vol I

BY THE COMPTROLLER GENERAL

Report To The Congress

OF THE UNITED STATES

112897

Domestic Aluminum Resources: Dilemmas Of Development

Volume I

Concerns about supply disruptions and price gouging that could endanger aluminum production in the United States have spurred research in this country on processes to manufacture aluminum from ores other than bauxite. The United States has no large bauxite deposits but it has plentiful resources of other aluminum ores if the technology can be developed to use them economically. In the absence of a successful technology, imports are projected to increase.

Support for primary aluminum research, including proprietary technologies, must replace the Department of Interior's present approach. The Bureau of Mines alumina research and development program is fundamentally misdirected. It is unlikely to

- --develop nonbauxitic aluminum resources,
- --reduce the costs of future aluminum manufacture, or
- --enhance supply security for existing aluminum smelters.

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COMPTROLLER GENERAL OF THE UNITED STATES
WASHINGTON, D.C. 20548

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To the President of the Senate and the
Speaker of the House of Representatives

This report provides an assessment of the nonbauxitic alumina and aluminum research and development trends in this country, and makes recommendations to redirect the Government's research assistance toward reducing the capital and energy costs associated with domestic aluminum manufacture. Unless the Government's aluminum research and development effort is refocused and revitalized in the context of other related policy decisions, its expenditures will come to naught, and increasing domestic demand for aluminum will be met by imports.

We made our review as part of our ongoing efforts directed at improving the Nation's capabilities to meet the materials requirements of our economy.

Copies of this report are being sent today to the Director of the Office of Science and Technology Policy, and to the Secretaries of Energy and Interior.

Comptroller General
of the United States

COMPTROLLER GENERAL'S
REPORT TO THE CONGRESS

DOMESTIC ALUMINUM RESOURCES: DILEMMAS OF DEVELOPMENT

DIGEST

For about 90 years, aluminum has been produced in much the same way. Bauxite, the conventional aluminum ore, is refined into alumina. Alumina is then reduced in smelters to aluminum. This last stage, reducing alumina to aluminum, is particularly capital and energy intensive.

Large deposits of commercial grade bauxite are very common in many foreign countries but are rare in the United States, consumer of about 30 percent of the world's aluminum. Plentiful nonbauxitic sources of aluminum in the United States might be developed to help reduce raw material imports and reduce the shift of aluminum production capacity overseas, if successfully addressed by research and development policies. GAO reviewed the Bureau of Mines' metallurgy R&D program for nonbauxitic aluminum resources to see if it met these needs.

GAO concluded that the Bureau of Mines nonbauxitic research effort is fundamentally misdirected. First, it has been focusing on alumina production and ignoring the fact that the primary obstacles to the use of domestic aluminous resources are the rapidly rising energy and capital costs of aluminum smelting. Without some means of reducing the capital and energy costs of aluminum manufacturing in the United States, primary metal capacity will continue to shift offshore, eliminating any new demand for alumina. Second, nonbauxitic alumina processing technology presently preferred by the Bureau is not economically competitive with conventional bauxitic alumina technology and, due especially to escalating energy costs, the competitive gap is steadily widening. Third, the Bureau's program has persisted in trying to develop a nonproprietary technology, disregarding proprietary research of both the Department of Energy and the private sector. As a consequence, the most promising new technologies are receiving inadequate research support.

Contrary to the Department of Interior approach, the Department of Energy, under statutory authority, supports proprietary aluminum technology research of private aluminum companies as part of its energy conservation program. Clearly the Bureau of Mines needs to reexamine the benefits of proprietary research in addressing alumina metallurgy program objectives.

ALUMINA RESEARCH: PROGRAM DESIGN AND COSTS

The Bureau's program was originally designed to create a series of 6 miniplants, each one embodying a different nonproprietary, nonbauxitic alumina process, in order to complete a technical information matrix. Based upon this matrix evaluation, a decision was to be reached as to which process alternative was to be tested for full feasibility through a major pilot plant.

The original miniplant program has undergone substantial modification. The actual program expenditures have greatly exceeded the original program cost estimates. A $1.6 million program proposed in 1973 has cost $15 million to date, and another $10 million is proposed for fiscal years 1980-1983 to complete it. This excludes the cost of a pilot plant, which GAO estimates could be as much as $100 million.

An even greater concern relates to program content. The Bureau of Mines' alumina miniplant research program is now almost exclusively devoted to developing one process, clay/hydrochloric acid, gas-induced crystallization technology, for an alumina pilot plant. Four of the five other materials/processes that were supposed to have been reviewed in miniplants have not as yet been examined. 1/ Other potentially promising proprietary alumina and aluminous materials

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1/They are: alunite, anorthosite, dawnsonite, and clay/sulfurous acid. Miniplants for clay/nitric acid, and clay/hydrochloric acid, gas-induced crystallization have been constructed.

processes were never included in the miniplant program.

VIABLE STRATEGY NEEDED FOR ALUMINIUM RESEARCH AND DEVELOPMENT

The metallurgical research task facing the development of nonbauxitic alumina resources should be oriented toward reducing the capital and energy related costs of new primary aluminum capacity in this country. Two proprietary processes, one producing aluminum chloride from kaolin clays and the other reducing aluminum chloride to aluminum, if combined, might offer significant capital and energy costs savings. Publicly available evidence is not conclusive on this point, however, demonstrating the need for further research support of these processes.

Energy costs in the smelting phase are far more critical to the cost of the finished product. For example, alumina requires only about 15 million British thermal units to manufacture, compared to 175 million British thermal units to smelt 1 ton of aluminum. Thus, any savings offered by research improvements to domestic alumina refining, even if not offset by much higher capital costs, would probably be too small to affect increased costs of future domestic energy for smelting aluminum with conventional technology.

Anticipated future energy costs are likely to be even more decisive for the location of aluminum production than they are now. The energy cost of aluminum smelting was said to be about 27 percent of the listed price of aluminum in 1978. According to an aluminum company official it could advance to 49 percent of the selling price by the year 2000. Clearly energy, not the location of cheaper alumina from domestic nonbauxitic materials, will influence the location of new aluminum smelters, even as replacement capacity.

Technology improvements must also be analyzed in light of other issues. Growing demands for aluminum from the automotive sector, for example, will create capacity shortfalls and steep price increases. But whether or not these price increases result in new domestic primary aluminum capacity using conventional or nonbauxitic alumina resources, or merely greater aluminum imports from expanding offshore smelting capacity, will depend in large part on technology reducing the capital and energy-related costs sufficiently to match the profitability of foreign locations.

At a minimum, the Bureau's program can no longer ignore proprietary research for (1) the direct reduction of aluminum from smelting constituent ore bodies, (2) the combination of carbo-chlorination and aluminum chloride reduction processes, and (3) the possibility of energy co-production processes resulting from developing nonbauxitic alumina resources in oil shales (dawsonite).

RECOMMENDATIONS TO THE CONGRESS

In light of the findings in this report, GAO recommends that the Congress:

(1) Refuse to consider as premature any requests for pilot-plant appropriations until the Secretary of Interior publishes, in summary form, the essential comparative economic assessment of all public and proprietary nonbauxitic technology processes.

(2) Direct the Office of Science and Technology Policy to review and coordinate the nonbauxitic alumina and aluminum research programs of the Departments of Interior and Energy, to assure proper coordination and consistent Federal support for the most promising technical options.

(See p. 72.)

RECOMMENDATIONS TO THE SECRETARY OF INTERIOR

GAO recommends that the Secretary of Interior, through the Director of the Bureau of Mines:

(1) Refocus the Department's alumina and aluminum metallurgy research program to identify and assist development of those technologies (using nonbauxitic ores) which offer promise of substantially reducing the energy and capital costs of making primary alimunum.

(2) Recalculate the operating and capital costs for each of the six nonbauxitic alumina processes reviewed in the mini-plant program and the pilot-plant feasibility study using proprietary company data, as well as explicit contingency and uncertainty funding allowances for each process.

(3) Conduct an analysis which specifies and evaluates technical unknowns of proprietary processes, and estimates the probable capital and operating cost implications for each process, for the purpose of identifying candidates meriting further research efforts.

(4) Re-examine the economic feasibility of developing alumina from alunite, dawsonite, and clay/carbo-chlorination, using economic credits from the potential production of associated materials.

(See p. 72.)

GAO also recommends that the Secretary of Interior, through the Office of Minerals Policy Research and Analysis:

(5) Prepare a report which analyzes the aluminum industry's capacity shift offshore, and includes U.S. Government policy op-

tions which could influence the development of domestic primary aluminum production capacity using nonbauxitic aluminous resources. Policy options might include: research and technology development support, energy infrastructure funding, concessionary credits and credit guarantees, exemptions from antitrust, tax incentives, and modification of environmental regulations. (See p. 73.)

RECOMMENDATIONS TO THE DIRECTOR, OFFICE OF SCIENCE AND TECHNOLOGY

GAO recommends that the Director of the Office of Science and Technology Policy:

(1) Initiate a review of the alumina/aluminum research objectives and programs of the Departments of Interior and Energy to assure compatibility of objectives and research support, particularly with regard to support of proprietary technologies.

(2) Accept responsibility for a substantial program-design-and-coordination role implementing a joint aluminum research program, consistent with the need for developing new primary aluminum reduction technology, should this objective be considered desirable.

(See p. 73.)

COMMENTS ON REPORT

This report raised complicated and controversial technical issues which generated lengthy and often critical responses from the Department of Interior's Bureau of Mines, The Office of Science and Technology Policy, in the White House, and five aluminium companies. These technical issues involve fundamental policy decisions and chapter 7 contains a summary of the comments and GAO's response. The comments are presented in their entirety for the public record in a second volume to this report, together with GAO's full response to the detailed comments. The head of each Federal agency to which GAO makes a recommendation is required by law to respond formally to the Congress within 60 days of this report's issuance, and of course, their positions could change at that time.

The Department of Interior's comments thus far on GAO's report indicate general disagreement with GAO's basic conclusions and recommendations and also indicate that it prefers to continue with its existing program.

The Office of Science and Technology Policy objected to GAO's recommendation that it review and coordinate alumina/aluminium programs of the Departments of Energy and Interior. The Office felt that the budget review cycle was the proper forum to deal with these issues.

The Department of Energy had no comments on GAO's recommendations.

(See pp. 74 to 81. See also volume II of the report.)

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GLOSSARY OF TERMS

To help the reader, we have defined certain words and phrases as used in this report.

alumina	An oxide of aluminum, the substance from which aluminum is smelted.
aluminum	Lightweight, ductile metal, one of the most abundant on earth, but found only in combination with other elements.
aluminum chloride	Substance derived from chlorination of aluminum metal or aluminous compounds, such as kaolin clays, in a chlorination process.
alunite	An alumina-bearing mineral and claimed as a domestic alternative to bauxite by a proprietary process which was not examined in the Bureau's cooperative miniplant program.
anorthosite	Alumina-bearing hardrock material of great abundance, claimed as an alternative to bauxite by a proprietary process and also used in a nonproprietary process, tested in a Bureau of Mines pilot plant in the early 1950s. Neither process was examined in the Bureau's cooperative miniplant program.
bauxite	An earth-like material from which virtually all alumina is extracted by the Bayer process. The United States provides only 13 percent of the bauxite needed to produce aluminum domestically, the balance, 87 percent, is imported.
Bayer-bauxite process	Process which dissolves the bauxite under heat and pressure in a caustic solution and precipitates alumina from sodium aluminate solution. This method, by which all alumina is produced, is an intermediate step in aluminum manufacture.
clay/carbo-chlorination	Proprietary and nonproprietary process used to produce aluminum chloride or alumina from kaolin clays by chlorination

ABBREVIATIONS

DOE	Department of Energy
GAO	General Accounting Office
EPA	Environmental Protection Agency
IBA	International Bauxite Association
NMAB	National Materials Advisory Board
OMB	Office of Management and Budget
OPEC	Organization of Petroleum Exporting Countries
OSTP	Office of Science and Technology Policy

International Bauxite Association (IBA)	Bauxite-rich, exporting nations formed to secure uniform, weighted price levels for bauxite, and to encourage economic development of indigenous industries.
Kaiser Engineers Feasibility Study	Consulting firm selected by the Bureau of Mines to evaluate six nonproprietary alumina processes based on joint Bureau-industry miniplant research, and other public sources, and to design a pilot plant for the most economically feasible process.
kaolin clay	An alumina silicate clay mineral proposed as the raw material for several alumina extraction processes. It has the highest aluminum oxide content and is abundant in Georgia, Arkansas, and other States.
miniplants	Small-scale metallurgical processing plants created by the Bureau of Mines and industry cooperators to evaluate various processes and technologies for producing nonbauxitic alumina at the Bureau's Boulder City Engineering Laboratory.
pilot plant	Demonstration-scale facility for producing alumina by the most commercially-feasible process of those tested in miniplants. It remains in the design stage at present.
Pullman-Kellogg	Consulting firm that analyzed the feasibility of producing aluminum chloride and alumina from domestic kaolin clays for Toth Aluminum Company in 1978 using a proprietary process.

	in the presence of powdered coal; neither process was examined in the Bureau's cooperative miniplant program.
clay/hydrochloric-acid, evaporative crystallization process	Proprietary and nonproprietary, nonbauxite procesees used to evaporate alumina from a hydrochloric-acid solution of clays, but not pursued in a miniplant by the Bureau of Mines/industry cooperative miniplant program.
clay/hydrochloric acid, gas-induced crystallization process	Nonproprietary, nonbauxitic process used to condense alumina crystals from a hydrochloric-acid gas acting upon kaolin clays. It was selected by the Bureau of Mines and industry cooperators as the most commercially feasible nonproprietary process to pursue in a demonstration-scale pilot plant, although not cost-competitive with Bayer-bauxite process.
clay/nitric acid process	Proprietary and nonproprietary processes for evaporating alumina-bearing, nitric-acid solution derived from clays, but examination in a miniplant was never completed.
clay/sulfurous acid process	Proprietary process to leach and evaporate alumina from nonbauxitic resources under high temperature and pressure used by Germany during World War II, not examined in miniplant program.
dawsonite	Alumina-bearing material found in oil shales of northwestern Colorado. Alumina from dawsonite could be a coproduct of an energy-producing process, but was not investigated by the Bureau of Mines/industry miniplant program.
Hall-Heroult process	Conventional method of smelting aluminum from alumina by electrolytic reduction in cryolite and aluminum fluoride, an energy-intensive process by which virtually all aluminum is now produced.
H-Plus process	Proprietary, nonbauxitic process using hydrochloric and sulfuric acids to produce alumina from aluminous ores, not examined in the Bureau's cooperative miniplant program.

CHAPTER 1

CONCERN ABOUT NONBAUXITIC ALUMINA RESOURCES

INTRODUCTION

In the early 1970s, concerns about the raw material supply interruptions and producer-country "price gouging" led to renewed interest in developing domestic nonbauxitic alumina resources. 1/ Commodity shortages in 1973 and unprecedented price increases by OPEC stimulated imitation by other raw-material-exporting countries, including formation of the International Bauxite Association (IBA). The emergence of the IBA was particularly ominous to U.S. aluminum companies dependent on imported bauxite, since almost all aluminum is smelted from alumina, a product of bauxite refining.

As a result of these concerns, the Bureau of Mines and cooperating aluminum companies began a jointly funded, nonbauxitic alumina research evaluation project at the Bureau's Boulder City, Nevada, engineering laboratory. The project was to evaluate existing nonbauxitic alumina process technology in order to identify the most feasible process for possible development in a demonstration-scale pilot plant. This project, together with the related pilot plant feasibility and design study, is the subject of our report.

Technology linkage of materials in aluminum production

Although aluminum can be recovered from several resources, almost all aluminum is conventionally derived from alumina, a product of bauxite. Aluminum is one of the most abundant metals on earth and the United States has huge deposits of aluminum-bearing materials. But most of these deposits are nonbauxitic.

The Bayer-bauxite process by which alumina is derived dissolves the bauxite under heat and pressure and precipitates alumina from a caustic soda solution. Aluminum is produced from alumina by the Hall-Heroult process of electrolytic reduction in cryolite and aluminum fluoride. Almost

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1/For example, Council on International Economic Policy, Special Report: Critical Imported Materials, December 1974.

all U.S. primary aluminum is presently derived from alumina and bauxite by these two methods.

The Bayer and Hall processes link bauxite, alumina, and aluminum materials technologically in one aggregate cost of aluminum production. Future primary aluminum capacity can only be enhanced if the costs of production of one or more of these materials could be so significantly reduced that it would affect the overall economics of the process.

