IC 8917

Bureau of Mines Information Circular/1983

Aluminum Availability--Market Economy Countries

A Minerals Availability Program Appraisal

By G. R. Peterson and S. J. Arbelbide

UNITED STATES DEPARTMENT OF THE INTERIOR

50272-101

REPORT DOCUMENTATION PAGE

1. REPORT NO. BuMines IC 8917

2.

3. Recipient's Accession No. PB83 197129

4. Title and Subtitle
Aluminum Availability--Market Economy Countries. A Minerals Availability Program Appraisal

5. Report Date
March 1983

6.

7. Author(s)
G. R. Peterson and S. J. Arbelbide

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Minerals Availability Field Office
U.S. Bureau of Mines
Building 20, Denver Federal Center
Denver, CO 80225

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G)

12. Sponsoring Organization Name and Address
Office of Assistant Director--Mineral Data Analysis
U.S. Department of the Interior
Bureau of Mines
Washington, DC 20241

13. Type of Report & Period Covered
Information Circular

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

To determine the availability of aluminum from world bauxite resources, the Bureau of Mines investigated 139 bauxite deposits worldwide and evaluated the potential production of aluminum based on the demonstrated resources of bauxite ore from 91 mines and deposits in 22 market economy countries. The demonstrated resources of the bauxite mines and deposits included in this study represent an in situ resource of 20.2 billion metric tons of bauxite. Total identified bauxite resources in market economy countries amount to roughly 31.9 billion tons. Of the demonstrated resource, some 18.8 billion tons of bauxite considered minable provide a production potential of 3.6 billion tons of primary aluminum. Given the wide geographic distribution of bauxite deposits, stable supplies of bauxite for aluminum production seem assured well into the next century. However, a tight market situation could develop during the 1990's unless the real price of aluminum increases enough to stimulate massive new investments in production capacity, particularly in refining and smelting. This study indicates that a real price of at least $0.85 per pound (in January 1980 dollars) would be necessary to stimulate the required investments and provide a sufficient rate of return on invested capital.

17. Document Analysis a. Descriptors

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement:
Release unlimited by NTIS.

19. Security Class (This Report)
Unclassified

20. Security Class (This Page)
Unclassified

21. No. of Pages
31

22. Price

(See ANSI–Z39.18) *See Instructions on Reverse* OPTIONAL FORM 272 (4–77) (Formerly NTIS–35) Department of Commerce

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11. Contract/Grant Number. Insert contract or grant number under which report was prepared.
12. Sponsoring Agency Name and Mailing Address. Include ZIP code. Cite main sponsors.
13. Type of Report and Period Covered. State interim, final, etc., and, if applicable, inclusive dates.
14. Performing Organization Code. Leave blank.
15. Supplementary Notes. Enter information not included elsewhere but useful, such as: Prepared in cooperation with . . . Translation of . . . Presented at conference of . . . To be published in . . . When a report is revised, include a statement whether the new report supersedes or supplements the older report.
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    (b). Identifiers and Open-Ended Terms. Use identifiers for project names, code names, equipment designators, etc. Use open-ended terms written in descriptor form for those subjects for which no descriptor exists.

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19. & 20. Security Classification. Enter U.S. Security Classification in accordance with U.S. Security Regulations (i.e., UNCLASSIFIED).

21. Number of pages. Insert the total number of pages, including introductory pages, but excluding distribution list, if any.
22. Price. Enter price in paper copy (PC) and/or microfiche (MF) if known.

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UNITED STATES DEPARTMENT OF THE INTERIOR
James G. Watt, Secretary

BUREAU OF MINES
Robert C. Horton, Director

This publication has been cataloged as follows:

Library of Congress Cataloging in Publication Data

Peterson, Gary R., 1948-

Aluminum availability--market economy countries.

(Information circular / Bureau of Mines ; 8917)

Includes bibliographical references.

Supt. of Docs. no.: I 28.27; 8917

1. Aluminum. 2. Bauxite. I. Arbelbide, S. J. (Sylvia J.) II. Title. III. Series: Information circular (United States. Bureau of Mines) ; 8917

TN490.A5P48 1982 553.4'926 82-600327

PREFACE

The Bureau of Mines Minerals Availability Program is assessing the worldwide availability of nonfuel minerals. It identifies, collects, compiles, and evaluates information on active and developing mines, explored deposits, and mineral processing plants worldwide. Objectives are to classify domestic and foreign resources, to identify by cost evaluation resources that are reserves, and to prepare analyses of mineral availabilities.

This report is part of a continuing series of reports that analyze the availability of minerals from domestic and foreign sources and factors affecting availability. Questions about the Minerals Availability Program should be addressed to Chief, Division of Minerals Availability, Bureau of Mines, 2401 E St., NW., Washington, D.C. 20241.

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A Minerals Availability Program Appraisal

By G. R. Peterson[1] and S. J. Arbelbide[2]

ABSTRACT

To determine the availability of aluminum from world bauxite resources, the Bureau of Mines investigated 139 bauxite deposits worldwide and evaluated the potential production of aluminum based on the demonstrated resources of bauxite ore from 91 mines and deposits in 22 market economy countries.

The demonstrated resources of the bauxite mines and deposits included in this study represent an in situ resource of 20.2 billion metric tons of bauxite. Total identified bauxite resources in market economy countries amount to roughly 31.9 billion tons. Of the demonstrated resource, some 18.8 billion tons of bauxite considered minable provide a production potential of 3.6 billion tons of primary aluminum.

Given the wide geographic distribution of bauxite deposits, stable supplies of bauxite for aluminum production seem assured well into the next century. However, a tight market situation could develop during the 1990's unless the real price of aluminum increases enough to stimulate massive new investments in production capacity, particularly in refining and smelting. This study indicates that a real price of at least $0.85 per pound (in January 1980 dollars) would be necessary to stimulate the required investments and provide a sufficient rate of return on invested capital.

[1] Mineral economist.
[2] Geologist.
Both authors are with the Minerals Availability Field Office, Bureau of Mines, Denver, Colo.

INTRODUCTION

Demand for aluminum has grown at nearly 8 pct annually over the past two decades. Although this rate of growth is expected to decline to less than 5 pct through the end of the century (*9*, p. 42),[3] new bauxite sources will have to be developed and new alumina refineries and aluminum smelters will have to be built to satisfy the demand.

Although the Bureau of Mines and aluminum companies have conducted extensive research into the potential of domestic nonbauxitic sources of alumina, such as alunite, anorthosite, and clays (*18*), for the foreseeable future bauxite ore will most likely remain the sole commercial source of alumina for smelting into aluminum. Reasons for this include the following (*15*):

1. The aluminum industry is based on Bayer processed bauxite. A significant shift to another process and material would involve major technological changes requiring massive capital investments.
2. The aluminum industry has major overseas investments in the mining and processing sectors and in shipping installations.
3. The present industry-Government joint ownership of mines and other installations in some countries is based upon long-term agreements.
4. Processes for producing aluminum from kaolin and alunite cannot yet compete economically with the Bayer-Hall-Heroult technologies for producing aluminum from bauxite ore. With current state-of-the-art technology, the higher energy requirements for processing nonbauxite sources of aluminum in an era of high energy costs drastically reduce their production potential.

The major world bauxite resources are in West Africa, Australia, northeastern South America, and the Caribbean. Significant bauxite resources also exist in Europe and Asia. Limited metallurgical-grade bauxite reserves in the United States amount to some 38 million tons[4] or about 1.8 pct of the reserve base for market economy countries.[5] Approximately 96 pct of the aluminum produced in the United States is derived from foreign-source bauxite. Because of this dependence on foreign sources for such an essential raw material and because of its importance to the U.S. economy, this report identifies and assesses the potential availability of aluminum produced from bauxite resources in market economy countries.

The data collected for this report are stored, retrieved, and analyzed in a computerized component of the Bureau of Mines Minerals Availability System (MAS). After a deposit was included in the analysis, an evaluation of the operation was begun. The flow of the MAS evaluation process from deposit identification to development of availability information is illustrated in figure 1. This flowsheet demonstrates the various evaluation stages required to estimate the potential availability of aluminum from bauxite ore.

It is assumed in this study that each bauxite mine or deposit is part of a vertically integrated aluminum operation and that the owner of each deposit either controls its refining and smelting capacity or has the downstream processing performed on a toll-charge basis. With this assumption, the quantity of aluminum potentially available from the bauxite ore of each deposit can be estimated, as well as the long-run aluminum price required to bring about production from each potential operation or to keep existing producers in operation. The following factors had to be determined before the total production potential of aluminum from each operation could be ascertained:

1. The approximate annual production level of each bauxite deposit over the life of the mine.
2. The total capital and operating costs for each bauxite mine and mill.

[3] Italicized numbers in parentheses refers to items in the list of references preceding the appendixes at the end of the report.

[4] Unless otherwise noted, "tons" in the report refers to metric tons.

[5] Market economy countries are defined by the Bureau of Mines as all countries that are not considered central economy countries. Central economy countries comprise Albania, Bulgaria, China, Cuba, Czechoslovakia, German Democratic Republic, Hungary, Kampuchea, Laos, Mongolia, North Korea, Poland, Romania, the U.S.S.R., and Vietnam.

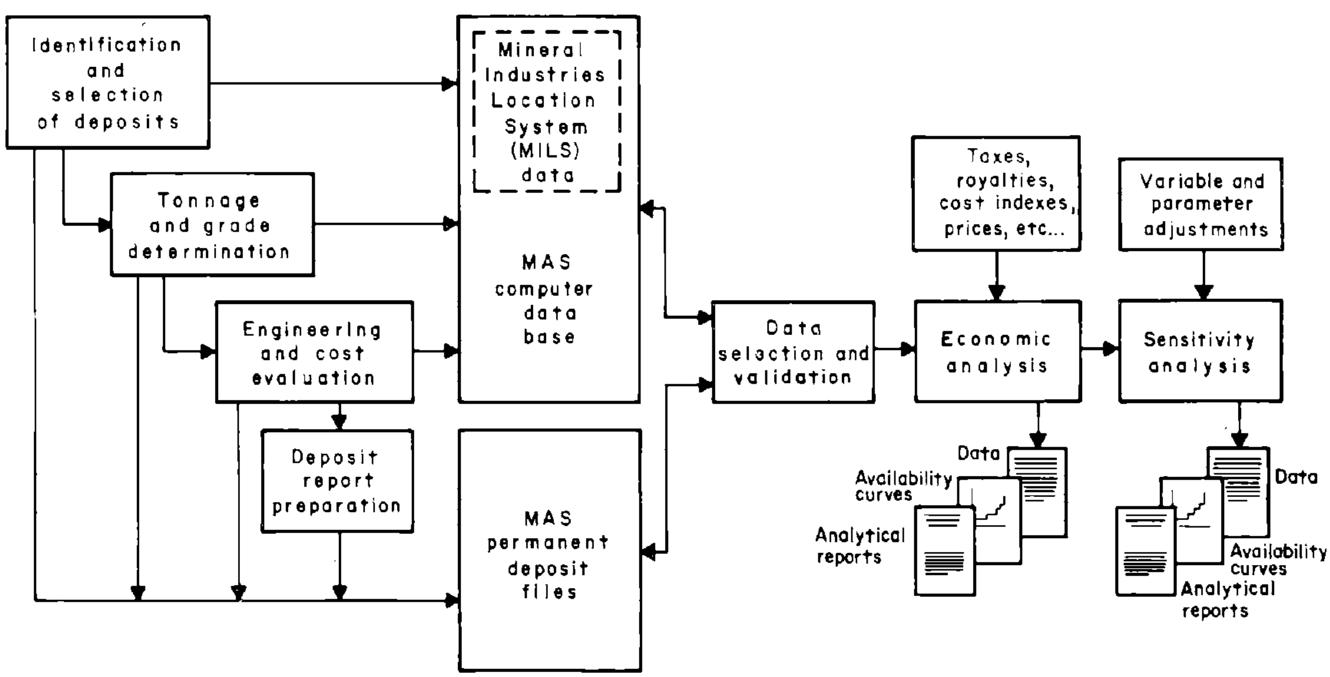

Figure 1.—Flowchart of the MAS evaluation procedure.

3. The cost of transporting bauxite to an alumina refinery or refineries.

4. The total capital and operating costs for each refinery or an estimate of the toll charge for alumina refining including depreciation and profit.

5. The cost of transporting alumina to an aluminum smelter or smelters.

6. The total capital and operating costs for each smelter or an estimate of the toll charge for aluminum smelting including depreciation and profit.

For currently producing aluminum operations, the designed mining, refining, and smelting production rates and capacities and other available production specifics were adapted for use in this study. For potential operations, appropriate mining and processing methods and production rates were based on existing mines, refineries, and smelters as models, and on current engineering principles.

When available, actual mining capital and operating costs were used. However, where actual cost data were not available, costs were either estimated by standardized costing techniques or developed by the Bureau of Mines Cost Estimating System (CES), a computerized version of the Bureau of Mines capital and operating cost manual (*22*). Data collection and cost estimation were performed under contract; personnel of the Bureau of Mines Minerals Availability Field Office in Denver, Colo., analyzed and evaluated the data. Actual refinery and smelter capital and operating costs were used when available; otherwise the capital and operating costs used were from cost models that were developed. Data were also collected from such other sources as professional journals, industry publications, and individual companies. Costs for nonproducing operations were derived from the above sources as well as from the International Bauxite Association (IBA) and feasibility studies on "greenfield"[6] refining and smelting projects.

Where an individual mine feeds more than one refinery, the transportation costs to the refineries and the refining costs were calculated on a weight-averaged basis. If the alumina goes to more than one smelter, the transportation, costs and smelting costs were also weight-averaged. Although an effort was made to simulate the actual flows from producing mines through the smelting stage, the scope of this study does not include an effort to match exactly the capacities of existing alumina refineries and aluminum smelters. For nonproducers, the materials flows are "best guess" estimates of where future capacity will be constructed. The assumed locations of alumina refineries and aluminum smelters to process the bauxite and alumina from each deposit are shown in table A-1 in appendix A. Refinery and smelter location is a critical assumption for a cost study of this type since refining and smelting account for the bulk of the capital and operating costs of an aluminum operation.

The following objectives served as guidelines in the conduct of this study:

1. To determine the demonstrated resources of significant bauxite deposits in market economy countries. Estimates of identified resources are also mentioned; however, in the availability analysis, only demonstrated resources are included. This was done because of the higher level of confidence in geologic and cost data at the demonstrated level and because of adequate demonstrated resources of bauxite to fulfill demand well into the future. Assuming that annual world production of bauxite remained steady at the 1980 level of 90 million tons, demonstrated resources of 22.8 billion tons would be adequate for about 253 years.

2. To evaluate the quantity of potential aluminum production from bauxite resources in market economy countries in relation to physical, technological, political, and other factors that affect bauxite production from each deposit.

3. To estimate (a) capital investments and operating costs for each bauxite deposit, (b) capital investments and operating costs (or toll charges) for downstream processing by alumina refineries and aluminum smelters, and (c) transportation charges to ship bauxite and alumina.

4. To perform an economic analysis of each operation to determine its average total production cost of aluminum over its producing life.

5. To aggregate and illustrate graphically total potential primary aluminum production and the average total cost of each operation, including a 15-pct discounted cash flow rate of return (DCFROR) on all investments.

ACKNOWLEDGMENTS

The authors express their appreciation to Luke Baumgardner, Bureau of Mines bauxite commodity specialist, for his assistance in determining the bauxite properties and the associated resource tonnages included in this report.

THE WORLD ALUMINUM INDUSTRY

Of the approximately 89.9 million tons of bauxite produced in the world in 1980 (table 1), 46 pct was provided by Australia and Guinea. Guyana, Jamaica, and Suriname accounted for an additional 21 pct. In all, the 11 IBA member countries accounted for 74 pct of the world's bauxite output in 1980. The United States imported 14.1 million tons of bauxite in 1980 (table 2), 70 pct from the Caribbean and eastern South America.

World alumina production in 1980 amounted to almost 33 million tons (table 3), with Australia and the United States accounting for 42.6 pct of total production. Although the United States produced 6.8 million tons of alumina in 1980, it also imported 4.4 million tons (table 4), of which 78 pct originated in Australia. The trend towards at-home alumina refining in bauxite-producing countries is a continuing structural change in the aluminum industry that began some 20 years ago. To reduce shipping costs and to take advantage of lower quality bauxite resources, the aluminum companies began to build alumina refineries in the bauxite-producing countries; thus, they convert the bauxite to alumina and cut the shipping costs in half. The bauxite-producing countries have also pushed for more at-home alumina production because of the economic contribution provided by the value added from the further processing of bauxite into alumina. Overall, 1 ton of alumina is worth approximately seven times as much as 1 ton of bauxite

[6] A "greenfield" project is a new project, often in a remote area, which must be developed from the ground up, including all necessary infrastructure.

Table 1.—World bauxite production[1]
(Thousand tons)

Country	1960	1970	1979p	1980e
IBA member countries:				
Australia	70	9,093	27,583	27,584
Dominican Republic	689	1,033	524	605
Ghana	228	339	214	225
Guinea	1,189	2,559	13,700	13,780
Guyana	2,511	4,015	2,312	2,348
Haiti	272	611	584	452
Indonesia	395	1,191	1,052	1,224
Jamaica	5,837	11,633	11,505	12,261
Sierra Leone	—	426	583	590
Suriname	3,455	5,174	5,010	4,696
Yugoslavia	1,025	2,033	3,012	3,138
Total IBA countries	15,671	38,107	66,079	66,903
Other countries:				
Brazil	121	484	2,388	3,970
France	2,068	2,956	1,969	1,665
Greece	884	2,207	2,915	2,950
Hungary	1,189	1,959	2,976	3,020
India	383	1,317	1,934	1,740
Malaysia	459	1,103	387	920
United States	2,030	2,049	1,821	1,559
U.S.S.R.[e 2]	3,556	4,134	4,600	4,600
Others	1,088	1,056	2,607	2,606
Total other countries	11,778	17,265	21,597	23,030
Grand total	27,449	55,372	87,676	89,933
Percent IBA countries	57	69	75	74

[e] Estimated. [p] Preliminary. — indicates 0 or negligible tonnage in the year shown.
[1] Table includes data available through July 1, 1981.
[2] In addition to the bauxite reported in the body of the table, the U.S.S.R. also produces alunite ore and nepheline syenite concentrates as sources of aluminum.

Table 2.—U.S. imports of crude and dried bauxite[1]
(Thousand tons)

Country	1960	1970	1980e
IBA member countries:			
Dominican Republic[2]	642	896	565
Guinea	—	—	4,112
Guyana	335	312	585
Haita	347	607	452
Jamaica[2]	4,242	7,384	6,146
Sierra Leone	—	—	75
Suriname	3,308	2,877	1,369
Total IBA countries	8,874	12,076	13,304
Other countries:			
Greece	—	57	—
Brazil	—	—	777
Other	5	287	6
Grand total	8,879	12,420	14,087
Percent IBA	99.9	97.2	94.4

[e] Estimated. — indicates 0 or negligible tonnage in the year shown.
[1] Includes bauxite imported to the U.S. Virgin Islands from foreign countries.
[2] Dry equivalent of exports to the United States.

exported as raw ore. Whereas in 1960 only 10 pct of the total world production of alumina was from the lesser-developed-country (LDC) bauxite producers, this percentage has grown steadily, to 34 pct in 1975 (*14*).

Primary aluminum production in market economy countries in 1980 was about 12,700,000 tons. As shown in table 5, the United States remained the largest aluminum producer in the world, producing 4,654,000 tons in 1980, which accounted for some 36.6 pct of the market economy countries' production that year. This share of world production will probably decline in the future because of the increasing cost of the electricity needed for aluminum smelting. Extremely energy intensive, the Hall-Heroult process requires 13,000 to 18,000 kWh of electricity per ton of primary aluminum produced. To produce 10.4 billion pounds of primary ingot, domestic aluminum smelters used some 78 billion kWh of electricity in 1978, 10 pct of the total electricity U.S. industry consumed in that year (*7*, p. 24).

