	(Cu_7FeGeS_{10})	"	8.7 per cent	"	,
Canfieldite	(Ag_8SnS_6)	"	1.8 per cent	"	and
Renierite	(a variant of germanite)	"	7.8 per cent		,

this metal is essentially a by-product of the smelting of lead and zinc ores.

II. SOURCES OF SUPPLY

1. <u>By-product of lead and zinc smelting</u>

Germanium is frequently found in zinc ores in amounts ranging from 0.01-0.1 per cent, and it was as a by-product of the zinc industry that the metal first appeared on the market.

The first industrial-scale operations were based on ores from the Tri-State district (Missouri-Oklahama-Kansas). Recovery of germanium was then extended to ores from a number of zinc ore-bodies in the Mississipi Valley, which are still one of the main sources of supply for the USA.

2. <u>Tsumeb deposit</u> (South-west Africa)

Thanks to its germanium-bearing lead and copper ores, <u>Tsumeb Corporation</u> has become the largest producer of germanium during the last few years.

Part of the germanium in the ore-body occurs as germanite and renierite, intimately associated with the copper, lead and zinc ores of the area.

The remainder of the germanium is scattered through the matrix of other minerals, being found in particular in enargite.

The free germanuim is recovered in the form of concentrates assaying 0.15 per cent of germanium.

The disseminated germanium collects in the copper-zinc matte at the smelter.

The throughput of the germanium plant is 15,000 kg of raw material a year.

3. Deposits in the Congo (Kinshasa)

The copper ores of Kipushi, in Katanga, contain a small percentage of germanium.

The metal is recovered in the copper smelters at Lubumbashi. The final stage of refining is carried out in Belgium.

4. Coals and fly ash (flyers)

Certain coals are germaniferous and their ash or flyers can assay up to 4 per cent of Ge.

It has been calculated that the ash and flyers of germaniferous coals in the United Kingdom carry away with them 2,000 tons of germanium every year. A small amount of germanium was indeed extracted from these wastes a few years ago.

III. PRODUCTION

Starting from nothing in 1948, production of germanium increased steadily to 20,000 lb. in 1953. The rate of growth has speeded up since then, production reaching 200,000 lb. in 1961.

Recent statistics are incomplete; moreover, they are distorted by the re-cycling of scrap and other wastes.

It seems that a peak was reached in 1961, followed by a bottom in 1964.

In 1965, consumption in the USA was 90,000 lb., including 60,000 lb. of re-cycling scrap and wastes.

Production appears to have been stationary in 1966.

Producers

The main producers are:

(a) in Europe:
  (i) Metallurgique de Hoboken (Belgium)
  Production capacity - 135,000 lb. of dioxide assaying 65 per cent of Ge.
  This is the largest plant in the world. It treats Congo ores.
  (ii) Société Vieille Montagne, at Balen in Belgium.
  (iii) The Viviers plant in France.
  (iv) Monteponi et Montevecchio (Italy)
  This company, which has a production capacity of 10,000 lb. a year, treats Sardinian lead-zinc ores. In 1966, the plant was working only at quarter capacity.

(v) Metall Gesellschaft (Federal Republic of Germany)
This company is reported to produce germanium, but its capacity is not known.

(b) in Japan:
There are five companies in Japan treating scrap and refining imported dioxide. They are reported to have produced some 35,000 lb. of germanium in 1966.

(c) in Africa:
The Tsumeb Corporation is believed to have a production capacity of about 30,000 lb.

Production capacity in the Congo is about 50,000 lb. Production reached this figure in 1960, but has declined sharply since; at present, it is running at about 30,000 lb. a year.

(d) in the USA:
There is a substantial number of producers/refiners in the USA, the chief of which are:

Eagle Picher Co.
American Zinc Co.
Sylvania Electric Products, Inc.
American Metal Climax, Inc.
Kawecki Chemical Co.
United Minerals and Chemical Corporation.

However, in 1966 the USA produced no more than about 7,000 kg of germanium; it appears, in fact, that this metal is being replaced by silicon to an ever increasing extent.

IV. PRICES

There has been a steady fall in the price of germanium over the past few years, as the following figures show:

	1963	1965
Pure metal	27 cents/gram	20.7-20.9 cents/gram
High-grade oxide	15 " / "	10.05 - 11.20 "/"

Prices dropped again in 1967: the pure metal was quoted at $175.25 per kg in April of that year, and the dioxide at $88.40 per kg (17.5 and 8.84 cents/gram respectively).

V. DEMAND

After having experienced a spectacular rise between 1948 and 1961, germanium production levelled off in the latter year.

The re-cycling of large quantities of manufacturers' scrap, the miniaturization of devices and the appearance of substitutes on the market have combined to weaken demand and push down prices right up to 1967.

Some experts believe, however, that consumption is likely to increase again, and foresee that it may reach some 150,000 kg. a year in about ten years' time.

They base their forecasts on the fact that competing materials, especially silicon, are not replacing germanium across the board, but are being used in neighbouring or complementary fields.

VI. COMMERCIAL PROSPECTS

It is difficult to foretell germanium's future. Its very remarkable physico-chemical and electrical properties, and the ease with which metal of high purity can be made, are still trump cards in its hand.

Lack of raw materials should not, it seems, impede its development. While not particularly abundant, reserves seem to be ample to keep the market supplied. In large measure a by-product of the zinc industry, its production seems certain to grow. The deposits of ores in Katanga and South-west Africa ought, moreover, to be able to cope with any unexpected increase in demand.

HAFNIUM

I. ORES

Hafnium and zirconium are always found together in nature, zirconium being the predominant partner.

The Hf/Zr ratio of the minerals rises with the degree of differentiation of the metalliferous matrix. The highest value is found in zircons paragenetically associated with minerals of niobium, tantalum and the rare earths.

However, generally speaking, zircons rich in hafnium are not found in sufficiently large quantities to be regarded as deposits.

The zircon ($ZrSiO_4$) in beach sands contains on average 1.5 per cent of hafnium.

The zircons from the hypercaline tin-bearing granites of Nigeria are distinctly richer in hafnium (close on 5 per cent) than those from ordinary non-differentiated running granites.

II. RESOURCES

It is estimated that reserves in the USA, Australia, India, the Ivory Coast, Korea, Madagascar, Nigeria and Uruguay total 23,400,000 tons of zircon, corresponding to approximately 234,000 tons of hafnium.

III. SEPARATION OF HAFNIUM

Hafnium is a by-product of zirconium. The separation of the two elements is a complicated matter. Two processes are at present in use:

(a) an American process, perfected at the National Laboratory at Oak Ridge; and

(b) a French process, perfected by the Commissariat à l'Energie Atomique /French Atomic Energy Authority/ (CEA).

IV. APPLICATIONS

Hafnium is mainly used in nuclear reactors.

Although belonging to the same group geochemically, zirconium and hafnium behave in diametrically opposite ways when exposed to thermal neutrons.

Whereas zirconium has a very low effective capture cross-section, hafnium has a very high one.

As the interest of these two metals for the nuclear industry lies in their diametricallic-opposed specific behaviour under neutron bombardment, it will be readily understood that they must be separated as completely as possible from one another.

Whereas zirconium is a non-absorbent cladding material, hafnium is a highly-sensitive coutrol material. Its very large neutron capture cross-section, its good mechanical properties and its excellent corrosion resistance in hot water make it a first-class material for the control rods of nuclear reactors.

It is also a good flux attenuator, used at points where there is a risk of the neutron flux becoming too strong, or increasing, if the distribution of some of the reactor fuel elements is modified.

Apart from nuclear uses, a number of other applications have been developed for hafnium: electric lamp filaments; electrodes for S-ray tubes; flash bulbs; ceramics; detonators; and as a constituent of various alloys. The cost of the metal is however a severe handicap in the development of these uses.

It is possible that hafnium-base alloys will find some uses in the space industry. The Illinois Institute of Technology is reported to have perfected, at the request of NASA /the National Aeronautics and Space Agency/, a "hafnium-tantalum" alloy which is regarded as of great interest as a material for sheathing the points or noses of rockets. This alloy is said to be on the point of industrial-scale production.

V. CONSUMPTION

It is the nuclear industry that has made the development of the hafnium industry possible. A good part of the metal available has, in particular, gone into the construction of the engines of nuclear submarines.

Current consumption in the USA is of the order of 50,000 to 70,000.lb.

VI. DEMAND

The very large programmes for building nuclear power stations that have seen the light since 1966 will entail large requirements in nuclear-reactor materials. Hafnium will no doubt have its share in this.

However, hafnium is not the only material with a large thermal neutron capture cross-section. Boron, cadmium, samarium, europium, gadolinium, golds silver and platinum are equally good in this respect.

Apart from hafnium, boron steels - stainless steels coated with silver, cadmium and indium alloys - have already been used for the control rods of certain types of reactor.

The existence of substitutes and the high cost of hafnium cast some doubt on the growth of demand for this metal, which may perhaps prove to be weaker than that for some other reactor metals.

VII. COMMERCIAL PROSPECTS

The output of hafnium will continue to be dependent upon the demand for zirconium even if, in order to increase it, those interested are obliged to turn to zircons with a high hafnium content.

The high price of hafnium - $ 100-150 per lb. - limits its field of application.

Production of hafnium in the USA should have risen to about 100,000 lb. in 1970, and it is believed that consumers will be in a position to absorb the whole of this output.

THE RARE EARTHS

I. ORES AND DEPOSITS

More than 170 minerals have been described that contain rare earths, though the latter are in most cases present only as accessory constituents. Most of the minerals also contain thorium, sometimes uranium, and often niobium, tantalum and zirconium as well.