Domestic aluminous materials

Bauxite

The most important domestic deposits of metallurgical bauxite are in Arkansas. Nearly 90 percent of U.S. origin

TABLE I-1
MAJOR POTENTIAL DOMESTIC SOURCES OF ALUMINUM
(Al_2O_3)

Source	Composition	Known reserves millions of short tons Al_2O_3
Bauxite	*	125
Alunite**	$KAl_3(SO_4)_2(OH)_6$	120
Anorthosite	A soda-lime feldspar igneous rock	158,000
Dawsonite**	$NaAl(CO_3)(OH)_2$	9,500
Kaolin Clay	$Al_2Si_2O_5(OH)_4$	1,076

SOURCE: U.S. Bureau of Mines, Information Circular 8335, 1967 and U.S. Geological Survey, Professional Paper 820. 1973.

*Bauxite is actually a heterogeneous earthy material containing a variety of minerals. Metallurgical grade bauxite ranges from 35% to 55% Al_2O_3 and may have as much as 15% SiO_2 and 30% Fe_2O_3. These latter materials are impurities which must be removed during the refining (Bayer) process. Approximately 5 to 7 tons of bauxite produce 2 tons of alumina which is refined further to produce 1 ton of aluminum.

**Unlike the other materials listed, dawsonite and alunite occur in assocation with other mineral resources whose recovery and use is dependent upon a variety of additional factors.

bauxite used for aluminum comes from two Arkansas mines. The Bureau of Mines estimates that the 1,950,000 tons of Arkansas bauxite mined in 1976 yielded about 433,000 of the 4.6 million tons of domestic primary aluminum produced. At this rate of use, Arkansas reserves could last 20 more years. There are about 12 to 13 million tons of aluminum contained in these deposits. 2/

Arkansas bauxite constituted only about 13 percent of the 15 million tons of bauxite domestically refined into alumina in 1976; the remaining 87 percent was imported. This domestically refined alumina satisfied about 70 percent of the alumina required for manufacturing primary aluminum in the United States. The remaining 30 percent of the alumina requirement was also imported.

There are other major domestic resources of bauxite, located in northwest Oregon, and on the islands of Kauai, Maui, and Hawaii. Although environmental standards and metallic purity standards presently preclude development of much of these alumina resources, estimated recoverable aluminum in these deposits is 18.3 million tons.

Clay

Kaolin clay offers promising alumina-extraction potential. The best kaolin regions, having about 35 percent alumina content and minimum deposits of at least 50 million tons, are in Georgia and Arkansas. Estimates of recoverable alumina from these deposits are 3.8 billion tons, or more than 400 years' supply based on the 1976 rate of domestic primary aluminum production.

Some form of clay-alumina refining process has been the most sought-after technological alternative to bauxite because of clay's high alumina content and because it is relatively inexpensive to mine. Several acid processes have been developed for refining alumina in clay, and these processes have been the primary focus of the Government's research program.

2/One Bureau document estimated that there was a 75 percent likelihood these reserves contained as much as 63 million tons of bauxite, suggesting the remaining ore reserve is about 20 percent alumina.

Anorthosite

Anorthosite deposits are contained in exposed rock masses located in many of the Western States, as well as in Oklahoma, Minnesota, Pennsylvania, and New York. These deposits are estimated by the Bureau of Mines to contain 162 billion tons of alumina. Potentially recoverable alumina from these deposits is thought to be almost 50 billion tons.

One aluminum company claims to have developed an anorthosite-alumina process that is competitive with the leading clay/acid process. However, the energy and materials handling requirements of anorthosite alumina seem much greater than those for bauxite and clay.

Dawsonite

Potentially large deposits of alumina have been discovered in association with deep oil shales of the Green River formation in northwestern Colorado. Dawsonite may also be present in other basins within the Western United States, but no comparable large deposits have been found. The Department of the Interior estimates the 27 billion tons of dawsonite in the northwestern Colorado area contain about 9.5 billion tons of alumina.

Only one oil company is known to be pursuing a multiple-minerals development approach to alumina contained in oil shale. It estimates its own alumina production could be as high as 260,000 tons per year within 3 years of initial oil shale production. The company claims to have a commercially feasible alumina production process, but its development has so far been thwarted by procedures for exchanging land with the Department of the Interior. No dawsonite alumina process seems economically feasible unless the oil shales and surrounding sodium minerals are also commercially marketable. 3/

Alunite

Alunite resources occur in Utah and Colorado and to a lesser extent in Nevada and Washington. Recoverable alumina

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3/We discuss these problems in "Legal and Administrative Obstacles to Extracting Other Minerals From Oil Shale " (EMD-79-65), September 5, 1979, as well as their policy related origins in a forthcoming review of the Department of Interior's minerals management process.

is estimated to be at least 100 million tons. A consortium of companies formed an operating company to produce alumina from alunite in Utah but production never occurred. The planned use of nearby coal and phosphate deposits in the proposed technology suggests a complex production and marketing process using coproducts, as well as transportation and fuel economies to offset capital and production costs.

While coproduct approaches to alumina production from dawsonite and alunite may be sound resource development, and technically closest to commercial realization, their unique credits and cost attributes create complex market calculations, large capital cost requirements, and somewhat arbitrary accounting of production costs per commodity.

National Materials Advisory Board (NMAB) report's focus on alumina technology

A 1970 NMAB report 4/ called attention to the potential for developing U.S. nonbauxitic alumina resources if an alumina extraction technology could be created that was economically competitive with the Bayer bauxite process. It focused on the alumina stage of aluminum production. In its letter responding to our report, the Department of Interior said that no process has been discovered that can produce alumina more cheaply than the Bayer process. 5/

The NMAB report called for the creation of two small pilot plants capable of 1 to 5 tons production per day that would develop two promising alumina technologies. Each plant was supposed to be jointly financed by the Bureau of Mines and domestic aluminum companies. If the results from either of these clay/acid technology development projects were promising, the report called for construction of a

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4/National Academy of Sciences-National Academy of Engineering National Research Council, "Processes for Extracting Alumina from Nonbauxite Ores: A Report of the National Materials Advisory Board," NMAB-278, December 1970.

5/Despite disclaimers by the Department of Interior in its response to our report, Bureau officials continue to publicly claim the pilot plant process is cost competitive with Bayer alumina. See for example: "Alumina Minerals-Still Overshadowed by Bauxite," Chemical Engineering, December 3, 1979, p. 58; and T.Y. Canby, "Aluminum the Magic Metal," National Geographic, August 1978, p. 201.

larger, 50-100 ton per day, pilot-demonstration plant to obtain necessary data for scaling up to commercial-size plants. 6/

Aluminum industry pilot plants

While industry has frequently lamented the Government's research emphasis on "unrewarding" materials, its own support and enthusiasm for alumina research has been sporadic and relatively modest compared to the size and capital base of the industry. Thus, the industry seems unconvinced that nonbauxitic alumina research investments offer very high payoffs.

Aluminum companies have constructed four nonbauxitic pilot plants. Each of these plants costs several million dollars to develop and they have so far offered less than satisfactory solutions to problems associated with commercial development of nonbauxitic alumina. All are now closed, having completed their research. From the perspective of one industry financial Vice President, all might be vulnerable to characterization after the fact as being "bad" business decisions, at least in the short term. This is because each probably cost more to develop technical information than appears reasonably recoverable from sales. Moreover, each of these technologies requires follow-on expenditures for large-scale pilot-demonstration plants in order to fully commercialize the processes they developed. A brief description of the four company ventures follows.

Alcan-Pechiney

Alcan Aluminum Ltd. of Canada and Pechiney Ugine Kuhlmann of France have developed the "H-Plus" acid/clay process at a pilot plant in southern France. They claim to have spent $30 million and used commercially available equipment in the process.

The pilot plant has produced alumina from Georgia clays, although the process can use coal shales or coal washings, and non-carboniferous shales containing alumina. Operating costs of this process could probably only be commercially competitive with Bayer-bauxite if a significant part of its own energy requirement came from the aluminous raw materials, such as shale and coal. This, in turn, would greatly increase

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6/The reports also recommend that the Bureau of Mines expand its dawsonite research, examining the economics of alumina production from sodium minerals contained in oil shale deposits.

its capital costs. Commercial-scale plants would probably require extensive public financing or assistance. The pilot plant was closed in 1978.

Anaconda

The Anaconda Company, during the late 1950s and early 1960s, operated a large-scale pilot plant using a hydrochloric acid leaching process. The alumina produced by this facility was actually converted to aluminum in an Anaconda aluminum smelter.

Anaconda's hydrochloric-acid, evaporative-crystallization process was technically sound but not competitive with Bayer-bauxite because of its greater energy requirements. Anaconda proposed certain tax modifications for clay ore depletion which it claimed would recover the existing 1965 cost differential of $12 per ton between conventional and nonbauxitic alumina, thereby enhancing domestic development.

Anaconda subsequently gained access to significant Jamaican bauxite reserves through a consortium of aluminum companies formed in 1968. Whether or not the company ever had a commercially viable process, subsequent energy price increases have made the more energy-intensive Anaconda process even less competitive than it was formerly.

Arthur D. Little

During the late 1960s, a nonintegrated, bench-scale, pilot-plant operation for clay/nitric acid was carried out by Arthur D. Little, Inc., a research and consulting company, under contract with the Environmental Protection Agency. Based on chemical analysis and the physical properties of the alumina produced, it was considered by an aluminum producer to be of adequate quality to use in Hall-Heroult aluminum process cells. Despite several patents and the transfer of the company's interest in them to an aluminum company, no effort has been made to develop this evaluation into a pilot plant.

Reynolds Metals

Reynolds has pursued nitric acid process research and it also ran a demonstration plant briefly in 1974 using Oregon laterite deposits. 7/ A Reynolds official said that the

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7/The company has not discussed the economic implications of this highly publicized demonstration.

company was at the "crossroads" with nitric acid. Although the company developed a great deal of proprietary information, it is reluctant to continue to invest in nitric acid alumina research without Government assistance.

Government nonbauxitic alumina research

Extraction of alumina from domestic resources has been investigated and reported by the Bureau of Mines for more than 60 years. Between 1914 and the NMAB report in 1970, the Bureau published 48 different bulletins, reports of investigations, and information circulars on domestic alumina research. Past efforts to develop this body of literature and research into engineering process technology in Government-assisted industry pilot plants, as well as present Bureau miniplant application efforts, indicate they cost much more than estimated by laboratory studies and the technical literature.

Government-industry pilot plant experience

The Government attempted to develop pilot plants using domestic nonbauxitic alumina resources during World War II. The Defense Plant Corporation created by the Defense Production Act to facilitate wartime production authorized construction of four experimental plants to produce alumina from domestic nonbauxitic resources during World War II. Each plant was supposed to produce from 50 to 100 tons of alumina per day using a different bauxitic material and technology. However, none achieved the production objectives.

The main purpose of this Defense Plant Corporation program was to secure technical and engineering data based on actual plant experience for use in large-scale production of alumina. A later evaluation by the Defense Plant Corporation found exaggerated claims by plant lessees for the processes, and that the lessees' preliminary development work did not warrant the expenditure of large sums of money. The report also criticized management planning for plant site selection, the lack of suitable commercially available equipment needed for production, ignoring delicate process control requirements that were beyond any means then available, and continuing revisions of plant and equipment design specifications after construction was underway.

Later, during the Korean War, the Bureau of Mines attempted to develop a commercially competitive alumina process for anorthosite at Laramie, Wyoming. The process still had unresolved technical problems when the project was abandoned.

The formation of the International Bauxite Association in 1974, an organization of major bauxite-exporting nations, stimulated renewed aluminum industry interest in Government-assisted development of domestic nonbauxitic alumina resources.

Even though past Government attempts to develop nonbauxitic alumina resources through technology-supporting assistance of private pilot plants had not been satisfactory, the miniplant program established in the mid-1970s was an attempt to avoid past errors and still retain the essense of the NMAB report's recommendations for alumina research.

Renewed supply concerns and miniplant objectives

The Government and several major aluminum companies have participated in a cooperative research program since July 1974, under the direction of the Bureau of Mines in the Department of the Interior.

The Bureau and aluminum industry, acting as research sponsors, have funded "miniplants"--small-scale, continuous process plants to create the technology linking the subprocesses of laboratory studies--in order to evaluate the processes for extracting alumina from nonbauxitic alumina resources. The evaluation was supposed to create an alumina-process technology information matrix. This matrix would permit identification of the best process technology, as well as provide a basis for deciding whether or not to build a larger alumina pilot-demonstration plant.

Like the objective of the NMAB report's small pilot plants, the six cooperative "miniplants" created in the Boulder City engineering laboratory were supposed to determine whether or not any of these nonproprietary technologies offered sufficient commercial potential for constructing a large, demonstration-scale alumina pilot plant.

Alumina miniplant and pilot plant development costs

The Bureau of Mines has spent about $4.9 million on alumina miniplant research through fiscal year 1979. According to Bureau estimates, another $11.3 million will be needed through fiscal year 1983 to complete the miniplant program; or about ten times as much as estimated by the Bureau ($1.6 million) in 1973.

In addition to these research funds associated with the miniplants, the Congress has already appropriated $2.5 million for engineering design and environmental research related to an alumina pilot plant. Additional funds are necessary for site procurement and development, one-half of which would be borne by Government, the rest by four industry cooperators. And, should the Congress approve the construction and management of an alumina pilot plant on a 50-50 basis with private industry, the cost to the Government would be significantly more--perhaps, by our analysis, as high as $100 million.

METHODOLOGY AND SCOPE

This report results from work under our basic statute and originated from a report to the Congress on the Department of Interior's Minerals Availability System (EMD-78-16). That System referred to large domestic, economically recoverable alumina-clay deposits. We planned the present work to evaluate the Department's research and development program and analyze any connection to the development of these reserves. We started by reviewing and evaluating the estimated process costs of the nonproprietary alumina technologies which were evaluated as part of the Bureau's miniplant program. We compared these process operating and capital cost estimates to the costs of conventional Bayer bauxite technology, and to estimates for a proprietary alumina clay process called carbo-chlorination, which the Bureau did not consider.

We also considered the availability and cost of competing foreign bauxite and alumina supplies following the formation of the International Bauxite Association, to see how they affected domestic alumina resource development. We focused on two questions: (1) could development of domestic deposits provide a ceiling for imported bauxite and alumina prices, deterring further foreign price increases? and, (2) could development of foreign bauxite and alumina deposits preclude development of domestic alumina resources?

Within this broad outline of potential resource development, we reviewed the management of the Bureau's alumina miniplant at Boulder City, Nevada, and the research support of the Bureau's regional metallurgy centers, in responding to program changes. We also considered the program's research objectives in light of future domestic aluminum capacity shortfalls, and the need to reduce aluminum's energy and capital costs in order to attract future capacity.

Finally, we considered five aluminum companies' opinions about future patterns of raw materials and technology development, and the outlook for global aluminum capacity. Four of these companies participated in the Bureau's alumina miniplant program. All had differing perspectives about alumina R&D emphasis.

Our review was conducted in the Bureau of Mines headquarters in Washington, D.C., and in the Bureau's Boulder City, Nevada, engineering laboratory as well as in the cities of Montreal, Canada, Caracas and Ciudad-Guayana, Venezuela, Georgetown, Guyana, Paramaribo, Surinam, Brazilia and Rio de Janeiro, Brazil, and Canberra, Australia, along with Richmond, Virginia, Oakland, California, and Pittsburgh, Pennsylvania. We interviewed Government, industry, and research personnel throughout the United States, as well as overseas.

Chapter 1 explains the Government's interest and experience with nonbauxitic alumina resources and the availability of domestic resources.

Chapter 2 describes the current and proposed alumina research program of the Bureau of Mines, as well as the implications of altered efforts to develop a pilot plant technology.

Chapter 3 discusses the problems with management of present alumina miniplant research efforts. It includes a discussion of the technical assumptions and nonproprietary research implications of miniplant research on the pilot plant design and feasibility study.

Chapter 4 discusses the global availability of aluminous materials and offshore processing trends, as well as aluminum demand and production trends. We conclude that the present program is the wrong approach for development of domestic nonbauxitic alumina resources, and for future primary aluminum capacity. The program should focus on the capital and energy costs affecting aluminum smelting rather than raw material availability.

In chapter 5, we offer our evaluation of nonbauxitic alumina technologies compared to the costs of conventional Bayer-bauxite alumina. We found all but one of them noncompetitive, but more important, the Bureau's research program seems largely irrelevant to reduction of future energy and capital costs of making primary aluminum in this country.

Chapter 6 contains our conclusions and recommendations.

Chapter 7 contains a summary of agency and industry comments and our response.

We retained the consulting services of Professor Joel P. Clark and Dr. George B. Kenney, Department of Materials Science and Engineering, Massachusetts Institute of Technology. Their technical and economic analyses made a significant contribution to this report and are contained in a paper presented as appendix I. This technical paper, evaluating the Bureau's feasibility study of nonbauxitic alumina processes, was reviewed by distinguished technical advisers proposed by Clark and Kenney for GAO. Their names appear at the back of appendix I, and in appendix V, volume II.