Table 3.—World alumina production[1]
(Thousand tons)

Country	1970	1979p	1980e
IBA member countries:			
Australia	2,138	7,415	7,247
Guinea	610	660	708
Guyana	305	154	219
Jamaica	1,689	2,074	2,478
Suriname	998	1,325	1,316
Yugoslavia	125	836	870
Total IBA countries	5,865	12,467	13,010
Other countries:			
United States	6,485	6,450	6,810
U.S.S.R.	1,814	2,600	2,700
Japan	1,285	1,545	1,950
Germany, Federal Republic of	758	1,352	1,400
France	1,130	1,075	1,173
Canada	1,105	824	1,138
Italy	314	854	900
Hungary	441	788	800
China	254	750	750
Brazil	119	449	540
India	327	493	500
Romania	210	500	500
Greece	312	496	490
Turkey	—	140	140
Czechoslovakia	73	100	100
United Kingdom	107	88	90
Taiwan	42	58	65
Spain	—	—	58
German Democratic Republic	54	41	41
Grand total	20,695	31,067	32,983
Percent IBA	28.3	40	39.4

[e] Estimated. [p] Preliminary. — indicates 0 or negligible tonnage in the year shown.
[1] Table includes data available through July 1, 1981

Table 4.—U.S. imports of alumina[1]
(Thousand tons)

Country	1970	1978	1980e
IBA member countries:			
Australia	1,075	2,879	3,408
Guyana	34	30	17
Jamaica	787	628	634
Suriname	314	382	246
Total IBA countries	2,210	3,919	4,305
Other countries	107	48	56
Grand total	2,317	3,967	4,361
Percent IBA	95.3	98.7	98.7

[e] Estimated.
[1] Includes aluminum hydroxide; excludes shipments from the U.S. Virgin Islands.

Some 35 pct of the total domestic aluminum smelting capacity is in the Pacific Northwest, which receives hydroelectric power from the Bonneville Power Authority (BPA). The existing power contracts with the BPA are to expire in the next few years; thus, the companies will have to renegotiate new long-term contracts with the BPA at much higher rates, with the aluminum producers experiencing an increase from a price level of 6.2 mills/kWh to a rate in the range of 15 to 21 mills. Moreover, an increase in population and industrial growth in the Northeastern United States provides further competition to the aluminum industry for energy.

Utilities in a position to negotiate regular price reviews, like the Tennessee Valley Authority (TVA), are insisting on new prices reflecting costs of coal- or oil-fired power stations (*14*, p. 31). Increased fossil-fuel costs, environmental restrictions on smelters, and the current moratorium on nuclear energy construction affect other domestic aluminum-producing areas as well. Consequently, the industry has been reluctant to expand domestic primary production capacity, and companies have instead focused their attention on developing "greenfield" projects overseas in such countries as Australia, Brazil, Cameroon, Ghana, and Indonesia.

Table 5.—World primary aluminum production[1]
(Thousand tons)

Country	1960	1970	1980[e]
Market economy countries:			
United States	1,828	3,607	4,654
Japan	133	733	1,092
Canada	691	973	1,068
Germany, Federal Republic of	169	309	731
Norway	165	530	652
France	238	381	432
Spain	24	115	387
United Kingdom	29	40	375
Venezuela	—	23	313
Australia	12	204	304
Italy	84	146	271
Netherlands	—	75	259
Brazil	18	44	256
India	18	161	185
Yugoslavia	25	48	185
Ghana	—	113	170
New Zealand	—	—	156
Greece	—	87	145
Bahrain	—	—	126
Egypt	—	—	120
Argentina	—	—	119
Austria	68	90	94
Switzerland	40	92	86
South Africa	—	—	83
Sweden	16	66	82
Iceland	—	38	74
Taiwan	8	27	64
Suriname	—	55	50
Mexico	—	34	44
Cameroon	44	53	40
Turkey	—	—	31
Dubai	—	—	25
Republic of Korea	—	15	21
Iran	—	—	10
Market economy country total	3,610	8,059	12,704
Central economy countries:			
U.S.S.R.	676	1,100	1,788
China	80	127	363
Romania	—	102	241
Poland	26	99	91
Hungary	50	66	74
German Democratic Republic	40	59	65
Czechoslovakia	40	31	38
North Korea	—	—	10
Central economy country total	912	1,584	2,670
Grand total	4,522	9,643	15,374

[e] Estimated.—indicates 0 or negligible tonnage in the year shown.
[1] Table includes data available through May 25, 1981.

The world aluminum industry has been described as an oligopoly made up of six multinational firms: Alcan Alunimum, Ltd., Aluminum Co. of America (Alcoa), Reynolds Metals Co., Kaiser Aluminum and Chemical Corp., Pechiney Ugine Kuhlmann (PUK), and Swiss Aluminum, Ltd. (Alusuisse). Fully integrated, these companies occupy strategic positions in the industry, from producing raw materials to marketing both metal and end products. About 35 pct of world production capacity for bauxite, 50 pct of world alumina capacity, and 40 pct of world aluminum capacity is under their control. Moreover, through a variety of consortia arrangements, one or more of these firms is associated with practically all new projects of international significance within the industry.

In addition to these major international firms are some 50 others whose somewhat restricted aluminum operations account for about one-fourth of world production capacity for bauxite, alumina, and aluminum metal. Most of these producers are nonintegrated, and some are owned by or associated with either governments or the six large international aluminum companies (*20*, p. 4). Some 19 pct of world aluminum production capacity is controlled by communist governments, and about 22 pct is controlled by governments of other countries.

Of the 12 domestic firms producing primary aluminum metal in the United States in 1979, 7 owned and imported raw materials from their bauxite and/or alumina facilities in the Caribbean area, South America, Guinea, or Australia.

The six large international aluminum companies dominate the market for aluminum metal and metal goods. Producers' prices have shown a high degree of correspondence and stability. On the growing free market, metal from nonintegrated producers is offered on the London Metal Exchange (LME) on both spot and forward bases. The prices on the LME, tenuously tied to the producers' prices, more commonly tend to fluctuate in consonance with those of the LME quotations for other nonferrous metals (*19*, p. 115). Throughout the 1960's, aluminum prices stayed remarkably stable, both in current dollar and in real terms. Since 1974, worldwide inflation, increased costs for bauxite from IBA member countries, and the rising costs of energy have been factors in causing the aluminum price to increase approximately threefold as of August 1980.

IMPORTANCE OF SECONDARY (SCRAP) RECOVERY TO THE INDUSTRY

Recovery of purchased scrap contributes some 25 pct of the total domestic supply of aluminum. Scrap is divided into two main categories, new scrap and old scrap. New scrap is generated in manufacturing primary aluminum, semifabricated aluminum mill products, or finished industrial and consumer products. New scrap includes solids, such as new casting scrap; clippings or cuttings of new sheet, rod, wire, and cable; borings and turnings from the machining of aluminum parts; and residues, drosses, skimmings, spillings, sweepings, and foil (*20*, p. 7). Old scrap, from discarded, used, and worn-out products, includes aluminum engine or body parts from junked cars, used aluminum cans and utensils, and old wire and cable. The proportion of total domestic metal consumption met by the recovery of old scrap amounted to about 10 pct in 1979 (*12*).

DEMAND FOR ALUMINUM

Between 1975 and 2000, domestic primary aluminum demand is expected to increase threefold, with an average annual rate of growth estimated from 4 pct (*13*) to 5.3 pct (*20*), or slightly lower than the estimated rate of growth for the world demand as a whole over the same period. The United States will likely remain the world's largest consumer and one of the world's largest producers of aluminum during this period.

U.S. dependence on foreign primary aluminum production is growing. One estimate (*25*, p. 33) forecasts that domestic bauxite production will satisfy a decreasing share of demand, that alumina refining will drop from over a 70-pct share in the U.S. market in 1977 to under 40 pct by the year 2000, and that domestic aluminum smelting will drop from over 90 to 80 pct during the same period. At the same time, user segments of the domestic market will continue to grow. In 1979, the major domestic markets, in descending order of market share, were building and construction, transportation, the electrical sector, consumer durables, and machinery and equipment. In housing, the demand is growing for roofing, window frames, aluminum siding, and insulation. In durables, more aluminum is being used to improve efficiency and to increase service life. In the electrical sector, aluminum is used mainly for overhead power transmission lines. Aluminum alloys are becoming more attractive as a substitute for steel in the automotive industry because of the weight factor, and aluminum is becoming more popular in packaging because much of it is recyclable.

THE IMPACT OF OPEC AND THE FORMATION OF THE IBA

The International Bauxite Association (IBA) was formally established at a meeting in Conakry, Guinea, in March 1974. Seven bauxite-producing nations became the original members: Australia, Guinea, Guyana, Jamaica, Sierra Leone, Surinam and Yugoslavia. The Dominican Republic, Ghana, Haiti, and Indonesia soon joined, for a current total membership of 11 nations which cumulatively produce approximately three-quarters of the total world bauxite output.

The objectives of the IBA are stated in the Final Act of the International Conference of Bauxite Producing Countries (also referred to as the Conakry accord), consisting of 28 articles expressing the objectives and ground rules for the organization. The basic objectives are (*17*, p. 166):

1. To promote the orderly and rational development of the bauxite industry.
2. To secure for member countries fair and reasonable returns from the exploitation, processing, and marketing of bauxite and its products for the economic and social development of their peoples, bearing in mind the recognized interests of consumers.
3. Generally, to safeguard the interests of member countries in relation to the bauxite industry.

Interest in developing a producer association for bauxite had existed for several years before 1974 because the bauxite-producing nations were dissatisfied with the fiscal revenues generated by their respective bauxite industries. Guyana took the extreme move of fully nationalizing the Demerara Bauxite Co. from Alcan Aluminum, Ltd., in 1971. The Guyana Government, wishing to use its hydroelectric potential to integrate into smelting primary aluminum, believed that nationalization was the means to achieve its (as yet unfulfilled) objective. Surina's net revenues from the industry had not improved since the 1950's, even though the country had a large alumina refinery and the only aluminum smelter in the Caribbean. Jamaica, the leading Caribbean producer, was frustrated by the lack of significant revenues from its large alumina output and anticipated no further expansion of its industry by the aluminum companies. Taxes paid to the Jamaican Government amounted to only $1.77 per long dry ton of bauxite output in 1973 (*4*, p. 121).

The final inducement for forming a producer association was supplied by the Organization of Petroleum Exporting Countries (OPEC) in the fall of 1973. From an earlier level of $1.80 per barrel, the price of OPEC crude oil was raised to $2.59 in early 1972, doubled to $5.11 in October 1973, and doubled again in December to $11.65—a six-fold increase (*17*, p. 83). Jamaica faced an oil-import bill that tripled from $55 million in 1972 to $165 million in 1974. Jamaica's international monetary reserves were reduced to a level equal to only 1 month's worth of its imports. In response to this OPEC-induced economic crisis, Jamaica unilaterally announced in January 1974 that it would seek to renegotiate the existing bauxite contracts with the aluminum companies, since the "doctrine of changed circumstances" was applicable because of higher oil prices. Once the aluminum companies acceded to Jamaican demands for a bauxite levy, the other Caribbean bauxite-producing nations followed suit by announcing their own versions of a bauxite levy. When the IBA was founded in 1974, all its members except Australia adopted some form of a bauxite levy or equity participation in their respective industries.

IDENTIFICATION AND SELECTION OF BAUXITE DEPOSITS

The only commercial source of primary aluminum in the market economy countries is bauxite ore. Because nonbauxitic sources of aluminum will not become economically competitive with bauxite in the foreseeable future, this study discusses only the availability of alumimun from bauxite ore. Information on the domestic availability of alumina from nonbauxitic sources is detailed elsewhere (*18*).

For the bauxite deposits analyzed in this report, tonnage estimates were made at the demonstrated resource level according to the mineral resource classification system (fig. 2) developed jointly by the U.S. Geological Survey and the Bureau of Mines (*24*). The demonstrated resource category includes measured plus indicated tonnages.

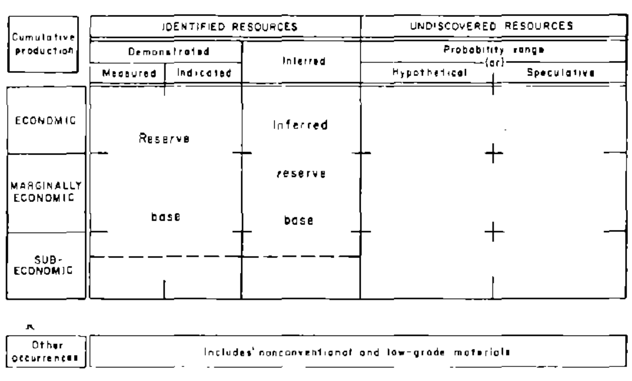

Figure 2. — Reserve-base and inferred reserve-base classification categories.

Selection of deposits for this study was limited to significant, known deposits that have demonstrated resources. Most reserve and resource tonnage and grade calculations presented herein have been computed partly from specific measurements, samples, or production data and partly from estimations made on geologic evidence.

The world bauxite reserve base, as estimated by the Bureau of Mines, amounts to 22.4 billion tons of bauxite ore, of which about 21.2 billion tons are in market economy countries. Based on data from the Bureau of Mines, U.S. Geological Survey, and IBA, the authors of this report estimate that world bauxite resources at the identified resource level (which includes measured, indicated, and inferred reserve categories) are 33.4 billion tons. Of that amount, 31.9 billion tons are in the market economy countries. In addition, the U.S. Geological Survey and the Bureau of Mines estimate that total world bauxite resources (identified plus subeconomic and undiscovered resources) amount to 40 to 55 billion tons (*16*). The IBA (*11*) reports a more optimistic total world resource figure of 103.4 billion tons. Regardless of the source of data, worldwide bauxite resources are extensive and will likely increase further as a result of exploration activities.

This study is based upon the availability of aluminum from 91 bauxite properties in 22 countries, which have demonstrated bauxite resources of 20.2 billion tons, accounting for almost 96 pct of the reserve base for market economy countries. An additional 48 bauxite properties also investigated for this study were not evaluated since many of them contain only inferred resources, were relatively small and/or low grade, contained only chemical or refractory-grade bauxite (which could be used to produce cell-grade alumina, but probably would not be because of its higher grade and therefore higher value), or were in countries where reliable cost data are unobtainable. The list of deposits investigated but not included in this study is shown in table A-4. Estimates of total bauxite resources in market economy countries (at the demonstrated and identified resource levels) are shown in table 6, and information on the individual properties included in the analysis is presented in table 7.

Table 6. — Bauxite resource information for market economy countries

Country	Number of deposits evaluated	Demonstrated in situ material[1]		Identified in situ material[2]	
		Thousand tons	Percent of total	Thousand tons	Percent of total
Caribbean:					
Dominican Rep.	1	15,600	0.08	45,000	0.14
Haiti	1	14,000	.07	14,000	.04
Jamaica	15	2,000,000	9.90	2,000,000	6.27
Total	17	2,029,600	10.05	2,059,400	6.45
United States	3	38,000	.19	40,000	.13
South and Central America:					
Brazil	7	2,270,300	11.22	4,070,000	12.75
Columbia	–	—	—	83,000	.26
Costa Rica	1	78,500	.39	150,000	.47
French Guiana	1	42,000	.21	170,000	.53
Guyana	11	519,000	2.56	1,016,000	3 18
Suriname	4	577,900	2 86	600,000	1 89
Venezuela	1	236,000	1 16	500,000	1.57
Total	25	3,723,700	18.40	6,589,000	20.65
Africa:					
Cameroon	1	800,000	3.95	1,500,000	4.70
Ghana	3	558,100	2.76	780,000	2.44
Guinea	6	5,625,000	27.80	8,200,000	25 69
Malawi	1	28,800	.14	70,000	.22
Mali	–	—	—	880,000	2 76
Sierra Leone	2	161,400	.80	161,400	.51
South Africa	–	—	—	20,000	.06
Total	13	7,173,300	35.45	11,611,400	36.38
Europe:					
France	6	43,800	.22	43,800	.14
Greece	4	600,000	2.96	700,000	2.19
Turkey	1	16,800	.08	30,000	.09
Total	11	660,600	3.26	773,800	2.42
Asia:					
India	8	1,181,000	5.83	1,900,000	5.95
Indonesia	2	805,000	3.98	805,000	2.52
Malaysia	–	—	—	15,000	.05
Philippines	–	—	—	60,000	.19
Total	10	1,986,000	9.81	2,780,000	8.71
Oceania:					
Australia	10	4,574,700	22.60	8,000,000	25.07
Solomon Islands	2	50,300	— .25	60,000	.19
Total	12	4,625,000	22.85	8,060,000	25.26
Grand total	91	20,236,200	100.00	31,913,200	100.00

— Indicates 0 or negligible tonnage in the year shown.

1 Excludes Yugoslavia. Demonstrated tonnage is from the 91 mines and deposits evaluated for this study.

2 Identified resources are measured plus indicated plus inferred resources. The identified tonnages are country totals, not just from the deposits evaluated.

Note. — Resource figures, by country, have been rounded to the nearest hundred thousand