The rare-earth minerals mainly belong to the groups comprising the phosphates, carbonates, fluocarbonates, fluorides, silicates, niobo-tantalates, rather complex tantalo-niobates and titanates.

Two minerals predominate as ores of the rare earths:

(a) monazite, a phosphate; and

(b) bastnaesite, a fluocarbonate.

At first, the rare earths were a by-product of the extraction of thorium for use in the manufacture of incandescent gas mantles.

When the gas-mantle industry started up at the end of the nineteenth century, the monazites from India and Brazil were greatly sought after because of their high thorium content (6-8 per cent); indeed, monazite was virtually the only ore used by mantle makers.

The interest evinced in radioactive minerals after 1945 led the principal producing countries to consider monazite as a strategic raw material and hence to forbid, or at least to control, its export.

The discovery, in 1949-1950, of the bastnaesite deposit at Mountain Pass provided the USA with a substitute ore which ended that country's dependence on foreign imports and gave a fresh impetus to the development of the rare-earth industry.

Accumulated stocks, and the introduction of greater flexibility into the quota system governing monazite exports, resulted in bastnaesite and monazite sharing the market from 1960 to 1965.

But since 1965 bastnaesite has been satisfying two thirds of the United States market, and its lead can no longer be denied.

In fact, the spread of the use of europium in colour television equipment gave a decisive advantage to the Mountain Pass bastnaesite, which is not only the largest known deposit of rare earths, but also one of the richest europium ores on the market.

1. Ores and deposits of monazite

Monazite - Ce, La, Y, Th(Si) PO_4 - is an orthophosphate of cerium (50-70 per cent) containing a small proportion of yttrium earths (1-5 per cent) and variable amounts of thorium and silica.

It is by far the most widely distributed rare-earth ore.

As a rule, monazite is a by-product of the working of beach sands (for the recovery of ilmenite, rutile and zircon) in Australia, India and Brazil; but in some cases - for example, in Madagascar - monazite may constitute the principal ore in such sands.

Monazite may also occur as a by-product of the working of detrital deposits of such primary ores as cassiterite and euxenite.

In Cape Province, in the Union of South Africa, a vein deposit of an unusual type, containing from 50 per cent to 60 per cent of monazite, was worked for several years and helped to supply the United States market during the embargo period.

World reserves of monazite are large. The following figures have been reported:

		Tons
South-west coast of India		1,400,000
Brazil	more than	400,000
Egypt		200,000
Madagascar		130,000
Malawi		13,000

2. Ores and deposits of bastnaesite

Bastnaesite - $(Ce,La,Pr,Nd,Sm)FCO_3$ - is a fluocarbonate of cerium containing a little thorium but practically free from yttrium. It assays from 29 per cent to 41 per cent of Ce_2O_3 and from 34 per cent to 46 per cent of $(La,Pr,Nd,Sm)_2O_3$, making a total of about 72 per cent of rare-earth oxides.

This mineral occurs in relatively few places.

The Mountain Pass deposit, in California, is the largest accumulation of rare earths yet discovered. It is genetically associated with a carbonatitic complex.

Reserves at Mountain Pass are estimated at 5 million tons of rare-earth oxides. The ore assays on average 7 per cent of rare-earth oxides and 20-25 per cent of barytes.

The ore is concentrated by flotation until it contains 63 per cent of oxides. The content is then brought up to 72 per cent by acid treatment, and finally, to 90 per cent, by roasting to expel the carbon dioxide and fluorine.

There is also a minor deposit of bastnaesite at Karonge, in Rwanda, from which a small amount of ore is mined.

3. Potential rare-earth deposits

A considerable number of minerals can be considered as potential sources of the rare earths: euxenite, gadolinite, fergusonite, brannerite, samarskite, allanite and apatite. Among these, apatite, despite its low rare-earth content, is of special interest, as the rare earths can be extracted from it as part of the process of manufacturing fertilizers (USSR, Poland, Finland).

II. PRODUCTION

The secrecy in which for a time nuclear materials were shrouded, the distaste of companies for disclosing their sources of supply and the very rapid development of the rare-earth industry over the last three years, have combined to make the relevant statistics far from precise.

1. Monazite

According to the United States Bureau of Mines, cumulative production of monazite between its inception in 1887 and 1963 can be broken down by source as follows:

Total world production	270,000 short tons
Source:	(percentage of world production)
Brazil	37.0
India	24.0
South Africa (since 1952)	22.0
United States of America	6.5
Australia	5.0
Malaysia	2.0
Indonesia, Ceylon, Korea, Thailand, Congo (Kinshasa), Madagascar and Nigeria } by difference	3.5

The next Table, taken from the same source as the last, gives the figures, in short tons, for world production of monazite concentrates for the years 1961 to 1965:

Producing country	1961	1962	1963	1964	1965
Australia	1,733	912	2,231	2,285	2,581
Brazil	1,263	4,277	2,448	733	658
Ceylon	83	-	-	25	40
India	-	3,233	2,678	-	-
Indonesia	111	153	169	154	28
Republic of Korea	854	755	-	-	-
Madagascar	503	702	678	1,063	1,196
Malaysia	779	702	991	340	777
Nigeria	9	10	12	13	9
Union of South Africa	5,326	2,300	-	-	-

(See also the following graph).

During the period 1960-1962, it seems, world production of monazite (excluding that in the USSR) can be roughly estimated at 15,000 tons.

From 1961 to 1963, the United States chemical companies processing rare earths imported 17,000 tons of monazite from the following countries:

Union of South Africa	75 per cent of total
Australia	15 " " " "
Malaysia and Ceylon	10 " " " "

The cessation of South African production in 1963 seems to have made Australia the largest producer of monazite in the world.

2. Bastnaesite

It was the introduction by the main producing countries of a system of quotas for their monazite exports that made it possible for work to begin at Mountain Pass. The opening up and exploitation of this deposit have pushed monazite into the background, and it looks as if Mountain Pass will play an even greater part in the years to come.

Before 1964, bastnaesite was used as a source of cerium compounds, and the sole interest attached to the Mountain Pass ore-body lay in the facts (a) that it was situated in the United States of America, and (b) that the marketing of the ore produced was not subject to quota. In practice, demand being weak, the deposit lay dormant.

When demand for europium began to rocket in 1965, the importance of Mountain Pass increased spectacularly, as the bastnaesite in this occurrence contains about one part per thousand of Eu_2O_3, which makes it a genuine europium ore. Hence, the Mountain Pass mineral can be regarded in two ways: either as an ore of cerium earths; ~~or~~ as an ore of europium. In the first place we are dealing with an ore containing 72 per cent of the valuable constituent; in the second, with one containing only 0.1 per cent. The demand for europium being the decisive factor, the cerium compounds have become a superfluous by-product, which at the moment is being stockpiled pending the discovery of an outlet for it.

The author has at his disposal no official statistics on the production of bastnaesite in the Unites States of America or Rwanda.

United States of America

Shipments of Mountain Pass concentrates increased twelve-fold between 1960 and 1963. Production again doubled between 1964 and 1965.

In 1965, the treatment of 37,500 tons of run-of-mine ore resulted in the production of a quantity of concentrates equivalent to nearly 3,000 tons of total oxides, or roughly three quarters of total consumption of oxides in the United States of America.

It is reported that in 1967 the capacity of the plant was to have been increased to 25,000 tons of concentrates, the production of which, with the plant operating at full capacity, would have meant milling 250,000 tons of run-of-mine.

Rwanda

Output at Karonge is not known. It seems that only parcels of a few tens of tons, or a few hundred tons, of concentrates are involved.

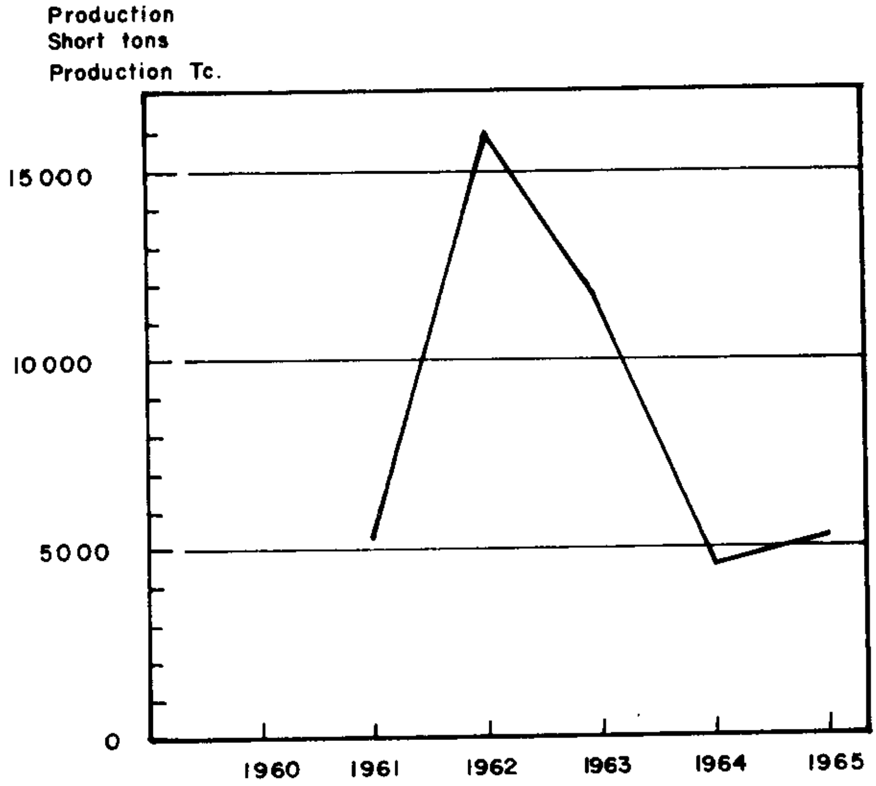
III. PRICES

The prices of rare-earth ores vary according to their content of total oxides and the nature or rarity of the latter.