Appendixes II through VII of our report, contained in volume II, concern agency, aluminum industry, and technical appendix advisers' comments, as well as our response to agency comments.

CHAPTER 2

THE BUREAU OF MINES' ALUMINA-METALLURGY RESEARCH PROGRAM AND PILOT-PLANT DESIGN CONTRACT

The alumina research program conducted by the Bureau of Mines has three major, overlapping elements, [8] (1) metallurgical research on alumina and aluminum , performed in the Bureau's seven regional metallurgical laboratories, (2) cooperative Bureau and aluminum industry alumina technology process evaluation, appraised in successive small-scale miniplants at the Bureau's Boulder City engineering laboratory in Nevada, and (3) pilot-plant, feasibility study and design, and environmental impact studies performed by private contractors for the Bureau of Mines.

Our organization of two of these elements in chapter 2--metallurgy and pilot plant--calls attention to the broader research program, of which the miniplant program was a part, and the implications for further Government expenditures. In chapter 3, we discuss the miniplant program and its deficiencies.

Our review of alumina metallurgy research and pilot-plant design program elements shows the growing importance and eventual domination of attempts to develop an alumina pilot-plant technology throughout the Bureau of Mines-related aluminum metallurgy organization. This attempt, organized through the miniplant program, increasingly committed all of the Bureau's aluminum-related research to the development of only one nonbauxitic alumina technology for use in a pilot plant. It has become the sum and substance of the Bureau of Mines' alumina research and pilot-plant design since 1974, the overwhelming recipient of resources and research efforts.

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[8] The Bureau of Mines contends there are four elements to the program. In its comments on our report the Bureau distinguishes between research at the regional metallurgical laboratories, and research support of the miniplant program conducted by these laboratories. We chose to retain the original three cost-accounting codes in order to show relative emphasis over time.

METALLURGY PROGRAM

The Bureau of Mines' metallurgy program includes support for alumina and aluminum research at seven regional centers. Several of the projects are directed toward: improving alumina extraction technology; secondary recovery of aluminum scrap from wastes; and, utilization of substitute materials for aluminum. Since mid-1975, with few exceptions, the alumina research conducted at the regional centers has been overwhelmingly concentrated on the problems of one technology--clay/hydrochloric acid, gas-induced crystallization.

Aluminum was not a significant commodity in the Bureau's metallurgical-base research program, however. Over five years, it averaged only 5.5 percent of the expenditures of the regional centers (table II-1).

Table II-1

Comparison of Total Metallurgical-Research Center Expenditures and Aluminum Research Expenditures Fiscal Years 1974 - 1978

($1,000)

Fiscal Year	1974	1975	1976	1977	1978	Total
Aluminum Base	$ 995	1,125	1,901	1,160	1,138	$ 6,551
Total Programs	15,500	23,800	27,980	23,100	28,650	118,930
Aluminum	6.4%	4.6%	6.6%	4.9%	4.8%	5.5%

Aluminum research expenditures between fiscal years 1974 and 1978 totalled just over $6 million, excluding the $538,000 in the transition quarter of fiscal year 1976, spent exclusively on alumina research to support the miniplant (table II-2).

Table II-2 9/

Metallurgical-Base Aluminum Program: Research Center Funding Fiscal Years 1974 - 1978 ($1,000)

Research Center	1974	1975	1976*	1977	1978	Total
Albany, Oregon	$180	$280	$156	-	$100	$ 716
Avondale, Maryland	190	285	475	405	400	1,755
Reno, Nevada	-	120	300	50	170	640
Rolla, Missouri	235	210	261	170	200	1,076
Salt Lake City, Utah	260	190	256	185	180	1,071
Tuscaloosa, Alabama	50	40	300	150	130	670
Twin Cities, Minnesota	80	-	143	200	200	623
	$995	$1,125	$1,901	$1,160	$1,138	$6,551

*1976 includes transition quarter expenditures of $1,363,000, $538,000 of which were for support of the miniplants alumina research program.

In the spring of 1976, the Bureau made administrative changes in the metallurgy research program to enhance alumina research. All subsequent Regional Metallurgical Center alumina research was to support the aforementioned Boulder City miniplant. A review of alumina research to be conducted at the various metallurgy centers during fiscal years 1978 and 1979 revealed that only three centers are doing any research unrelated to the technical problems of the clay/hydrochloric acid, gas-induced crystallization process (table 3).

9/Transition quarter expenditures in the base aluminum program in direct support of the miniplant alumina program by metallurgical research center were:

Albany	$ 84,000	Rolla	70,000	Twin Cities	48,000
Avondale	157,000	Salt Lake	79,000		
Reno	60,000	Tuscaloosa	60,000		
Total					$538,000

Table II-3

Concentration of Metallurgical Research Centers on Hydrochloric Acid Gas-Induced Crystallization Technology Fiscal Years 1978 - 1979

Center	Total Alumina Research Projects	Total Nonhydrochloric Acid Projects
Albany, Oregon	2	1*
Avondale, Maryland	4	-
Reno, Nevada	3	1
Rolla, Missouri	1	-
Salt Lake City, Utah	2	2
Tuscaloosa, Alabama	1	-
Twin Cities, Minnesota	-	-
	13	4*

*This fluidized bed project for nitric acid is not equally applicable to the hydrochloric acid process, according to the Bureau.

Alumina metallurgy laboratory research expenditures, only about one-tenth of the small aluminum metallurgy program when the first Bureau miniplant began in 1973, have grown in two significant surges. In the transition quarter of fiscal year 1976, they were increased to $538,000 and maintained at roughly this level through fiscal year 1978. And in fiscal year 1979, the funds were increased to $945,000, all to support regional metallurgy laboratories aiding the Boulder City miniplant. Between fiscal years 1980 and 1984, these expenditures are expected to average about $840,000 per year, or $3.4 million.

The increases in alumina research expenditures in 1976 and 1978 and the parallel concentration of alumina research projects on one nonbauxitic process suggest the Bureau has made several significant and consequential decisions about alumina metallurgy research:

(1) it has decided such research must support the effort to create an alumina pilot plant;

(2) it has decided the content of alumina research should be to resolve the technical problems of the clay/hydrochloric acid, gas-induced crystallization process; and

(3) it has decided that the Boulder City miniplant will be the principal administrative vehicle for accomplishing these objectives.

PILOT-PLANT PROGRAM

The 1970 NMAB report, cited in chapter 1, endorsed the idea of Government-industry pilot plants to develop nonbauxitic alumina extraction technology. Industry disagreement about which process should receive Government assistance in a pilot plant, and the Administration's refusal to fund several pilot plants, resulted in the defeat of several Bureau attempts to create such a program in fiscal years 1971, 1972, and 1973.

Efforts by the Jamaican government to unilaterally impose new bauxite levies and the formation of the International Bauxite Association led to renewed aluminum industry interest in Government-assisted nonbauxitic alumina pilot plants in 1974. The Congress appropriated over $2 million in fiscal year 1976 for engineering designs for the most promising processes.

In furtherance of the growing concern about potential vulnerability of U.S. aluminum companies, the Director of the Bureau of Mines accepted the miniplant-industry cooperators' suggestion that the congressionally funded design study be used to evaluate the commercial feasibility of each of the six nonbauxitic alumina processes based on miniplant data, and submit engineering designs of the best process as a candidate for a pilot plant. The implications of this proposal were far-reaching, and are discussed in the next chapter. Essentially, the miniplant process evaluations were tied to a Government-assisted, demonstration-scale pilot plant by the process feasibility evaluation and pilot plant design study. The miniplant program was re-oriented to developing technology for only one process.

The steering committee of Bureau officials and industry cooperators also recommended that a private contractor perform the process-feasibility-and-design study.

KAISER ENGINEERS FEASIBILITY STUDY

The contract to evaluate six nonbauxitic alumina processes, and prepare a preliminary pilot-plant design for the most commercially feasible one, was awarded to Kaiser Engineers in September 1976. The Bureau's request for proposals was reviewed by the miniplant steering committee prior to its publication. However, the six processes Kaiser Engineers subsequently reviewed were not the same as those the Bureau had proposed to the steering committee for examination. The steering committee changed the proposed processes. A variation of the clay/hydrochloric acid, evaporative crystallization process--gas-induced crystallization--was substituted for dawsonite in the Kaiser Engineers review. The Kaiser study subsequently found this process to be the most commercially feasible one for a pilot plant.

The contract with Kaiser Engineers was completed in three separate phases. The contractor was required to make technical appraisals of the six processes, including economic comparisons. Kaiser Engineers reported on Phase I in July 1977. This report identifid two clay/hydrochloric acid processes as being the most economical after considering both capital and operating costs. Phase I reduced the number of processes to be tested from 6 to 2.

In Phase II, Kaiser Engineers developed a technical analysis of the two processes selected in Phase I, so that a single process could be selected which had the greatest potential for supplying alumina. But the Bureau had also requested Kaiser Engineers in Phase II to compare the clay/nitric acid process with the best of the two hydrochloric acid processes. Kaiser Engineers reported on Phase II in February 1978, and again recommended clay/hydrochloric acid, gas-induced crystallization as the preferred process for a pilot plant.

Phase III requires Kaiser Engineers to submit a preliminary engineering design for a 50-ton-per-day pilot plant using the process it recommended. At the time of our review, Kaiser had not completed Phase III, but subsequently submitted a design for a considerably smaller plant.

Cost for a pilot plant

Cost estimates for an alumina pilot plant are subject to conjecture. There are huge economic implications for many technical unknowns. Miniplant technology cost estimates of these unknowns have been greatly understated in the past. They suggest substantial ignorance about process R&D requirements necessary to conserve energy without substantially increasing the cost of capital equipment.

In addition to the economic consequences of technical unknowns, working from probable to possible programs expenditures, pilot-plant costs for a 50-ton-per-day plant as summarized in Table 4 are substantially understated as a result

Table II-4

Historical, Probable, and Possible Pilot-Plant Appropriations Fiscal Year 1976 - Present

I.	HISTORICAL	Spending	Authorized
	Feasibility Study	1,826,132	FY 1976
	Environmental Studies	337,365	FY 1977
	Fluid-bed decomposition of aluminum chloride hexahydrate	75,000	Advancing Minerals Technology FY 1978
	Clay ore content	83,000	FY 1979
	TOTAL	$2,321,497	
II.	PENDING	Probable	Authorized
	Anorthosite alumina process	225,000	FY 1979
	Pilot-plant site procurement and development--50%*	875,000	FY 1980
	TOTAL	$1,100,000	
III.	PROPOSED	Possible	Authorized
	Pilot-plant engineering--50%	4,500,000	FY 1981
	Pilot-plant construction--50%	12,500,000	FY 1982
	Pilot-plant start-up--50%*	4,625,000	FY 1982
	Pilot-plant operations--50%*	7,500,000	FY 1983 - 1984
	TOTAL	$29,125,000	
	TOTAL PILOT-PLANT FUNDING:	$32,545,000	

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*The other 50% of the funds to come from aluminum industry cooperators, for:

--site procurement = $ 1,750,000
--plant engineering = 9,000,000
--plant construction = 25,000,000
--plant start-up = 9,250,000
--plant operations = 15,000,000

Total $60,000,000

of inflation. They are based on data compiled by the Bureau in May 1977. Allowing for a 15-percent increase in construction and capital equipment categories and a 10-percent per-year increase in all other costs, as a result of inflation, we estimate in Table II-5 the same pilot plant might cost closer to $100 million. 10/ About half of this amount would be borne by the Government.

Table II-5

Estimated Current Dollar Pilot-Plant Costs
($ Millions)

Activity	Planned start*	Number of years since estimate and annual inflation rate until start of work		Adjusted costs
Site selection	.600	2.5	10%	.762
Site procurement and start engineering design	1.150	3.17	10%	1.557
Complete engineering design	9.000	3.5	10%	12.569
Begin construction	12.500	3.7	15%	21.007
Complete construction	12.500	4.5	15%	23.503
Start-up operations	9.250	4.5	10%	14.220
Begin operations	2.500	5.0	10%	4.027
Operate plant	10.000	5.5	10%	16.910
Complete operations	2.500	6.5	10%	4.652
Total	60.000			98.909

*1/2 of $99 million, or about $49.5 million from private cooperators.

10/The Department of Interior said that it agreed with our estimate of inflation. However, we do not believe that these inflationary costs were the reason for the Bureau's belated halving of the pilot-plant design size. Rather, it was the desire to reduce process operating and capital costs imposed by unresolved technical problems.

SUMMARY OF ALUMINA RESEARCH PROGRAM COSTS

The three program elements--metallurgy research, miniplant, and pilot plant--have already cost the Government at least $15 million through fiscal year 1979. Proposed expenditures for further alumina research in the metallurgy program ($3,360,000), the miniplant program ($5,650,000) and the pilot-plant program ($26,000,000) totaled $35,010,000 for fiscal years 1980 through 1983. 11/ Moveover, we feel these, and subsequent proposed expenditures, particularly those for the pilot plant, still may be considerably understated.

Of the total $50 million in previously proposed alumina research expenditures, only about $3 million more would be spent on research for all processes other than the clay/hydrochloric acid, gas-induced crystallization process, in addition to the $6 million already spent. We frankly doubt that existing knowledge of other processes is sufficient to support the conclusion that research is concentrated on the most economical process, or that this research concentration is justifiable if commercial feasibility is a major criterion.

The contrast in the Bureau's original program cost estimates for the miniplant's process information matrix ($1.6 million) and costs through fiscal year 1979 ($15 million), combined with the $10 million estimated to complete the original research objective, suggest a possible misunderstanding about how much technical research was necessary, or a change in the program objectives in order to justify developing a nonproprietary technology. Chapter 3 will explain our misgivings about the Bureau's miniplant research for this purpose.

11/The size of the pilot plant was changed following our review to engineering designs for a 25-ton-per-day plant. A modified pilot plant of 25 tons per day is estimated to cost $52 million, one-half borne by the Government, rather than $99 million for a 50-ton-per-day plant, but more important, there does not appear to be any capital equipment large enough to accommodate the originally designed process that would not also be prohibitively expensive.

CHAPTER 3

MINIPLANT PROGRAM DEFICIENCIES

We found little support in our examination of the miniplant program for the Bureau's assertion in November 1977 that the choice of alumina materials and processes was still an open one, particularly since the Assistant Secretary for Energy and Minerals has assured the Congress that Interior should be ready to request pilot-plant funds for a nonbauxitic alumina process by December 1979. On the contrary, if there is to be a pilot-plant decision based on Kaiser Engineers' feasibility study and miniplant work, the choice of a clay/hydrochloric acid, gas-induced crystallization process seems unavoidable. We believe that this would be unfortunate.

The first Bureau of Mines miniplant program, begun in July 1973, was intended to construct a series of small-scale, continuously operating alumina miniplants for testing each of several nonbauxitic alumina technologies. From these miniplants, promising processes for an alumina pilot plant, and the kinds of equipment it required, could be identified. The Bureau originally estimated this program would cost about $1.6 million and require 8 years to complete.

The program was publicly ordered expanded by the Secretary of Interior in December of 1973. Apparently the Secretary was responding to industry concerns of bauxite and alumina supply disruptions. As a result, White House-sponsored discussions took place in January 1974. A cooperative alumina research program managed by the Bureau of Mines and major aluminum company cooperators, creating a series of miniplants in the Bureau's Boulder City engineering laboratory, emerged from these discussions.

The cooperative miniplant program began July 1, 1974. Cooperating aluminum companies agreed to contribute $50,000 each, per year, for a period of three years. The Bureau claimed that with a minimum of 8 cooperators, it could complete the original miniplant research program two years ahead of its 8-year schedule, by fiscal year 1979. Industry cooperators participated in quarterly miniplant steering committee meetings, where they reviewed the program's progress and recommended changes. [12]

The nonbauxitic alumina materials/processes the Bureau originally proposed for miniplant testing and evaluation were:

--Clay/nitric acid.

--Clay/hydrochloric acid.

--Anorthosite/lime-soda sinter.

--Clay/sulfurous acid.

--Alunite.

--Dawsonite.

The Bureau told potential industry cooperators that no decision on a pilot-plant process would be made until an information matrix for all six processes was completed. Subsequently, this idea was significantly amended. Because aluminum company cooperators were unenthusiastic about reviewing dawsonite, this process was eliminated from the feasibility study.

Since 1974, the Bureau has operated only one other nonbauxitic alumina miniplant besides the clay/hydrochloric acid gas-induced crystallization process. The first miniplant to be constructed in the original program was for a clay/nitric acid process. However, a change in program direction in 1975 indefinitely deferred completion of this nitric acid work.