Table 7. — Bauxite property information, January 1980

Location and property name	Ownership	Status[1]	Type[2]	Stripping ratio[e] (waste to ore)	Type of ore
Arkansas:					
Alcoa Bauxite	Alcoa	P	S	6.1:1	Gibbsite, some boehmite, 50 pct Al_2O_3, 13 pct silica.
Quapaw bauxite mine	American Cyanamid	P	S	2.6:1	Gibbsite, some cliachite and kaolinite, 43 pct Al_2O_3 (wet)
Reynolds surface mine	Reynolds Metals	P	S	8:1	Gibbsite, some boehmite, 50 pct Al_2O_3, 13 pct silica.
Australia:					
Aurukun	Billiton-Pechiney	N	S	0.1:1 to 1:1	Mixed, 53 pct Al_2O_3, 6 to 8 pct silica.
Cape Bougainville	Alumax-Mitsui-Nippon Steel	N	S	0.13:1	Gibbsite, some boehmite, 36 pct Al_2O_3, 1.9 pct silica.
Chittering (Muchea)	Pacminex-Hanwright-Metals Miniere	N	S	0.33:1	Gibbsite, some boehmite, 30 to 35 pct Al_2O_3, 1 to 2 pct reactive silica.
Gove	Swiss Aluminum Australia Ltd.-Gove Alumina Ltd.	P	S	0.29:1	Gibbsite, some boehmite, 50.4 pct Al_2O_3, 2 to 6.5 pct silica.
Huntly-Del Park	Alcoa Australia	P	S	0.13:1	Gibbsite, some boehmite, 32.5 pct Al_2O_3, 15 to 22 pct silica, 1 to 2 pct reactive silica.
Jarrahdale	do	P	S	0.13:1	Gibbsite, some boehmite, 32.5 pct Al_2O_3, 15 to 22 pct silica, 2 to 3 pct reactive silica.
Mitchell Plateau	Mitchell-Alumax-Sumitomo	N	S	0.13:1	Gibbsite, some boehmite, 47 pct Al_2O_3, 2 to 3 pct silica.
Mount William (Wagerup)	Alcoa of Australia	N	S	0.13:1	Gibbsite, some boehmite, 32.5 pct Al_2O_3, 15 to 22 pct silica, 1 to 2 pct reactive silica.
Weipa-Andoom	Kaiser-Rio Tinto-public	P	S	0.31:1	Mixed, mainly gibbsite, 48 to 56 pct Al_2O_3, 4.5 to 9 pct silica.
Worsley (Mount Saddleback)	Reynolds-Worsley Alumina Pty. Ltd.	N	S	0.33:1	Pisolitic gibbsite, 32.2 pct Al_2O_3, 15 to 22 pct silica, 1 to 2 pct reactive silica.
Brazil:					
Almeirim-Jutai	Companhia Vale do Rio Doce	N	S	3:1	Gibbsite, 51.6 to 57.5 pct Al_2O_3, low silica.
Ouro Preto	Alcan	P	S	0.2:1	Gibbsite, 37 pct Al_2O_3 in situ, 47 pct washed, 2.23 pct reactive silica.
Paragominas	Mineracao Vera Cruz S.A.	N	S	5:1 to 7:1	Gibbsite, 53 to 58 pct Al_2O_3, 3 to 7 pct silica.
Poco de Caldas-Alcominas	Alcoa-Hanna-State Minas Gerais	P	S	0.1:1	Gibbsite, 46 to 54 pct Al_2O_3, 5 to 6 pct silica.
Pocos de Caldas	Companhia Brasileira do Alum.	P	S	0.1:1	Gibbsite, 46 to 54 pct Al_2O_3, 5 to 6 pct silica.
Trombetas	Mineracao Rio do Norte	P	S	1:1	Gibbsite, 50 pct Al_2O_3, 4 pct reactive silica.
Trombetas-Alcoa	Alcoa-Shell	N	S	1:1	Gibbsite, 50 pct Al_2O_3, 4 pct reactive silica.
British Pacific Islands:					
Rennell Island	Mitsui Mining and Smelting Co.	N	S	0.4:1	Gibbsite, 48 pct Al_2O_3, low silica.
Wagina Island	Pacific Aluminum-CRA Exploration.	N	S	0.1:1	Gibbsite 47.1 pct Al_2O_3, low silica.
Cameroon: Minim Martap	Pechiney-BRGM-VAG	N	S	0.33:1 to 1:1	Gibbsite, 42 pct Al_2O_3, 3 pct silica.
Costa Rica: San Isidro del General	Costa Rican Government	N	S	0.2:1	Gibbsite, some boehmite, 33.8 pct available Al_2O_3, 7.5 pct reactive silica.
Dominican Republic:					
Cabo Rojo	Alcoa	P	S	0:1	Gibbsite and boehmite (5:1), 42 to 50 pct Al_2O_3, 1.6 to 10 pct silica.
France:					
Blanquette-Combecave	Bauxites et Alumines de Provence	P	U	NAp	Boehmite and diaspore, 54 pct Al_2O_3.
Canonnettes	Aluminum Pechiney	P	U	NAp	Boehmite and diaspore, 50 pct Al_2O_3, 6.8 pct silica.
La Rouquette-Mont. Plaisir	do	P	U	NAp	Boehmite and diaspore, 55.5 pct Al_2O_3, 4.3 pct silica.
Mazaugues (Var)	Aluminum Pechiney	P	U	NAp	Boehmite and diaspore, 54 pct Al_2O_3, 3.5 pct silica.
Peygros (Var)	do	P	U	NAp	Boehmite and diaspore, 50 pct Al_2O_3, 7 pct silica.
St. Julien-Tourves	Alusuisse	P	U	NAp	Boehmite and diaspore, 48.5 to 52.2 pct Al_2O_3, 15.7 to 23 pct silica.
French Guiana: Kaw Mountains	Cie. Minière de Guyane	N	S	0.1:1	Gibbsite, 42 pct Al_2O_3, 2 pct silica.
Ghana:					
Awaso	Ghana Bauxite Co.-Kaiser	P	S	1:1	Gibbsite, some boehmite, 48.7 pct Al_2O_3, 1.7 pct silica.
Kibi (Atewa)	Kaiser and Ghana Government	N	S	0.63:1	Gibbsite, 44 pct Al_2O_3, 3 pct silica.
Nyinahin	Ghana Government	N	S	0.1:1	Gibbsite and boehmite (5:1), 40 pct Al_2O_3, 3.2 pct silica.
Greece:					
Eleusis	Eleusis Bauxite Mining Co.	P	U	NAp	Boehmite, 51 pct Al_2O_3, 0.7 to 2 pct silica.
Helikon	Greek Helikon Bauxites Co.	P	U	NAp	Boehmite and diaspore, 60 pct Al_2O_3, 4 pct silica.
Itea	Eleusis Bauxite-Skalistiri	P	U	NAp	Boehmite and diaspore, 60 pct Al_2O_3, 4 pct silica.
Parnasse	Bauxite Parnasse Mining Co.	P	S	3:1	Boehmite and diaspore, 57.5 pct Al_2O_3, 2 pct silica.
Guinea:					
Aye-Koye	Guinea Government	N	S	0:1	Gibbsite, 49 pct Al_2O_3.
Dabola	Guinea Government-Bauxite de Dabola.	N	S	0:1	Gibbsite and boehmite (9:1), 45 pct Al_2O_3, 1.33 pct silica.
Fria	Friguia	P	S	0:1	Gibbsite, 48 pct Al_2O_3, 2.5 pct silica.
Kindia	Guinea Government	P	S	0:1	Gibbsite, some boehmite, 48 pct Al_2O_3, 1 to 3 pct silica.
Sangaredi	Halco Inc.-Guinea Government	P	S	0:1	Gibbsite, some boehmite, 48 to 60 pct Al_2O_3, about 4 pct silica.
Tougue	Guinea Government-Alusuisse	N	S	0:1	Gibbsite, 43 pct Al_2O_3, 3.8 pct silica.

[e] Estimated. NAp—Not applicable. [1]P — producer; N — nonproducer. [2]S — surface; U — underground.

Table 7. — Bauxite property information, January 1980 — Continued

Location and property name	Ownership	Status[1]	Type[2]	Stripping ratio[e] (waste to ore)	Type of ore
Guyana:					
Arrowcane East	Guyana Government	P	S	9:1	Gibbsite, some boehmite, 59 pct Al_2O_3, 1 to 10 pct silica.
Arrowcane South	do	P	S	9:1	Gibbsite, some boehmite, 59 pct Al_2O_3, 1 to 10 pct silica.
Coomacka	do	P	S	9:1	Gibbsite, some boehmite, 59 pct Al_2O_3, 1 to 10 pct silica.
East Mombaka	do	P	S	9:1	Gibbsite, some boehmite, 59 pct Al_2O_3, 8.3 pct silica.
East Montgomery	do	P	S	9:1	Gibbsite, some boehmite, 59 pct Al_2O_3, 1 to 10 pct silica.
Ituni District	do	P	S	8:1	Gibbsite, boehmite (20:1), 50 to 63 pct Al_2O_3, 8.3 pct silica.
Kara-Kara	do	P	S	9:1	Gibbsite, some boehmite, 59 pct Al_2O_3, 1 to 10 pct silica.
Manaka	do	P	S	9:1	Gibbsite, some boehmite, 59 pct Al_2O_3, 8.3 pct silica.
West Bank #3	do	P	S	9:1	Gibbsite, some boehmite, 59 pct Al_2O_3, 1 to 10 pct silica.
West Mombaka	do	P	S	9:1	Gibbsite, some boehmite, 59 pct Al_2O_3, 8.3 pct silica.
Yararibo	do	P	S	9:1	Gibbsite, some boehmite, 59 pct Al_2O_3, 1 to 10 pct silica.
Haiti: Miragoane	Reynolds Haitian Mines Inc.	P	S	0:1	Mixed, 50 pct Al_2O_3, 3.4 to 4.7 pct silica.
India:					
Amarkantak	Bharat Aluminum Co. Ltd.	P	S	4:1	Mixed, 37 to 54 pct Al_2O_3, 2 to 7 pct silica.
Anantagiri	do	N	S	0:1	Gibbsite, some hematite, 48 pct Al_2O_3, 2.5 pct silica.
Bagru Hills	Indalco-Alcan	P	S	1.1:1	Gibbsite, 53.2 pct Al_2O_3, 3.3 pct silica.
Chandgad	Indalco	P	S	1.5:1	Gibbsite and hematite, 48.6 pct Al_2O_3, 3.2 pct silica.
Chintaplee	Bharat Aluminum Co. Ltd	N	S	0.11:1	Gibbsite, 46 pct Al_2O_3, 2 pct silica.
Gandhamardan	do	N	S	NA	Gibbsite, 47 pct Al_2O_3, 2.6 pct silica.
Lohardaga (Hindalco)	Hindustan Aluminum Co	P	S	3:1	Gibbsite, some boehmite, 45 pct Al_2O_3, 3 pct silica.
Panchpatmali-Orissa	Bharat Aluminum Co. Ltd	N	S	0.4:1	Gibbsite, 42 to 56 pct Al_2O_3, 1 to 3 silica.
Indonesia:					
Bintan Island	P.N. Aneka Tambang	P	S	0.1:1	Gibbsite, 45 to 50 pct Al_2O_3, 8 to 13 pct silica.
Singakawang	do	N	S	0.1:1	Gibbsite, 54 pct Al_2O_3, 5 pct silica (washed).
Jamaica:					
Alpart	Kaiser-Reynolds-Anaconda	P	S	0.125:1	Gibbsite, some boehmite, 42 to 50 pct Al_2O_3, 1 to 20 pct silica.
Breadnut Valley	Alcoa-Jamaica Government	P	S	0:1	Gibbsite, some boehmite, 43.5 pct Al_2O_3, 1.5 pct silica.
Cambridge	Jamaica Government	N	S	0.125:1	Gibbsite, some boehmite, 43 pct Al_2O_3.
Ewarton	Alcan-Jamaica Government	P	S	1:1	Gibbsite, some boehmite, 43 pct Al_2O_3, 1.8 pct silica.
Kirkvine	do	P	S	0:1	Gibbsite, some boehmite, 45 pct Al_2O_3, 1 pct silica.
Lydford	Reynolds-Jamaica Government	P	S	0:1	Gibbsite, some boehmite, 42.5 pct Al_2O_3, 1 pct silica.
Maggotty	Jamaica Government	P	S	0.1:1	Gibbsite, some boehmite, 43 pct Al_2O_3.
New Market East	do	N	S	0.1:1	Gibbsite, some boehmite, 42 pct Al_2O_3.
Samalco	do	N	S	0.4:1	Gibbsite, some boehmite, 44 pct Al_2O_3.
Schwallenburgh West	do	N	S	0:1	Gibbsite, some boehmite, 42 pct Al_2O_3.
Spanish Town West	do	N	S	0:1	Gibbsite, some boehmite, 42 pct Al_2O_3.
Trelawny	do	N	S	0:1	Gibbsite, some boehmite, 42 pct Al_2O_3, less than 3 pct silica.
Trelawny Central	do	N	S	0.1:1	Gibbsite, some boehmite, 43 pct Al_2O_3.
Water Valley	Kaiser Jamaica Bauxite Co	P	S	0.1:1	Gibbsite, some boehmite, 45 pct Al_2O_3.
Williamsfield East	Jamaica Government	N	S	0:1	Gibbsite, some boehmite, 43 pct Al_2O_3, less than 3 pct silica.
Malawi: Mulanje Mountain	Malawi Government	N	S	0:1	Gibbsite, 43.9 pct Al_2O_3, 2.2 pct reactive silica.
Sierra Leone:					
Moyamba	Sierra Leone Government-Alusuisse.	P	S	0:1	Gibbsite, 47 pct Al_2O_3, 4.5 pct silica.
Port Loko	do	N	S	0.5:1	Gibbsite, 49 pct Al_2O_3, 4 pct silica.
Suriname:					
Bakhuis Mountains	N.V. Grassalco (Government)	N	S	0.2:1	Gibbsite, 48.4 pct Al_2O_3, 3.1 pct silica.
Moengo	Suralco	P	S	1:1	Gibbsite, 54 pct Al_2O_3.
Onverdacht	Billiton N.V.	P	S	1.7:1	Gibbsite, 52 pct Al_2O_3, 4.5 pct reactive silica.
Suralco (Lelydorp)	Suriname Aluminum Co	P	S	NA	NA.
Turkey: Seydisehir	Etibank	P	S	1:1 to 3:1	Boehmite, 56 to 59 pct Al_2O_3, 7 to 8 pct silica.
Venezuela: Los Pijiguaos	Industria Venezolana de Aluminio.	N	S	0.05:1	Gibbsite, 49 pct Al_2O_3, 9.3 pct silica, (2.2 pct reactive silica.

[e] Estimated. NA — Not available. [1]P — producer; N — nonproducer. [2]S — surface; U — underground.

BAUXITE MINING AND PROCESSING

GENERAL

Bauxite, the principal ore of aluminum, is composed of aluminum hydroxide minerals with impurities of free silica, clay, silt, and iron hydroxides (*23*). The types of bauxite are (1) trihydrate, consisting mainly of gibbsite, $Al_2O_3{\cdot}3H_2O$; (2) monohydrate, consisting mainly of boehmite, AlO (OH), or diaspore, $Al_2O_3{\cdot}H_2O$; and (3) mixed bauxite, consisting of both gibbsite and boehmite (*16*). Bauxite is believed to be formed as a residual soil in humid, tropical, or subtropical regions with good drainage. Extreme weathering conditions common to tropical climates decompose the iron and aluminum silicates, and leaching through downward percolation of water removes the silica and many other elements. Bauxite deposits typically assay 28 to 55 pct Al_2O_3. The aluminum industry consumes nearly 90 pct of the bauxite mined; the remainder is used as abrasives, chemicals, refractories, and miscellaneous minor products.

Although many technological improvements have been made in producing aluminum from bauxite, the basic processes are unchanged since the metal first became available in commercial quantities over 90 years ago. These processes consist mainly of surface mining of bauxite, followed by hydrometallurgical processing to produce alumina (99.5 pct Al_2O_3), and then reducing the alumina to aluminum metal by fused-salt electrolysis in a molten bath of fluoride salts (*20*, p. 1). Generally, for each 4.5 tons of bauxite fed into the alumina refinery, 2 tons of alumina is extracted, from which about 1 ton of aluminum is produced.

MINING

Bauxite ore is mined mostly by open pit methods. This entails stripping away the overburden, which can subsequently be replaced to restore the land surface after mining, and then the actual mining of the ore. In Arkansas, where as much as 13 ft of overburden must be removed for every foot of bauxite ore exposed, draglines, scrapers, shovels, and trucks are used in the stripping operations. In Jamaica, because the bauxite deposits lie very close to the surface, the overburden of vegetation and topsoil is easily removed. The ore is mined with shovels, draglines, and scrapers; blasting is not usually necessary. The ore is then transported by truck, rail, or aerial tram to the alumina refinery or port. Deposits in Australia and Guinea also lie very close to the surface, with very little stripping of overburden required; however, the bauxite in some of these deposits requires blasting to loosen the ore. Underground mining, by room-and-pillar methods, accounts for most of the bauxite production from deposits in France and other European countries.

In their crude state, bauxites may contain from 10 to 25 pct free moisture. If the bauxite is to be transported over a long distance to the alumina refinery, most of this moisture is usually removed by drying at the mill, usually located at the mine site or at the port. Apart from crushing, drying is often the only processing applied to a metallurgical-grade bauxite before it reaches the alumina plant. Ores of different composition are often blended before milling to ensure as uniform a feed as possible and thus enhance alumina recovery from the refinery.

BAYER PROCESS FOR ALUMINA PRODUCTION FROM BAUXITE

The Bayer process is the only commercial-scale method of converting metallurgical-grade bauxite to alumina. In the classic Bayer process, aluminum and other soluble elements in bauxite are dissolved at elevated temperatures and pressures in a strong alkali solution, generally NaOH, to form sodium aluminate ($NaAlO_2$). After separation of the "red mud" tails, the sodium aluminate solution is cooled and seeded, and aluminum trihydrate is precipitated in a controlled form. The trihydrate is dewatered and calcined to the anhydrous crystalline form, alumina.

Depending on the mineral content of the ore, variations occur in the digestion temperature, pressure, and caustic concentration. In addition, higher silica ores (greater than 8 pct SiO_2) require additional steps, known as the lime-soda-sinter process, to recover alumina and soda lost by combination with silica. Addition of the lime-soda-sinter steps to a Bayer process for high-silica ores is known as the Combination process, processing trihydrate ore is known as the American Bayer process, and processing monohydrate ore is known as the European Bayer process. Trihydrate ores containing up to 25 pct monohydrate recently have been processed by a method known as the Modified Bayer process.

All variations of the Bayer process include caustic leaching and precipitation. Ore is typically wet-ground in a 40-pct-solids (by weight) solution to minus 20 to minus 28 mesh. The grinding takes place in a caustic medium. The ore is then placed into a digestor where steam is introduced and leaching occurs. Easily leached, trihydrate ores require a temperature in the range of 120° to 150° C, 30 to 100 psi, and a caustic concentration of 130 to 190 g Na_2CO_3 per liter. Monohydrate ores are leached at higher temperatures (175° to 250° C), higher pressures of 300 to 500 psi, and a greater caustic concentration of 250 to 400 g Na_2CO_3 per liter. Trihydrate ores containing up to 25 pct monohydrate are leached at 240° to 250° C, 525 psi, and 240 g Na_2CO_3 per liter.

After digestion, thickeners and filters separate the unleached material containing the iron and nonreactive silica impurities (red mud) from the leach solution (green liquor). Starch is often added as a flocculating agent during this separation. The leach solution is cooled in precipitators for 34 to 36 hr. After precipitation, the coarse alumina is separated from the fines and the spent liquor. The coarse alumina is calcined (in the United States) at 950° to 1,050° C and then stored for shipment to an aluminum smelter. The fines are returned to the precipitators, where they act as seed for the next batch. The spent liquor is returned to the digestor after evaporation of some of the excess water.

Typical recoveries of aluminum in producing alumina from bauxite ores are 90 to 96 pct for the American Bayer process and 80 to 85 pct for the Modified Bayer process or the Combination process. Loss of aluminum is due principally to washing steps and silica-alumina reactions. The percent of alumina lost to silica is roughly equal to the weight-percent of reactive silica present in the ore. Miscellaneous losses account for 3 to 5 pct.

For high-silica ores (above 8 pct silica content), enough aluminum is lost to justify the addition of the lime-soda-sinter process. In this process, the red mud tails from the Bayer process are combined with soda ash and limestone and sintered at 1,150° to 1,260° C. This sinter is then ground in the presence of water, which leaches the alumina from the sinter. The leach solution is separated from the remaining sinter (brown mud) and returned to the digestor of the Bayer process. The brown mud is discarded.

THE HALL-HEROULT PROCESS (*12*)

Primary aluminum is produced by the electrolysis of alumina in a molten bath of natural or synthetic cryolite (Na_3AlF_6), which serves as an electrolyte and a solvent for the alumina. The reduction cells or pots containing the bath are approximately 10 to 15 ft wide, 20 to 40 ft long, and about 3 to 4 ft deep, lined with carbon, and connected in electrical series of 100 to 240 cells to form a potline. From 800 to 3,000 lb of aluminum is produced per day in each pot. The carbon lining which serves as the cathode usually must be replaced every 3 to 4 years. Compounds of aluminum, fluorine, and sodium absorbed in the used pot linings are recovered and recycled. as is the carbon.

Cryolite and aluminum flouride are added to the electrolyte to maintain the desirable ratio of sodium and aluminum fluoride and to replace fluorine lost from the cell in pot linings or through volatization. The melting point of the bath is lowered by the addition of small quantities of fluorspar or, in some instances, lithium compounds. The carbon anode, which is consumed during the operation, is replaced by the Soderberg continuous method or by the prebaked method.

The molten bath or electrolyte may be as deep as 14 in, but the anode is usually only 2 in from the pad of molten aluminum. The resistance of the bath is sufficient to maintain an optimum operating temperature of 950° to 980° C. At this temperature, the maximum alumina content of the bath ranges from 3 to 10 pct.

Every 1 or 2 days the molten aluminum is removed from the bottom of the cell by a vacuum-siphon technique. Thermally insulated cast iron pots with airtight lids and downward-sloping spouts are used to withdraw the molten metal. The pots are evacuated, and the molten metal is sucked into the cast iron pot. The molten metal, blended in a holding furnace with other batches, may be fluxed, alloyed, and cast into various solid forms, or transported molten to fabricating plants as far as 300 miles away.

The cells utilize direct current ranging from 65,000 to 150,000 amp; most plants have 80,000- to 100,000-amp cells. Anode current densities range from 600 to 800 amp/ft^2. The voltage drop across a single cell is 4.5 to 5.0 v; across a potline, it may be as high as 1,000 v.