From 1930 to 1947, the market price of monazite containing not less than 8 per cent of thorium was	\$60-65 per short ton
Between 1947 and 1956, it varied between	\$150 and \$440 per short ton

WORLD PRODUCTION OF MONAZITE CONCENTRATES, IN SHORT TONS
excluding USA and, for 1964 and 1965, India

PRODUCTION MONDIALE DE CONCENTRES DE MONAZITE
en Tonnes Courtes, sans USA (ni Indes en 1964–1965)



Sourse: Minerals Yearbook, 1965

In 1959, monazite containing 55 per cent of rare-earth oxides (excluding thorium) was worth	\$100 to \$150 per short ton
In 1965, Australian monazite was quoted on the London market at	\$126 to \$175 per short ton, c.i.f.
In 1967, sales of both monazite and bastnaesite were being negotiated on the basis of approximately	\$0.20 per lb. of oxide content.

The market for ores rich in europium has been highly speculative over the past two years. This speculative phase is now over, and prices are tending to fall.

At the end of 1967, the prices of europium ores had settled down to between \$150 and \$200 per lb. of Eu_2O_3 content, and were being fixed in terms of the content, the percentage and the chemical composition of the total oxides.

IV. GROWTH OF DEMAND

Up to 1940, the rare earths had virtually only two uses: as lighter flints; and for incandescent gas mantles. From that time on, cerium began to be used in polishing powders, and lanthanum in the glass industry. Demand was low, barely exceeding 2,000 tons of total oxides in the USA.

In fact, it was not until 1964 that the rare-earth industry really got off the mark.

In that year, the Sylvania Electric Company, a subsidiary of the General Telephone and Electronics Corporation, perfected a red phosphor for colour television based on europium and yttrium, the properties of which very definitely surpassed those of all other combinations capable of giving the desired red chrominance. This discovery was very quickly put to practical use.

In July 1965, Molycorp began to produce 500 lb a month, or three tons a year, of Eu_2O_3 from Mountain Pass bastnaesite.

The commercial prospects of the new product encouraged Molycorp to step up its production to 1,700 lb per month (or 20,400 lb per year corresponding to 10 tons of Eu_2O_3 at the beginning of 1967. Later, as the result of the sustained interest in europium and the debut of neodymium, the Corporation decided to build a plant with a capacity of 50 million lb (25,000 tons) of total oxides a year, or ten times the average yearly production between 1960 and 1963. Such an output would require the treatment of some 40,000 tons a year of bastnaesite concentrates and would yield about 20 tons of Eu_2O_3. In addition to europium and various pure oxides, Molycorp intends also to produce 200 tons a year of neodymium oxide.

The advent of colour television has led other europium producers also to increase their production capacity.

In France, the production of pure oxides at Pechiney-Saint-Gobain has so far amounted to about 10 per cent of world turnover in this sector.

V. COMMERCIAL PROSPECTS

It is not the author's intention to deal here with the conventional uses of the rare earths. As numerous as they are varied, they will certainly keep up with, and undoubtedly outstrip, the average rate of growth for industry as a whole.

In 1965, United States industries used the equivalent of 4,400 tons of rare-earth oxides, involving, after treatment, a turnover of $16 million, which can be broken down as follows on a percentage basis:

Yttrium and europium	39%
Misch metal, ferro-cerium and rare-earth alloys	20%
Polishing powders and glass industry	15-20%
Oil refinery catalysts	5-10%
Electric-arc electrodes	5%
Research, nuclear uses and other applications (by difference)	6-16%

The boom enjoyed by the rare-earth market thanks to the use of phosphors in colour television is quite remarkable.

In 1965, production, in lb of oxide, was double that in 1964.

In 1966, production rose by a further 20 per cent, while the turnover of marketed products was twice that in 1964.

The increase in availabilities of various oxides, by-products of the preparation of europium, cannot fail to stimulate research into the possibilities of using them.

The production of oxide for television phosphors will gradually work up to a steady rate of output. But the discovery of new applications could touch off an expansion of demand for, or even a fresh boom in, one oxide or another. It seems that this has already happened in the case of neodymium, as a result of the perfection of an "opticolour" screen-glass based on this metal, which enhances at one and the same time the brightness, the colour and the contrast of the picture. The amount of neodymium oxide required for each television set being, according to some sources, about $\frac{1}{4}$ lb, it will be readily understood that a market of several hundred tons a year could open up for this product if the "opticolour" technique is developed.

The substantial progress made in the field of rare-earth catalysts for the petroleum industry similarly opens up a vast field for expansion in a sector whose rate of growth is not to be denied.

The use of rare earths in metallurgy also seems set for some degree of development. The same is true of their use in mercury-vapour lamps, fluorescent lamps, special ceramics and the ferrite industry.

Having first left the cradle in 1964, the rare-earth industry has made remarkable progress in less than three years. Its growth is now ensured, and its future appears to be brilliant.

Bastnaesite, an ore of both europium and cerium, has taken the place of monazite as the major source of supply. In this respect, the market is dominated by the Mountain Pass deposit, which puts the rare-earth industry in the United States of America in general, and the Molycorp company in particular, in a favourable position.

TANTALUM

I. ORES

Although geochemically associated with niobium in various minerals, tantalum is much the rarer of the two. Demand by far exceeds supply. For this reason, consumers are not very particular about the tantalum content of the ores, treating, according to availabilities, rich tantalites, columbite-tantalites (containing 37-40 per cent of Ta_2O_5), stanniferous slags (containing up to 20 per cent of $Nb_2O_5 + Ta_2O_5$) **and, as opportunity offers, various other ores.**

The basically tantaliferous minerals are:

Tantalite: $(Fe,Mn)\ Ta_2O_6$.
Microlite: $CaTa_2O_6$.
Tapiolite: $FeTa_2O_6$.

The mixed minerals of niobium and tantalum are:

Columbite-tantalite: $(Fe,Mn)(Nb,Ta)_2O_6$.
Fergusonite: $(Y,Er,Ce,Fe)(Nb,Ta,Ti)O_4$.
Samarskite: $Ta_2O_5.Nb_2O_5.(Fe,Cu)O.UO_2.(Y,Ce)_2O_3$.
Euxenite: $(Y,Ca,Ce,U,Th)(Nb,Ta,Ti)_2O_6$.

In practice, the industrially important minerals are columbite-tantalite, tantalite and microlite.

Tin slags are also an important source of supply.

Turnings, scrap and other wastes from industries working tantalum-base materials are eagerly sought after and there is a truly international trade in them.

II. DEPOSITS

1. Columbite-tantalite, tantalite and microlite

Tantalite and columbite-tantalite are associated with the paragenesis of some types of pegmatite. These rocks are often stanniferous, in which case the tantalum minerals are a by-product of the extraction of cassiterite.

In most cases the workings involve weathered pegmatites or their alluvial secondary deposits.

With tantalite and columbite-tantalite no one country has a predominant position comparable to that of Nigeria in the case of columbite.

There are many occurrences of mineralized pegmatites in Africa and South America. Although some workings have been mechanized, many are still of the handicraft type.

The content of Ta_2O_5 and Nb_2O_5 varies from deposit to deposit. Assays of tantalum concentrates imported into the USA in 1965 gave the following values according to their origin:

	% Ta_2O_5	% Nb_2O_5
Australia	47	26
Brazil	45	13
Congo (Kinshasa)	38	4
French Guyana	44	37
Malaysia	41	26
Mozambique	56	17
Nigeria	42	5
Portugal	37	9
Union of South Africa	56	18

A. Reserves

Whereas reserves of niobium ores are large, those of tantalum in the western world are strikingly low, being estimated at less than 100,000 tons of Ta_2O_5 content, and the greater part of them not being economically workable.

Eighty per cent of the economically exploitable reserves are to be found in South America and in Africa.

B. Production

(a) World production

The table on the next page, and the graph on the next page but one, show the figures, in lb., for the world production of tantaliferous concentrates for the years 1961-1965.

Where the ore consists of equal proportions of Ta_2O_5 and Nb_2O_5, only half the production of concentrates has been included in the figures.

(b) Producers

There are many producers of columbite-tantalite and of tantalite, but information about their activities is fragmentary. What there is relates to 1965.

Portugal

Metallium Corporation is the largest Portuguese producer. The tantalite it markets is a by-product of its tin workings. The company recovers not only tantalite assaying 60 per cent of Ta_2O_5, as other producers do, but also columbite-tantalites containing from 35 per cent to 40 per cent of the oxide.

WORLD PRODUCTION OF TANTALUM CONCENTRATES
in lb.

	1961	1962	1963	1964	1965
South America					
Argentina (exports to USA)	4,444	3,637	4,519	-	-
Brazil (exports)	264,519	322,804	231,000	180,177	281,308
French Guyana	-	-	2,515.5	1,102.5	937
Europe					
Portugal (exports to USA)	29,793	95,692	72,711	32,281	47,772
Spain (" " ")	11,148	2,645	-	-	13,484
Africa					
Rwanda-Urundi	-	-	-	2,208	15,432
Congo (Kinshasa)	164,277	228,185	147,257	101,160	159,627
Madagascar	23,375	10,360	18,960	3,970	4,410
Mozambique	185,973	173,258.5	168,963.5	208,335	276,391
Nigeria	26,230	38,013	33,600	22,400	29,030
Southern Rhodesia	138,380	159,820	151,000	141,320	62,960
Union of South Africa	20,000	8,000	64,000	14,000	6,000
South-west Africa	5,790	10,444	4,143	1,027	1,135
Uganda	8,120	14,425.5	9,920.5	6,429	8,960
Australia	15,904	21,548.5	15,044.5	16,318	10,830
Total	897,953	1,088,832.5	923,634	740,727	918,276

Congo (Kinshasa)

No recent information is available.