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[12] Eight companies joined the miniplant program initially and two others joined later. Industry support, however, has steadily declined since 1975. Five companies remained in fiscal 1979, but a Bureau official said that only four companies expressed any interest in participating in fiscal year 1980, and probably none would after that. Although the Bureau disputed this statement in commenting on our report, a recent article based on industry and Bureau interviews has reported essentially the same findings. See "Alumina Minerals-Still Overshadowed by Bauxite," Chemical Engineering, December 3, 1979, p. 58.

All other planned materials/processes miniplants, i.e., alunite, anorthosite, dawsonite, and clay/sulfurous acid, were also postponed in 1975. Also, despite favorable mention in published research and preliminary review by the Bureau, the carbo-chlorination of clay was dismissed as unsuitable technology for miniplant review. 13/ We discuss this process and its potential implications in chapter 5.

The program subsequently concentrated exclusively on a contractor-proposed variation of one of the Bureau's original six processes--clay/hydrochloric acid, gas-induced crystallization.

NEW MINIPLANT OBJECTIVE: A NONPROPRIETARY TECHNOLOGY

In 1975, the Director of the Bureau of Mines began redefining the Bureau's interests and priorities for the miniplant program. The information matrix research objective was subordinated to developing the most commercially feasible, nonproprietary, nonbauxitic alumina technology for development in an alumina pilot plant. 14/ Plans for the use of previously funded pilot-plant design money in a multiple process feasibility study, and the latter's relationship to the miniplant, were discussed by the miniplant steering committee.

Most economic nonproprietary technology

At a May 1975 steering committee meeting, several aluminum company representatives emphasized to the Bureau Director that the principal criterion for selecting a nonproprietary process for pilot-plant design should be the lowest probable operating cost of a commercial-scale plant, using one of the miniplant alumina processes. In short, implicit economic criteria were urged as the means of selecting a nonproprietary process for a pilot plant.

The efficacy of least-cost criteria for Government-nonproprietary, nonbauxitic alumina research assistance was hotly debated among aluminum industry and Bureau participants on the miniplant steering committee. In an August steering

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13/In commenting on our report 4 aluminum companies said they would like to see this process examined as part of the miniplant program.

14/A nonproprietary technology is one that is based entirely on public sources of information. The Department of Interior says the decision to create such a technology for a pilot plant was made outside the Department, and implies it was imposed on the Bureau.

committee meeting, the Director of the Bureau of Mines said an alumina pilot plant was a worthwhile objective even if the nonbauxitic process it developed was not commercially feasible.

Alcoa Aluminum Company took issue with this approach. The company considered a decision was premature at the outset as to which process was most economically feasible, and therefore most worthy of miniplant development for use in a pilot plant. Alcoa wanted all the nonbauxitic processes reviewed in miniplants before any decision was made about which processes' technical feasibility and economic potential merited pilot-plant development. 15/

While Alcoa clearly agreed with the original information matrix objective of the program, it said data in the public domain from which to determine the most economical nonproprietary pilot-plant process had not increased since the program's inception. Therefore, any judgment on the most economical process before the miniplant review of the six processes was based on the same public information previously deemed "inadequate." To go further, and link the construction of a pilot plant to the miniplant findings, under these criteria, meant only the most economic nonproprietary process would be generating new miniplant research information. It would be the obvious choice for a pilot plant.

This was a major change in program objectives according to Alcoa officials. They said their company did not agree to join a cooperative program to develop a Government-assisted, nonproprietary, nonbauxitic alumina pilot-plant technology. Alcoa agreed to jointly develop an information matrix for six nonproprietary processes. For this reason, Alcoa officials believed the miniplant program no longer served their company's interests and they did not renew the cooperative contract with the Bureau. The Bureau's objectives obviously excluded proprietary processes as candidates for a pilot plant.

15/Reynolds Metals Corporation's response to our draft report suggests that any of these nonproprietary processes, if adequately researched and funded, could provide results comparable to those achieved by the HCL-gas-induced crystallization method.

PROPRIETARY DATA AND TECHNICAL ASSUMPTIONS LIMITING MINIPLANT REVIEW AND PILOT-PLANT FEASIBILITY

Proprietary commercial interests and process exclusions

Some aluminum companies have devoted substantial resources of their own to develop proprietary nonbauxitic alumina research processes, briefly described in chapter 1. At the present time, at least 3 major aluminum companies, one smaller company, one consortium, and one oil company claim different proprietary nonbauxitic-alumina processes are as economically competitive as the preferred clay/hydrochloric acid, gas-induced crystallization process of the feasibility study.

Four major aluminum companies have told us that they believe clay/hydrochloric acid, gas-induced crystallization may not be the most economical nonbauxitic alumina process, but only the most economic nonproprietary process of the ones described in the feasibility study.

It seems abundantly clear, for example, that Alcoa's reasons for objecting to the nonproprietary miniplant and proposed pilot-plant development of clay/hydrochloric acid, gas-induced crystallization could be based in part on commercial self-interest. Alcoa owns technology for at least 2 proprietary processes which it claims would permit extraction of nonbauxitic alumina as cheaply as the process proposed for publicly-assisted development. 16/

Other companies that developed proprietary processes for alunite and dawsonite said that they were also cost-competitive with the clay/hydrochloric acid, gas-induced crystallization alumina.

Both dawsonite and alunite proprietary processes, for example, developed by Alumet and Superior Oil, respectively, may be more likely to produce alumina in initially large quantities. But dawsonite and alunite also involve more extensive capital investment than conventional alumina and have related coproduct marketing problems. Although these processes do not interest major aluminum companies, they are being pursued by companies that are not vertically integrated aluminum manufacturers. Kaiser Engineers' feasibility study used the environmental-impact statement as the source of

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16/Alcoa claims proprietary fluidized bed calcining, for hydrochloric acid evaporative crystallization and anorthorsite processes relevant to nonbauxitic alumina.

its technical information on the alunite process since it was never examined in a miniplant. Dawsonite was not even reviewed in the feasibility study, and is currently being pursued in a grant unconnected to the miniplant program.

A promising proprietary process involving the carbo-chlorination of clay has been developed by the Toth Aluminum Company. The process involves treating calcined kaolin clay with low-grade lignite or sub-bituminous coal and chlorine in the presence of a catalyst. The capital and production costs of such a plant might be considerably less than new Bayer plants, although the economic success of the process is probably linked to the fortunes of a proprietary chloride process for reducing aluminum from aluminum chloride controlled by Alcoa. Neither carbo-chlorination nor chloride reduction were examined in the Bureau's miniplant program.

Another promising proprietary nonbauxitic alumina process which was not part of either the miniplant program or in Kaiser Engineers' feasibility study is the so-called "H-Plus," or dual acid, process developed by Pechiney Ugine Kuhlmann of France and Alcan Aluminium, Ltd., of Canada. It is probably 5 years more technically advanced than any of the other acid processes described in the feasibility study according to Alcan officials, who also participated in the miniplant steering committee.

Although the process is designed for a variety of aluminous ores, such as carboniferous shales or kaolin clays, it seems designed for materials which might be more likely to attract Government financial assistance for a demonstration plant. Although the capital costs of using such materials may be higher, they suggest the possibility of satisfying energy-related national-policy objectives associated with aluminum production, as well as providing indigenous supply security to the Government.

The Bureau purchased equipment in 1975 to create an anorthosite miniplant but never built it. It has been indefinitely postponed. Although the steering committee was briefed by Alcoa on a promising, proprietary anorthosite process, it was not convinced that miniplant examination of anorthosite would be worthwhile. The nonproprietary anorthosite process evaluated by Kaiser Engineers in the feasibility study required large materials-handling capabilities and was considered uneconomical.

Sulfurous-acid, alumina-extraction technology is also proprietary, although considered "mature" by most standards. Developed in Germany during World War II, it has prohibitive, identified costs which seem to preclude commercial development. Because the process requires large amounts of energy and has significant pollution problems, of the four processes excluded it alone merited deferral from miniplant review.

Companies with proprietary, nonbauxitic alumina processes are presently prevented from achieving any financial benefits from Bureau-assisted alumina research and development. Whatever the social equity of precluding support for proprietary processes, it may be contrary to the Government's interest in least-cost nonbauxitic alumina. In this field, proprietary processes are believed to be the potentially valuable ones. Nonproprietary processes are not supposed to offer any promise for private development because they could be duplicated, allowing little for recovery of developmental expenses.

The bulk of the world's output of primary aluminum is currently produced by large, vertically-integrated manufacturers. These major aluminum producers perform many different functions as they proceed from mining to marketing final products. They (1) mine bauxite ore, (2) refine the ore into alumina, (3) smelt alumina into aluminum, (4) alloy virgin aluminum, (5) produce mill products, and (6) fabricate mill products into different shapes and lengths.

Today, the four largest companies dominating markets at various stages of aluminum production are North American multinationals--Alcoa, Reynolds Metals Company, Kaiser Aluminum and Chemical Corporation, and Alcan Aluminium of Canada, Ltd.

Past Government policies have tried to make the United States aluminum industry less concentrated. In 1945 the Government sold many of its wartime smelters and refineries, built and managed by Alcoa, to two new producing companies: Kaiser and Reynolds. This included the transfer of a great deal of Alcoa's proprietary technology to these two companies.

Later, in 1950, a Federal court ruled that owners of Alcoa had to divest themselves of Aluminum Limited, a Canadian holding company owning the Aluminium Company of Canada, Ltd. Government procurement, development loans, and rapid amortization also encouraged affiliates of major European producers, Alusuisse and Pechiney, as well as a competitive fringe of smaller firms.

We were told by industry and Justice Department officials that the vertically-integrated and oligopolistic nature of the aluminum industry created a substantial antitrust impediment to cooperative proprietary alumina research. As a result of this, participation in the Bureau's cooperative miniplant program was gained through a series of memoranda of agreement with individual aluminum companies. In these memoranda, the companies agreed to contractual language that all jointly developed technology would be public, but standard contractual language that would normally require company cooperators to disclose all technical information they possessed about relevant subjects of joint inquiry was explicitly excluded.

The process finally selected by the steering committee for miniplant inquiry and technology development--clay/hydrochloric acid, gas-induced crystallization--was really a hybrid of existing proprietary processes. It was conceived around lapsed patents, published literature, and deductive physical chemistry. It avoided the existing or pending patents of aluminum industry cooperators, although it directed inquiry toward potentially patentable processes. 17/

OTHER AGENCY APPROACHES TO PROPRIETARY RESEARCH AND IMPLICATIONS FOR PROGRAM AND POLICY COORDINATION

The trade-offs between relying on widely-disseminated, nonproprietary alumina research and supporting proprietary-process aluminum development have never been specifically examined by the Government.

Contrary to Department of Interior policy, the Department of Energy (DOE) supports proprietary research of private aluminum companies on aluminum reduction as part of its energy-conservation program. Both Kaiser Aluminum and Chemical and Alcoa have received DOE funds for enhancing proprietary research processes. 18/ This research, according to Department of Energy officials, is justified under a

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17/E.g., Alcoa withdrew from the program after it received patent protection on a related fluidized bed calcining process for clay/hydrochloric acid, evaporative crystallization.

18/Efforts by the Toth Aluminum Corporation to secure funds under this program in order to develop a proprietary clay/carbo-chlorination process have not been successful, despite company data suggesting potentially significant energy savings.

section of the Federal Energy Research and Development Act (1974) that supports non-energy materials research in order to enhance energy conservation.

Aluminum research efforts in the Department of Energy are associated with proprietary corporate efforts to reduce the energy and capital requirements of domestic aluminum production. The premise of the Bureau of Mines' alumina research is to reduce the need for imported bauxite and alumina supplies in periods of crisis. By supporting the development of an alumina technology that could be used to make aluminum from abundant, nonbauxitic, domestic ores, the Bureau hoped to reduce the likelihood and impact of supply disruptions.

While we understand the concerns that motivate the Bureau's research, as the following chapter indicates, we see the threat to future aluminum supplies not so much in terms of supply cut-offs from cartel-like actions by bauxite exporters, but rather as a by-product of changing domestic energy costs and availability. That is the problem addressed by DOE's research. The direct reduction technology being developed through DOE's research, conversely, might also meet the Bureau's objective of making use of domestically abundant nonbauxitic alumina clays.

Both departments may claim to be pursuing research that is in harmony with their respective missions. It is clear that their differing approaches toward supporting proprietary research may make any meaningful fusion of the most promising proprietary alumina and aluminum technologies impossible. The preferred nonproprietary nonbauxitic alumina technology of the Bureau is compatible only with DOE-supported, proprietary Hall-Heroult process improvements, not proprietary direct reduction, oil shale, or alunite technologies. Conversely, DOE-supported proprietary aluminum research does not include the most promising proprietary alumina process, clay/carbochlorination.

Differing missions give each agency a slightly differing perspective toward two distinct aspects of an interrelated problem. What is less apparent is that their differing approaches toward proprietary aluminum-related research has resulted in poorly coordinated, potentially incompatible "solutions."

The Office of Science and Technology Policy (OSTP) is charged under the National Science and Technology Policy, Organization and Priorities Act of 1976, with assisting the Office of Management and Budget (OMB) with "an annual review and analysis of funding proposed for research and development." 19/ As the Comptroller General has testified before the House Committee on Science and Technology:

> "* * * We are facing changing social and economic conditions which are generating a greater diversity of needs while increasing the constraints on our resources. Therefore, we are going to have to make some tough choices. I believe many of those choices must be made centrally, based on information and analysis about the full scope and nature of both Government and private R&D." 20/

We believe the Office of Science and Technology Policy has a role to play in situations such as these. The substantive, science-related issues that require technical review in the Departments of Energy and Interior aluminum and alumina research programs are incorporated in their diverse approach to proprietary research. OSTP is the appropriate agency to review and to promote coordination of these programs.

ECONOMICALLY CONSEQUENTIAL TECHNICAL ASSUMPTIONS

Kaiser Engineers' pilot-plant design and feasibility study assumed technical solutions to economically very consequential research problems for all of the major materials/processes it evaluated. These assumptions, necessitated by the absence of miniplant process data, might have altered the relative operating and capital costs of all the major processes evaluated. Actual differences in these costs could affect the selection of the most economic process for a pilot plant. It is important that these technical unknowns of the major processes requiring more definitive miniplant research data be identified prior to a process selection

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19/GAO has urged the Office of Science and Technology Policy to accept this legislative mandate with respect to assuming an active materials policy role in "Management of Federal Materials Research Should Be Improved" (EMD-78-41, 7/14/78), and in a letter report on institutional options for materials research and development to the Chairman, House Science and Technology Committee (B-18336), February 4, 1980.

20/Testimony of Elmer Staats, Comptroller General of the United States, before the House Science and Technology Committee Hearings, April 5, 1979.

for a pilot plant. We have identified (app. I) several of these assumptions and their cost implications for the 3 leading clay/acid processes reviewed in phase two of the Kaiser study.

Clay/hydrochloric acid, gas-induced crystallization

The detailed description presented by Kaiser Engineers of the alumina from clay (via hydrochloric acid, gas-induced crystallization) is the most energy-efficient of the six alternatives Kaiser Engineers considered, and therefore the cheapest.

Essentially, the process that was developed in the Bureau miniplant "invented" a gas-induced crystallization technology for which no commercially manufactured equipment exists. This was necessary to reduce the energy requirements and other operating costs the known evaporative technology used for manufacturing non-bauxitic alumina from clay with hydrochloric acid. Consequently, the new process capital cost estimate is critical to its success, but, we believe, suspect. This is because the reduced operating costs for the process are achieved largely by assumptions about the cost and operating efficiency of yet-to-be-manufactured, commercial-scale capital equipment.

We identified in the appendix of our report specific technical areas of the process for which adequate data are lacking, as well as their potentially adverse impact on Kaiser Engineers' assumed operating and capital costs. Together with less significant assumptions, they could understate operating and capital costs per ton of alumina (produced by Kaiser Engineers' preferred process) of $38 and $150, respectively.

Clay/nitric acid evaporative crystallization

The operation of the thermal decomposition-acid recovery process steps represents a serious potential problem to the nitric acid process. The feasibility study specifies a loss of up to 14 percent of the nitrate fed to a decomposer operating at 750 F. Unfortunately, the nitrate losses are critically dependent on the actual operating temperature and accurate data are not available. 21/

Another potential problem for nitric acid involves the treatment and disposal of large volumes of waste iron-sulfate sludge, and chloride-bearing waste from the solvent extraction system. Although the nitric-acid process creates pollutants for which there are presently no standards, one company official characterized them as "potentially carcinogenic." Since these wastes cannot be expelled into the environment, their reprocessing/utilization from the waste streams requires additional energy and capital costs.

The nitric acid process also has a potential corrosion problem in the mixture of hydrochloric acid (used to remove iron from the ore) and nitric acid. A slow leakage of even small quantities of chloride into the nitric-acid stream could add significantly to the repair-and-maintenance labor and materials costs, already estimated as 18 percent of total operating costs by Kaiser Engineers.