Current efficiency ranges from 85 to 90 pct. Losses are principally caused by physical losses of metal through spillage and vaporization from the bath and by reoxidation of aluminum. Because of electrical resistance, the voltage efficiency is only 40 pct, with heat being lost by radiation and in the exhaust gases, in tapped metal, and in electrodes removed from the cell. Consequently, the overall energy efficiency is only about 35 pct. A further and more detailed description of the Bayer and Hall-Heroult processes appear elsewhere (*12*).

COSTS OF ALUMINUM PRODUCTION

Capital expenditures were calculated for exploration, acquisition, development, and mine plant and equipment; and for constructing and equipping the crushing, washing, and drying facilities. Capital expenditures for existing or new "greenfield" alumina refineries and aluminum smelters were also calculated for nonproducers. The capital expenditures for the different mining and processing facilities include the costs of mobile and stationary equipment, construction, engineering, infrastructure (facilities and utilities), and working capital. The broad infrastructure category includes the costs of access and haulage facilities, water facilities, power supply, and personnel accommodations. Working capital is a revolving cash fund required for such operating expenses as labor, supplies, taxes, and insurance.

The total operating cost of a project is a combination of direct and indirect costs. Direct operating costs include materials, utilities, direct and maintenance labor, and payroll overhead. Indirect operating costs include technical and clerical labor, administrative costs, facilities maintenance and supplies, and research. Other costs in the analysis are fixed charges, including local taxes, insurance, depreciation, deferred expenses, interest payments (if any), and return on investment.

The cost elements of aluminum production are discussed in the following sections.

MINE AND MILL CAPITAL COSTS

Mine and mill capital costs (in 1980 dollars) for a new bauxite-mining operation can range from about $19 million for a relatively small operation requiring little or no infrastructure to almost $500 million for a large operation requiring extensive infrastructure such as rail and port facilities. Most new mining operations, either planned or under construction, tend to be quite large with planned capacities of 3 to 11 million tons per year (tpy). A typical example of a new bauxite operation is the recently completed Trombetas Mine in Brazil, which has a capacity of 3.35 million tpy and cost approximately $230 million. Following are other examples of capital costs (in 1980 dollars) for developing or potential operations:

According to MAS estimates, the planned Paragominas Mine in Brazil will produce about 6.9 million tpy and will cost around $480 million (including $240 million for infrastructure).

The Mount Saddleback Mine and adjacent Worsley refinery in Western Australia are estimated to cost $1 billion. The mine plant and equipment and conveyor system are estimated to cost $320 million, the refinery approximately $300 million, and related infrastructure about $380 million.

An integrated operation at Aurukun in northern Queensland, Australia, is estimated at approximately $1.3 billion. The mine plant and equipment for a 2.3-million-tpy bauxite operation would cost about $300 million, the refinery about $300 million, the smelter some $260 million, and related infrastructure for the entire operation about $440 million.

The Tougue deposit in Guinea, if developed as an 8-million-tpy operation, is estimated at $98 million for the mine plant and equipment, and at least $144 million for the railroad, expansion of the port at Conakry, power supply, and housing. If a 1-million-tpy refinery were built at Dabola, the estimated additional capital cost would be $825 million.

Development of the Kibi bauxite deposit in Ghana as a 2-million-tpy operation would cost approximately $12.5 million for preproduction development, $11 million for mine equipment, and $8 million for mine plant. Related infrastructure for railroad, power, and townsite facilities would cost approximately $150 million. A proposed 600,000-tpy alumina refinery at Tema would cost approximately $600 million; if a second smelter of 200,000-tpy capacity is built at Tema, the cost is estimated at $1 billion.

MINE AND MILL OPERATING COSTS

The direct operating costs of bauxite mining and milling are composed of five factors, broken down by percentage of mining and milling operating costs:

Labor—27 to 32 pct.
Fuel oil—8 to 9 pct.

Diesel fuel, lubricants, and tires—15 to 19 pct.
Maintenance—21 to 27 pct.
Miscellaneous costs—18 to 21 pct.

Although mine and mill operating costs around the world vary widely, these differences have little effect on variations of the total cost of aluminum ingot. An analysis of actual and potential mines in five of the major producing countries shows which factors contribute to the variability of operating costs. The following countries are discussed: Australia, Brazil, Guinea, Guyana, and Jamaica.

Australia

Ten bauxite mines and deposits with actual or potential capacities ranging from 2,100,000 to 13,200,000 tpy were evaluated. Overburden is generally less than 1 m thick, and the average ore thickness ranges from 2.4 to 5.5 m. Most of the gravelly overburden is removed by scrapers, with dozers, front-end loaders, and, to a lesser extent, off-highway trucks. Blasting is required to break the hard-rock cap present at the surface of the bauxite in the western part of Australia, but this does not apply to the other deposits in the country. In the Darling Range, most of the overburden is removed by Euclid TS-14 scrapers and Caterpillar D9 bulldozers with attendant front-end loaders and off-highway trucks. When most of the gravel overburden has been removed in this manner, material in the hollows of the undulating cap rock is removed by backhoe and, with the gravel overburden, is hauled to a special surface stockpile reserved for use in land reclamation. The cap rock in the Darling Range must be blasted. Del Park uses Gardner Denver RDC-16B rotary blasthole drills to drill 115-mm holes on a 3.5- by 3.5-m pattern. Averaging 3 m in depth, the holes are loaded with an ammonium nitrate-fuel oil (ANFO) mixture and detonated with Anzomes primers and Cordtex. About 5,400 tons of bauxite is blasted per pattern. Mining is performed with 12- to 15-ton. front-end loaders, which load the bauxite into rear-dump off-highway trucks that haul the ore from the pits to the crusher. The more scattered occurrences of ore bodies at Del Park, Huntly, and Mount William have led to the use of mobile crushing stations and conveyor haulage to the refineries.

Bauxite in the Northern Territory and Queensland is usually loose and friable with little or no cap rock. Minor drilling may be necessary, and ripping the cap rock is occasionally required. Clearing topsoil and removing overburden are usually done during the dry season; mining the bauxite continues year round. At Weipa, mining begins by clearing trees and scrub in the wet season; the amassed windrows are burned during the dry season. Topsoil and overburden are removed during the dry season by tandem-powered push-pull scrapers of 33-m^3 capacity or, in some cases, 29-m^3 standard-wheel tractor scrapers. Often the topsoil and overburden are placed directly on the floor of adjacent mined-out areas and made ready for revegetation during the following wet season. Mining operations are carried out on a two-shift-per-day, 10-hr-per-shift basis. A 5-day workweek is normal, unless the stockpile gets low.

The ore at Weipa is free flowing with only occasional areas of cap rock that require ripping. The in situ bauxite is sufficiently loose to permit excavation without drilling and blasting. At the Andoom Mine, track-mounted hydraulic excavators with 10-m^3 buckets load the friable ore into 80-ton rear-dump trucks. Andoom is connected to the Lorim mill by a 19-km railway, limiting the average haul distance per truck to 3,000 m. The railhead at Andoom can be relocated so the mining operations are kept within a certain radius of the railhead.

Mine operating costs throughout Australia range from \$2.80 to \$6.60 per ton, including removal of the overburden and ore, reclamation, transportation to the crusher, crushing, drying (for exported ore), and stockpiling for transportation to the refinery. Calcining costs for abrasive-grade bauxite are not included. Haulage methods include truck, rail, and conveyors, with the different methods occasionally being used at the same mine. As distances to crushers increase, mobile crushers and conveyors are sometimes used to combat rapidly escalating haulage costs. The distance to the crusher varies widely between mines and even between different areas within the same mine. Transportation costs to the refinery (or port) range from \$0.10 to \$4.10 per ton of ore, depending on the method of transport and distance. The most variable cost factor affecting operating cost appear to be the size of operation, haulage method and distance, continuity of the ore, and presence of a cap rock that requires blasting.

Brazil

The seven mines and deposits evaluated have actual or potential production capacities ranging from 400,000 to 15,000,000 tpy. For removing overburden, the mines use scrapers, shovels, front-end loaders, dozers, and/or draglines. Ore is mined by backhoe, and the average ore thickness ranges from 2 to 7 m. At Trombetas, overburden is removed by two 13-m^3 Bucyrus Erie walking draglines; lesser amounts are removed by four Caterpillar 631 scrapers pushed by D8 bulldozers. Consisting of clay, gravel, or nodular bauxite and ferruginous laterite, the overburden is removed to expose the bauxite bed in a 254-m-wide strip. Blasting is occasionally required in the hard layer, which is about 1.5 m thick on the top of the massive bauxite bed. Blastholes 90 mm in diameter are drilled with two truck-mounted auger units. The blasting agent, ANFO, is used at the rate of 77 g per ton of broken material.

Normally, the hard bauxite at Trombetas is loaded with three 4.6-m^3 190 Northwest backholes. Five Caterpillar 988 front-end loaders equipped with 4.5-m^3 buckets are also available for loading in the mine and reclaiming from stockpile. The bauxite is loaded into Caterpillar 939 trucks outfitted with lightweight aluminum beds to increase their capacity from 32 to 35 tons. The haulage distance to the crusher, currently 2 km, will increase to 4 km as mining continues.

Mining and milling costs in Brazil range from \$4.20 to \$7 per ton with beneficiation costs for refractory-grade bauxite ranging from \$40 to \$66 per ton of calcined bauxite. Transportation costs to the port or refinery range from \$1 to \$7.80 per ton, depending on distance and terrain. Most of the variations in operating costs are due to the varying haulage distances from the mine to the mill.

Guinea

Six mines and deposits with actual or potential capacities from 1,500,000 to 9,000,000 tpy were evaluated. The typical Guinea bauxite deposit forms the cap of a flat-topped mountain about 100 m higher in elevation than the surrounding valley. The overburden is up to 0.5 m thick, and the bauxite is up to 30 m thick. Mining may be done by either electric shovels or front-end loaders, with haulage by truck or rail. All ore is drilled and blasted.

At Sangaredi, the ore is drilled, blasted, and loaded from 12- to 15-m-high benches into 70-ton railroad cars. Loading is by means of two P&H 1900 electric shovels on each shift, with a third shovel as standby. A 1,000-hp locomotive pulls 20 to 25 cars around the loop in front of each shovel. As the shovels progress along the face, panels of prefabricated track, each 18 m long, are laid on the graded ground behind them. When the cut has been completed, the new track is connected to the loop, and the old track is ready for the next stage of track laying. The loaded train is moved back to the switchyard where 80- to 90-car trains are made up to haul to the Kamsar plant, where the ore is unloaded, crushed, dried (or calcined), stockpiled, and shipped. The ore is loaded 21 shifts per week at the rate of 650,000 tons per month.

Although mining and milling costs in Guinea range from

$2.25 to $6.45 per ton, transportation costs to the port from several deposits in the interior are very high because of haulage distances of up to 500 km. Transportation costs to the refinery or port range from $0.50 up to $11 per ton.

Guyana

The 11 Guyanese mines evaluated are all open pit mines, with a stripping ratio between 8:1 and 10:1. Output ranges from 108,000 to 1,500,000 tpy. Overburden is 15 to 69 m thick, and the bauxite ore may be up to 15 m thick. Primary stripping is usually done by bucket-wheel excavator systems, with scrapers and hydraulic mining being used to a lesser extent. The remaining overburden is removed by walking draglines. At some mines, the top of the bauxite is cleaned off with bulldozers. A cap rock from 0.3 to 2 m thick on top of the ore is discarded because of its high silica content. The bauxite is blasted, mined, loaded, and trucked to a stockpile to await until rail or barge transport to the Linden or Everton mills. Heavy rainfall, inadequate drainage, and clayey soil result in difficult mining conditions. No land reclamation is in progress since the mines are in remote areas and do not affect any major agricultural areas or population centers. Total mining and milling costs range from $6.50 to $8.25 per ton of ore, with transportation costs to the refinery or port ranging from $0.25 to $3.50 per ton. Mines with lower stripping costs usually have higher haulage costs; thus, there is little variation in the total cost. The cost for beneficiating refractory-grade bauxite runs from $58 to $61 per ton of calcined bauxite.

Jamaica

Fifteen Jamaican mines and deposits with actual or potential capacities of 1,000,000 to 5,000,000 tpy were evaluated. Filling karst depressions and sinkholes in highly fractured limestone, these deposits reflect the fault systems and lineation patterns of the limestone. The areal extent of each deposit varies greatly, with the thickness of the bauxite extending up to 43 m. Only one mine had overburden exceeding 1 m in thickness. Overburden is usually stripped by scrapers or bulldozers; and most mining is done by draglines and shovels, with loading by front-end loaders. Transportation from mine to mill or mine to refinery is by truck, rail, conveyor, or aerial tram.

At the Kirkvine Mine, Caterpillar 631B tractor scrapers strip the overburden; the stripped overburden (topsoil) is stockpiled for reclamation. Mining is conducted by one 5.7-m^3 Baldwin Lima Hamilton 2400B dragline, one Caterpillar 992 7.7-m^3 loader, and one Warner Swasey 3.5-m^3 backhoe. The dragline and front-end loader work with a Caterpillar D9 bulldozer, which rips and cleans the pit face. Ore is hauled in eight Caterpillar 773 50-ton trucks to a central stockpile. Haulage distances average 2.6 km on 15-m-wide haul roads with a maximum 6-pct grade. The ore from the stockpile is transported to the alumina plant by a 1.8-km-long English cable belt conveyor.

Mining costs in Jamaica range from $4 to $5 per ton, including haulage costs for locally refined bauxite. Milling costs, mainly drying, for exported bauxite range from $1.80 to $2 per ton. Locally refined bauxite is not dried and incurs no milling cost.

LEVIES, ROYALTIES, AND TRANSPORTATION

Other elements that greatly affect the cost of bauxite include capital charges, production taxes or levies, royalties, and transportation to the refinery. The bauxite levies and royalties charged by the main bauxite-producing countries are shown in table 8.

Table 8. — Bauxite levies and royalties in the main bauxite-producing countries

Country	Levy	Royalty[1]	Comments
Australia	None	Variable; ranges from nil to $1.20/ton.	Nil applies to Alcoa, which pays royalties on alumina.
Dominican Republic.	7.7 pct of U.S. ingot price.	$0.60/ST	Alcoa now pays a minimum of $17 per ton in lieu of levy.
Ghana	None.	6 pct of realized value of ore plus mineral duty of 10 pct on realized ore selling price.	
Guinea	Ranges from 0.5 to 0.75 pct of price of ingot depending on grade of bauxite.	None	
Guyana	None	$0.04 to $0.10 per LDT.	All operations Government owned.
Haiti	7.5 pct of U.S. ingot price.	$0.50/ST	Levy indexed to Reynolds U.S. ingot price. Use ratio of 5 ST = 1 ST metal.
Indonesia	10 pct of FOB export value.	Mineral tax of $0.60/ton.	
Jamaica	5.5 to 6.8 pct of U.S. ingot price.	$0.55/LDT	Levy variable depending on base price; rate decreases as base price increases.
Sierra Leone	None	$0.27/ton	
Suriname	5.2 pct of U.S. ingot price.	$0.50/LDT	Levy based on Alcoa U.S. ingot price.

[1] LDT — long dry ton; ST — short ton.

Sources: The World Aluminum Industry, v. 1; Australian Mineral Economics Pty. Ltd., Sydney, Australia, 1981, 410 pp.; the Jamaica Bauxite Institute; and the International Bauxite Association.

Calculations for determining the amount of levy charged by a producing country are exemplified in the following sample levy:

If the rate of a sample levy on 1 LDT (long dry ton) of bauxite is 6 pct of the ARP (average realized price) of 1 ST (short ton) of primary aluminum, the levy is related to the average realized price of aluminum according to the following formula (*3*):

$$L = \frac{P}{F}\,(\mathrm{PARC}),$$

where L = the production levy per LDT of bauxite, P = the bauxite tax per pound of aluminum as a percent of PARC, F = the LDT of bauxite required to produce 1 ST of aluminum, and PARC = the average realized price of primary aluminum per ST in U.S. dollars. At an average price of $0.72 per pound for primary aluminum, the total levy per LDT of bauxite is equal to:

$$\frac{0.06}{4.3}\,(2000)\,(0.72) = \$20.09.$$

The 4.3 in the denominator is the bauxite equivalent in LDT of 1 ST (2,000 lb) of metal. This figure is based on a bauxite-alumina conversion factor of 2.2 LDT/ST and an alumina-aluminum factor of approximately 1.95/1. The bauxite-equivalent factor will vary among countries, depending on their average grade of bauxite. The 4.3 factor applies to Jamaica and some other countries.

Table 9. — Selected bauxite shipping costs[1]

Source of bauxite	Destination of shipment	Freight cost, U.S. dollars per ton	Date of freight cost
Australia:			
Gove, Northern Territory	Stade, Germany	10.50–12.50	Feb. to June 1979.
		20.00–21.50	Jan. to June 1980.
		17.00	Nov. 1980.
		18.75	Jan. to April 1981.
Weipa, Queensland	Gladstone, Queensland	8.00	May 1981.
	Porto Vesme, Italy	12.50–12.65	Jan. to May 1979.
	Netherlands-Germany	18.00	Nov. 1980.
	Germany	17.50	Mar. 1981.
Weipa-Gove	Japan	15.00–20.00	May 1981.
Brazil: Amazon	U.S. gulf	7.50	Nov. 1979.
	United States	8.00– 9.50	Sept. 1980.
Dominican Republic:			
Cabo Rojo	Texas, U.S.A.	5.50	April 1980.
Greece: Itea	Taranto, Italy	5.50	Mar. 1980.
Guinea:			
Port Kamsar	U.S. gulf	10.25	May 1981.
	Canada (Port Alfred, Quebec)	10.50	May 1981.
	Europe	10.50	May 1981.
	Yugoslavia	20.00	Aug. 1980.
Indonesia:			
Bintan Island	Rotterdam, Netherlands	14.00–14.50	Mid-1979.
Jamaica:			
Various ports	United States	4.40– 4.90	Sept. 1980.
Port Rhoades	Louisiana, U.S.A.	5.50	May 1981.

[1] Costs shown are "spot prices," which would normally be higher than prices paid under long-term contracts or on company-owned ships.

With the exception of the Dominican Republic, all the countries listed in table 9 also charge corporate income tax on any profits earned by mining companies engaged in producing bauxite within the individual country.

An overview of bauxite shipping costs is presented in table 9 based on cost data collected and published by Australian Mineral Economics Pty. Ltd. (*2*, p. 247). As shown in table 9, the Caribbean countries have a significant cost advantage in shipping to the United States compared with the shipping costs of bauxite from Brazil or Guinea. This advantage is overshadowed, however, by the higher bauxite levies the Caribbean countries charged.

The IBA has furnished a comparative cost estimate (in 1980 dollars) for bauxite delivered to the United States from new operations in Australia, Brazil, and Jamaica. These estimates of the total cost per ton of bauxite (including servicing of capital) ranged from $22.70 to $25.60 for Australia, $21.00 to $23.90 for Brazil, and $37.60 to $39.00 for Jamaica. Of these costs, transportation accounted for 57 pct of the total delivered cost of bauxite from Austraila, about 38 pct for Brazil, and slightly over 11 pct for Jamaica. The higher cost for Jamaican bauxite is caused by the bauxite levy, which accounted for over 63 pct of the total cost of Jamaican bauxite at the end of 1979.

Estimated operating costs for the bauxite operations analyzed in this study, by country, are shown in table 10. Since showing cost data for individual operations would divulge confidential information, the data shown for each country are a weight average of individual-property cost data.