Mozambique

The two principal producers are:

Sociedade Mineria de Morropino and
Emoresa Mineria de Alto Ligonha

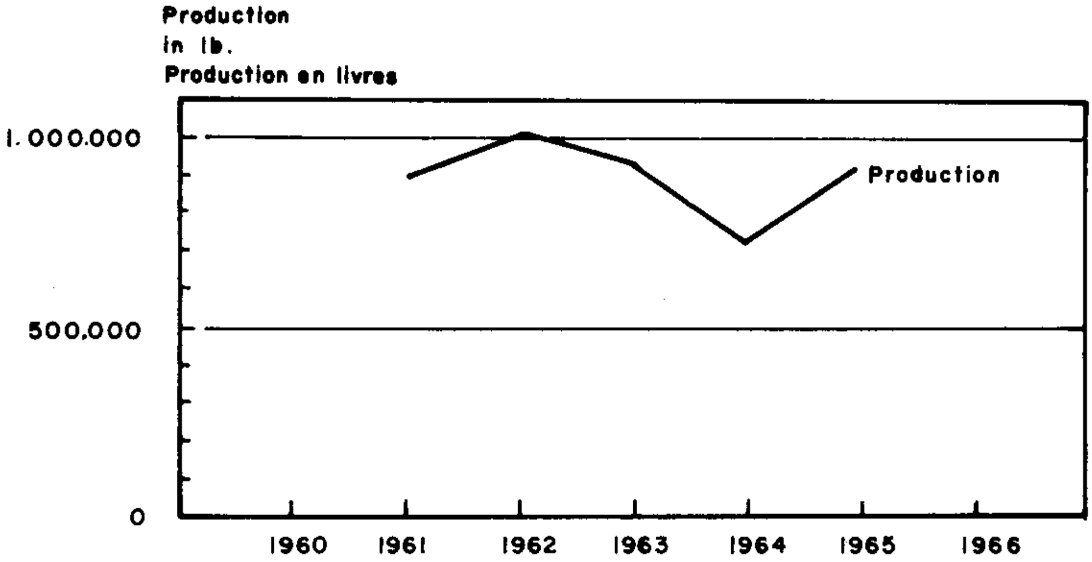
Southern Rhodesia

In 1965, the Benson Mine, north of Mtoko, was producing titanium concentrates from microlite.

At Kamativi, columbite-tantalite is a by-product of tin mining.

WESTERN PRODUCTION OF TANTALITE–COLUMBITE CONCENTRATES in lb.

PRODUCTION OCCIDENTALE DE CONCENTRES DE TANTALITE-COLUMBITE EN LIVRES



Source: Minerals Yearbook, 1965

South-west Africa

The three main producers are:

SWA - Lithium Mine (Pty), producing columbite-tantalite as a by-product of a beryl mine,

Atlantic Exploration Co. (Pty) Ltd. and

Tantalite Valley Mineral (Pty) Ltd.

Malaysia

Malaysian columbite-tantalite is a by-product of tin mining.

Thailand

The Thai Smelting and Refining Co., a subsidiary of the Union Carbide Corporation and the Eastern Mining Development Co., produces enriched slags with a high tantalum content as a by-product of its tin-smelting operations.

Australia

The Greenbushes Tin N.L. company started up a tin and tantalite mine at Greenbushes, Western Australia, in 1965. Output, only 3,800 lb. in 1965, should rise to 450,000 lb. in 1968. The concentrates assay 53 per cent of Ta_2O_5 and 19-20 per cent of Nb_2O_5.

The Pilbara and Yalgoo districts of Western Australia also produced 900 and 7,661 lb. respectively in 1965.

2. Tin slags

Tin slags may assay up to 20 per cent of Nb_2O_5 + Ta_2O_5.

The rarity of mineral ores of tantalum makes these wastes a highly-prized raw material for the tantalum industry.

Such figures as are available relate to US imports during the years 1963-1965.

	1963	1964	1965
		(lb. of oxide content)	
Stanniferous slags	30,968,743	2,516,153	8,822,136
Nb_2O_5 content	1,627,641	280,459	563,886
Ta_2O_5 "	1,410,778	140,538	428,911

If it is remembered that imports of tantalum concentrates into the USA amounted to 1,196,487 lb. in 1965, the great potential value of tin slags as a source of tantalum is plain. They alone accounted for nearly 34 per cent of the total Ta_2O_5 imported.

III. MARKET FEATURES

No new sources of raw material, like those unearthed in the case of niobium, have been discovered for tantalum, whereas the use of the metal is growing spectacularly.

The gap between supply and demand cannot fail to widen, and the exceedingly high prices accordingly commanded by tantalum ores are likely to hold up the justified expansion of utilization of the metal.

The latest available statistics bring out the following facts:

The largest producer - Brazil - put only 281,308 lb. on the market in 1965;

Mozambique came a very close second with 276,391 lb.;

Congo (Kinshasa) followed with 159,627 lb.;

Southern Rhodesia took fourth place with 62,960 lb.

Output by other producers was insignificant; in no single case did it exceed 30,000 lb.

Tantalite and columbite-tantalite are often by-products of the mining of cassiterite, beryl and other ores. The rhythm of their production thus depends on the demand for the main ore, and is therefore highly inelastic.

IV. PRICES

Their eminently strategic status as ores makes the market for tantalite and columbite-tantalite highly speculative. Prices can double, or even quadruple, from one year to the next.

A graph showing how the price per lb. of Ta_2O_5 content varied between 1940 and 1967 will be found on the following page. The fluctuations can be summarized as follows:

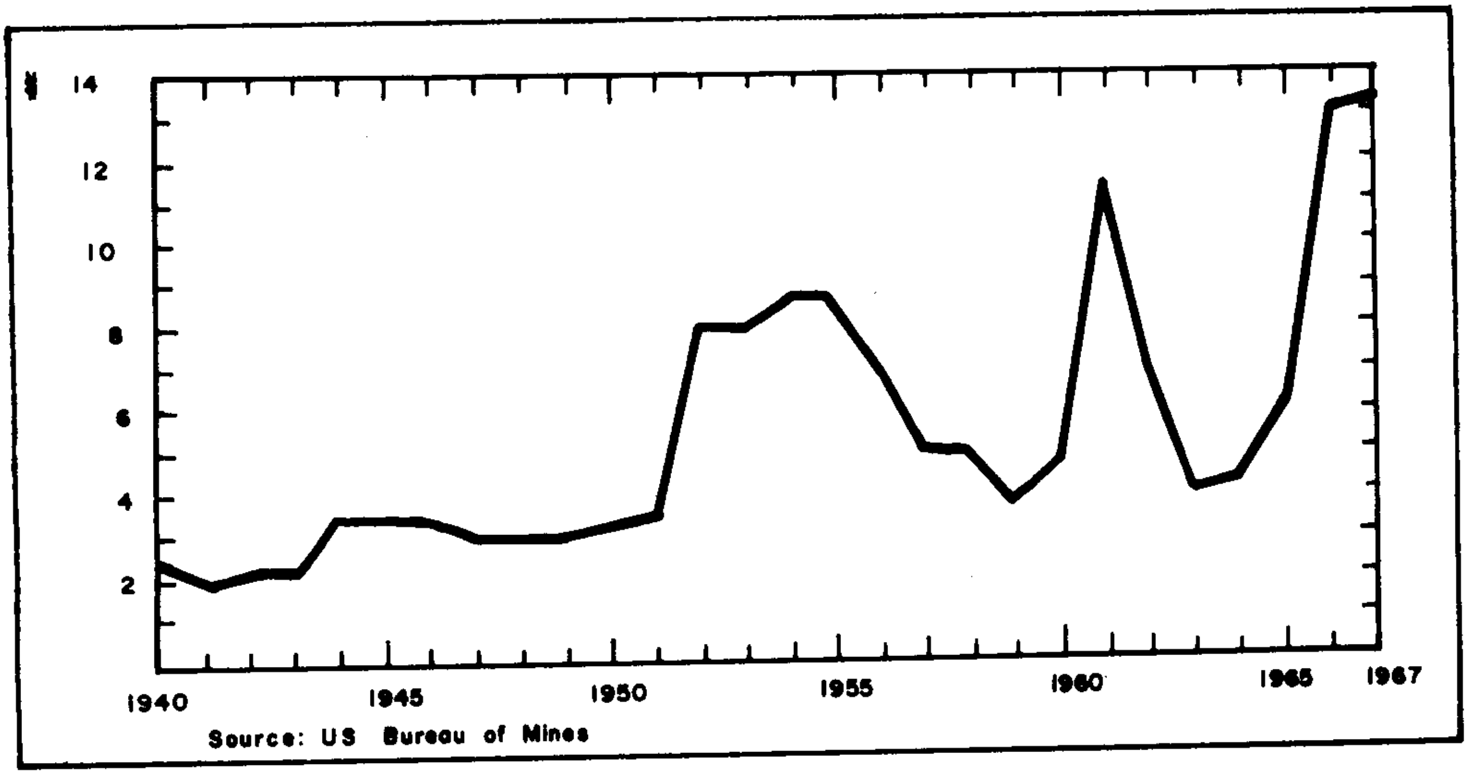
From 1940 to 1943 prices were of the order of	$ 2;
Between 1944 and 1946 they rose to	$3.50;
From then until the end of 1950, they settled down in the neighbourhood of	$ 3;
In 1951 they jumped to	$ 8;

VARIATIONS IN THE PRICE OF TANTALITE

$/lb. Ta_2O_5

EVOLUTION DES PRIX DE LA TANTALITE

en dollars par livre de Ta_2O_5



Source: US Bureau of Mines

Reproduced from: Engineering and Mining Journal
American Metal and Minerals Market, 1967

They reached a ceiling, maintained throughout the year, in 1954 of	$8.70;
From 1955 to 1959 there was an almost unbroken fall in the market, with the result that at the beginning of the latter year prices were down to just below	$ 4;
This fall was followed by a fresh spurt, as a result of which, by the beginning of 1960, prices had recovered to	$ 5;
Prices then rocketed during 1960, reaching at the beginning of 1961 a peak of	$11;
The ensuing collapse was as abrupt as had been the rise, and by the end of 1962 quotations had again fallen to	$ 4;
Relatively steady in 1963, prices rocketed again at the beginning of 1966 to a new record height of	$13;
Finally,	
Prices flattened out at this level for the whole of 1966, though with a slight tendency to rise even higher.	