Optimization of any of these processes could also affect the costs assumed by Kaiser Engineers. For example, ore quality variations alone could add $113 more per ton of alumina to capital costs, and $25 more per ton of alumina to operating costs.

Clay/hydrochloric acid, evaporative crystallization

In the hydrochloric acid, evaporative crystallization process, it is necessary to evaporate the liquid containing the alumina completely. This consumes more energy than the gas-induced, hydrochloric acid process. On the other hand, the technology and capital costs for the evaporative crystallization process are better known. Thus, the tradeoffs between process energy and acid makeup requirements as operating costs in the evaporative process, versus the more expensive capital equipment in the gas-induced process, could have been identified.

21/Nitrate losses of 14 percent and 7.4 percent have been reported by the Idaho National Engineering Laboratory for thermal decomposition operating temperatures of 750 F. and 400 F., respectively. If higher operating temperatures are required, nitrate losses will be significantly greater than 14 percent.

Unfortunately, the hydrochloric acid, evaporative process described by Kaiser Engineers did not use the same indirect-fired thermal decomposer, and similar acid concentrations as those assumed for the hydrochloric acid gas-induced process. If it had, the operating costs could have been significantly reduced. Conversely, its capital cost estimate might suggest a more realistic baseline for known capital equipment.

CHAPTER 4

REAL PROBLEMS FACING FUTURE

U.S. ALUMINUM INDUSTRY

Development of domestic nonbauxitic alumina resources is frequently justified as reducing unhealthy and pronounced dependence on foreign sources of bauxite and alumina, reducing our susceptibility to resource cartels, and thereby contributing to our national security. 22/ But increased energy costs and availability concerns, combined with industrial development efforts of foreign governments, not resource cartels or supply interruptions, are creating significant cost differentials favoring new overseas primary aluminum capacity. Rational U.S. resource policy compels inquiry as to whether or not abundant nonbauxitic alumina resources could be adapted by technology to alter future aluminum capacity trends.

Central to the future demand for nonbauxitic alumina in this country is the effect of future domestic energy availabilty and prices on the cost of making primary aluminum. Huge amounts of energy are consumed smelting aluminum from alumina. Energy consumed in extracting alumina from bauxite is minimal by contrast. To conserve this expensive resource, on the other hand, requires extensive capital investment.

Countries with both large undeveloped energy resources and bauxite reserves offer attractive alternatives to domestic investment in primary aluminum capacity. Because energy-related demand for aluminum make future prices more inelastic, the lower costs of such foreign aluminum capacity would be highly profitable. Under these circumstances, U.S. companies will create new primary aluminum capacity overseas. This is the real problem of import dependence, not that posed by the existence of an International Bauxite Association (IBA).

Previous and ongoing alumina research and development in the Department of Interior provide no answers to these energy-related future capacity policy problems. Thus, the real problem of developing domestic nonbauxitic resources is inextricably bound to the problem of reducing energy and capital costs of future U.S. primary aluminum capacity, a concern shared by the Department of Energy. Cheaper alumina, by itself, is unlikely to match the energy economies of foreign production.

22/This is how the Department of Interior justifies the program in commenting on our draft.

Considering dramatic increases in the amount of aluminum likely to be demanded by the transportation sector, particularly the automotive industry (as shown below), we believe Government aluminum research-and-development programs may need to be rejuvenated, providing there is sufficient economic justification for trying to use research to make future U.S. primary aluminum capacity price-competitive with foreign locations.

AVAILABILTY OF ALUMINOUS MATERIALS

Aluminum metal, as explained earlier, is the product of a three-phase industrial process. Bauxite is mined; aluminum oxide (alumina) is extracted from the bauxite; and aluminum is then smelted from the alumina.

Bauxite and alumina availability

The supply of alumina is directly related to the availability of bauxite. Yet neither one is in short supply. Internationally, bauxite reserves are large enough to satisfy projected demand for many years to come. On the other hand, even if the United States had the bauxite-mining capacity to fully meet its domestic aluminum demand, its reserves would probably be inadequate to meet total national needs for more than about 5 years without imports.

Bauxite is found on all continents in more than 28 countries. Table IV-1 presents the major bauxite reserves, their recoverable aluminum equivalent, existing mining capacity, and bauxite production tonnage in 1977.

Table IV-1

Bauxite Reserves, Mine Capacity, and Production in 1977

(thousands of tons)

		Recoverable Aluminum Equivalent		
Country	Bauxite Reserve	Reserve Equivalent	Mine Capacity	Mine Production
Guinea	9,184,000	1,190,000	3,300	2,900
Australia	5,040,000	1,000,000	6,700	5,800
Brazil	2,800,000	600,000	300	250
Jamaica	2,240,000	450,000	3,800	2,630
India	1,568,000	320,000	400	330
Guyana	1,120,000	260,000	1,100	750
Cameroon	1,120,000	200,000	-0-	-0-
Greece	840,000	170,000	900	670
Indonesia	784,000	150,000	-0-	-0-
Ghana	638,000	130,000	100	50
Venezuela	560,000	145,000	-0-	-0-
Surinam	549,000	130,000	2,000	1,250
Yugoslavia	448,000	85,000	800	480
Haiti	11,000	5,610	74	65
U.S.	44,800	10,000	*	2,091
Total	26,946,800	4,845,610	19,174	17,266

Source: Data provided by the Bureau of Mines.

The total amount of aluminum produced in the world in 1977 (17.266 million tons) required 90 million tons of bauxite according to the Bureau of Mines. Even individually, most of the countries with significant reserves have enough bauxite to meet this total global requirement for several years. Clearly, there is no physical shortage.

Processing trends

At present, the United States depends on imported bauxite and alumina, smelting them into aluminum domestically. This U.S. primary aluminum capacity, however, is inadequate to meet all of our metal demands. Moreover, the proportion of value added to aluminous raw-material imports in this country is significantly decreasing. More money is spent on alumina imports each year. This shift to importing products of greater value--alumina and aluminum--in place of bauxite is indicated in table 2. It shows the dollar value of net

U.S. trade in various aluminous metals between 1970 and 1977, and the shift to more expensive, processed imports.

Table VI-2

Net U.S. Trade (Imports - Exports)* in Aluminum and Aluminum Raw Material
(millions of $)

	1970 a/	1971 a/	1972 b/	1973 b/	1974 b/	1975 b/	1976 b/	1977 b/
Bauxite	173	165	163	167	220	270	339	371
Alumina	65	67	118	104	165	236	245	371
Aluminum	(134)	128	165	(52)	(80)	(27)	86	294
Total	$104	$360	$441	$219	$305	$479	$670	$1,036

*Net exports in parentheses.

a/Constant 1971 dollars.

b/Current dollars.

Source: Data provided by Bureau of Mines.

Table IV-2 shows that only part of this aluminous-materials deficit is for bauxite imports required to satisfy domestic alumina refineries. The increasing trend of alumina imports now contributes just as much to that deficit. This is the result of increased foreign refining by U.S. companies. The levies and taxes in bauxite-producing countries are designed, in part, to encourage this trend to foreign alumina manufacture. Higher energy prices also create an incentive to transport alumina rather than bauxite. About 30 percent of U.S. alumina is now imported.

The International Bauxite Association (IBA)

Political efforts to restrict development of bauxite have been made by some bauxite-producing countries in order to promote their domestic industrial alumina development and enhance foreign exchange earnings. Ostensibly, these policies are embodied in the operations of members of the International Bauxite Association. In fact, this organization has had only limited success as a resource cartel.

The IBA was established in 1974 to promote the development of bauxite and to secure "fair" returns for member bauxite-exporting countries. Australia, Jamaica, Guinea, Surinam, Haiti, Ghana, Sierra Leone, the Dominican Republic, Yugoslavia, and Indonesia are members. IBA's immediate inspiration was OPEC energy price increases which simultaneously damaged raw material exporting countries that lacked domestic energy, yet inspired them to hope for a "new international economic order."

National economic interests and collective prices

In 1974 and 1975, most of the member countries followed Jamaica's lead in adopting new levies and royalties to increase revenues from bauxite exports. They did not follow Jamaican price leadership to the same extent, however, and many producers attempted to improve their market positions against Jamaican prices. It is safe to assume that all but a few countries benefited from Jamaican price increases by not agreeing on a uniform pricing policy. Australia, for example, remained a member of the IBA without ever raising levy and royalty payments but it significantly expanded bauxite production.

Although some of the energy-rich nations with large bauxite deposits and the greatest potential for developing vertically integrated aluminum industries--Australia and Guinea--are members of the IBA, they are not active adherents of the association's quest for a uniform pricing policy. To date, the IBA has not replaced individual countries as the mechanism for establishing bauxite and aluminum prices and we believe it is unlikley to do so in the future.

The IBA is still trying to establish minimum prices for various characteristics and grades of bauxite with allowances for transportation, and to relate these prices to the price of an aluminum ingot. Its future appeal may be with those producers lacking any prospects for an integrated aluminum industry, facing depressed bauxite prices, and with desperate needs for foreign exchange.

Australia's past independence from the IBA's price-increasing action, the nonmembership of Brazil and Venezuela, and the huge reserves of Guinea significantly reduce the potential effectiveness of IBA collective action. These four countries, each with very large bauxite reserves, are interested in expanding their relative market share to maximize their production advantage and develop a domestic aluminum industry. Other producers cannot substantially revise their own bauxite prices without risking market and revenue losses, as well as endangering development funds, from price competition with these countries.

A country with more than a billion tons of identifiable bauxite reserves, such as Australia, Brazil, Guinea, or Venezuela, also faces the virtually certain risk that most or a significant part of these economic resources may never be developed without enhancing market forces. Once supplanted by development elsewhere, economic benefits from such resources are forever lost to the economy. Such countries have a very real incentive to expand production as rapidly as possible, regardless of price, in order to capture investment before it goes elsewhere in pursuit of a ubiquitous resource.

In summary, future IBA pricing policy will be limited by: (1) lack of trust between members; (2) varying costs of production elements and limitations of policies maintaining comparably adjusted production levies to uphold uniform prices; (3) the possibility that some national levy increases might result in production cutbacks, reducing needed revenues; and (4) fear that price increases might discourage development, or lead to exploration and development of alternative bauxite resources elsewhere.

Collective strength for weak economies

Because of these problems, the IBA is the vehicle of small Caribbean, bauxite-producing countries, faced with desperate needs to increase revenues from a major exportable raw material. These countries lack both energy potential and national development policies conducive to foreign aluminum investment.

The national resource strategies of these Caribbean countries hinge on using the leverage gained from past foreign investment in alumina refineries to enforce higher bauxite levies. Officials of these countries claim to believe higher bauxite prices will serve as a stimulus favoring still more indigenous alumina refining.

After energy price increases made it obvious that future forward integration of the aluminum industry would occur in countries possessing both bauxite and abundant energy potential, small, highly dependent Caribbean bauxite exporters used increased levies to facilitate a transition to other industries. Unfortunately, the lack of attractive alternatives did not preclude their efforts to extract monopoly rents.

In future years, these small countries are likely to maintain existing bauxite-alumina refining capacity only by modifying existing policies. Otherwise, they will not be able to compete with major new producers whose massive bauxite deposits are augmented by cheap energy potential and national policies which encourage foreign investment.

As new bauxite, alumina, and aluminum investment shifts to countries such as Australia, Brazil, and Guinea to meet future aluminum demand, the economic leverage of existing Caribbean alumina refineries will diminish. We believe the likelihood of future significant bauxite and alumina price increases, similar to those which occurred in 1974, is minimal for the next decade.

Even if such levy and tax increases occur in the late 1980s, they are likely to be far less expensive than the alternative costs of refining alumina from nonbauxitic domestic resources. A study by Virginia Polytechnic Institute (VPI), 23/ for example, suggests that bauxite prices would have to be as high as $75 per ton in 1977 dollars before clay/hydrochloric acid, gas-induced crystallization becomes an economic alternative method of producing alumina. This is about three times current bauxite prices. Bauxite price increases of this magnitude are most unlikely.

The VPI study accepts the Bureau's assumptions about the cost of the preferred nonbauxitic alumina process which we consider optimistic. As a result, we consider one of the major private company objectives for Government-assisted research unattainable; there is no technological ceiling on bauxite prices created by present nonbauxitic alumina research. Bauxite producers like Guinea need not be deterred from increasing future prices by the threat of nonbauxitic alumina resources.

ALUMINUM DEMAND AND PRODUCTION TRENDS

Aluminum supply and demand

All indicators suggest an impending capacity-related shortage of aluminum before 1985. Barring long-term economic recession, global aluminum demand should exceed existing

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23/Hibbard, W. R., Jr., et al., "Midas: Mineral Development and Supply Model of the U.S. Aluminum Industry from Mineral to Wire," Virginia Polytechnic Institute, Blacksburg, December, 1978, Vols. 1 and 2.

smelting capacity by 1982 or 1983, forcing aluminum prices significantly upward. Much of this shortfall will be created by the new aluminum requirements of the automotive industry's fuel economy regulations. 24/

Historically, since 1950, the demand for aluminum has doubled every 8 years, but only minimal expansion of the world's primary aluminum capacity is currently under construction or even planned. In May 1977, the chief executive of a major U.S. aluminum company said domestic primary aluminum capacity would grow by only .4 percent annually through 1981. The Bureau of Mines has identified only 346,000 tons of planned additional U.S. aluminum capacity between early 1976 and the end of 1983.

The cost of new aluminum capacity has more than doubled since the early 1970s. An annual ton of new aluminum--including bauxite mining, alumina manufacturing, and aluminum smelting--costs at least $3,000. 25/ Of this amount, about two-thirds, or $2,000, is the direct cost of smelting aluminum from alumina. 26/ Assuming a 5-1/2-percent annual growth in aluminum demand for the next decade, the President of Alcan estimated in 1977 that the required mines, power plants, refineries, smelters, and fabricating facilities necessary to increase global supplies by the same amount would cost $4 billion per year. The industry's previous profitability could not support such expenditures, according to Alcoa officials. Thus, capacity will expand more slowly than demand and prices will rise.

24/We have recently completed a report on the materials implications of fuel economy standards for automobiles. See "Policy Conflict-Energy, Environment, and Materials--A Case Study of the Automotive Fuel Economy Standards" (EMD-80-22), February 5, 1980.

25/An annual ton consists of all capital costs involved in the production of aluminum divided by the annual capacity for aluminum production. Recently, an Alcoa representative publicly suggested this cost is now $4,500 per annual ton in 1979 dollars as a result of inflation.

26/Capital costs from aluminum production facilities vary, depending on such factors as location, type of plant, type of production process to be used, and environmental costs.

Even if current prices are adequate to support such expansion, previous capacity-expanding pricing patterns may be changing. Many aluminum company officials and industry analysts are increasingly confident that continued energy cost increases will only make aluminum prices more inelastic. This is because related transportation needs, especially automotive uses, will increase disproportionately. They anticipate a high-cost, specialized, aluminum market.

Automotive demand for aluminum

Increased energy costs, of course, have created a tremendous need to reduce the weight of automobiles and trucks in order to achieve mandated fuel economy. 27/

In 1976, automotive shipments of aluminum for cars and trucks totaled 1.89 billion pounds, or about 14.7 percent of total United States aluminum production. For that year, the Bureau of Mines estimated an average of 84 pounds of contained aluminum per car, but an average of about 146 pounds of aluminum per car was actually shipped, only part of which is contained in the car. As table IV-3 indicates, automotive shipments used in trucks, trailers, and buses totaled about half again the amount used for automobiles. 28/

27/By 1985, the average new American car must be able to generate at least 27.5 miles per gallon. In 1974, the new car average was about 15 miles per gallon. This difference in fuel economy will be achieved largely by size reduction and increased use of lighter materials.

28/The study cited in Table IV-3 was invaluable for our purposes, but it also suggests the kind of sectoral materials research necessary to formulate regional industrial policies which could be usefully pursued by the Department of Commerce and other Federal agencies.

Table IV-4

Aluminum Requirements of Fuel Economy--Standard Cars

Model Year	Contained Aluminum (lb/car)	Required a/ Aluminum (lb/car)	Recoverable New b/ Aluminum Scrap (lb/car)	Net c/ Aluminum (lb/car)
1977	100	150	25	125
1978	114	171	29	142
1979	129	194	32	162
1980	150	225	38	187
1981	200	300	50	250
1985	250	375	63	312

Source: Harbeck, et al., as modified.

a/Based on 3 of the last 4 years of aluminum shipments to automobile manufacturers shown in table 3, about 60 percent of the aluminum shipped is contained in the cars. Because future aluminum will be more expensive, we say two-thirds of the aluminum shipped will be contained in cars.

b/New aluminum scrap recoverable by the manufacturer was assumed by Harbeck, et al., to be 25 percent of the amount of aluminum contained in the car.

c/Net aluminum is the total requirement less new scrap recovery, expressed in pounds per car.