Table 10. — Operating costs of bauxite production[1]

Country	Mine and mill operating cost	Transportation to port or refinery	Levy or severance tax	Total cost at port or local refinery
Australia	$4.47	$1.12	$1.20	$6.79
Brazil	5.64	4.13	1.00	10.77
Costa Rica	6.28	0	.30	6.58
Dominican Republic	7.19	1.00	[2]23.20	31.39
France	9.08	5.96	0	15.04
French Guiana	17.58	2.00	0	19.58
Ghana	6.38	4.95	3.42	14.75
Greece	12.81	4.00	0	16.81
Guinea	5.44	6.56	9.50	21.50
Guyana	7.77	1.27	.05	9.09
Haiti	8.73	1.36	23.69	33.78
India	3.24	2.96	.49	6.69
Indonesia	8.51	3.46	1.05	13.02
Jamaica	5.61	.85	[3]21.00	27.46
Malawi	2.80	2.50	0	5.30
Sierra Leone	7.10	4.25	.27	11.62
Suriname	8.42	2.17	18.50	29.09
Turkey	15.05	4.20	9.00	28.25
United States	15.09	0	0	15.09
Venezuela	5.00	7.76	0	12.76

[1] Costs presented for each country are a weight average of estimated operating costs for all the mines and deposits evaluated in this study. The assumptions used in determining whether bauxite was exported or refined domestically are presented in appendix A.

[2] Alcoa pays a flat rate of approximately $17 per ton of bauxite in lieu of the levy or corporate income taxes. Using a $17-per-ton rate of tax would reduce the FOB (port) cost of bauxite to $25.19.

[3] The Jamaican bauxite levy was reduced at the end of 1979. The average levy for Jamaica in 1980 was closer to $16 per ton. Using a $16 levy would reduce Jamaica's average cost at the port or local refinery to $22.46.

COST ELEMENTS OF ALUMINA REFINING

Capital and operating costs for typical alumina refineries in the United States, Western Europe, and Australia have been estimated for this study. Although these refineries are hypothetical, the costs are typical of those a new refinery of 800,000-tpy capacity would incur in each of the three areas. All the capital and operating costs for new refineries in this study use or adapt these models.

Capital Costs

Capital costs for alumina refineries, or for any large construction project, are strongly influenced by many factors, including (*8*, p. 33)—

- access to site
- topography of site
- environmental penalties
- availability of infrastructure
- time scale of construction
- climate
- availability of skilled labor
- industrial relations
- labor rates
- access to materials
- import duties

The cost models for new refineries were developed on the following assumptions:

Table 11. — Typical alumina refinery capital costs[1]

	Bayer high temperature, United States	Bayer low temperature: United States	Europe	Australia
Bauxite source	Caribbean	Africa	Africa	Australia
Capital cost, thousand U.S. dollars:				
Onsite	470,000	445,000	465,000	485,000
Offsite	75,000	75,000	75,000	90,000
Total fixed	545,000	520,000	540,000	575,000
Working capital	20,000	20,000	20,000	20,000
Total	565,000	540,000	560,000	595,000
Cost per annual ton capacity	$710	$675	$675	$745

[1] Capital costs are in 1979 dollars because of the assumption that the refinery began production in that year. A refinery beginning production in 1980 would have a higher capital cost.

1. The economic life of the plant over which the assets are depreciated is 20 years.
2. Of the total capital cost of the plant, 70 pct is funded through long-term (20-year) loans on which the real rate of interest is 5 pct; the remaining 30 pct is funded through equity capital on which the real pretax rate of profit is 10 pct.
3. The rated capacity of the refineries is 800,000 tpy; they would operate at 95 pct of capacity with annual production of 760,000 tpy of metal-grade alumina. The year of plant startup is 1979.
4. The cost estimates refer to new plants at new sites, with adequate basic infrastructure assumed to exist at the plant locations.

Estimated capital costs for the three regions, in 1979 U.S. dollars, are shown in table 11; published estimates of capital costs for worldwide refinery projects are presented in table A-2.

Operating Costs

The operating cost models of the four typical refineries included in this study are shown in tables 12, 13, 14, and 15. For each refinery, input requirements of raw materials, utilities, and operations have been estimated. In addition, the costs for these input factors—as well as administrative costs, capital charges, and profit—have been calculated. Following is a discussion of some of these factors.

Raw Materials

Excluding the bauxite cost, raw-material input cost for alumina production is not a major element of the refining process total cost. However, the chemical composition of the bauxite used is an important determinant of alumina-refining costs. The main factors determining the raw-material inputs and, therefore, the conditions for digestion and energy requirements for alumina refining are as follows:

1. The "available" alumina content of the bauxite ore.
2. Impurities in the bauxite, especially the reactive silica content.
3. The proportions of monohydrate to hydrate in the ore.
4. The degree of recovery and recycling of the caustic soda.
5. The caustic makeup.
6. The moisture content of the bauxite ore feed.

Table 12. — Estimated refinery operating costs for processing Caribbean bauxite in the United States[1]

Units of input	*Unit cost per ton Al_2O_3*
Raw materials:	
Caribbean bauxite (2.52 tons/ton)	NAp
Caustic soda (89 kg/ton at $140/ton)	$12.46
Other materials	2.29
Subtotal	14.75
Utilities:	
Fuel oil (400 l/ton at 13.1¢/l)	52.32
Electricity (200 kWh/ton at 2.94¢/kWh)[2]	5.88
Subtotal	58.20
Operations:	
Direct labor and supervision (1.0 worker-hr at $12.43/worker-hr)	12.43
Direct labor overhead (60 pct of direct labor)	7.46
Maintenance (2.5 pct of fixed capital cost)	17.93
Subtotal	37.82
Administration:	
Administration and sales (10 pct of direct labor)	1.24
Property tax and insurance (1.5 pct of fixed capital cost)	10.76
Subtotal	12.00
Cash cost of production	[3]122.77
Capital charges:	
Depreciation	35.86
Loan interest	26.02
Subtotal	61.88
Total costs of production FOB	184.65
Pretax equity profit	22.30
Total cost and profit FOB	206.95

NAp Not applicable.
[1] Cost of bauxite excluded; costs are 1980 U.S. dollars.
[2] Estimated average kilowatt-hour charge for new operations.
[3] For this study, when it was assumed that a new refinery would be built; the operating cost used in the economic analysis is the cash cost of production, since depreciation and profit are accounted for in the cash-flow analysis. If a toll charge is assumed, the cost charged is the total cost and profit FOB.

Table 13. — Estimated refinery operating costs for processing West African bauxite in the United States[1]

Units of input	*Unit cost per ton Al_2O_3*
Raw materials:	
West African bauxite (2.22 tons/ton)	NAp
Caustic soda (36 kg/ton at $140/ton)	$5.04
Other materials	2.29
Subtotal	7.33
Utilities:	
Fuel oil (400 l/ton at 13.1¢/l)	52.32
Electricity (200 kWh at 2.94¢/kWh)[2]	5.88
Subtotal	58.20
Operations:	
Direct labor and supervision (1.0 worker-hr at $12.43/worker-hr)	12.43
Direct labor overhead (60 pct of direct labor)	7.46
Maintenance (2.5 pct of fixed capital cost)	17.11
Subtotal	37.00
Administration:	
Administration and sales (10 pct of direct labor)	1.24
Property tax and insurance (1.5 pct of fixed capital cost)	10.26
Subtotal	11.50
Cash cost of production	[3]114.03
Capital charges:	
Depreciation	34.21
Loan interest	24.87
Subtotal	59.08
Total costs of production FOB	173.11
Pretax equity profit	21.32
Total cost and profit FOB	194.43

NAp Not applicable.
[1] Cost of bauxite excluded; costs are 1980 U.S. dollars.
[2] Estimated average kilowatt-hour charge for new operations.
[3] For this study, when it was assumed that a new refinery would be built, the operating cost used in the economic analysis is the cash cost of production, since depreciation and profit are accounted for in the cash-flow analysis. If a toll charge is assumed, the cost charged is the total cost and profit FOB.

Table 14. — Estimated refinery operating costs for processing West African bauxite in Western Europe[1]

Units of input	Unit cost per ton Al_2O_3
Raw materials:	
West African bauxite (2.22 tons/ton)	NAp
Caustic soda (36 kg/ton at $158/ton)	$5.70
Other materials	2.17
Subtotal	7.87
Utilities:	
Fuel oil (400 l/ton at 14.3¢/l)	57.11
Electricity (200 kWh at 3.02¢/kWh)[2]	6.04
Subtotal	63.15
Operations:	
Direct labor and supervision (1.0 worker-hr at $11.16/worker-hr)	11.16
Direct labor overhead (50 pct of direct labor)	5.58
Maintenance (2.5 pct of fixed capital cost)	17.76
Subtotal	34.50
Administration:	
Administration and sales (10 pct of direct labor)	1.12
Property tax and insurance (1.5 pct of fixed capital cost)	10.66
Subtotal	11.78
Cash cost of production	[3]117.30
Capital charges:	
Depreciation	35.53
Loan interest	25.79
Subtotal	61.32
Total costs of production FOB	178.62
Pretax equity profit	22.11
Total cost and profit FOB	200.73

NAp Not applicable.
[1] Cost of bauxite excluded; costs are 1980 U.S. dollars.
[2] Estimated average kilowatt-hour charge for new operations.
[3] For this study, when it was assumed that a new refinery would be built, the operating cost used in the economic analysis is the cash cost of production, since depreciation and profit are accounted for in the cash-flow analysis. If a toll charge is assumed, the cost charged is the total cost and profit FOB.

Table 15. — Estimated refinery operating costs for processing Australian bauxite in Australia[1]

Units of input	Unit cost per ton Al_2O_3
Raw materials:	
Australian bauxite (3.47 tons/ton)	NAp
Caustic soda (56 kg/ton at $159/ton)	$8.91
Other materials	2.27
Subtotal	11.18
Utilities:	
Fuel oil (400 l/ton at 16.1¢/l)	64.51
Electricity (200 kWh at 2.708¢/kWh)[2]	5.41
Subtotal	69.92
Operations:	
Direct labor and supervision (1.0 worker-hr at $9.39/worker-hr)	9.39
Direct labor overhead (50 pct of direct labor)	4.70
Maintenance (2.5 pct of fixed capital cost)	18.91
Subtotal	33.00
Administration:	
Administration and sales (10 pct of direct labor)	.94
Property tax and insurance (1.5 pct of fixed capital cost)	11.35
Subtotal	12.29
Cash cost of production	[3]126.39
Capital charges:	
Depreciation	37.83
Loan interest	27.40
Subtotal	65.23
Total costs of production FOB	191.62
Pretax equity profit	23.49
Total cost and profit FOB	215.11

NAp Not applicable.
[1] Cost of bauxite excluded; costs are 1980 U.S. dollars.
[2] Estimated average kilowatt-hour charge for new operations.
[3] For this study, when it was assumed that a new refinery would be built, the operating cost used in the economic analysis is the cash cost of production, since depreciation and profit are accounted for in the cash-flow analysis. If a toll charge is assumed, the cost charged is the total cost and profit FOB.

7. The choice of temperatures, pressures, concentrations, times, and tank sizes used in the digestion process.

The quantity of bauxite input required to produce 1 ton of alumina can range from a minimum of 2.1 tons to a maximum of 3.5 tons from some of the newer Australian deposits, depending on Al_2O_3 grade and silica content. Generally, 1.1 units (unit weight) of alumina and 1.2 units of soda are lost for each unit of reactive silica in the ore. Thus, the reactive silica content of the ore will increase both the quantity of bauxite required and caustic soda consumption. The loss of soda is made up by adding caustic soda or soda ash to the spent leach solution to reach the appropriate caustic concentration before recycling. The reactive silica content of different bauxites can vary considerably: for West African and Western Australian bauxites, it is low (1-2 pct); for Jamaican bauxite, it is moderate (approximately 3 pct); and it may reach 5 pct (after washing) in the case of the Weipa deposit in Northern Queensland, Australia.

Energy Requirements

Most of the energy required for alumina refining is consumed in producing steam and power and in calcining alumina. A clean fuel source such as fuel oil or natural gas is used to avoid contaminating the calcination product; coal-derived gases may become economic in the future. Any type of fuel may be used for steam and power generation, but common practice is to use the same fuel source as used for calcination. A "typical" refinery would consume 400 1 of fuel oil and 200 kWh of electricity to produce 1 ton of alumina, which (excluding the cost of bauxite) would represent some 24 pct of the total operating cost of the refinery.

Labor Costs

Direct-labor inputs per unit of output, relatively low in producing alumina, constitute a small percentage of total operating costs. Based on the cost models used, direct labor and supervision, overhead, and maintenance would amount to some 19 pct of the total operating cost of a U.S. alumina refinery. This percentage would be similar to other developed countries.

Transportation

As with bauxite, shipping costs for alumina are a significant factor in the overall delivered cost of alumina. A sample of freight rates for shipment of alumina is shown in table 16.

COST ELEMENTS OF ALUMINUM SMELTING

Capital Costs

With the same methodology as used for alumina refineries, capital and operating costs for "typical" new aluminum smelters in the United States, Western Europe, Japan, and Australia have also been estimated. These estimates represent the typical costs that would be incurred by the construction of a new smelter of 200,000-tpy capacity in each

Table 16. — Freight rates for shipment of alumina on principal international routes in 1980

Origin	Destination	Freight rate, U.S. dollars per ton
Australia	Japan-Taiwan	19–20
	U.S. east coast	25–30
	U.S. west coast	16–18
	New Zealand	8–10
	South Africa	18–20
	Argentina	50
	Persian Gulf	21.50–23
	Egypt	23–25
	Western Europe	35–40
	Iceland	31
	U.S.S.R. (Black Sea)	30–35
Caribbean	United Kingdom	19.50–22
	Western Europe (excluding U.K.)	23–25
	U.S. east coast	8–10
	Ghana	20–22
	Venezuela (origin Suriname)	4–5
	Canada (east coast)	10
France	Norway	11–12
Greece	Netherlands	10
Guinea	Western Europe	12–15
	Southern Europe (Italy, Austria)	13–16
	Cameroon	8
Italy (Sardinia)	Western Europe	11–12
Japan	Canada (west coast)	16
	Egypt	23–25
Yugoslavia	U.S.S.R.	10

Source: Commodities Research Unit, Ltd. (CRU).

of the four areas. The cost models for new smelters were developed on the following assumptions:

1. The economic life of the plant over which the assets are depreciated is 20 years.
2. Of the total capital cost of the smelter, 70 pct is funded through long-term (20-year) loans with a real rate of interest of 5 pct; the remaining 30 pct is funded through equity capital on which the real pretax rate of profit is 10 pct.
3. The rated capacity of each of the smelters is 200,000 tpy, with a 95-pct-capacity utilization and annual production of 190,000 tpy of aluminum ingot. The year of startup is 1979.
4. Although the cost estimates are for new smelters, it is assumed that adequate basic infrastructure exists at the smelter site and sufficient electric power is available.

Estimated capital costs for the four regions are shown in table 17. Published estimates of capital costs for worldwide smelter projects are presented in table A-3 in the appendix. Many of the costs presented in the appendix for projects not yet completed may be understated owing to continuing inflation; however, they do give a valid comparison of the costs associated with different areas of the world. The lesser developed countries have higher associated capital costs than the developed countries because of a combination of higher construction costs and basic infrastructure costs, such as power generation and transport systems.

Table 17.—Capital costs of typical aluminum smelters for cost model[1]

(Thousand U.S. dollars)

Facilities	United States	Western Europe	Japan	Australia
Onsite	440,000	440,000	440,000	470,000
Offsite	20,000	20,000	20,000	80,000
Total fixed	460,000	460,000	460,000	550,000
Working capital	50,000	50,000	50,000	70,000
Total	510,000	510,000	510,000	620,000
Cost per annual ton capacity	2,550	2,550	2,550	3,100

[1] Capital costs are in 1979 dollars because of the assumption that the smelter began production in that year. A smelter beginning in 1980 would have a higher capital cost.

Operating Costs

The operating costs of the four typical smelters included in this study are presented in tables 18, 19, 20, and 21. The operating costs are broken down into three factor-input categories, as described in the following paragraphs.

Raw Materials

Raw material costs are the costs for petroleum coke and pitch for anode manufacture and for fluorine products for the electrolytic bath. Variations in the requirements for raw material inputs depend upon a number of factors, including—

1. Cell operating variables, such as current, voltage and size of pots, and anode type.
2. Age and capacity of plant.
3. Degree of control exercised in maintaining optimum operating conditions.
4. Gas scrubbing systems for the recovery of fluorides.

The cost of raw materials (not including alumina) constitutes some 8 to 10 pct of the total cost of aluminum smelting.

Labor

Although labor costs per worker-hour vary significantly around the world, the differences in labor costs as a percentage of total operating cost at different smelter locations are not substantial since labor constitutes a small percentage of the total operating cost. In the United States, direct labor costs are approximately 6 pct of the total aluminum production costs.

Energy Costs

Often accounting for up to 60 pct of the total operating cost of aluminum ingot production, electricity is the critical cost factor in aluminum smelting. Electric power costs charged to aluminum smelters vary widely throughout the world and are the principal reason for the variation in aluminum ingot production costs between producing locations. With an assumed average electricity consumption of 14,200 kWh per ton of aluminum produced, a price change of 1 mill/kWh can result in a variation in operating costs of $14.20 per ton of aluminum. Table 22 provides an overview of electric power costs for various aluminum smelters in 1980.

For many years, the aluminum industry has benefited from low-cost, essentially subsidized power, as typified by the historic pricing policies of the BPA and TVA in the United States. In the past decade, however, increasing electricity demand, slow growth of nuclear power, and lack of new hydropower resources in the industrialized countries have caused growing competition for available electrical power. To conserve suppliers for residential and light industrial users, power suppliers in industrialized countries have sought to renegotiate contracts with aluminum companies. Consequently, industry has faced rapidly rising energy costs, particularly in those countries such as Japan and Italy that use electricity generated from imported oil. Furthermore, the tendency of alternative fuel sources to align their price structure to higher oil prices has brought about steep increases in the cost of electricity generated from natural gas and coal (*10*, p. 42).

Rising energy costs have caused a net shift of new smelting capacity away from the traditional locations in industrialized nations and have caused some countries to cut back on existing capacity. For example, Japan reduced its operating capacity by 540,000 tons per year to 1.1 million tons in 1978 and planned cuts of an additional 400,000 tons by 1985 (*6*, p. 10). Most new smelting capacity announced in the past few years is to be in nations offering a comparative advantage in energy costs with nearby sources of bauxite and alumina, such as Australia, Brazil, and Indonesia. Other countries announcing new smelter capacity include the oil-producing nations in the Middle East, such as Bahrain and

Table 18. — Estimated operating costs for smelting aluminum in the United States[1]

Units of input	*Unit cost per ton Al*
Raw materials:	
Alumina (1.93 tons/ton)	NAp
Petroleum coke (0.40 ton/ton at $149/ton)	$59.64
Pitch (0.10 ton/ton at $229/ton)	22.90
Other materials	28.70
Subtotal	111.24
Utilities: Electricity (14,200 kWh at 2.94¢/kWh)[2]	417.20
Operations:	
Direct labor and supervision (4.0 worker-hr at $12.43/worker-hr)	49.72
Direct labor overhead (50 pct of direct labor)	24.86
Maintenance (3 pct of fixed capital cost)	72.63
Subtotal	147.21
Administration:	
Administration and sales (70 pct of direct labor)	34.80
Property tax and insurance (1.5 pct of fixed capital cost)	36.31
Subtotal	71.11
Casting cost	81.35
Cash cost of production	[3]828.11
Capital charges:	
Depreciation	121.05
Loan interest	93.95
Subtotal	215.00
Total costs of production FOB	1,043.11
Pretax equity profit	80.53
Total cost and profit FOB	1,123.64

NAp Not applicable.
[1] Cost of alumina excluded; costs are 1980 U.S. dollars.
[2] Electricity charge represents an average for new producers. Actual rates, by region, are shown in table 22.
[3] For this study, when construction of a new smelter was assumed, the operating cost used in the economic analysis is the cash cost of production, since depreciation and profit are accounted for in the cash-flow analysis. If a toll charge is assumed, the cost charged is the total cost and profit FOB.