V. GROWTH OF DEMAND

Virtually invulnerable to corrosion; with the highest melting point of all the elements; having a very low coefficient of expansion; remarkably ductile; very easily welded; insoluble in most acids and most molten metals - including plutonium - tantalum possesses properties which make it irreplaceable for many purposes. It undoubtedly has a brilliant future before it - a future bounded only by its rarity and its price.

The table on the next page shows how demand for and the use of tantalum have developed in US industry over the periods 1956-1960 and, in greater detail, 1961-1966.

In 10 years, the production of tantalum metal quadrupled, while that of ferro-columbium and ferro-colombium-tantalum increased five-fold.

Here we have a basic trend which, despite inevitable fluctuations, should certainly persist.

VI. COMMERCIAL PROSPECTS

Whereas niobium is mainly used in the manufacture of ferro-alloys, the remarkable physico-chemical properties of tantalum have conferred on it a much wider range of application.

At the moment, the electrical condenser industry is the largest consumer of tantalum metal.

Tantalum is also used in the chemical industry; in the manufacture of electronic equipment and in that of crucibles; in nuclear reactors; in blast-furnace hearths and heat exchangers; in jet engines and rocket motors; for the production of special steels and surgical appliances; and, lastly, for the production of tantalum carbides.

Irreplaceable for some of these purposes, tantalum is a metal of the future, demand for which must inevitably grow. Over-pricing of the metal alone can hinder its development and retard its rate of expansion.

Whereas there seems to be no limit to growth of demand, the same is not true of the quantities likely to find their way on to the market.

Tantalum is a rare metal and reserves are limited.

Recovery of old tin slags may provide some momentary relief, but cannot solve the problem of long-term supply.

Prospecting for new deposits - or for new types of deposit - of tantalum ores is therefore a very sound objective, since any discovery of any importance is bound to prove workable.

In the meantime, tantalum will remain a rare metal with a speculative market, and it can be assumed that quotations will be at the mercy of the release of strategic stocks; of international crises; of the whim of short-term demand; and of the use of substitute materials.

Growth of demand for and expansion of the use of tantalum metal

	Average 1956-1960	1961	1962	1963	1964	1965	1966
				All figures in lb.			
Tantalum metal produced	248,000	484,000	514,000	418,000	448,302	712,137	1,000,000
Tantalum concentrates imported	907,899	1,004,151	1,211,757	944,459	980,702	1,196,487	1,900,000
Consumption of ferro-columbium and ferro-columbium-tantalum (Nb + Ta content)	533,375	1,052,181	1,397,638	1,345,789	1,478,770	2,193,786	2,800,000

TITANIUM

I. ORES

Practically speaking, the titanium industry uses only two ores: ilmenite and rutile:

Ilmenite, $FeTiO_3$, accounts for roughly 90 per cent of supplies to the market;

Rutile, TiO_2, provides the rest.

II. DEPOSITS

Ilmenite is extracted either from beach sands or from the mother rock.

The mineral is present in many beach sands. Beaches in tropical countries are of special interest, for in such conditions weathering results in enrichment of the ilmenite, the TiO_2 content of which may rise to as much as 60 per cent, as compared with 53 per cent in the ordinary mineral.

Massive ilmenite is associated with the paragenesis of lodes of magnetite and haematite, met with in charnockitic and anorthositic complexes. The percentage of ilmenite varies from deposit to deposit. The grain size and structural features of the ore sometimes make it difficult to separate the ilmenite by straightforward physical methods. However, the metallurgical treatment of this type of ore yields slags very rich in TiO_2 (those from the Sorel smelter in Canada assay 70-72 per cent of TiO_2) which, together with ilmenite itself and rutile, constitute the basic raw materials for the titanium industry.

1. Reserves

Reserves of ilmenite and rutile are large. Estimates made in 1955 gave a figure of 2,000 million tons of known reserves at that date in the non-communist countries, equivalent to 250 million tons of TiO_2.

The USA and Canada each control about 25% of the tonnages just mentioned.

The Canadian ores, and a good part of those in the USA, consist of massive ilmenite.

Norway and Finland also possess large deposits of massive ilmenite, that at Tellnes in Norway containing about 350 million tons of ore.

There are deposits of grain ilmenite and rutile on the beaches of many countries: the largest are to be found in Australia, Florida (USA) and India.

Ceylon, Malaysia, Brazil, Madagascar, Egypt, the Union of South Africa and Senegal also have deposits of various sizes.

An alluvial deposit rich in rutile, and estimated to contain 30 million tons of ore, is at present being opened up in Sierra Leone. Planned output is 100,000 tons of concentrates a year.

2. Production

The table on the next page gives the figures for world production of titanium concentrates published by the US Bureau of Mines.

The ilmenite figures comprise grain ilmenite, massive ilmenite and Sorel slags.

The figures as a whole show the great progress made by Australia, whose output of ilmenite almost trebled in five years (1961-1965). Its production of rutile, too, more than doubled over the same period.

World production of titanium concentrates (excluding the USSR)

Producing country	1961	1962	1963	1964	1965
Ilmenite					
Australia	186,369	200,332	225,102	340,248	503,686
Canada	463,361	301,448	379,320	544,721	545,916
Finland	21,272	96,110	103,461	127,937	117,947
India	192,018	152,241	28,619	11,849	33,132
Malaysia	119,693	113,854	164,656	144,774	136,154
Norway	342,723	276,788	267,090	299,608	311,017
USA	782,412	807,725	888,400	1,001,132	969,459
Totals	2,331,500	2,170,200	2,190,200	2,587,700	2,728,000
Rutile					
Australia	113,603	133,499	205,251	201,640	240,746
India	898	1,781	2,062	2,062	1,452
Union of South Africa	3,483	3,575	1,385	-	-
USA	9,045	9,981	11,915	8,062	-
Totals	128,700	150,200	221,800	212,100	242,500

In 1965, Australia was virtually the only producer of the latter mineral.

The following facts emerge from the table:

The USA is by far the largest producer of ilmenite in the world, having by itself accounted for more than one third of total production in 1965.

Canada comes second, slightly ahead of Australia. All its output – representing approximately one fifth of world production of ilmenite – came from a single deposit – that at Allard Lake, Quebec, regarded as the largest occurrence of massive ilmenite in the world. The ore is marketed in the form of titaniferous slags produced during the treatment of the iron ores with which the ilmenite is associated.

With an output of more than 500,000 tons of concentrates of grain ilmenite from its beaches, Australia follows closely on Canada's heels. It is also in a most commanding position in respect of rutile in which it accounted for 93 per cent of world production in 1963, a share that rose to 97.5 per cent in 1965.

With an output of more than 300,000 tons of ilmenite, Norway comes fourth, accounting for a little more than 10 per cent of world production.

The only figures available for 1966 relate to Australia, which produced in that year 516,000 long tons of ilmenite and 245,000 tons of rutile.

These figures are appreciably more than 10 per cent higher than the corresponding figures for 1965.

The start up of operations at Sherbro Mineral's deposit in Sierra Leone will very greatly increase world output of rutile, as the plant will be producing 100,000 tons a year when it gets up to normal working capacity.

The graphs on the next two pages show variations in the production and prices of ilmenite and rutile since about 1956.

III. PRICES

The basic TiO_2 content on which prices of ores offered for sale are fixed has changed several times. Two rates are now quoted: one for ores containing 54.5 per cent of TiO_2, the other for those containing 59.5 per cent.

1. Ilmenite

The prices given below apply to shipments f.o.b. Atlantic port per long ton.