Table IV-4 indicates the net amounts of aluminum per car required for manufacturing, defined as shipments minus recoverable new scrap. Using the midpoint of the range of contained aluminum estimates, or 250 pounds per car, would result in a net requirement of 312 pounds of aluminum per car. Light truck requirements are assumed to total one-half net auto needs.

Thus, as the following table indicates, even under conservative automotive sales, aluminum requirements are going to increase significantly for the automotive industry. A much greater proportion of domestic aluminum capacity will be allocated to automotive needs than in the past, since these increased needs will not be met by new capacity. Other users of aluminum may be forced to use substitute materials as prices rise.

Our conclusion about domestic aluminum scarcity is no less true for the rest of the world. In 1982, the major industrial regions of the capitalist world--the United States, Western Europe, and Japan--will require more aluminum smelting capacity to fill their projected needs than exists in these countries or elsewhere in open economies. Total aluminum-deficit-nation demand will exceed total aluminum surplus-nation supply. Unlike international trade of primary aluminum in the past, when economic cycles produced periodic surpluses which were dumped in international markets, industrial nations will face a period of chronic and increasing deficiency during the mid-1980s.

Metal import trends

The Bureau of Mines estimates that demand for aluminum in the United States will increase at an average annual rate of 5.2 percent between 1976 and 2000. Domestic aluminum capacity, as explained earlier, has remained largely unchanged since 1971 and is likely to increase by only about 350,000 tons by 1983 according to the Bureau's capacity monitoring data. Any shortfall during this period will be met largely by price-induced rationing and imported metal. Thus we will import more aluminum but also more expensive aluminum. How much more aluminum the United States will import depends on how much price increases will curtail demand, how much secondary production can be increased, and how much variation in automotive materials usage can be achieved.

There seem to be quite different implicit assumptions made about domestic aluminum prices by the Bureau of Mines and the aluminum industry. Forecast primary aluminum demand in 1981 will exceed domestic supply by 800,000 tons according to Alcan and 925,000 tons according to Alcoa, but 1.1 million tons according to a Bureau of Mines estimate for the Federal Preparedness Agency. 30/

Whatever the exact number, it is abundantly clear that the pattern of demand exceeding primary production capacity is different from past experience. While 94 percent of the primary aluminum consumed in the United States between 1968 and 1977 was produced here, future domestic aluminum capacity might provide much less than 85 percent of the primary metal estimated by the Bureau for 1985 unless there are radical changes in projected consumption.

30/Bureau of Mines estimate in "Long Range Aluminum-Mobilization Outlook: 1985-1990," Federal Preparedness Agency, February 1978, p. 15.

Global aluminum production trends

The energy required for aluminum production represents a global problem requiring world-wide production and marketing adjustments. For example, about one-third of the Japanese aluminum industry has been closed because it is no longer economically viable due to high energy costs. Conversely, attractive sites for hydroelectric power exist in several developing countries, and some of these are being developed by governments and international agencies as part of ambitious industrial infrastructure programs. Other petroleum-exporting countries are building aluminum smelters to operate on natural gas, formerly flared at oil fields.

To the extent private U.S. companies are able to participate in these new ventures, they offer attractive opportunities to rationalize future aluminum production. 31/ Most efficient ingot production by overseas affiliates would permit the development of specialized alloys and fabrication production in the United States, permitting more profitable operation for the industry.

American companies appear to be shifting new aluminum capacity overseas because of the convergence of cheaper aluminous materials and energy resources in foreign countries, and the active role of Governments and international funding agencies defraying necessary infrastructure expenditure, on the one hand, and on the other, penalizing unprocessed, raw material exports. 32/

ENERGY, ALUMINUM PRODUCTION, AND RESEARCH OBJECTIVES

Energy and U.S. aluminum production

These emerging patterns of aluminum production are caused, in large part, by the vast amounts of energy required to produce aluminum and disadvantageous future U.S.

31/GAO has undertaken a review of the power requirements of the aluminum industry and the technological opportunities for energy savings. Our review suggests a great deal could be done to extend the productive life of existing capacity.

32/Some foreign locations may actually be more expensive in terms of capital and productivity than domestic ones, before these public entity actions are considered.

energy supplies. More than 1.3 percent of our national energy consumption and over 4 percent of our electricity are used by the aluminum industry. Moreover, the Bureau of Mines projected growth in U.S. aluminum consumption would consume 7 percent of the Nation's electricity by the year 2000, and 2.7 percent of our total energy, an unlikely occurrence if the Bureau's own primary capacity data are to be believed.

Historically, the industry's growth has been closely linked to the development of abundant, cheap hydroelectric power. There is virtually no abundant, cheap, undeveloped hydroelectric power potential left in the country. Alternative energy sources like nuclear, coal, and oil are less certain supplies, more expensive, and less resistant to inflationary pressures.

It is doubtful whether future energy supplies will be adequate to support any significant new growth in conventional primary aluminum capacity in the U.S. Price increases for imported oil, and increased competition for limited hydroelectric power and electricity, plus environmental costs for coal, will push domestic aluminum industry energy costs up at a faster rate than the costs of any other factor of production.

The industry's energy requirement, as we pointed out before, is used almost entirely in the smelting of aluminum. About 175 million Btu's are required to smelt each ton of aluminum from alumina, 70 percent in the form of electricity. Future rates paid by the domestic aluminum industry for Government-provided electricity is likely to increase substantially as both the Bonneville Power Authority and the Tennessee Valley Authority try to accommodate rising demand. Even more important than these rates is the industry's need for an uninterruptible supply.

Energy and new overseas aluminum capacity

The energy availability constraint on domestic production makes aluminum production in foreign countries increasingly attractive, despite their distance from the U.S. market. The proximity of huge bauxite reserves to abundant, relatively cheap energy, and the reduced risk to individual companies afforded by multiple-company and Government-sponsored investment projects, make countries like Guinea, Venezuela, Australia, and Brazil logical places for enlarging aluminum production.

To encourage development of an aluminum industry, for example, the Brazilian government is constructing a hydroelectric plant with a power capacity of 2,115 megawatts in northeastern Brazil. The energy from this plant is scheduled to support development of an integrated aluminum industry. Whether Brazil will be merely self-sufficient in aluminum or a factor in the world market is still not clear.

Similarly, Venezuela's untapped hydroelectric energy and extensive bauxite reserves have resulted in government efforts supporting development of an integrated aluminum industry. A series of 3 dams could potentially produce more than 9,000 megawatts of industrial power. If plans for constructing new facilities and expanding existing ones are fulfilled, Venezuela will increase aluminum production available for export in the 1980s, but perhaps not as significantly as substantial foreign investment would allow.

The major new aluminum producer before 1990 might well be Australia. While it has limited hydroelectric potential, Australia has abundant high-sulfur coal and environmental standards accommodating large-scale development. It is, therefore, energy-rich, a secure country for foreign investments, and near the Japanese market. However, significant coal-powered smelters are required along with technological advances reducing their costs. Such advances, combined with higher aluminum prices, could make Australia a major aluminum producer.

Needed revisions in research objectives

The Bureau's miniplant program and pilot plant feasibility and design study are focused exclusively on alumina, an intermediate material conventionally derived from bauxite, to make aluminum. The relative value of alumina in total bauxite-alumina-aluminum production costs is quite small. 33/ According to an aluminum industry model developed at Virginia

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33/Reynolds Aluminum took issue with this, stating that costs up through the alumina process could be over 40 percent of the aluminum cost, given a combination of Australian bauxite, new alumina refineries, and old aluminum smelters. Conversely, using domestic bauxite, old alumina refineries, and new aluminum smelters, alumina costs could be as little as 13% of the cost of aluminum. We believe such data support our basic contention.

Polytechnic Institute, past aluminum prices have been insensitive to bauxite and alumina costs. 34/ Massive technical improvements in alumina production would probably be necessary in order to beneficially affect the economics of primary aluminum production in the United States.

We believe that capital equipment and energy costs of aluminum production will continue to dominate the location of global primary aluminum capacity. Unless the total costs of domestic primary aluminum manufacture are substantially reduced. Therefore, there will probably be inadequate demand for new, nonbauxitic aluminous resources development.

If the major objective of the Bureau's alumina research is domestic resource development, the present program will fail. As presently organized, the Bureau's nonbauxitic alumina research is misdirected. It will not substantially reduce the probable future costs of making aluminum in the United States.

As we point out in the next chapter, the Bureau's program ignores potentially promising proprietary aluminum technologies which use nonbauxitic alumina resources, as well as processes that could produce other intermediate products, like aluminum chloride from carbo-chlorination of clays. Such technologies might require substantially less capital and energy. A great deal more rigorous thought needs to be given to relating the problems of creating new aluminum capacity in the United States to domestic nonbauxitic alumina resource development.

34/See: "Midas: Mineral Development and Supply Model of The U.S. Aluminum Industry From Mineral To Wire," 2 Vols., Virginia Center for Coal and Energy Research, Virginia Polytechnic Institute and State University, Blacksburg, (NSF Contract 77-12539), December, 1978.

CHAPTER 5

ENERGY AND FINANCIAL COMPARISON OF ALUMINA AND ALUMINUM TECHNOLOGIES

Trends in the location of primary aluminum capacity are caused by anticipated future energy-cost differentials, and by resource-development policies of countries possessing large bauxite reserves. We believe that future U.S. primary aluminum capacity would be increased to match future U.S. aluminum demand only if the energy and/or capital costs of making primary aluminum in this country were significantly reduced. In addition, only if these projected cost decreases were a result of using domestic nonbauxitic alumina resources, would the latter's development be assured. This should be the goal of the Bureau's aluminum-related research.

There is inadequate information to make refined, quantitative judgments about the relative economic attractiveness of nonbauxitic alumina processes. Nevertheless, enough is known to eliminate all of the Bureau's miniplant processes for a pilot plant as at least premature. None of the Bureau's candidate processes are likely to be economically competitive with conventional Bayer-bauxite alumina in the foreseeable future.

Thus, from the standpoint of either developing domestic nonbauxitic alumina resources or maintaining future U.S. primary aluminum capacity to meet domestic demand, alumina research appears misdirected. We have identified one proprietary process--clay/carbo-chlorination (and there are undoubtedly others)--which seems to meet our requirements for fruitful research and development assistance. When combined with other potentially licensable technology, this process might offer substantial capital reductions. Carbo-chlorination also uses low-grade coal as a fuel source for energy, suggesting lower overall energy costs. And, like the Bureau's candidate, this process is based on kaolin clay as the source of aluminous ore. However, the clay/carbo-chlorination process requires a great deal more development before it can be considered a prime candidate for a large-scale pilot plant.

As stated before, the Kaiser Engineers' feasibility study conducted for the Bureau of Mines culminated in an engineering design for a pilot plant using a clay/hydrochloric acid, gas-induced crystallization process. The Office of Management and Budget (OMB) has not supported Federal Preparedness Agency (now Federal Emergency Management Agency --FEMA) requests under authority of title III of the Defense

Production Act for pilot-plant funding. We concur with OMB's judgment that pilot-plant funding is still premature.

This chapter reviews the comparative costs and their economic implications of three acid processes included in phase two of Kaiser Engineers' feasibility and pilot plant design study, as well as those of the clay/carbo-chlorination process examined in a separate study by the Pullman-Kellogg Engineering Company. Because of the cost claims for this process we included it in our comparisons of the Kaiser processes and the conventional Bayer-bauxite alumina process. We were particularly interested in process energy and capital cost requirements. Our review shows that only one of these non-bauxitic technologies appears to compare favorably with new conventional Bayer bauxite alumina in this regard and that is clay/carbo-chlorination.

EVALUATION OF NONBAUXITIC ALUMINA PRODUCTION PROCESSES

It is highly probable that each of the processes described by Kaiser Engineers and Pullman-Kellogg could produce commercial-grade alumina. Whether any could do so economically is quite another question.

The issue for our analysis was at what cost alumina from the leading clay/acid and clay/chlorination processes could be produced, and how these costs compare with conventional Bayer-bauxite technology. All unresolved technical problems with each process represent current economic problems. Because many of the former costs are based on unknowns, they represent significant risks for which contingency funds must be available. Making adequate allowance for these unknowns is as important for current investment decisions as proven costs.

Clay/carbo-chlorination

The carbo-chlorination process for the production of alumina and/or aluminum chloride from domestic kaolin clays as developed by the Toth Aluminum Corporation, New Orleans, was analyzed in detail by Pullman-Kellogg Company in a report issued in August 1978. The results of this report indicate that the clay/carbo-chlorination process is more competitive with Bayer-bauxite alumina than any of the six processes in the Bureau's feasibility study reported by Kaiser Engineers. It may also be the cheapest way to make alumina, but clay/carbo-chlorination seems to lack sufficient economic incentives or development assistance to demonstrate this.

Our review of Pullman-Kellogg's cost data suggests a capital cost range of $313 - $875 per annual ton of alumina produced from a 500,000-ton plant. Production costs, based on this range, could be as low as $207 or as high as $415 per annual ton of alumina produced. As subsequent Bayer-bauxite alumina production costs will suggest (p. 84), this might be a promising way to make alumina, but there are too many uncertainties.

Even more economically promising from the standpoint of domestic resource development would be the carbo-chlorination of clays--not to produce alumina, but to produce aluminum chloride. Such technology might then be paired with licensable energy-conserving aluminum chloride technology being developed by Alcoa for the production of aluminum. Together, the carbo-chlorination of clays and aluminum chloride processing suggest the kind of potentially significant savings in new primary aluminum capacity capital equipment and energy costs necessary if domestic nonbauxitic alumina resources are to be developed.

The integration of the Toth clay/carbo-chlorination process and the Alcoa aluminum-chloride process would eliminate a step in each process. This suggests that significant potential capital costs savings might be possible.

Energy-related production cost savings are suggested by Table V-1. These numbers may be somewhat understated. They were taken by Pullman-Kellogg from a 1975 study by Arthur D. Little for the Environmental Protection Agency (EPA) and updated to reflect 2nd Quarter 1978 costs using 6.7 percent per year escalation, a rather low cost escalator. They are illustrative, however, of potential savings that might make further inquiry worthwhile.

Table V-1

Aluminum Production Costs
and Possible Savings Using
Toth Clay Carbo-Chlorination**
(per annual ton of aluminum)

Process	Capital Cost		Cumulative Capital Cost Savings ($ less than Bayer)	Production Cost		Cumulative Production Cost Savings ($ less than Bayer)
Bayer/bauxite-alumina Hall/aluminum	$3280			$1724		
Bayer/bauxite-alumina Alcoa/aluminum	$3070	=	$ 210	$1627	=	$ 97
Toth/Clay-aluminum chloride Alcoa/aluminum	$2220	=	$1,060	$1335	=	$389

*Assumes 20 percent pretax return on investment.

**Cost basis 2nd Quarter, 1978.

Source: Toth Aluminum Company, "Estimated Costs and Projected Savings of TAC Processing Over Conventional Alumina and Aluminum Production Methods", (public briefing document based on Pullman-Kellogg study), September 11, 1978, p. 15.

The primary constraint on clay/carbo-chlorination, like that on other nonbauxitic processes, is that it needs a great deal more development work. Pullman-Kellogg concludes that the clay/carbo-chlorination process for extracting alumina from kaolin clay is chemically feasible, but that additional work is required to quantify many of the engineering process components. Current development of the clay/carbo-chlorination process has only been fully demonstrated at the bench-scale level.

The process research-and-development costs for clay-carbo-chlorination were estimated by Pullman-Kellogg to be between $31 and $62 million through the demonstration plant phase. A Kaiser Engineers representative unofficially concurred in this estimate, favoring the higher end of the range.

This amount is comparable to our estimate of the cost of developing clay/hydrochloric acid, gas-induced crystallization through a pilot plant, cited in chapter 2. 35/

Our analysis of the processes reviewed in the Kaiser feasibility study indicates that they are not commercially feasible now, nor are they likely to impose a significant enough price ceiling on conventional bauxite-alumina prices in the foreseeable future to permit much use as replacement capacity without substantial alteration of market forces. Whether the most likely kind of supply interruption would be substantial enough to employ this technology has never been considered by the Department of Interior. Technical problems encountered with each of the three leading clay/acid, pilot-plant candidates directly affect estimates of process economics. The way in which they are resolved could even alter the competitive positions of these processes. 36/

Clay/hydrochloric acid, gas-induced crystallization

Our analysis of this process suggests that technical problems could add significantly to the operating and capital costs of a commercial-scale plant based on Kaiser Engineers' design.