Table 19. — Estimated operating costs for smelting aluminum in Western Europe[1]

Units of input	*Unit cost per ton Al*
Raw materials:	
Alumina (1.93 tons/ton)	NAp
Petroleum coke (0.40 ton/ton at $169/ton)	$67.46
Pitch (0.10 ton/ton at $244.80/ton)	24.48
Other materials	27.20
Subtotal	119.14
Utilities: Electricity (14,200 kWh at 3.015¢/kWh)[2]	428.13
Operations:	
Direct labor and supervision (4.0 worker-hr at $11.16/worker-hr)	44.64
Direct labor overhead (50 pct of direct labor)	22.32
Maintenance (3 pct of fixed capital cost)	72.63
Subtotal	139.59
Administration:	
Administration and sales (70 pct of direct labor)	31.25
Property tax and insurance (1.5 pct of fixed capital cost)	36.32
Subtotal	67.57
Casting cost	81.79
Cash costs of production	[3]836.22
Capital charges:	
Depreciation	121.05
Loan interest	93.95
Subtotal	215.00
Total costs of production FOB	1,051.22
Pretax equity profit	80.53
Total cost and profit FOB	1,131.75

NAp Not applicable.
[1] Cost of alumina excluded; costs are 1980 U.S. dollars.
[2] Electricity charge represents an average for new producers. Actual rates, by region, are shown in table 22.
[3] For this study, when construction of a new smelter was assumed, the operating cost used in the economic analysis is the cash cost of production, since depreciation and profit are accounted for in the cash-flow analysis. If a toll charge is assumed, the cost charged is the total cost and profit FOB.

Table 20. — Estimated operating costs for smelting aluminum in Japan[1]

Units of input	*Unit cost per ton Al*
Raw materials:	
Alumina (1.93 tons/ton)	NAp
Petroleum coke (0.40 ton/ton at $227.00/ton)	$90.83
Pitch (0.10 ton/ton at $293.00/ton)	29.30
Other materials	36.62
Subtotal	156.75
Utilities: Electricity (14,200 kWh at 7.49¢/kWh)[2]	1,063.58
Operations:	
Direct labor and supervision (4.0 worker-hr at $10.04/worker-hr)	40.15
Direct labor overhead (60 pct of direct labor)	24.09
Maintenance (3 pct of fixed capital cost)	72.63
Subtotal	136.87
Administration:	
Administration and sales (70 pct of direct labor)	28.10
Property tax and insurance (1.5 pct of fixed capital cost)	36.31
Subtotal	64.41
Casting cost	81.50
Cash costs of production	[3]1,503.11
Capital charges:	
Depreciation	121.05
Loan interest	93.95
Subtotal	215.00
Total costs of production FOB	1,718.11
Pretax equity profit	80.53
Total cost and profit FOB	1,798.64

NAp Not applicable.
[1] Cost of alumina excluded; costs are 1980 U.S. dollars.
[2] Electricity charge represents an average for new producers. Actual rates, by region, are shown in table 22.
[3] For this study, when construction of a new smelter was assumed, the operating cost used in the economic analysis is the cash cost of production, since depreciation and profit are accounted for in the cash-flow analysis. If a toll charge is assumed, the cost charged is the total cost and profit FOB.

Table 21. — Estimated operating costs for smelting aluminum in Australia[1]

Units of input	*Unit cost per ton Al*
Raw materials:	
Alumina (1.93 tons/ton)	NAp
Petroleum coke (0.40 ton/ton at $176.00/ton)	$70.43
Pitch (0.10 ton/ton at $289.70/ton)	28.97
Other materials	28.40
Subtotal	127.80
Utilities: Electricity (14,200 kWh at 2¢/kWh)[2]	284.03
Operations:	
Direct labor and supervision (4.0 worker-hr at $9.39/worker-hr)	37.56
Direct labor overhead (50 pct of direct labor)	18.78
Maintenance (3 pct of fixed capital cost)	86.84
Subtotal	143.18
Administration:	
Administration and sales (70 pct of direct labor)	26.29
Property tax and insurance (1.5 pct of fixed capital cost)	43.42
Subtotal	69.71
Casting cost	81.93
Cash costs of production	[3]706.65
Capital charges:	
Depreciation	144.74
Loan interest	114.21
Subtotal	258.95
Total costs of production FOB	965.60
Pretax equity profit	97.89
Total cost and profit FOB	1,063.49

NAp Not applicable.
[1] Cost of alumina excluded; costs are 1980 U.S. dollars.
[2] Electricity charge represents an average for new producers. Actual rates, by region, are shown in table 22.
[3] For this study, when construction of a new smelter was assumed, the operating cost used in the economic analysis is the cash cost of production, since depreciation and profit are accounted for in the cash-flow analysis. If a toll charge is assumed, the cost charged is the total cost and profit FOB.

Table 22.—Electric power prices at selected aluminum smelters, 1980

Country	Plant and/or utility location	Price, U.S. cents/kWh
Australia	Portland smelter,	1.7-1.8
	Tomago project.	1.2-1.3
Canada	NA	0.5 or less
France	NA	2.8
Germany, Federal Republic of	NA	2.0 minimum
Japan	NA	5.0 minimum
Norway	NA	1.0
United Kingdom	NA	3.0
United States	Northwest, BPA	0.9[1]
	Southeast, TVA	2.7
	South and North Carolina	2.1-2.5
	New York, PASNY[2]	0.5-0.8

NA Not available.
[1] Has subsequently been increased to 1.5 to 2.1 cents/kWh.
[2] PASNY—Power Authority of the State of New York.
Source: Commodities Research Unit, Ltd. (CRU).

Dubai, which offer low-cost byproduct natural gas which is currently being flared off.

Estimated total operating costs of aluminum production by country or region for producers and potential producers are shown in tables 23 and 24. The cost breakdowns shown, the result of the cost analysis performed on each operation during the course of this study, are presented, by country, on a weight-averaged basis. The assumed materials flows from mine to smelter shown in table A-1 are the basis of the costs presented. The salient statistic provided from tables 23 and 24 is the percentage of total operating costs accounted for by refining and smelting. For both producers and potential producers, refining and smelting account for over 90 pct of total operating costs. Costs for aluminum smelting alone average 66 to 70 pct of the total operating costs of the producers and potential producers analyzed in this study. This statistic, underscoring the need to develop smelting capacity near sources of cheap energy, explains the shift of new smelter capacity to energy-rich countries.

Table 23. — Average operating costs of producing aluminum operations

(All costs in U.S. cents per pound of primary aluminum in 1980 dollars)

Bauxite origin	Mine cost	Mill cost	Refinery cost	Smelter cost	Transport to refiner and/or smelter	Royalty and/or levies	Total cost	Total cost minus byproduct credit
Caribbean.								
Jamaica	1.0	0.2	13.9	49.9	2.0	4.6	71.6	71.6
Others[1]	1.0	.1	17.5	44.6	3.3	4.9	71.5	71.5
Latin America:								
Brazil	1.4	1.2	15.6	50.3	2.6	3.1	74.0	74.0
Guyana	1.1	3.9	14.0	50.5	2.1	.0	71.6	64.3
Suriname	1.1	1.5	16.5	47.5	1.5	3.6	71.8	69.5
Europe:								
France	1.7	.0	18.5	52.5	1.5	.0	74.2	74.2
Greece	1.2	.2	15.4	54.1	1.0	.0	71.9	71.9
Turkey	W	W	W	W	W	W	W	W
Asia:								
India	1.2	.0	13.9	23.0	2.3	.1	40.5	40.5
Indonesia	W	W	W	W	W	W	W	W
Oceania:								
Australia	.8	.1	15.9	45.0	1.6	.2	63.6	63.5
Africa:								
Guinea	.9	1.0	16.5	51.7	2.9	2.1	75.1	63.8
Other[2]	1.2	.3	13.6	50.9	2.6	.1	68.7	68.7
United States	3.0	.0	13.9	51.2	.8	.9	69.9	69.9
Other countries[3]	1.7	.3	14.3	53.5	.5	.6	70.9	70.9
Average for market economy countries:	1.0	.9	15.7	49.3	2.1	1.7	70.7	66.7

W Withheld to avoid disclosing individual deposit data; included as "Other countries."
[1] Includes the Dominican Republic and Haiti.
[2] Includes Ghana and Sierra Leone.
[3] Includes Indonesia and Turkey.

Table 24. — Estimated average operating costs of nonproducing (potential) aluminum operations

(All costs in U.S. cents per pound of primary aluminum in 1980 dollars)

Bauxite origin	Mine cost	Mill cost	Refinery cost	Smelter cost	Transport to refiner and/or smelter	Royalty and/or levies	Total cost	Total cost minus byproduct credit
Caribbean:								
Jamaica	1.0	0.2	15.4	50.0	2.7	4.6	73.9	73.9
Latin America:								
Brazil	1.0	1.1	17.9	45.6	2.4	3.0	71.1	70.9
Other[1]	1.0	.4	14.7	49.9	1.3	.7	68.0	68.0
Asia:								
India	.8	.0	18.2	44.7	2.3	.1	66.0	66.0
Indonesia	W	W	W	W	W	W	W	W
Oceania:								
Australia	.9	.2	9.6	49.3	1.3	.4	61.7	61.7
Solomon Islands	W	W	W	W	W	W	W	W
Africa:								
Ghana	.5	.1	14.6	47.9	1.9	.6	65.6	65.6
Guinea	1.3	.0	25.7	43.9	6.2	1.9	79.1	79.1
Other[2]	1.0	.0	15.0	48.8	5.3	3.6	73.9	73.9
Other countries[3]	1.7	.6	9.0	36.4	1.9	.3	49.8	49.8
Average for market economy countries:	1.1	.2	17.3	46.2	3.4	1.8	70.0	70.0

W Withheld to avoid disclosing individual deposit data; included as "Other countries."
[1] Includes Costa Rica, French Guiana, Suriname, and Venezuela.
[2] Includes Cameroon, Malawi, and Sierra Leone.
[3] Includes Indonesia and the Solomon Islands.

RESOURCE-AVAILABILITY CURVES

Once the cost data were determined, an economic analysis was performed for each operation. For aluminum operations not in production, all capital and operating cost estimates were expressed in January 1980 dollars. For producing operations, the undepreciated capital investment remaining in 1980 was calculated and all reinvestment, operating, and transportation costs were converted to January 1980 dollars. All costs for non-U.S. operations were converted to U.S. dollars based on foreign exchange rates, productivity factors, and inflation rates to reflect the U.S. dollar-equivalent cost of doing business within a foreign country.

The Bureau of Mines has developed the Supply Analysis Model (SAM) to perform discounted cash-flow-rate-of-return (DCFROR) analyses to determine the price of the primary commodity required for an operation to obtain a specified rate of return on all of its investments (*5*). This determined value for the aluminum price is equivalent to the average total cost of production for the operation over its producing life under the set of assumptions and conditions (e.g., mine plan, full capacity production, and a market for all output) that are necessary in order to make an evaluation and is sometimes referred to as "incentive price". The DCFROR is most commonly defined as the rate of return that makes the present worth of cash flow from an investment equal the present worth of all after-tax investments (*21*, p. 232). For this study, a 15-pct DCFROR was considered the necessary rate of return to cover the opportunity cost of capital plus risk.

Based on MAS methodology, all capital investments incurred 15 years before the initial year of analysis are treated as sunk costs. Capital investments incurred less than 15 years before the initial year of the analysis have the undepreciated balances carried forward to that year, with all subsequent investments reported in constant 1980 dollars. This method generally results in a lower average total cost for currently producing operations since the undepreciated balance of capital investment for producing operations is generally much less than the capital investment required to develop new operations.

A separate tax-records file maintained for each U.S. State and individual country contains the relevant fiscal parameters under which the mining firm would operate. This file includes corporate income taxes, royalties, severances taxes, and bauxite levies. These tax parameters are applied to each operation under evaluation with the implicit assumption that each bauxite deposit represents a separate corporate entity.

The system also contains an additional file of worldwide economic indexes to update cost estimates for producing and nonproducing operations.

Commodity-price tables are maintained for all byproducts and coproducts relevant to the availability analysis. In this study, the only assumed byproduct of aluminum production is calcined refractory bauxite, with a January 1980 price of $225 per ton.

Detailed cash-flow values are generated for each preproduction and production year of an operation beginning with 1980, the first year of the analysis. For each of the individual operations, an "incentive price" is determined at which a firm would generate sufficient revenues over the long run to cover full costs of the integrated operation, including a return on investment high enough to attract new capital (*1*). This represents the average total cost of mining bauxite from the individual deposit, including transportation costs to a refinery, refining costs, transportation costs to an aluminum smelter, smelting costs, and a 15-pct DCFROR on invested capital.

Upon completion of the individual analyses, all operations included in the study were aggregated onto total and annual resource-availability curves. The total resource-availability curve is a tonnage-cost relationship that shows the total quantity of recoverable product potentially available at each operation's average total production cost including a stipulated rate of return. That is, the curve is an aggregation of the total potential aluminum that could be produced over the entire producing life of each operation, ordered from operations with the lowest average total cost of production to those with the highest. The curve provides a concise, easy-to-read, graphic analysis of the comparative costs associated with any given level of potential total output, together with an estimate of what the average long-run aluminum price (in January 1980 dollars) would likely have to be in order for a given tonnage to be potentially available.

Certain assumptions are inherent in these curves:

1. For all of the Jamaican deposits (and several other deposits), actual or estimated time schedules to develop the nonproducing operations were used; otherwise it was assumed that all nonproducing operations began development in 1980.
2. All operations produce at full operating capacity throughout the life of the bauxite mine, and all output can be sold at a price that is equal to or greater than the average total production cost.
3. Level of output for each operation (capacity) is assumed to remain constant over the entire producing life of the operation, except where planned expansions are known.
4. All costs after January 1980 are expressed in January 1980 dollars. No escalation of either costs or prices was included in the study.

Annual curves are also presented in this report, and are constructed by disaggregating the total resource-availability curve on an annual basis. The assumptions inherent in the total resource-availability curve also apply for the annual curves. These curves reflect the time lags involved in achieving total production potential as well as the levels of full capacity output for each operation. Because of the tremendous bauxite reserves in the world, many deposits need not be developed for many years. Whenever possible, published estimates of the development schedules for nonproducers and planned expansions by producing operations were utilized; in particular, the Jamaican Government, in order to plan the orderly growth of its bauxite industry, has provided a detailed plan of development for all of its known deposits. In most cases, however, published estimates of development schedules were not available; therefore, preproduction development was assumed to begin in 1980. This assumption leads to more potential aluminum production during the late 1980's than will likely appear, and the reader should keep this in mind when interpreting the annual curves presented later in this report.

AVAILABILITY OF ALUMINUM FROM WORLD BAUXITE RESOURCES

GENERAL

This study analyzed potential aluminum production based upon the demonstrated resources of 91 bauxite mines and deposits in 22 market economy countries; of this resource, representing an in situ tonnage of 20.2 billion tons of bauxite, some 18.8 billion tons are considered to be minable, providing a production potential of 3.6 billion tons of primary aluminum. The resource tonnage includes refractory-grade bauxite contained in 15 of the properties studied which have a production potential of 616 million tons of calcined refractory bauxite. In the analysis, the revenues generated from the production of calcined refractory bauxite are credited against the cost of producing primary aluminum.

POTENTIAL TOTAL ALUMINUM PRODUCTION

The potential production of aluminum based on the average total cost of production for each operation is illustrated in figure 3. The individual costs for aluminum range from about $0.47 per pound to $1.13. At a constant-dollar aluminum price of $1.13, a total of 3.6 billion tons of aluminum would potentially be available. With a price of $0.66—equal to the producer price of aluminum in January 1980—some 470 million tons of aluminum would be available. This tonnage is approximately 37 times the actual primary aluminum production of market economy countries in 1980 (*10*). At $0.75, 1.3 billion tons would be available; and at $0.85, about 3 billion tons would be available. Generally, the operations showing an average total cost of less than $0.75 are currently producing, whereas the higher cost operations are not yet in production. Estimated average total costs for producing and potential operations are illustrated in table 25; the average total cost of aluminum production for all producers on a weight-averaged basis is $0.70 per pound, whereas the average for nonproducers is $0.84. This differential is largely accounted for by the huge capital investments, particularly in infrastructure and refining and smelting capacity, required to bring nonproducing operations into production.

The total resource-availability curve can be disaggregated to illustrate potential aluminum production from the ore of each of the six major bauxite-producing regions. No curve was constructed for the United States, since the three U.S. mines included in the study account for only 8.5 million tons of potential aluminum production.

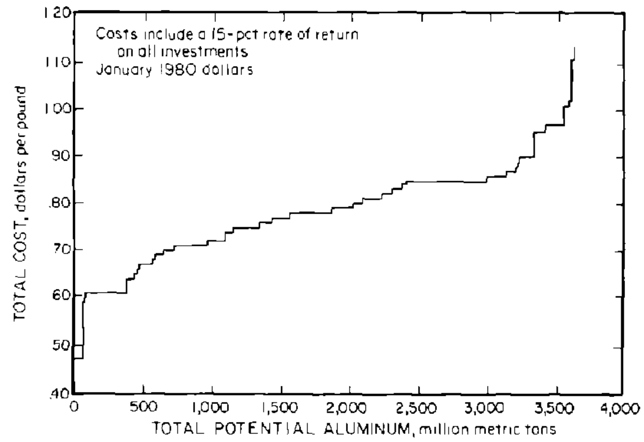

Figure 3.—Total potential aluminum production from bauxite resources in market economy countries.

Table 25. — Potential aluminum production and average total cost for producing and potential operations in market economy countries

Bauxite source	Producing operations		Potential operations	
	Potential Al production, thousand tons	Average total cost, U.S. dollars per pound (weight averaged)	Potential Al production, thousand tons	Average total cost, U.S. dollars per pound (weight averaged)
Caribbean:				
Jamaica	144,692	0.73	245,522	0.79
Others[1]	6,303	.75	—	—
Total	150,995	.73	245,522	.79
Latin America:				
Brazil	156,139	.78	182,624	.77
Guyana	104,047	.66	—	—
Others[2]	109,573	.70	97,589	.81
Total	369,759	.72	280,213	.78
Europe:				
France	3,449	.75	—	—
Greece	135,302	.77	—	—
Turkey	W	W	—	—
Total	138,751	.77	—	—
Asia:				
India	17,972	.50	181,407	.80
Indonesia	W	W	W	W
Total	17,972	.50	181,407	.80
Oceania:				
Australia	349,105	.70	371,721	.83
Solomon Islands	—	—	W	W
Total	349,105	.70	371,721	.83
Africa:				
Guinea	454,329	.66	609,643	.84
Others[3]	15,721	.75	288,171	.88
Total	470,050	.67	897,814	.86
United States	8,535	.71	—	—
Other countries[4]	15,963	.86	141,815	.97
Total	1,521,130	.70	2,118,492	.84

W Withheld to avoid disclosing individual operation data; included as "Other countries."
— indicates 0 or negligible.
[1] Includes the Dominican Republic and Haiti.
[2] Includes Costa Rica, French Guiana, Suriname, and Venezuela.

The Caribbean

Figure 4 shows potential aluminum production from bauxite in the Dominican Republic, Haiti, and Jamaica. Total potential aluminum production from the bauxite in these countries amounts to about 397 million tons, 38 pct from producing operations and 62 pct from potential producers. Total production costs range from $0.59 to $0.85 per pound, with an average of $0.73 for producers and $0.79 for potential producers.

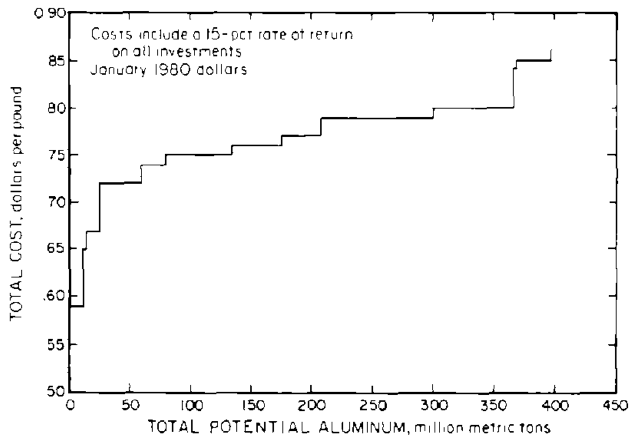

Figure 4.—Total potential aluminum production from Caribbean bauxite.