In 1939 and 1940, the prices quoted for 45-55 per cent TiO_2 ores ranged from	$10 to 12
From 1941 to 1944, for concentrates containing 60 per cent of TiO_2, they rose to	$28 to 30
From 1946 to 1948, 57-60 per cent TiO_2 concentrates changed hands at between	$18 and 20

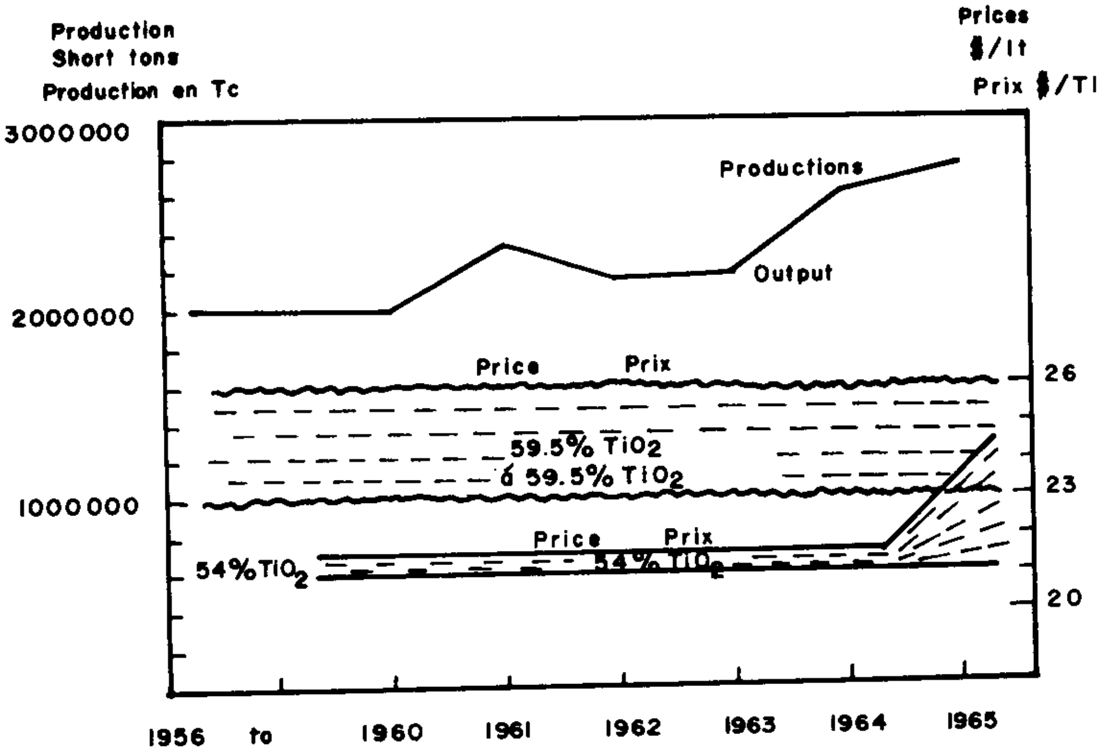
WORLD PRODUCTION OF ILMENITE CONCENTRATES
(excluding the USSR) in short tons

and

VARIATIONS IN THEIR PRICES F.O.B. US ATLANTIC COAST PORTS
in $/long ton

PRODUCTION MONDIALE DE CONCENTRES D'ILMENITE (sans l'URSS)
en Tonnes Courtes

ET EVOLUTION DE LEURS PRIX, F.O.B. PORTS USA DE L'ATLANTIQUE EN
dollars par tonne longue



NB: The price of slags was $ 43/long ton, f.o.b. Sorel, Canada, in 1965

N.B Le prix des scories était de $ 43/Tl, F.o.b. Sorel, Canada en 1965

Source: Minerals Yearbook, 1965

(Prices) Engineering and Mining Journal, American Mining and Metals Market

Prix. Source– AMMM de Engineering & Mining Journal

The fall steepened, a bottom being reached in 1949-1959, when the prices of 56-59 per cent TiO_2 ores dropped to no more than $14 to 16

From 1951 to 1955, prices recovered to between $18 and 20 but the basic content was raised to 59.5 per cent TiO_2. This figure, which had varied rather widely previously, has not changed since.

Since then, quotations themselves have not changed much, fluctuating during the period 1956-1964 over a range of $23 to 26

Finally, ores containing 54 per cent of Tio$_2$, for their part, were quoted at $21-21.5 from 1959 to 1965. In 1967, sales were being negotiated at between $21 and 24.

2. Titaniferous slags

The price of titaniferous slags assaying 70 per cent of TiO_2 hardly seems to have moved at all in recent years. Slags were quoted at $43 in 1965 and were still at the same level two years later.

3. Rutile

In 1950 rutile containing 94 per cent of TiO_2 was changing hands at between $ 50 and 90.

Prices continued to rise in 1951 to $105 - 125.

In 1952 they reached the then record height of from $140 to 170.

In 1953 there was an abrupt but short-lived fall to $100 - 200;

but in 1954 prices recovered to between $135 and 140,
rocketing in 1955 to between $230 and 300.
Thereafter a steady decline brought prices down to

in 1957 between $120 - 125

in 1958 " $ 95 - 100.

in 1959 $85.
and finally in 1960-1961 $80.

In 1962 quotations rose again to more than $100,

and in 1963-1964 they settled down at $104.

Finally, in February 1967, 96 per cent TiO_2 was rutile being quoted at between $119 and 121.

IV. GROWTH OF DEMAND

Titanium metal is much spoken about. Will not each US supersonic airliner (SST) absorb some 50 tons in its construction?

At the present time, however, practically all available titanium ores are consumed by the pigments industry in the form of the dioxide, TiO_2.

Up to 1965, 99 per cent of all the ilmenite consumed in the USA was going into this industry, and in 1965 itself demand from pigments manufacturers was still accounting for 95 per cent of total consumption of titaniferous minerals.

The consumption of rutile is less dependent on the pigments industry than is that of ilmenite. But it can be assumed that in 1965 more than half the rutile produced went into that industry, the welding industry and the titanium-metal industry taking the rest.

These figures show that the growth of demand for ilmenite and rutile will be mainly governed by the expansion of the pigments industry.

In the USA, the average annual rate of growth of requirements in TiO_2 by the pigments industry was 5 per cent over the period 1950-1963. This rate is expected to be maintained until 1980, which would bring demand up to 800,000 tons of TiO_2-equivalent in 1970, and to 1,200,000 tons in 1980.

The rarity and high cost of rutile will shift the burden of meeting the growth in demand on to the shoulders of ilmenite and slags. Experts believe, indeed, that the chloridization process used for the treatment of rutile will possibly become normal practice for the processing of ilmenite and slags too by 1970, and that it will certainly do so by 1980.

So far as rutile is concerned, the prospects of expansion differ greatly according to the end use to which it is to be put.

In the USA, coatings for welding rods should absorb about 23,000 tons of rutile in 1970, and 35,000 tons in 1980. However, ilmenite and slags will doubtless be able to meet part of this demand.

The use of rutile as a raw material for the production of titanium metal has brilliant prospects of development.

Between 1948 and 1963, the average annual rate of growth of titanium metal production in the USA was 15 per cent; between 1959 and 1963 it rose to 20 per cent. It appears that it might decline temporarily to 10-15 per cent a year, or even to below 10 per cent, shortly before 1970, but from then on the introduction of civilian supersonic aircraft should push it up above 20 per cent, as each SST will require 50 tons of titanium metal.

In 1964, some experts forecast that US demand for raw materials for the production of titanium metal would rise from 7,500 tons in that year to 17,000 tons in 1970 and to 70,000 in 1980. This forecast has already been overtaken by events, production of sponge titanium having increased to 20,000 short tons in 1966.

In principle, the growth of demand will largely affect rutile, though it could favour slags as well, should the price of rutile rise above $120 per short ton.

The requirements in titanium of the chemical industries and of plants for the desalination of sea-water can also be relied upon to expand; it is believed that the use of the metal in these fields will account for 25 per cent of the total output of titanium in 1970.

Development of the use of titanium in abyssal submarines could also open up very large outlets for the metal.

One obstacle to the expansion of the use of titanium is the price of the metal which is still high. Although this had already fallen very considerably, titanium metal was still about six times as costly as aluminium in 1967. There can be no possible doubt that, if prices continue to fall, the future of titanium, already highly promising, will set off a truly explosive expansion of demand.

V. COMMERCIAL PROSPECTS

The consumption of titanium ores depends on the liveliness of the pigment and paint industries. As these are expanding very steadily, demand for titanium ores cannot fail to increase.

Reserves of ilmenite are plentiful, especially of the massive variety. By contrast, reserves fo rutile are limited.

Technological progress gives ground for hope that ilmenite and slags will, in the medium term, be able to replace rutile for the uses for which it is specifically indicated.

Hence, ilmenite's part seems certain to increase. If the processes for treating ilmenite and enriching slags, now being perfected, come up to expectations, it is to be foreseen that expansion will largely affect ilmenite and, in particular, the massive variety.

YTTRIUM

Yttrium is distinguished by its atomic number - 39 - from the rare earths, which occupy numbers 57 through 71; but it is often classed with them because of the great common similarities in chemical properties.

We shall treat it here on its own merits, for it has its own ores and its own market.

The last to make its appearance on the economic scene, yttrium, like europium, owes its flying start to its use as a television phosphor. Europium plays the active part in assuring the desired red chrominance, but is effective only in the presence of yttrium. Each colour-television tube therefore requires some 3 grammes of europium and about 20 grammes of yttrium.

Still a laboratory curiosity in 1964, yttrium achieved the status of an industrial raw material within twelve months.

I. ORES

1. Xenotime

Xenotime is yttrium phosphate, YPO_4, and contains 61 per cent of Y_2O_3.

Yttrium is present in small quantities in many complex rare-earth minerals. It is true that it has its own specific mineral, xenotime, but this, relatively rare, is, very generally speaking, merely a by-product of various mining operations; it had not even been produced by selective separation when a market first opened up for it.

Detrital xenotime, which assays from 25 per cent to 30 per cent of Y_2O_3, is, however, now on the commercial market, Malaysia producing 200-300 tons a year.

Mauritania is also starting to produce vein xenotime, and this source will doubtless be able, if prices do not collapse, to supply one of the two European transforming companies.

2. Euxenite

Euxenite - $(Y, Ca, Ce, U, Th)(Nb, Ta, Ti)_2O_6$ - contains from 18 per cent to 21 per cent of yttrium compounds.

When demand began to develop, while waiting for yttrium ores to be located and for a market to be created, consumers were obliged to fall back on any of the range of yttrium minerals on which they could lay their hands: euxenite, gadolinite, etc.