Conversations with research officials at several major aluminum companies suggested that Kaiser Engineers' estimated operating and capital costs were overly optimistic. Several officials told us that even if the clay/hydrochloric acid, gas-induced crystallization process were operational today, reflecting only conventional unknowns of domestic plant construction, a capital-cost estimate of $700 - $800 per annual ton of alumina using this process in a commercial-scale domestic plant would reflect wishful thinking. Our own capital-cost estimates, reflecting contingency and confidence level

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35/The Toth Aluminum Company claimed that development costs for a plant producing aluminum chloride, rather than alumina, for use in an aluminum chloride reducing aluminum plant should be significantly lower due to capital equipment savings and recovery of titanium by-products.

36/Alcan Aluminum Corporation does not believe the relative position of these processes would be affected by further process research, while Reynolds Aluminum believes that roughly comparable investment in any of the processes could yield results about equal to the Bureau's process. Alcoa implicitly took the Reynolds position in withdrawing from the program.

allowances, ranging from $755 - $1,132 per annual ton of alumina in a 500,000-ton plant, show the cost of this uncertainty. This capital cost range means that production costs in a 500,000-ton plant would probably be no less than $378 per annual ton, and they might be as high as $517.

Bayer-bauxite alumina operating and capital cost comparisons

Bureau officials have provided an operating cost estimate of $139 per ton of alumina for clay/hydrochloric acid, gas-induced crystallization technology. This is about $4 per ton cheaper than our own estimate of the operating cost of alumina from a new Bayer-bauxite plant built in the United States in 1977. Aluminum industry officials considered this result impossible. They said alternative plant investments, considering their magnitude, are reviewed very carefully. There was no chance that this kind of nonbauxitic alumina capacity could have been created for anything like the cost of conventional domestic Bayer plants in 1977.

We estimated operating and capital costs per ton of alumina for 350,000- and 500,000-ton domestic Bayer plants in 1977. Our operating costs were $139 and $143, respectively, while our capital costs were $625 and $572, respectively. The larger plant had higher operating costs and lower capital costs per unit of output. These operating and capital cost estimates resulted in production cost of $301 and $310, per annual ton of capacity, respectively. This is clearly cheaper than the lowest possible production cost of the preferred hydrochloric acid process ($378), and might even be as much as $200 per ton cheaper.

Clay/nitric acid, evaporative crystallization

Our discussion of this process in chapter 3 suggested potential environmental problems too severe to estimate the cost of technical solutions. Nevertheless, using capital cost data provided by Kaiser Engineers from their work on Phase I of the pilot plant feasibility study, and simply allowing for contingency funds and confidence levels discussed in section 5 of appendix I, our capital costs for the process described by Kaiser Engineers ranged from $1,098 to $1,647 per ton of capacity. These estimates did not suggest much commercial payoff from further miniplant examination of this process. 37/ Its production costs could be in excess of $573 per annual ton.

37/Reynolds Aluminum disagreed with our conclusion, largely because they used a different method of cost accounting.

Clay/hydrochloric acid, evaporative crystallization

In chapter 3, we suggested that the process described by Kaiser Engineers could be usefully reexamined. Potentially substantial reductions in operating costs could result from making uniform technical assumptions for both hydrochloric acid processes. Without reference to these possible reductions, and using Kaiser Engineers' Phase I capital-cost data, this process would have capital costs somewhere between $904 - $1,355. Its total production cost would be no lower than around $400 per annual ton. In light of Alcoa's proprietary fluidized-bed calcining modifications of the hydrochloric acid evaporative process, and our own cost analysis of standardized assumptions, we think this process might merit further examination in a miniplant.

Summary of leading nonbauxitic alumina costs

Without prejudice to all other proprietary processes the miniplant and feasibility study excluded from examination, such as those for alunite, anorthosite, and dawsonite, we considered another excluded proprietary process--clay/carbo-chlorination--which suggests promising and potentially important economic implications for the development of domestic nonbauxitic alumina resources, and for domestic aluminum capacity. It is not ready for development in a large pilot plant, but certainly merits further examination to develop additional process information.

Clay/carbo-chlorination should be considered as a potential candidate technology for any future pilot-plant demonstration. While its alumina production costs may not merit development expenses for new domestic refinery capacity, 38/ its potential linkage to Alcoa's cheaper aluminum reduction process through production of aluminum chloride is potentially significant.

Table V-2 shows all of our estimated alumina production cost determinations for a 500,000-ton domestic plant. We consider these cost estimates subject to further refinement, but certainly the best publicly available. 39/ The major

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38/The Toth Aluminum Company disagrees with this statement, but offered no new technical information to refute the inference of inattention from other major aluminum manufacturers.

39/The reader should especially note the caveats expressed in the technical appendix regarding the 37 percent rule and estimates of production costs.

cost ordering of the processes in this manner suggest that only one is cheaper than the Bayer process, but that hydrochloric acid, gas induced crystallization appears to be the most economical of the three leading acid processes Kaiser Engineers described in the feasibility study, since it received all the miniplant funds.

Finally, to understand why no new conventional Bayer bauxite refineries are being built in the United States, when studying Table V-2, the reader should know the mean, intracorporate transfer price of Alcoa's Australian alumina, delivered to the West Coast in 1977, was $120.91 per ton. 40/

Table V-2
Alumina Production Costs Per Annual Ton

Process	Production Costs ($)
Clay/carbo-chlorination	$207
Clay/HCL-gas induced	378
Clay/HCL-evaporative	400
Clay/HNO3-evaporative	573
Bayer-bauxite alumina	310

Source: Clark and Kenney, operating and capital costs (Tables 2, 3, 4, 5) in appendix I.

ENERGY AND NONBAUXITIC ALUMINA RESOURCES' DEVELOPMENT

We reported that nonbauxitic alumina processes desribed in Kaiser Engineers' study were not economically competitive with Bayer-bauxite alumina. Energy and capital cost requirements are the major reasons the production costs for these processes exceeded those of Bayer-bauxite alumina.

Excepting the clay/carbo-chlorination process, we are suggesting not only that future improvements in the energy and capital cost requirements of these nonbauxitic alumina technologies are unlikely to alter the location of new primary aluminum capacity, but that without very significant and unlikely improvements in these processes they will not even be used to replace old alumina refineries, used for existing aluminum smelting capacity. Commitment to these processes

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40/FT 135 Series, Schedule A #5136540, Bureau of the Census.

and process more materials to derive comparable amounts of alumina. This requires more process energy, as well as more capital equipment. Contrary to the Bureau's earlier optimistic assumption about the long-range, upward trend in bauxite prices made before the energy crisis of 1973, the passage of time has widened the cost differential between the Bayer and nonbauxitic alumina processes. In part, this is because more is known about the probable cost of nonbauxitic technologies now, but in large part it is because energy has become more expensive.

The relative direct costs of energy for the nonbauxitic processes are suggested by table V-3. Findings for the processes show the same relative order as those process costs represented by capital and operating expenses. The two are directly related.

Multiple-mineral development

A conspicuous exception to our process energy formulation might be where the alumina is a coproduct of energy production. For example, oil shale deposits are a potential source of alumina. Dawsonite, an aluminum-bearing mineral, was one of the original materials scheduled for miniplant review. Alumina from dawsonite in oil shale would be a coproduct of an energy-producing process. Not only aluminum and shale oil, but soda and nahcolite as well, are potential products of oil shale which might favorably influence domestic energy production. Earlier in chapter 3, however, we said the aluminum company cooperators were not interested in this kind of research.

One oil company claims it can demonstrate the commercial viability of such a multiple-mineral market approach, if it can exchange private for public lands with the Department of Interior. 42/ In addition to the technical feasibility of oil shale development, a number of institutional barriers, such as conflicting Federal leasing and claim policy, and lack of experience, have impeded the progress of a multiple-mineral approach to oil shale.

Capital costs of uncertainty

Huge amounts of capital are required to build a nonbauxitic alumina plant, given present technological uncertainties and resulting contingency funds stemming from the need to recover and conserve valuable process energy. The cost of these uncertainties is added to additional capital and operating costs of recovering energy, and is still another reason that nonbauxitic alumina refineries are unattractive for private lenders and investors.

Size-adjusted capital costs per ton of alumina from new 500,000-ton plants, discussed earlier and drawn from the technical appendix (table V-3 and V-4), are summarized in Table V-4. They show that base estimates suggest a greater gap between the cost of carbo-chlorination and Bayer alumina than between Bayer alumina and the best hydrochloric acid alumina. However, once these data are adjusted for uncertainty, the real capital costs of unknowns become apparent.

42/GAO has reviewed the problems of multiple-minerals development under existing Federal leasing programs in a report entitled: "Legal and Administrative Obstacles to Extracting Other Minerals from Oil Shale" (EMD-79-65), September 5, 1979.

For example, while capital required for Bayer alumina could be $715 per ton in the worst case, that for hydrochloric acid alumina would be around this amount in the best case possible. Similarly, the carbo-chlorination process might require $140 less capital per ton of alumina than the Bayer process, but it might also require $160 more capital per ton than the worst Bayer contingency.

Table V-4

Alumina Plant Capital Costs: Base Case and Contingencies (500,000 TYP Plant, 1977 Dollars)

Process	Base Case Capital Costs $/Annual Ton	Contingent Capital Costs $/Annual Ton
Clay/carbo-chlorination	$429	$ 313 - 875
Bayer-Bauxite alumina	572	429 - 715
Clay/HCL - gas induced	629	755 - 1,132
Clay/HCL - evaporative	753	904 - 1,355
Clay/HNO - evaporative	915	1,098 - 1,647

Other policy options

Other policy options besides research and technology development may be far more effective in reducing the costs of domestic aluminum production using domestic raw materials to compete with off-shore location. These might include energy infrastructure funding, concessionary credits and credit guarantees, certain exemptions from antitrust, tax incentives, and modification of environmental standards. Whether any or some combination of such measures could materially enhance domestic production, and at what costs, is unknown. The Department of Interior has not conducted such studies of benefits and costs.

To date, policies affecting demand for aluminum and energy, such as fuel economy regulations, energy allocations, and price ceilings, have had a very direct impact on prices and investment.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

For about 90 years, aluminum has been produced in much the same way. Bauxite, the conventional aluminum ore, is surface mined and then refined into alumina. Alumina is then reduced in smelters to aluminum. This last stage, reducing alumina to aluminum, is particularly capital and energy intensive.

Large deposits of commercial-grade bauxite are very common in many foreign countries but are rare in the United States, consumer of about 30 percent of the world's aluminium. Plentiful nonbauxitic sources of aluminium in the United States might be developed to help reduce raw material imports and reduce the shift of aluminium production capacity overseas, if successfully addressed by research and development policies. We reviewed the Bureau of Mines' metallurgy R&D program for nonbauxitic aluminium resources to see if it met these needs.

We concluded that the Bureau of Mines nonbauxitic research effort is fundamentally misdirected. First, it has been focusing on alumina production and ignoring the fact that the primary obstacles to the use of domestic aluminous resources are the rapidly rising energy and capital costs of aluminium smelting. Without some means of reducing the capital and energy costs of aluminum manufacturing in the United States, primary metal capacity will continue to shift offshore, eliminating any new demand for alumina. Second, the nonbauxitic alumina processing technology presently preferred by the Bureau is not economically competitive with conventional bauxitic alumina technology and, due especially to escalating energy costs, the competitive gap is steadily widening. Third, the Bureau's program has persisted in trying to develop a nonproprietary technology, disregarding proprietary research of both the Department of Energy and the private sector. As a consequence, the most promising new technologies are receiving inadequate research support.

Contrary to the Department of Interior approach, the Department of Energy supports proprietary aluminum technology research of private aluminum companies as part of its energy-conservation program. Clearly the Bureau of Mines needs to reexamine the benefits of proprietary research in addressing alumina metaullurgy program objectives.

Alumina research: program design and costs

The Bureau's program was originally designed to create a series of 6 miniplants, each one embodying a different nonproprietary, nonbauxitic alumina process, in order to complete a technical information matrix. Based upon this matrix evaluation, a decision was to be reached as to which process alternative was to be tested for full feasibility through a major pilot plant.

The original miniplant program has undergone substantial modification. The actual program expenditures have greatly exceeded the original program cost estimates. A $1.6 million program proposed in 1973 has cost $15 million to date, and another $10 million is proposed for fiscal years 1980-1983 to complete it. This excludes the cost of a pilot plant, which we estimate could be as much as $100 million.

An even greater concern relates to program content. The Bureau of Mines' alumina miniplant research program is now almost exclusively devoted to developing one process, clay/hydrochloric acid, gas-induced crystallization technology, for an alumina pilot plant. Four of the five other materials/processes that were supposed to have been reviewed in miniplants have not as yet been examined. [1] Other potentially promising proprietary alumina and aluminous materials processes were never included in the miniplant program.

Viable strategy needed for aluminum research and development

The metallurgical research task facing the development of nonbauxitic alumina resources should be oriented toward reducing the capital and energy related costs of new primary aluminium capacity in this country. Two proprietary processes, one producing aluminum chloride from kaolin clays and the other reducing aluminum chloride to aluminum, if combined, might offer significant capital and energy costs savings. Publicly available evidence is not conclusive on this point, however, demonstrating the need for further research support of these processes.

Energy costs in the smelting phase are far more critical to the cost of the finished product. For example, alumina

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[1] They are: alunite, anorthosite, dawnsonite, and clay/sulfurous acid. Miniplants for clay/nitric acid, and clay/hydrochloric acid, gas-induced crystallization have been constructed.

requires only about 15 million Btu's per ton to manufacture, compared to 175 million Btu's to smelt one ton of aluminum. Thus, any savings offered by research improvements to gas in domestic alumina refining, even if not offset by much higher capital costs, would probably be too small to affect increased costs of future domestic energy for smelting aluminum with conventional technology.

Anticipated future energy costs are likely to be even more decisive for the location of aluminum production than they are now. The energy cost of aluminum smelting was said to be about 27 percent of the listed price of aluminum in 1978. According to an aluminum company official it could advance to 49 percent of the selling price by the year 2000. Clearly energy, not the location of cheaper alumina from domestic nonbauxitic materials, will influence the location of new aluminum smelters, even as replacement capacity.

Technology improvements must also be analyzed in light of other issues. Growing demands for aluminum from the automotive sector, for example, will create capacity shortfalls and steep price increases. But whether or not these price increases result in new domestic primary aluminum capacity using conventional or nonbauxitic alumina resources, or merely greater aluminum imports from expanding offshore smelting capacity, will depend in large part on technology reducing the capital and energy-related costs sufficiently to match the profitability of foreign locations.

At a minimum, the Bureau's program can no longer ignore proprietary research for (1) the direct reduction of aluminum from smelting constituent ore bodies, (2) the combination of carbo-chlorination and aluminum chloride reduction processes, and (3) the possibility of energy co-production processes resulting from developing nonbauxitic alumina resources in oil shales (dawsonite).

The pilot-plant feasibility and design study sponsored through the Bureau and conducted by Kaiser Engineers, to serve as the basis for process selection and based on miniplant data, was inadequate for the purpose of selecting the best nonbauxitic process. Clay/hydrochloric acid, gas-induced crystallization was not demonstrated to be economically feasible, merely technically possible. The Kaiser Engineers' feasibility study was simply an inadequate vehicle for quantitative, process-cost comparisons without more consideration being given to the processes selected, and to the generation of the necessary technical data in process engineering miniplants. Nor was nearly enough attention given to establishing conventional Bayer-bauxite cost parameters for comparative study.

The Bureau's requirement that process information used in its evaluation be nonproprietary, but that the selection of the best process be based on commercial feasibility, not only determined the outcome of the miniplant program, it substantially precluded the most promising research possibilities in deference to aluminum company cooperation.

Despite the aluminum industry's interest in Government-assisted alumina research, basing such assistance solely on data or other technical information in the public domain puts the Bureau in the curious position of supporting only research on nonproprietary technologies, while ignoring the fact that such technologies are in the public domain because they are believed to be economically unattractive. Contrary to this Department of Interior policy, the Department of Energy (DOE) supports proprietary research of private aluminum companies on aluminum reduction as part of its energy-conservation program. Clearly the Bureau of Mines needs to reexamine the benefits of proprietary research in addressing alumina metallurgy program objectives.

The Department of Interior continues to stress availability issues and concern about U.S. dependence on foreign sources of raw materials as the justification for developing nonbauxitic alumina technology. However, we found a global abundance of identified bauxite reserves, and little indication that the IBA represents a serious threat to raw material supply availability.

Several foreign countries with very large bauxite reserves and potentially abundant energy resources are actively encouraging the development of an integrated aluminum industry. They are using bauxite development, undeveloped energy potential, and private investment incentives, including joint ventures, to achieve this objective.

Given these trends, the proper conceptual focus for nonbauxitic aluminous resources research must be the comparative cost of future primary aluminum production. Relevant nonbauxitic technologies must produce substantially reduced aggregate energy and capital costs for making primary aluminum in the United States. Unless it is economically attractive to make primary aluminum in the United States, we believe there will be no market for nonbauxitic resources. We believe it is unlikely that sufficient economies in future primary-aluminum production can be achieved through improving alumina technology simply because alumina constitutes too small a portion of the cost of making aluminum.