Latin America

Figure 5 shows potential aluminum production from bauxite in Brazil, Costa Rica, French Guiana, Guyana, Suriname, and Venezuela. Total potential aluminum production from bauxite in these countries is about 650 million tons, 57 pct from producing operations and 43 pct from potential producers. Total production costs range from $0.64 to $1.02 per pound, with an average of $0.73 for producers and $0.79 for potential producers.

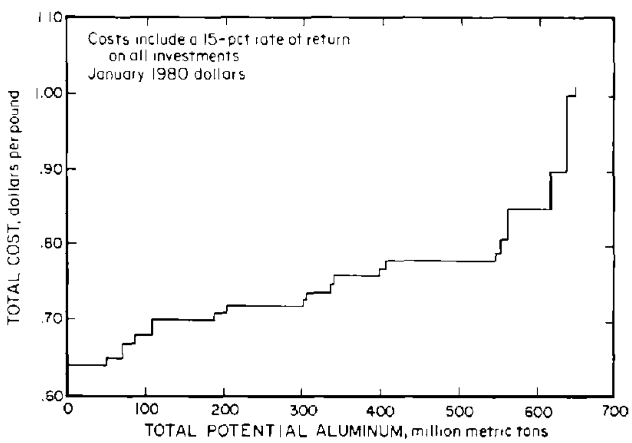

Figure 5.—Total potential aluminum production from Latin American bauxite.

Europe

Figure 6 shows potential aluminum production from bauxite in France, Greece, and Turkey. Total potential aluminum production from the bauxite in these countries amounts to 143 million tons, all from producing operations. Total production costs range from $0.72 to $0.79 per pound, with an average of $0.77 per pound.

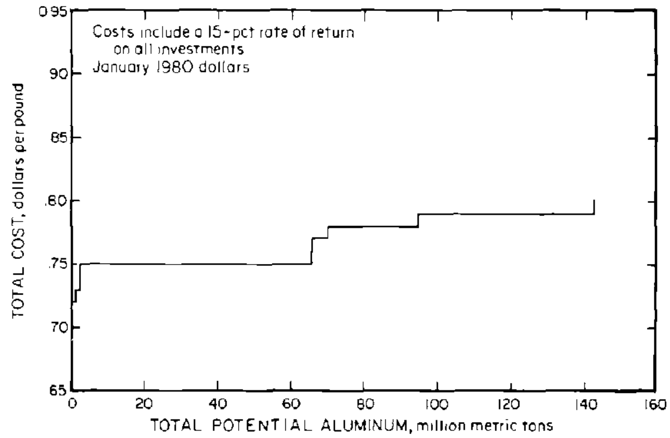

Figure 6.—Total potential aluminum production from European bauxite.

Asia

Figure 7 shows potential aluminum production from bauxite in India and Indonesia. Total potential aluminum production from the bauxite in these countries amounts to 343 million tons, 9 pct from producing operations and 91 pct from potential producers. Total production costs range from $0.47 to $1.11 per pound, with an average of $0.65 for producers and $0.87 for potential producers.

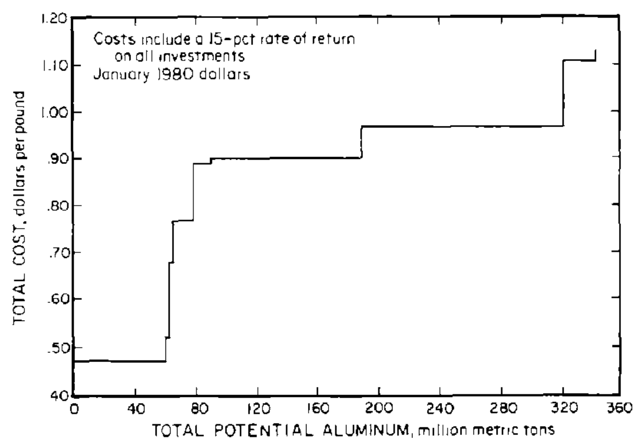

Figure 7.—Total potential aluminum production from Asian bauxite.

Oceania

Figure 8 shows potential aluminum production from bauxite in Australia and the Solomon Islands. Total potential aluminum production from the bauxite in these countries amounts to about 731 million tons, 48 pct from producers and 52 pct from potential producers. Total production costs range from $0.66 to $1.13 per pound, with an average of $0.70 for producers and $0.83 for potential producers.

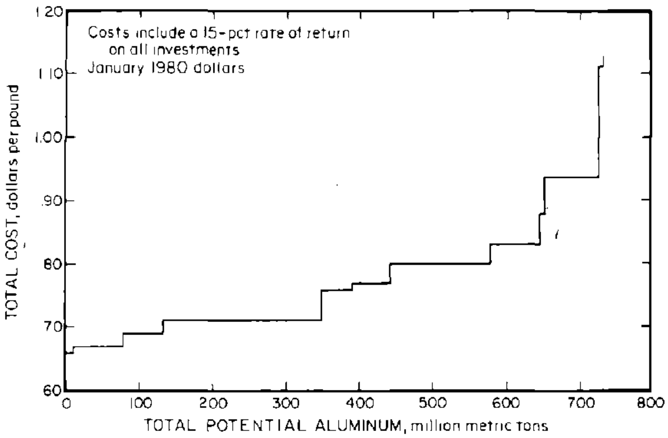

Figure 8.—Total potential aluminum production from bauxite in Oceania.

Africa

Figure 9 shows potential aluminum production from bauxite in Cameroon, Ghana, Guinea, Malawi, and Sierra Leone. Total potential aluminum production from the bauxite in these countries amounts to 1.368 billion tons, 34 pct from producers and 66 pct from potential producers. Total production costs range from $0.61 to $1.01 per pound, with an average of $0.67 for producers and $0.86 for potential producers.

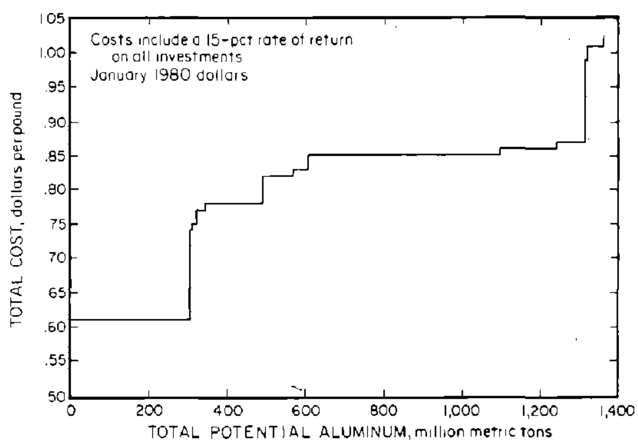

Figure 9.—Total potential aluminum production from African bauxite.

POTENTIAL ANNUAL ALUMINUM PRODUCTION

Another method of illustrating aluminum availability is to disaggregate the total resource-availability curve and show potential production on an annual basis. Figure 10 shows the potential annual production of aluminum at selected cost levels between the years 1980 and 2000. The curves are based on current and estimated production capacities for producing and potential operations. Also reflected in the curves are estimates of capacity expansions of existing operations (when published expansion plans were available) and development schedules for nonproducers. The development schedule reflects the time lag inherent in developing "greenfield" mining, refining, and smelting capacity. This study does not take into account possible further delays caused by environmental, legal, fiscal, financial, market, or other problems. With the exception of deposits in Jamaica, where the Jamaican Government provided estimated development plans and several other deposits where actual development plans were known, all the nonproducing operations were assumed to begin preproduction development in 1980.

Potential aluminum production on the annual curve increases substantially during the 1980's but remains relatively flat from 1990 through 2000, largely because of the assumptions underlying the curve. The assumption of preproduction beginning in 1980 for nonproducers causes potential production capacity to increase dramatically during the mid-1980's. Furthermore, the assumption that capacities remain constant (with a few exceptions) throughout the life of the operation makes output constant throughout the 1990's. In reality, production capacities of existing bauxite mines can generally be expanded at a much lower cost than that for developing new bauxite operations. Significant expansion of existing bauxite mines, however, would be the result of concomitant expansion of existing refining and smelting capacity or the development of new refining and smelter capacity to process the bauxite into aluminum. Thus, the quantity of potential aluminum production is probably overstated for the mid-1980's and the estimates of production potential through the 1990's may be conservative. However, the costs of achieving new production potential, either from the expansion of existing capacity or from the development of "greenfield" operations (in january 1980 dollars), are accurately reflected in the curves based on the cost analyses performed for this study. The cost of developing new refining and smelting capacity for the potential operations analyzed in this study is basically the same as would be incurred in developing new refining and smelting capacity to process additional bauxite from existing operations.

A gradual expansion of aluminum production potential is illustrated in figure 10. At a production cost of $0.75, potentially recoverable aluminum increases from slightly less than 14 million tons in 1981 to 17 million tons in 1985 and 19 million tons in 1990. At $1.15, the amount of potentially recoverable aluminum increases from about 17 million tons in 1981 to approximately 44 million tons in 1990. If demand for primary aluminum continues to increase at rates of 4 to 6 pct annually, however, the market economy countries will require annual production between 30 and 40 million tons of

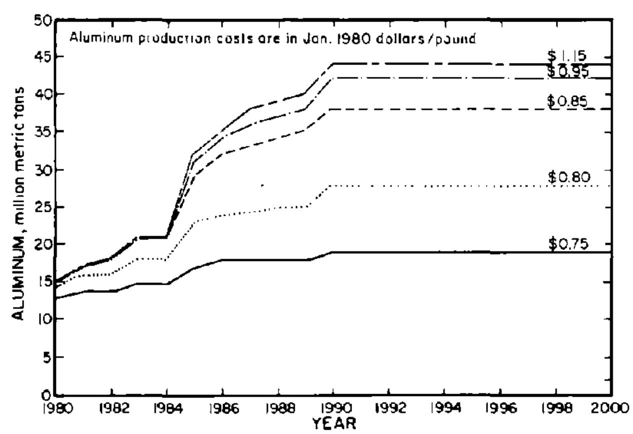

Figure 10.—Potential annual aluminum production from bauxite resources in market economy countries at various cost levels including a 15-pct DCFROR.

primary aluminum in the year 2000. Based on the results of the analysis illustrated in figure 10, a net increase in the real price of aluminum will be needed as an incentive for the development of sufficient refinery and smelter capacity to satisfy demand, irrespective of whether the bauxite source is from the expansion of existing mines or from the development of new ones. A real price of at least $0.85 per pound (in January 1980 dollars) would be required, mainly because of rising construction and energy costs and the high cost of capital. If aluminum prices continue at low levels, a tight market situation could occur before the end of the century. Any shortfalls of aluminum supply would not be caused by a lack of bauxite resources, but rather by a lack of growth in smelting and refining capacity.

Ironically, an industry that has been plagued with overcapacity throughout the 1970's could face future shortfalls of capacity. However, even in booming Australia, five of six planned smelter projects have been put on hold, largely because of uncertainties concerning the availability or cost of electric power (*6*, p. 16).

CONCLUSIONS

The demonstrated resources of bauxite ore contained in the 91 deposits analyzed in this study amount to approximately 20.2 billion tons, out of a total identified bauxite resource of roughly 31.9 billion tons in market economy countries. From this demonstrated resource, an estimated 3.6 billion tons of primary aluminum is recoverable. The analyses indicate that at a long-run aluminum price of $1.13 per pound (in January 1980 dollars), all this aluminum is potentially available. At $0.75 per pound, an estimated 1.3 billion tons of aluminum is potentially available; at $0.85 about 3 billion tons of aluminum would be available; and $1 could bring potential production of slightly under 3.6 billion tons. In January 1980 dollars, the average total cost of production (on a weight-averaged basis) for producing operations is $0.70 per pound of aluminum; for potential producers the average is $0.84. Bauxite mining, milling, and levies (also on a weight-averaged basis) account for slightly over 6 pct of the total operating cost of aluminum production. Alumina refining accounts for 22 pct of the total operating cost, transportation accounts for about 3 pct, and aluminum smelting accounts for over 69 pct. Refining and smelting costs, on average, amount to over 90 pct of the total operating cost of aluminum production.

Demonstrated resources of bauxite are sufficient to serve as the source of primary aluminum well into the next century. Also, as new bauxite deposits are discovered, and as bauxite deposits with tonnage estimates at the identified resource level are further explored, they will be included as reserves, significantly increasing future availability of bauxite. Any improvement in refining technology that would make low-grade bauxites economic would increase bauxite reserves even further. Furthermore, bauxite is widely distributed geographically, lessening the risks of dependence on imported sources.

About 12 million tons of aluminum was potentially available in 1980 at a total production cost of $0.75 per pound, an output very close to the actual Western World production in 1980 of 12.6 million tons. With the same criterion of $0.75, approximately 17 million tons of aluminum could be potentially available in 1985, and almost 19 million tons could be available in 1990. Assuming continued growth in demand for aluminum, a tight market situation could develop during the 1990's, unless the real price of aluminum increases enough to stimulate the massive new investments required to develop new mining, refining, and smelting capacity. Any possible shortfalls of aluminum supply would be due not to a lack of bauxite resources, but mainly to a lack of growth in refining and smelting capacity. This study indicates that the real price of aluminum would have to be $0.85 per pound (in January 1980 dollars) before 1990 to attract the required investments and provide aluminum companies with a sufficient rate of return on invested capital.

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APPENDIX A. — TABLES

Table A–1. — Assumed location of refineries and smelters for the study

Deposit	Status	Location of refinery	Percentage to each refinery	Location of smelter	Percentage to each smelter
		AUSTRALIA			
Aurukun	Nonproducer	Australia	100	Holland	50
				Korea	50
Cape Bougainville	do	do	100	U.S.	50
				Japan	50
Chittering (Muchea)	do	do	100	Japan	100
Gove	Producer	Australia	50	Europe	25
		U.S.	25	U.S.	25
		W. Germany	25	Iceland	25
				South Africa	25
Huntly-Del Park	do	Australia	100	Australia	100
Jarrahdale	do	do	100	do	100
Mitchell Plateau	Nonproducer	do	100	Australia	50
				U.S.	20
				Japan	20
				Europe	10
Mount Saddleback	do	do	100	U.S.	50
				Japan	50
Wagerup (Mount William)	do	do	100	Australia	100
Weipa	Producer	Australia	43	Australia	43
		Italy	40	Italy	40
		Japan	17	Japan	17
		BRAZIL			
Almerim-Jutai Para	Nonproducer	Brazil	50	Brazil	50
		U.S.-Canada	50	U.S.-Canada	50
Ouro Preto	Producer	Brazil	100	Brazil	100
Paragominas	Nonproducer	Brazil	30	Brazil	30
		U.S.-Canada	70	U.S.-Canada	70
Pocos De Caldas	Producer	Brazil	100	Brazil	100
Pocos De Caldas-Alcominas	do	Brazil	86	Brazil	86
		U.S.	14	U.S.	14
Trombetas-Alcoa	Nonproducer	Brazil	100	Brazil	100
Trombetas-MRN	Producer	Canada	100	Canada	100
		BRITISH PACIFIC ISLANDS			
Rennel Island	Nonproducer	Rennel Island	100	Japan	100
Wagina Island	do	Japan	100	do	100
		CAMEROON			
Minim Martap	Nonproducer	Cameroon	34	Cameroon	34
		France	66	France	66
		COSTA RICA			
San Isidro Del General	Nonproducer	Costa Rica	100	Costa Rica	100
		DOMINICAN REPUBLIC			
Cabo Rojo	Producer	U.S.	100	U.S.	100
		FRANCE			
Blanquette-Combecave	Producer	France	100	France	100
Cannonnettes	do	do	100	do	100
La Roquette-Montplaisir	do	do	100	do	100
Mazauges (Var)	do	do	100	do	100
Pegros (Var)	do	do	100	do	100
St. Julien-Tourves	do	do	100	do	100
		FRENCH GUIANA			
Kaw Mountains	Nonproducer	Suriname	100	U.S.	100
		GHANA			
Atewa (Kibi)	Nonproducer	Europe	41.2	Europe	62.4
		Ghana	58.8	Ghana	37.6
Awaso	Producer	U.K.	34		
		W. Germany	33	Ghana	100
		Spain	33		
Nyinahin	Nonproducer	Ghana	27.5	Europe	100
		Europe	72.5		
		GREECE			
Eleusis	Producer	Greece	100	Greece	100
Helikon	do	do	100	Europe	100
Itea	do	do	100	do	100
Parnasse	do	do	100	do	100
		GUINEA			
Aye Koye	Nonproducer	Guinea	37.8	Guinea	6.6
		Europe	62.2	Europe	93.4
Dabola Mine	do	Guinea	47.6	Guinea	13.7
		Europe	52.4	Europe	86.3
Debele (Kindia)	do	Europe-USSR	100	Yugoslavia	50
				Europe	50
Fria	Producer	Guinea	100	Europe	80
				Cameroon	20
Sangaredi (Boke)	do	U.S.	74	U.S.	74
		Europe	26	Europe	26
Tougue	Nonproducer	Guinea	14	Guinea	8.1
		Europe	86	Europe	91.9

Table A–1. — Assumed location of refineries and smelters for the study — Continued

Deposit	Status	Location of refinery	Percentage to each refinery	Location of smelter	Percentage to each smelter
		GUYANA			
Arrowcane East	Producer	Guyana	100	U.S.	76
				Europe	21
				Venezuela	3
Arrowcane South	do	do	100	U.S.	76
				Europe	21
				Venezuela	3
Coomacka	do	do	100	Europe	50
				Venezuela	50
East Mombaka	do	U.S.	34	U.S.	34
		Europe	33	Europe	33
		Japan	33	Japan	33
East Montgomery	do	Guyana	100	U.S.	76
				Europe	21
				Venezuela	3
Ituni District	do	Guyana	38	U.S.	50
		U.S.	31	Europe	50
		Europe	31		
Kara Kara	do	Guyana	100	U.S.	76
				Europe	21
				Venezuela	3
Manaka	do	U.S.	34	U.S.	34
		Europe	33	Europe	33
		Japan	33	Japan	33
West Bank #3	do	Guyana	100	U.S.	76
				Europe	21
				Venezuela	3
West Mombaka	do	U.S.	34	U.S.	34
		Europe	33	Europe	33
		Japan	33	Japan	33
Yararibo	do	U.S.	34	U.S.	34
		Europe	33	Europe	33
		Japan	33	Japan	33
		HAITI			
Miragoane	Producer	U.S.	100	U.S.	100
		INDIA			
Amarkantak	Producer	India	100	India	100
Anantagiri	Nonproducer	U.S.S.R.	100	U.S.S.R.	100
Bagru Hills	Producer	India	100	India	100
Chandgad	do	do	100	do	100
Chintaplee	Nonproducer	do	100	U.S.S.R.	100
Gandhamardan	do	do	100	India	100
Lohardaga	Producer	do	100	do	100
Panchpatmali	Nonproducer	do	100	do	100
		INDONESIA			
Bintan Island	Producer	Japan	100	Japan	100
Singakawang	Nonproducer	Indonesia	100	Indonesia	100
		JAMAICA			
Alpart	Producer	Jamaica	100	U.S.-Canada	52.2
				Europe	30.3
				Ghana	8.0
				Venezuela	9.5
Breadnut Valley	do	do	100	U.S.	50
				Europe	50
Cambridge	Nonproducer	do	100	U.S.-Canada	52.2
				Europe	30.3
				Ghana	8.0
				Venezuela	9.5
Ewarton	Producer	Jamaica	100	Canada	100
Kirkvine	do	do	100	do	100
Lydford	do	U.S.	100	U.S.	100
Maggotty	Temporary shutdown	do	100	do	100
New Market East	Nonproducer	U.S.	100	U.S.	100
Samalco	do	Jamaica	100	U.S.	34
				Europe	33
				Venezuela	33
Schwallenburgh West	do	Jamaica	100	Canada	100
Spanish Town West	do	U.S.	100	U.S.	100
Trelawny	do	U.S.	100	U.S.	100
Trelawny Central	do	Jamaica	100	U.S.	34
				Europe	33
				Venezuela	33
Water Valley	Producer	U.S.	100	U.S.	100
Williamsfield East	Nonproducer	Jamaica	100	U.S.	50
				Europe	50
		MALAWI			
Mulanje Mountain	Nonproducer	Malawi	100	Malawi	100
		SIERRA LEONE			
Moyamba	Producer	Sierra Leone	100	Europe	45
				Canada	45
Port Loko	Nonproducer	U.S.	43	Europe	45
		Sierra Leone	57	Canada	55