Even so, the market could not have kept abreast of demand in 1966 had not two astute dealers lighted on the idea of recovering some 200 tons of the metal from euxenite tailings from the United States Government surplus stocks. This euxenite had been processed in 1950 to extract its uranium, and the tailings, packed in drums, were committed to the Mississippi. The drums would no doubt have succombed to corrosion and the tailings have been dispersed among the waters of the river had not the public, rightly or wrongly, objected to the dumping on the grounds that it would endanger the fish. The drums were thereupon fished out again and stored in a quarry taken over for the purpose, which thus later became the first "deposit" of yttrium to be worked.

Euxenite was also mined by more conventional methods in Idaho, and it seems that some of these diggings are still in production.

3. Spent liquors from the leaching of the uraniferous ores of Elliot Lake, Canada

The bright idea we have just described and the marketing of a number of parcels of xenotime, gadolinite and euxenite, and also of yttrium fluorite, gave the experts time to look for other, more regular and less chancy, sources of supply.

Such sources exist, and one of them is very attractive: the spent liquors from the leaching of the uraniferous ores of the Elliot Lake district of Ontario, Canada.

Each ton of Elliot Lake conglomerates contains on average:

2.5 lb of uranium oxide;
1.0 lb of thorium oxide; and
0.5 lb of rare-earth oxides (including, in all probability, 0.3 lb of Y_2O_3).

The carrier of the rare-earths being brannerite - $(U, Ca, Fe, Y, Th)_3 Ti_5O_{16}$ - the spent liquors after the leaching out of the uranium is complete constitute an important source of yttrium.

Rio Algom and Stanrock were the first producers to treat their spent liquors, beginning in 1966.

Denison Mine followed suit in 1967.

II. PRODUCTION

World production of yttrium oxide in 1967 can be put at between 110 and 120 tons.

The market seems to have been supplied:

(a) as to 80 per cent by spent liquors from the Canadian uraniferous ores; and

(b) as to the rest by Malaysian xenotime and, as an accessory source, by various rare-earth ores.

III. PRICES

When the market for yttrium came into being, conditions were highly speculative.

The prices cited below are per lb of Y_2O_3 content for ores assaying 30 per cent of the oxide:

(a)	In 1965, sales were negotiated at between	\$1.25 and \$4
(b)	During the first six month of 1967, a very lively rise sent quotations up to	\$20
	and even to	\$22
(c)	At the end of 1967, prices had again fallen to between	\$6 and \$7
(d)	In January 1968 offers for 30 per cent Y_2O_3 ores varied between	\$4.50 and \$6
	Offers of high-grade concentrates assaying 60 per cent of Y_2O_3 were also recorded at	\$11

IV. RESERVES

Reserves in the different types of deposit from which yttrium ores can be extracted as a by-product are large:

(a) The Canadian uranium deposits in themselves must contain 15-20 thousand tons of Y_2O_3 that could be recovered by treating the spent liquors. In this event, the amount of Y_2O_3 available would clearly depend on the demand for uranium.

(b) On average, yttrium accounts for 2.5 per cent of the rare-earths found in monazite, and the oxide is recovered during their extraction.

Bastnaesites are less rich in yttrium than monazites, their total oxide content including less than 0.2 per cent of yttrium. Despite this low content, the size of the Mountain Pass deposit makes it a large potential reserve of yttrium, estimated at 10,000 tons of yttrium oxide.

(c) Euxenite reserves in Idaho are put at 7,500 tons. As the mineral assays 20 per cent of Y_2O_3, this makes 1,500 tons of the oxide.

(d) Still in the USA, the rare-earth and thorium ore-bodies at Powderhorn, New Jersey, and at Wet Mountain, California, probably comprise potential reserves that could prove of economic interest.

Similar occurrences have recently been discovered in Mauritania and the deposit is now being surveyed.

(e) It is difficult to form an idea of potential reserves of detrital xenotime in Malaysia, but it seems that this region is in a position to continue to put some 200 to 300 tons of xenotime on the market each year.

(f) Apatite often contains appreciable amounts of Y_2O_3 which can be recovered during the manufacture of fertilizer from apatites rich in rare earths.

A Finnish company, Typpi Oy, is already engaged in such recovery, and produced 43.2 tons of the combined oxides of yttrium, europium, thulium, erbium and gadolinium in 1966. The company is said to be thinking of increasing its output of oxides to 400-500 tons, which could represent about 5 per cent of world production, which it is estimated will reach 10,000 tons a year by 1970.

If other companies follow the Finnish example, the treatment of apatites could provide 4,000 to 5,000 tons a year of rare-earth oxides.

The apatites associated with the magnetic iron ores at Mineville, New York state, USA, are particularly rich and may assay several per cent of yttrium oxide. They could be turned to economic advantage in the same way as the Finnish mineral.

The foregoing figures show that potential resources of yttrium are varied, and, in some cases large. After a brief period of gropping around, the mining industry has found a number of sources of supply, the development of which will depend on the evolution of demand and prices.

V. TRANSFORMING COMPANIES

Installed capacity in the transforming industries in 1967 could be put at some 250 tons of pure Y_2O_3. This was about double the figure for world production in the same year.

The main transforming countries are:

USA:	which accounts for 60 per cent of world production
United Kingdom:	which accounts for 20 per cent of world production
France:	which also accounts for 20 per cent of world production.

VI. GROWTH OF DEMAND

The main outlets for yttrium are the colour-television and electronics industries.

It is estimated that out of a world production of about 120 tons of Y_2O_3 in 1967:

(a) 110 tons went into the manufacture of colour-television phosphors; and

(b) 5-10 tons went into the ferrite industry.

VII. COMMERCIAL PROSPECTS

A mere three years ago, one might have wondered whether technical advances would not have made the use of yttrium in the colour-television industry a transitory phenomenon. It does not now seem that this will be the case. Yttrium has built up a sound position for itself, and fear of the appearance of substitutes is receding.

Colour television being, beyond any shadow of doubt, destined for very great development, demand for yttrium must continue to grow.

Known reserves are amply sufficient to keep up with the expansion of the market.

As ores, yttrium minerals are, in the great majority of cases, simply a by-product. Their marketing therefore depends on the demand for the ore or metal with which they are associated. As the market for uranium is on the point of opening up, it can be assumed that the spent liquors from the Canadian uranium mines will continue to be the main source of supplies of Y_2O_3 for a long time to come.

Indeed, this source seems to occupy a position rather like that of the Mountain Pass deposit in the rare-earth and europium fields.

It is nonetheless possible that some consumers of apatite rich in rare earths will start to recover the latter as the Finns are already doing; this factor could affect the relative importance of the two sources of raw material.

Xenotime, whether detrital or vein, will continue to provide a secondary source of supply capable of playing its part in stabilizing the market and in helping independent producers to avoid complete subjection to the consolidated Canadian producers.

After a very lively speculative phase in 1966 and 1967, sparked off by massive demand in a non-existent market, prices appear to have settled down for the time being around $5. However, the general trend is still downhill, and there can be no doubt that the market has still not found its lasting balance.

ZIRCONIUM

I. ORES

The zirconium ores used by the industry are:

Zircon ($ZrSiO_4$); and

Baddeleyite (ZrO_2), as a secondary raw material.

The main mineral worked is the zircon in beach sands. It contains on average 1.5 per cent of HfO_2.

About a dozen varieties of zircon are known; some contain various other constituents (rare earths, radio-active minerals); the others are the end-product of the alteration of zircon proper.

Hafnium always accompanies zirconium; the Hf/Zr ratio generally falls between 0.5:1 and 1.5:1. In some cases, the hafnium content is relatively high (Norwegian zircon, 5.1 per cent; cyrtolite, 14.4 per cent; and alvite, 13.6 per cent).

Zircons relatively rich in hafnium are usually altered. The alteration is probably promoted by the presence of thorium, the rare earths and/or uranium.

The hafnium content of Brazilian baddeleyite is less than 1 per cent.

Eudalite - $[(Na, Ca, Fe)_6 Zr [OH, Cl)(SiO_2)_6]]$ and Eucolite $[Na 13(Ca, Fe)_6 Cl(SiZrO_2, O_{52})]$, rather poor ores containing only about 13-14 per cent $ZrO_2 + HfO_2$ are apparently being worked in the USSR.

II. DEPOSITS

The only deposits of zircon and baddeleyite being currently worked are detrital in nature.

They comprise:

(a) black beach sands, where they are associated with ilmenite, rutile and monazite; and

(b) cassiterite and columbite placers in Nigeria.

In Brazil, baddeleyite is recovered either from stream gravels or from beach sands, or even mined from massive deposits.

1. Reserves

Known reserves in the free world are estimated at 23 million tons of concentrates, distributed as follows among the main producing countries:

USA	12,600,000 tons
India	3,400,000 tons
Australia	2,900,000 tons
Brazil	2,500,000 tons
Ceylon	1,000,000 tons
Union of South Africa	600,000 tons
Other countries	400,000 tons

2. Production

The following figures are expressed in short tons of ore containing 66-67 per cent of ZrO_2:

Main producing countries	1963	1964	1965	1966
Australia	187,800	183,940	227,840	240,000
USA a/	50,000	50,000	60,000	-
Brazil	2,400	520	NA	-
Senegal	3,070	550	-	-
Union of South Africa	2,400	-	-	-
Nigeria	800	-	-	-
Madagascar	390	510	640	-
Estimated world production	246,000	235,000	290,000	310,000

Source: United States Bureau of Mines - Estimates.

NA = Not available.

a/ Estimates, no production figures being available for the USA.

Production in the western world in 1966 can be estimated at about 310,000 tons, an increase of 3 per cent over the 1965 figure.

In that same year, Australian output rose by 5.5 per cent. Several producers in that country have announced development plans, and it is believed that total availabilities there could rise to around 340,000 tons in 1970.

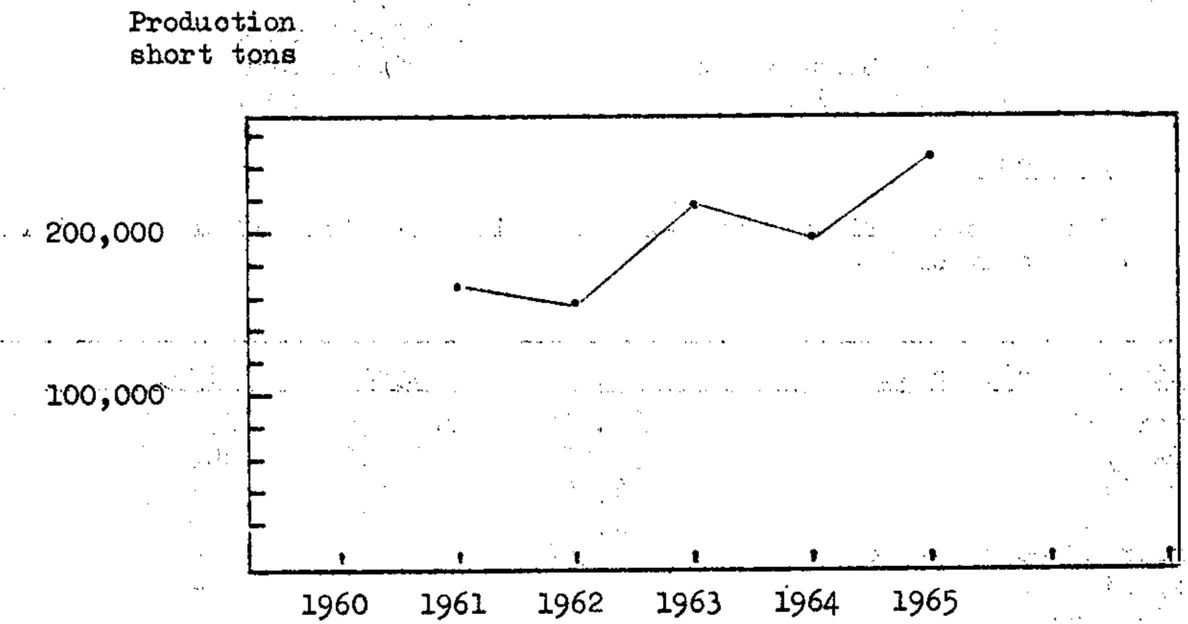
Thus, Australia has almost doubled its output since 1961, and is now capable of satisfying world demand for zirconium ores.

The Mineral Resources Office at Canberra estimates that world production will reach 415,000 tons in 1970, and that Australia itself should be capable of supplying 80 per cent of this.

The graph below recapitulates the general production figures previously given:

WESTERN PRODUCTION OF ZIRCON CONCENTRATES

in short tons (excluding USA and India)



Source: Minerals Yearbook, 1965.

III. PRICES

Zircon containing 66-67 per cent of ZrO_2, c.i.f. prices

	1963	1964	1965	1966
Francs	210 - 231	265 - 292	380 - 408	343 - 360
£ sterling	15.10.0 - 17	19.10.0 - 21.10.0	28 - 30	25.5.0 - 26.10.0

In 1967, zircon prices continued to decline slowly from the high levels reached in 1965:

(a) At the beginning of 1966, the ore was quoted, c.i.f. European port, at	£27.10.0 per ton
(b) After having fallen during the second half of 1966 to	£ 25 per ton
(c) It settled down at the beginning of 1967 at around	£25 - 26 per ton
The zircon produced in Florida was marketed in 1965-1966 at	£47.25.0 per ton f.o.b. Starke, Florida.

IV. CONSUMPTION

Zircon has many uses in a number of industries.

The USA is the largest world consumer of the ore.

Consumption by American industry in 1966 is estimated at some 110,000 tons. The breakdown by branch is roughly as follows:

	tons
Foundries	65,000
Refractories	25,000
Ceramics	10,000
Production of zirconium metal and compounds	10,000

V. USES

Consumption by the various branches of American industry gives a good idea of their relative importance, and an analysis of their needs will give some idea of the growth of demand.

1. Foundries

Zircon is better than silica quartz as foundry sand because of its higher thermal conductivity. It will replace silica for many purposes. This is a growth factor to be added to increase in demand linked with general industrial expansion.

2. Refractories

Zircon begins to soften only at temperatures approaching 2,000°C. It has good resistance to abrasion and to sudden changes of temperature, and a low coefficient of expansion. It is used in particular for the linings of aluminium-casting furnaces and glass furnaces.

Zirconia - ZrO_2 (melting point, 2,715°C) - and zirconium boride - ZrB_2 (melting point, 3,000°C) - are also excellent refractories. ZrB_2 in particular is used in the aeronautical industry and in space-rocket technology (for coating the shields of space capsules).

Finely ground zircon and powdered zirconia are used as opacifiers in the manufacture of enamels, as well as in that of porous cellular porcelains for electrical insulators.

Lastly, zircon is used in the production of special ceramics (especially for sanitary ware).

3. Other uses

Zirconium compounds are also used for a variety of other purposes, such as:

(a) the manufacture of welding electrodes;

(b) optical glasses (incorporated in the form of oxide or silicate, zirconium increases the refractive index of the glass and reduces its coefficient of expansion);

(c) as an abrasive for polishing optical glass;

(d) for leathing tanning agents;

(e) as mordants in dyeing;

(f) for waterproofing cloth; and

(g) as catalysts.

4. Zirconium

Although in the metallic form zirconium does not account for more than 10 per cent of total consumption of its ores, the use of the metal in the nuclear industry deserves some mention.

(a) Nuclear uses

The recent development of the zirconium-metal industry is directly bound up with the expansion of the nuclear industry. This is because the metal processes to a fairly high degree several of the properties sought after in this field, especially:

(i) low absorption of thermal neutrons;

(ii) good corrosion resistance;

(iii) satisfactory mechanical properties;

(iv) acceptable behaviour under irradiation; and

(v) a highly refractory nature (the metal melts only at 1,850°C).

The main use to which zirconium is put is for canning uranium fuel rods. It is necessary to cool the rods inside the reactor, but uranium itself is far too reactive to be allowed to come into contact with the liquid coolant. It must therefore be enclosed within a protective can which will not absorb thermal neutrons. The can also serves to prevent diffusion of the fission products - 25 per cent of which are in the gaseous state - into the coolant.

Moreover, in some types of reactor, in particular those intended for marine propulsion, zirconium forms part of the fuel itself in the form of a zirconium-uranium alloy.

Zirconium or its alloys are also used in the guide tubes, pressure piping and coolant-channel units in various types of reactor.

The part played by zirconium in the nuclear industry explains why production of this metal has risen from a few kilogrammes to more than 1,000 tons in about 20 years.

Demand has increased proportionately with the start-up and subsequent success of the new industry. A peak was reached in 1961 with an output of 170 tons.

The gradual improvement of competitive nuclear stations will later cause a decline in the rate of production.

The placing of orders for 25 nuclear power stations in some ten months of 1966 will certainly be a red-letter day in the history of zirconium.

The most recent developments in the technology of nuclear power plants have not belied the interest of the metal. It is to be expected that up to 1980 at least, and possibly also beyond that date, zirconium will remain the basic canning material for commercial reactors yet to be built.

The record output in 1961 was the work of six producers: four in the USA, one in Japan and one in France. A number of plants has been shut down since then, and at the time of writing only three (two American and one French) are still in operation.

The zirconium-metal industry is again keeping abreast of demand. Whereas production capacity for zirconium sponge fell to 2 million lb in 1965, it rose again to 3.5 million lb in 1967, and will have increased to 5 million lb by 1970.

(b) Other uses

Zirconium is also used in:

(i) The pyrotechnics industry, for the manufacture of flash bulbs, smokeless gunpowder, caps and fireworks;

(ii) The electronics industry as a "getter" for removing the last traces of oxygen and nitrogen from vacuum tubes;

(iii) Equipment for the chemical industry, because of its corrosion resistance in both acid and alkaline media; and

(iv) In surgery, for plates, screws and similar prosthetics to be inserted in the human body.

Demand arising out of the manufacture of flash bulbs is rising sharply. It doubled between 1963 and 1965, increasing from 20,000 to 40,000 lb.

VI. COMMERCIAL PROSPECTS

Any attempt to forecast the commercial prospects of zirconium ores must take the following factors into account:

(a) zircon, the most important ore, is a by-product of the working of titaniferous sands. A comparison of the rates of growth of demand for the two metals will make it possible to work out the general trend. Titanium itself being in a state of vigorous expansion, it is possible that at some periods production of zircon will outstrip demand;

(b) world reserves of zircon are relatively large. Those already proved are capable by themselves of keeping the market supplied for several decades;

(c) the foundry, refractories and ceramics industries are the largest consumers of zircon. Their expansion seems certain, so that their requirements in zircon should increase fairly steadily, unless economically interesting substitutes are developed;

(d) the zirconium-metal industry accounts for less than 10 per cent of total consumption of zircon. The massive surge in the construction of nuclear power stations will result in a very heavy demand for metallic zirconium. For some time, this will have only a moderate effect on world consumption of zircon. Indeed, demand for the metal would have to increase ten-fold before the consumption of zircon doubled; and

(e) the USA controls directly in Florida and, sometimes indirectly, in Australia a good part of the zircon-mining industry. It also has a dominating position in the zirconium-metal industry. But some European countries have started operations in this field, and their production capacity is not negligible.

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