Table A–1. — Assumed location of refineries and smelters for the study — Continued

Deposit	Status	Location of refinery	Percentage to each refinery	Location of smelter	Percentage to each smelter
		SURINAME			
Bakhuis Mts.	Nonproducer	Suriname	100	U.S.	100
Moengo	Producer	Suriname	50	Suriname	50
		U.S.	50	U.S.	50
Lelydorp	do.	Suriname	75	Suriname	75
		U.S.	25	U.S.	25
Onverdacht	do.	U.S.	52	U.S.	52
		Suriname	48	Suriname	48
		TURKEY			
Seydisehir	Producer	Turkey	100	Turkey	100
		UNITED STATES			
Alcoa Bauxite	Producer	U.S.	100	U.S.	100
Quapaw Bauxite	do.	U.S.	100	U.S.	100
Reynolds Bauxite	do.	U.S.	100	U.S.	100
		VENEZUELA			
Los Pijiguaos	Nonproducer	Venezuela	100	Venezuela	100

Table A–2. — Capital costs of alumina refineries

Country	Location	Type[1]	Capacity, thousand tons	Cost,[2] million U.S. dollars	Year[3]	Cost per annual ton of capacity, U.S. dollars
			SOUTH AMERICA			
Brazil	Belem	N	800	409	1978	511
Venezuela	Mantanzas	N	1,000	650	1979	650
			CARIBBEAN			
Jamaica	Manchester	N	600	500	1980	636
Do	Clarendon	E	550	350	1980	636
Virgin Islands	St. Croix	E	550	350	1979	636
			AUSTRALIA			
Queensland	Gladstone	E	350	242	1980	692
Western Australia	Pinjarra	E	300	33	1980	110
Do	Wagerup	N	500	427	1980	854
Do	Worsley	N	1,000	1,000 (a)	1980	1,100
			EUROPE			
Greece	Distomon	E	100	120	1980	1,200
Greece	Gulf of Corinth	N	600	600	1980	1,000
Ireland	Aughinish	N	800	700	1979	870
Italy	Portoscuso	E	720	670	1980	930
Norway	Mongstad	N	350	244	1979	697
			ASIA			
India	Orissa	N	800	861 (b)	1979	1,077
Do	Kutch	N	300	258 (b)	1979	861
Iran	Teheran	N	500	600	1979	1,200
Indonesia	Kuala Tanjung	N	600	502	1979	836
Do	Kalimantan	N	500	325	1978	650
Philippines	Mindanao	N	800	500	1979	625
			AFRICA			
Guinea	Friguia	E	350	350	1978	1,000
Guinea	Aye Koye	N	2,000	1,200 (b)	1978	600
Ghana	Kibi	N	600	240 (b)	1978	400

[1]N — new plant; E — expansion of existing plant
[2]a — includes cost of new mine; b — includes cost of mine development
[3] Year in which cost information announced.
Note. — In North America, the proposed Alumet refinery is to process alunite rather than bauxite: capital cost is $920 per ton of new capacity.
Source: Commodities Research Unit, Ltd. (CRU). Data compiled from various publications.

Table A–3. — Capital costs of aluminum smelters — new (N) and expansion (E) projects

Plant location	N or E	Capacity, tpy	Total cost, million U.S. dollars	Unit cost per annual ton
NORTH AMERICA				
La Baie, Canada	N	57,000	100 (1979)	$1,754
Mount Holly, U.S.A.	N	180,000	400 (1979)	2,200
Sebree, U.S.A.	E	54,000	97 (1979)	1,796
Tabor City, U.S.A.	N	181,000	400 (1980)	2,210
EUROPE				
St. Jean De Maurienne, France[1]	N	27,000	45.8 (1979)	1,698
Inwerk, West Germany	E	16,000	89.6 (1978)	5,601
Ardal, Norway	E	32,000	58.7 (1978)	1,836
Hoyanger, Norway[2]	E	46,000	197.5 (1979)	4,293
Karmoy, Norway	E	50,000	138.2 (1979)	2,764
San Ciprian, Spain[3]	N	180,000	298 (1979)	1,655
Lochaber, U.K.	N	37,000	74.3 (1979)	2,007
Mostar, Yugoslavia	N	90,000	214 (1978)	2,378
AUSTRALIA AND NEW ZEALAND				
Farley, Australia	N	236,000	700 (1980)	2,966
Gladstone, Australia (Alcan)	N	100,000	290 (1979)	2,900
Gladstone, Australia (Gladstone Aluminum)	N	206,000	700 (1980)	3,398
Kurri Kurri, Australia	E	22,500	45 (1979)	2,000
	E	45,000	107 (1979)	2,378
Port Henry, Australia	E	57,000	96 (1979)	1,684
Portland, Australia	N	120,000	395 (1979)	3,292
Bluff, New Zealand	E	75,000	200 (1980)	2,666
SOUTH AMERICA				
Belem, Brazil	N	320,000	960 (1978)	3,000
Saramenha, Brazil	E	28,000	90 (1979)	3,214
Sepetiba Bay, Brazil	N	85,000	370 (1979)	4,353
Vera Cruz, Mexico	E	45,000	56 (1978)	1,244
Puerto Ordaz, Venezuela	E	70,000	160 (1978)	2,286
San Felix, Venezuela	N	280,000	715 (1979)	2,555
MIDDLE EAST AND FAR EAST				
M'Sila, Algeria	N	127,000	375 (1979)	2,953
Alba, Bahrain	E	45,000	120 (1979)	2,667
Jebelali, Dubai[4]	N	135,000	1,000 (1980)	7,407
Hirakud, India	E	34,000	76.3 (1980)	2,244
Orissa, India	N	220,000	1,200 (1980)	5,454
Kuala Tanjung, Indonesia	N	225,000	2,300 (1980)	10,222
Sabah, Malaysia	N	90,000	800 (1979)	8,888
Oraco City, Philippines	N	70,000	400 (1980)	5,714
Mindanao, Philippines	N	140,000	540 (1980)	3,857
Kaohsiung, Taiwan	N	14,000	16.7 (1978)	1,193

[1] Replacing old smelter by a new smelter.
[2] Includes new powerplant.
[3] Part of integrated complex, 40 pct of capital cost.
[4] 49 pct smelter, rest: power plant, desalination complex.
Source: Commodities Research Unit, Ltd. (CRU). Data compiled from various publications.

Table A–4. — Mines and deposits investigated but not included in this study

Location and name	*Comments*
Angola: Luanda	Small resource.
Australia:	
Gidgiegannup	Do.
Mirboa North	Do.
Moss Vale	Do.
Brazil:	
Carajas	Resource not delineated yet at the demonstrated level.
Serra do Acapuzal	All refractory grade.
Serra do Almeirim	Do.
Cameroon:	
Fongo Tongo	Tonnage is inferred.
Ngadundal	Do.
Chile: Bio Bio	Resource is high-alumina clay — not bauxite.
Colombia: Popayan-Cali	Tonnage is inferred.
Fiji: Vanna Levu Island	No information available.
France:	
Le Recoux	Small tonnage — almost depeleted.
Maran-Pereille	Reserves depleted.
Greece:	
Elaion Mine	No information available.
Florina	Refractory grade only.
Guyana: Blue Mountains	Inferred resource only.
Hungary:	
Bakonys Zentlaszho	Cost data not reliable.
Fejer	Do.
Fenyofo	Do.
Italy:	
San Guovanni	Small reserves.
Sava	Do.
Madagascar: Manantenina	Inferred resources only
Malaysia:	
SE Jahore-Pengerang	Small reserves.
Telok Ramunia	Reserves depleted
Mali: Bamako	Inferred resources only.
Turkey: Milas	Refractory bauxite.
Venezuela:	
Delta Amacuro	Raw prospect.
Nuria Plateau	Do.
Serrania De los Guaicos	Do.
Yugoslavia:	
Bosanska Krupa	Cost data not reliable.
Bracan	Do.
Cetinje	Do.
Jajce	Do.
Jesenica	Do.
Klina	Do.
Krusevo	Do.
Mostar	Do.
Niksic	Do.
Obrovac	Do.
Ornis	Do.
Posusje	Do.
Pristina	Do.
Rovinji	Do.
Sumarnic	Do.
Vlasencia	Do.
Zadar	Do.
Zaton	Do.

APPENDIX B.—GEOLOGY OF SELECTED DEPOSITS IN MAJOR BAUXITE-PRODUCING REGIONS

AUSTRALIA

Darling Range

Bauxite operations in the Darling Range area of Western Australia include the Jarrahdale, Huntly, and Del Park Mines and the deposit being developed at Mount William. The Darling Range bauxite is essentially an alumina-rich laterite with a variable content of iron oxides and quartz. Believed to be of Tertiary age, these bauxites have been derived from the basement granites by a process of leaching and redistribution of the dissolved minerals by ground water. Subsequent removal of excess iron and silica from the parent laterite was effected by good drainage.

These bauxitic laterites form a discontinuous surface horizon with the higher grade deposits occurring on a dissected peneplain between 250 and 300 m above sea level. Individual ore bodies range in size from less than 100,000 tons to more than 4 million tons. The average thickness of the bauxite is 4.5 m, overlain by about 0.5 m of gravelly overburden. A typical bauxite profile consists of a hardcap averaging 1 m in depth underlain by a friable zone which passes abruptly into decomposed bedrock. Numerous diabase dikes throughout the Darling Range, and their intrusion into ore bodies, make mining-grade control and development extremely complex.

The Darling Range bauxites consist essentially of hydrated iron and aluminum oxides and quartz in varying proportions. The principal alumina mineral is gibbsite with boehmite occurring as a minor mineral. Suggested is a progressive increase in kaolinite and quartz with depth, with a corresponding decrease in gibbsite and goethite. The Darling Range bauxites are of a lower grade than many other major deposits. Individual ore bodies include material ranging from 25 to 45 pct available alumina, with mean values of 30 to 35 pct. Reactive silica averages between 1 and 2 pct. Although the Darling Range bauxites are of relatively low grade, they are close to existing refineries and the port at Perth.

Weipa

The Weipa operation is on the western side of the Cape York Peninsula in Northern Queensland. The Cape York Peninsula comprises the northern end of a regional anticlinal trend, with Mesozoic and younger sediments being gently arched around a central core of older basement rock. Occurring mainly on the western limb of the regional fold, the aluminous laterite is developed on arkosic sands, clays, and siltstones of probable Tertiary age. The aluminous laterites are almost entirely restricted to the thicker Tertiary sediments close to the present coastline. Farther inland, where older sediments are involved, the laterite profiles are nonbauxitic.

The pisolitic Weipa bauxites are mainly free flowing when mined, but can be weakly to strongly cemented. Cementation occurs locally as cap rock up to 1 m thick. Some local zones of cementation occur in the lower part of the ore body as irregular blocks or bars, but generally the bauxite is loose and friable; minor occurences are of an earthy form. Pisolites are from less than 1 mm to 20 mm in diameter and generally held in a losse sandy, clayey matrix. The bauxite has a thin overburden of soil, generally less than 1 m in thickness.

The bauxite occurs as a series of flat-lying to gently dipping surface deposits averaging 2.4 m in thickness, with overburden ranging from 0.5 to 1 m. The bauxite consists almost exclusively of the ore minerals gibbsite and boehmite plus gangue minerals hematite, goethite, kaolinite, quartz, and anatase.

BRAZIL

Trombetas, Paragominas, and Almeirim Deposits

On the northern side of the lower Amazon Basin bauxite-source rocks of continental origin form a youthful topographic surface characterized by isolated, jungle-covered, and highly dissected plateaus. Extending along the northern side of the Amazon River from Oriximina to the Jari River, these plateaus have a relief of 70 to 120 m with side slopes of about 30°. They are flat topped with a dip of 1° to 5° towards the Amazon and dissected by youthful streams whose courses are partly contolled by regional jointing. The bauxite-source rocks are Pliocene or Plio-Pleistocene in age.

Bauxitization is believed to have resulted from extreme leaching of preexisting rock material by downward-percolating meteroic water. The necessary environmental conditions include a moist climate, temperature in excess of 25° C, and free water circulation in aluminous rock above a permanent water table. The general source-rock lithology is described as poorly consolidated clays, shales, and sands, sometimes containing coarser layers and beds with pebbles of various sizes. Not always well rounded, the pebbles are composed principally of varicolored quartz and crystalline rock fragments. The beds are generally horizontal, but occasionally inclined, and the strata are commonly cross bedded. Nodules, concretions, and iron staining are conspicuous in outcrops.

The mineralogy consists essentially of kaolin, quartz, hydrated iron oxides, and gibbsite. Kaolin-type clay minerals are dominant and are locally present in thick beds of high purity. Quartz is abundant in iron-cemented sand, in conglomerate layers, and as dispersed grains in a clay matrix. The quartz grains are poorly sorted, clear, and subangular to angular. Hydrated amorphous iron oxides are abundant as coloring agents and cements throughout the section. Iron oxides also form a 1- to 2-m-thick amorphous iron laterite layer 5 to 10 m below the plateau level. Gibbsite, sparsely distributed through the upper portions of the section, is concentrated into a potential ore horizon 0.5 to 1.5 m thick below the iron laterite. Barite, tourmaline, and zircon are found among the heavy minerals, together with lesser amounts of anatase, garnet, rutile, and staurolite.

The parent rock is kaolinitic sedimentary materials, and the only possible bauxitization route is by desilication to yield gibbsite. This genesis is consistent with the stratigraphy of the deposits, which clearly show bauxite layers formed as an enriched zone at the base of a thick weathering profile.

GUINEA

Boke Region (Sangaredi)

The Boke deposits are part of a structural-morphologic alignment which trends south-southwest from Guinea-Bissau to the Boke region, and further to the Konkoure near Fria and to Kindia. In the Boke region, a number of bauxite deposits occur on both sides of the Cogon River. The bauxite is usually covered by a ferruginous crust and grades downward into ferruginous laterite. The ferruginous laterite lies either on fresh dolerite or on a layer of veriegated clay and decomposed rock 9 m or more thick. The basement rocks may consist of paleozoic sandstone, siltstone, or shale or their metamorphosed equivalents.

The Sangaredi deposit is a plateau of solid bauxite up to 30 m thick and about 1.5 km wide in all directions. The eastern and southern slopes are steep, and the northern and western flanks slope gently to the surrounding countryside of low hills and plateaus. The mineralization in the Boke region consists mainly of gibbsite and hematite, with minor amounts of boehmite, goethite, kaolinite, and quartz. Boehmite, comprising as much as 4 to 5 pct of the bauxite at the surface, is believed to have been formed by dehydration of a more hydrous form of aluminum by the tropical sun. The minor quartz in the laterites commonly decreases in quantity with depth. Kaolinite, probably a major constituent of the clay-rich layer below the laterite, is most abundant in the lower parts of the laterite.

Tougue

The bauxite deposits at Tougue formed on diabase sills and dikes of Mesozoic age. These rocks overlie and intrude Paleozoic and Proterozoic conglomerates, sandstones, siltstones, shales, argillites, and archean gneisses. The section of the Fouta Djallon Palteau on which the Tougue deposits are located was uplifted and eroded during the early Cenozoic (African) orogeny. Bauxitization probably occurred during the quieter Miocene period in a humid tropical environment.

The laterite profile at Tougue, 20 to 53 m thick, consists of an upper layer of fragmental ferruginous laterite that may be up to 10 m thick on stream divides, a zone of aluminous laterite as much as 13 m thick, and an underlying unit of lithomarge often more than 30 m thick.

Individual bauxite deposits at Tougue range from 8 to 24 km^2 areally. The average thickness is 8 to 10 m. The deposits mantle the hills and ridges. The principal bauxite mineral at Tougue is gibbsite; the gangue minerals consist of goethite, hematite, and quartz.

Dabola

The Dabola bauxite deposits formed on Mesozoic diabase sills and dikes and on Precambrian granites, schists, and gneisses. The section of the Fouta Djallon Plateau on which these deposits occur was uplifted and eroded to a peneplain during the early Cenozoic (African) orogeny. Laterization occurred during the quieter Miocene period in a humid tropical environment. Twenty to 68 m thick, the laterite profile at Dabola consists of as much as 18 m of fragmental ferruginous laterite and bauxite and an underlying zone of lithomarge up to 50 m thick.

The principal ore mineral is gibbsite. Boehmite, the monohydrate bauxite mineral, comprises only 11 pct of the total alumina content in the Dabola deposits. Major gangue minerals are goethite, hematite, and quartz.

Guyana

Guyana deposits are similar to those found on the opposite side of the Atlantic on Africa's Gold Coast. The two regions have the same climatic conditions and latitude, and both overlie residual clays produced from weathering of Precambrian crystalline basement rocks. The West African deposits, however, are at a much higher elevation and have practically no overburden. The Guyana bauxites are believed to be eroded remnants of an Prepliocene peneplain which was later downwarped. It is believed that bauxite peneplains were covered with the Berbice Formation of unconsolidated deltaic clays, sands, and lignites during the Pliocene or Pleistocene age.

The near-horizontal ore zones, which range in thickness from a few meters to 15 m, are usually capped with material produced by weathering and ground water movement. The 0.3- to 2-m cap is not considered ore because its silica content is greater than 10 pct. It is, however, used for road construction.

The principal ore mineral in Guyana bauxite deposits is gibbsite (trihydrate) with minor amounts of boehmite (monohydrate). Gangue minerals in the economic zones are limited to silica. The alumina content in Guyana deposits is estimated to average about 59 pct.

JAMAICA

The bauxite deposits in Jamaica occur primarily as infillings in vertical walled depressions formed by the coalescence of cylindrical vertical pipes in the highly fractured white limestone. The location and orientation of the deposits reflect the fault systems and lineation in the White Limestone Formation. The deposits are generally at the surface, except in a limited number of down-faulted valleys. The principal ore mineral in Jamaica is gibbsite with minor boehmite. Gangue minerals include iron oxides, kaolin, phosphorite, and silica.

SURINAME

Two types of bauxite deposits are the coastal-plain bauxites and the plateau bauxites. The most important features are generally the same for all occurrences in the coastal plain, with the exception of a few deposits buried under postbauxite sediments. The coastal-plain bauxite deposits occur stratigraphically on top of the Onverdacht Formation. The bauxitic layer is believed to have been an arkosic or silty material with a grain size and porosity greater than those of the underlying kaolinitic clays. Slightly domed, the bauxite layer tends to be undulating, varying in thickness (2 to 12 m), and wedging at the ends. The generally exposed bauxite deposits near Moengo occur on low hills 10 to 60 m high. Near Onverdacht, the deposits generally plunge northwards beneath younger sediments down to a depth of 45 m.

The major bauxite occurrences in the basement area are in the Lely and Nassau Mountains in eastern Suriname, Brownsberg in the northeast central part, and the Bakhuis Mountains in the west. The parent rocks are of basaltic to gabbroic composition in eastern Suriname and are anorthosite, leuco gabbronorites, and enderbites in the Bakhuis Mountains. The bauxite deposits in the Nassau Mountains occur as horizontal to gently sloping parts of plateaus that mostly coincide with swampy areas. Overburden consists of a topsoil with a humus-rich lateritic clay. In the Bakhuis Mountains, the bauxite, frequently found on steep slopes in this area, occurs as lensoid bodies and irregular masses within the lateritic crusts.

The principal ore mineral of Suriname bauxite is gibbsite. The gangue minerals include clays, iron oxides, and silica.

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INT.-BU.OF MINES,PGH.,PA. 26719