It is in the present and prospective context of future primary aluminum capacity shifting to countries with large bauxite resources and relatively cheap energy, that U.S. aluminum supply-demand and related policies should be assessed. Rapidly growing automotive aluminum demand dictated by fuel economy standards could, by 1985, consume the equivalent of about one-half of the projected primary capacity in the United States. Such consumption could cause both significant aluminum price increases and substantially higher aluminum import levels. By 1985, aluminum imports could be over 1.7 million tons, or equal to about 30 percent of primary aluminum capacity. This demand bulge, occurring globally between 1981 and 1986, could create price levels capable of sustaining capacity increases. Whether or not such capacity is created, who owns it, and where it is located, however, are all major public policy concerns. There is no evidence whatsoever that they are being addressed by Government.

We believe that substantial benefits could accrue from OSTP review and coordination of alumina and aluminum research in the Departments of Energy and Interior. Differing approaches to proprietary information may confound potentially compatible research objectives. OSTP might be able to reconcile these approaches. This would set the stage for consideration of other policy matters. Alumina-aluminum research and development may be a crude tool with which to address future primary aluminum capacity size-and-location issues. It nevertheless could be far more effective than the program presently conceived in the Bureau of Mines.

For example, we reviewed one proprietary clay process --carbo-chlorination--whose alumina might be cheaper than that from a new, conventional Bayer-bauxite plant. But the cost to the private sector of resolving its research unknowns appears unattractive compared to the potential gains of the existing Bayer process at overseas locations. In large part, this may be because even cheaper new alumina plants are not economically attractive until uncertainties about the location of new primary aluminum facilities are resolved.

Similarly, some data suggest that clay/carbo-chlorination offers the potential for very substantial energy-and-capital cost reductions. They seem to merit combining with proprietary aluminum chloride reduction technology being developed for aluminum. Although this combination might produce aluminum chloride from clays more cheaply than alumina from bauxite, and aluminum from aluminum chloride more cheaply than aluminum from alumina, it depends on combining two separate proprietary research efforts. Together, they might use less energy, less capital, and more domestic raw materials. Separately, neither may ever be commercially successful. Attempting to support development of both these proprietary technologies by two different companies, even through two different departments, should not be an insurmountable problem if OSTP does a proper job of coordination. 43/

Whether or not advances in alumina technology can ever be sufficient to materially alter the energy and capital costs of making primary aluminum in the United States, there is no chance that the three, leading, nonproprietary, clay/acid alumina technologies reviewed in the Bureau's feasibility study are likely to accomplish this objective. The Bureau's 5-year-old multimillion dollar research investment provides little basis for optimism about pilot-plant expenditures.

Technology for developing nonbauxitic alumina resources presently suggests some future possibilities requiring a great deal more work. The Bureau did not consider carbo-chlorination of clays in the miniplant program, nor any direct-reduction aluminum technology. Most experts would agree that these approaches offer the kind of potential energy and capital cost savings in aluminum production that would be needed if a market for new, domestic, nonbauxitic alumina resources is to be created. How great these savings would have to be can only be established by carefully examining the costs of conventional technology in other countries, and expected future aluminum prices.

Existing data clearly cannot justify construction of a nonbauxitic alumina pilot-plant. Further research is required for proprietary clay/carbo-chlorination, dawsonite, and alunite processes, as well as supporting direct reduction smelting technologies. The Bureau's miniplant research regimen clearly must also be revised to examine proprietary processes for alunite, anorthosite, and dawsonite. No decision regarding a large-scale pilot or demonstration plant for any of these technologies should be made until a miniplant review of all these processes is completed.

The Department of Interior should take the lead in assembling and publishing pertinent cost data for all potentially viable nonbauxitic production technologies. With

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43/In responding to Department of Interior and Bureau of Mines comments in volume 2, we note that the Bureau may not be precluded from supporting proprietary research. See p. 75 below.

such data in hand, the Government can then consider the larger question of the role of an R&D option in framing national policies which affect the location and cost of primary aluminum production. Certainly the magnitude and potential implications of diminished future U.S. aluminum production capacity deserve serious thought and attention.

RECOMMENDATIONS TO THE CONGRESS

In light of the findings in this report, we recommend that the Congress:

(1) Refuse to consider as premature any requests for pilot-plant appropriations until the Secretary of Interior publishes in summary form the essential comparative economic assessment of all public and proprietary nonbauxitic technology processes.

(2) Direct the Office of Science and Technology Policy to review and coordinate the nonbauxitic alumina and aluminum research programs of the Departments of Energy and Interior, to assure proper coordination and consistent Federal support for the most promising technical options.

RECOMMENTATIONS TO THE SECRETARY OF INTERIOR

We recommend that the Secretary of Interior, through the Director of the Bureau of Mines:

(1) Refocus the Department's alumina and aluminum program metallurgy research to identify development of those technologies (using nonbauxitic ores) which offer promise of substantial energy and capital cost savings in primary aluminum manufacture.

(2) Recalculate the operating and capital costs for each of the six nonbauxitic alumina processes reviewed in the miniplant program and the pilot plant feasibility study using proprietary company data, as well as explicit contingency and uncertainty funding allowances for each process.

(3) Conduct an analysis which specifies and evaluates technical unknowns of proprietary and nonproprietary processes, and estimates the probable capital and operating cost implications for each process, for

the purpose of identifying candidates meriting further research.

(4) Re-examine the economic feasibility of developing alumina from alunite, dawsonite, and clay/carbochlorination, using economic credits from the coproduction of associated materials.

We also recommend that the Secretary of Interior, through the Office of Minerals Policy Research and Analysis:

(5) Prepare a report which analyzes the aluminum industry's capacity shift offshore, and other policy options affecting primary aluminum production. Policy options other than research and technology development might include energy infrastructure funding, concessionary credits and credit guarantees, exemptions from antitrust, tax, and modification of environmental regulations.

RECOMMENDATIONS TO THE DIRECTOR, OFFICE OF SCIENCE AND TECHNOLOGY POLICY

We recommend that the Director of the Office of Science and Technology Policy:

(1) Initiate a review of the alumina/aluminum research objectives and programs of the Departments of Energy and Interior to assure compatibility of objectives and research support, particularly with regard to support of proprietary technologies.

(2) Accept responsibility for a substantial program-design-and-coordination role implementing a joint aluminum research program consistent with the need for developing new primary aluminum reduction technology, should this objective be considered desirable.

CHAPTER 7

SUMMARY COMMENTS ON THE REPORT AND RECOMMENDATIONS

AGENCY AND COMPANY COMMENTS AND OUR RESPONSE

This report raised complicated and controversial technical issues which generated lengthy and often critical responses from the Department of Interior's Bureau of Mines, and five aluminum companies. These technical issues involve fundamental policy decisions and are presented in their entirety for the public record in volume II, together with our full response to the detailed agency comments. We have summarized below the Department of Interior's comments, as well as those of five aluminum companies, and our responses to the major themes of our report.

Bureau processes are not economical

The first theme of our report is that only one of the seven nonbauxitic alumina processes we reviewed, used in combination with an aluminum chloride reduction process, appears to offer significant enough potential energy and capital savings to create new aluminum capacity in this country. This technology was not part of the Bureau's program. None of the six nonproprietary alumina processes the Bureau reviewed appear to be even economically competitive with conventional alumina, much less suggest savings sufficient to create new U.S. domestic aluminum capacity. No Federal agency and only one of five aluminum companies disagreed with this finding.

Bureau research objective is wrong

Second, the new miniplant research objective was fundamentally misdirected because it (a) focused on alumina, rather than aluminum, and (b) ignored promising proprietary processes in favor of developing a public technology. Although neither Federal agencies commenting on our report nor aluminum companies publicly agreed with our characterization of the Bureau's research program as "fundamentally misdirected," their opinions were almost evenly divided on each of the specific points supporting this conclusion, as follows:

Proprietary-nonproprietary processes

All but one of the five aluminum companies agreed there were more economical proprietary processes than the nonproprietary process the Bureau proposes for pilot-plant development. The Department of Interior's response suggests that the Bureau cannot support potentially patentable information without assignment of all private interests to the Government. We understand that the Department is subject to the patent provisions of the Federal procurement regulations (FPR 1-9.107), and that under those regulations the Government usually takes ownership to the rights to any invention made under research contracts aiming to commercialize a product or process.

However, the above provisions also allow the head of an agency or department, in exceptional circumstances, to certify that the public interest is served by permitting the contractor to retain exclusive rights in such an invention (FPR 1-9.107 3(a)). The Bureau's policy with respect to cooperative arrangements parallels the FPR patent provisions. Normally, any invention made by a private firm's employee would belong to the Government. However, in exceptional cases, the Bureau also can provide a private party with exclusive rights to such an invention.

The Solicitor's Office of the Department of Interior has informally confirmed our understanding of Interior's policies concerning patentable inventions.

Alumina-aluminum research emphasis

Two aluminum companies agreed that research should focus on the capital and energy saving potential of aluminum reduction technologies, and two did not. The Department of Interior said it was conducting such research, but not as part of the miniplant program.

The Bureau's research support for aluminum reduction technologies has been both limited and recent. The Bureau did not pursue the chloride reduction process. Its work on clay/carbo-chlorination was discontinued in 1975, despite an aluminum company's effort to refute all of the Bureau's technical objections to the process in early 1976. This work was not re-authorized by the Bureau until the fall of 1978. The Bureau has not supported research on direct reduction smelting technologies for aluminum-containing ores. It contracted for an examination of dawsonite extraction from oil shales, despite the materials inclusion in the original miniplant program, only after our review was completed, five years after the fact. In addition, there has been a consistent refusal to support proprietary nonbauxitic aluminum research which encompasses the most promising and advanced processes.

In light of these facts, we did not find adequate the Department's claim that aluminum research was being pursued elsewhere in the Bureau.

Regarding the benefits of alumina research, four of the five responding aluminum companies disagreed with our contention that because nonbauxitic alumina did not appear to be economically competitive with Bayer bauxite alumina, its potential for developing domestic nonbauxitic resources was limited. One, Alcoa, agreed with us. The Department of Interior's response on this point relied, in part, on the national security justification for focusing on alternative domestic alumina supplies, and, in part, on the previously discussed assertion that the Department could not support proprietary research.

All of the aluminum companies who disagreed with us on this point emphasized the importance of local alumina for extending the productive life of domestic aluminum smelters. However, these companies actually emphasized two different kinds of interest in domestic alumina. Three companies believed nonbauxitic alumina could be developed as cheaply as new <u>domestic</u> Bayer alumina capacity, although they concede that such new, conventional alumina capacity is not economically competitive with overseas locations at present.

One of these three companies suggested that its own proprietary process could make nonbauxitic alumina more cheaply than new overseas Bayer capacity. It argued such technology could replace alumina imports.

Another of the three companies, joined by a fourth company, argued that such technology should be developed because future bauxite and alumina prices were vulnerable to supply interruptions and simply not predictable. Because six million tons of North American aluminum smelting capacity is dependent on alumina, both these companies believed potential replacement technologies using domestic ores, even if more costly, were a worthwhile investment. Both of these companies invested liberally in such technologies in the past without conspicuous success.

Bureau research does not address real problems

The third theme of our report cites (a) the greatly increased projected demand for aluminum and (b) the likely absence of future price escalations of imported bauxite and alumina, together with (c) the creation of new primary aluminum capacity by U.S. companies off-shore, as the real problems demanding a re-ordering the Bureau's nonbauxitic resource research priorities.

No Federal agency or company denied that new, U.S. owned, aluminum capacity was being created off-shore.

One of the aluminum companies also said our projected automotive aluminum demand was overstated, although the Department of Interior did not comment on this. The company argued that automotive requirements in 1988 would be equivalent to about 30 percent of the future U.S. primary aluminum capacity. Since automotive use in 1977 was only the equivalent of 14 percent of then-existing capacity, even these figures suggest considerable tightening of demand. Our report suggests a range that could go over 50 percent of capacity equivalent for automotive use.

The Department of Interior and three of the five aluminum companies contested the second of these three findings, stating that long-term bauxite and alumina prices were not entirely predictable.

Admittedly nothing about the future of bauxite supplies is fully certain. Nevertheless, the real cost of bauxite has declined since 1975. Jamaica has recently negotiated its bauxite levees downward to increase production and foreign exchange earnings, while bauxite and alumina capacity has been greatly expanded elsewhere. Meanwhile energy prices, detrimental to the more energy-intensive nonbauxitic processes, continue to increase. In the absence of overt political collapse in a major bauxite or alumina supplying country, or shipping interruptions, we concluded real prices would remain stable as future demand increased.

Miniplant research objective changed

Fourth, in 1975-76 the Bureau of Mines changed its miniplant research objective from creating a technical information matrix for 6 nonproprietary, nonbauxitic processes to developing a specific, nonproprietary technology and its associated pilot-plant design. On this point there was general agreement with our report. However, while not really contesting this point--the Department of Interior claimed we unfairly criticized the Bureau for carrying out the policy of other agencies--the Department later said it had not abandoned the information matrix approach. One aluminum company responded to this point by saying the objective was not so much changed as suffused in a new awareness of what adequate research to modify each of these non-proprietary processes, in order to conserve energy, would cost.

According to two aluminum companies, it simply costs too much money to develop all these nonproprietary technologies to the point where they appear economically competitive. One company said it was silly to spend comparable amounts of money trying to develop the other 5 nonproprietary processes to the same degree as the preferred one.

The real issue is what processes the Bureau should have been examining _after_ its research objective changed, and a decision made to develop a nonbauxitic alumina technology, rather than an information matrix. Its refusal to alter the program's commitment to nonproprietary--and uneconomic--nonbauxitic alumina technologies or focus on aluminum reduction entails a lost opportunity to develop domestic aluminum resources.

Pilot-plant funding premature

The fifth theme of our report was that in light of the above problems, selection and funding of a nonproprietary demonstration pilot plant for nonbauxitic alumina was premature. All promising alumina and aluminum proprietary and nonproprietary processes using domestic resources must be first adequately reviewed by the Bureau of Mines.

The Department of Interior defended its program emphasis by saying it was precluded by internal and national security policy considerations (cited earlier) from examining either proprietary processes, or using economic criteria for selecting the best nonbauxitic technology for a pilot plant. No decision would be made until miniplant work was completed.

Aside from the millions already spent in pursuit of a nonproprietary nonbauxitic alumina pilot plant technology, the Government stands at the threshold of incurring very large expenditures--almost an order of magnitude higher--in pursuit of the Bureau's research objective. In light of the findings of this report, we believe further appropriations for development of the presently preferred technology in a pilot plant is grossly premature.

We must face the dilemma of either abandoning this past investment, or continuing to finance the development of a nonproprietary process offering only nominal benefits to the Nation, and which forecloses other potentially significant proprietary process options.

AGENCY RESPONSE TO OUR RECOMMENDATIONS

Department of Interior

(1) The Department said the proprietary data necessary to recalculate the operating and capital costs of the six nonbauxitic alumina processes the Bureau reviewed in the feasibility study, as we recommended, would not be available to the Bureau of Mines.

We do not understand why the Department of Interior could not have obtained proprietary process information to conduct such a comparison under a pledge of confidentiality. If this approach were rejected, the Department still could consider supporting proprietary research in exceptional cases. In such situations a private party to a joint venture agreement or research contract might receive an exclusive right to any invention made as an inducement for his participation in the activity.

(2) The Department said the miniplant steering committee's technical audit committee is already evaluating and specifying the cost implications of technical unknowns for the nonproprietary processes reviewed by the Bureau, as GAO recommended.

We believe this was done for only one nonbauxitic alumina process, and that the technical audit committee has not and will not function in the way we recommended. Moreover, there was no publication of its findings and their implications for the cost estimates of the preferred process as we recommended.

(3) The Department said it opposed our recommendation to shift research emphasis from alumina to aluminum until after the Bureau completed the miniplant program.

Our report indicates the miniplant program will not only remain incomplete under the Bureau's proposed funding until the end of fiscal year 1983, but that it will continue to pursue economically unpromising nonproprietary alumina processes. By that time, primary aluminum imports will already significantly exceed domestic supply and an effective remedial research program will still not have been implemented.

(4) Finally, the Department does not believe the proprietary data necessary to reexamine the economic feasibility of alumina from alunite, dawsonite, and the carbo-chlorination of clays as coproducts would be forthcoming under the existing cooperative miniplant program, precluding our recommendation regarding coproduct impacts on process economics.

Frankly, under the existing program, neither do we. One aluminum company said even proprietary data would not have had much effect on the costs of the six processes the industry cooperators agreed to review in the Bureau's miniplant program. Four companies said they doubted proprietary process data would ever be provided by aluminum companies for review in the industry-Bureau miniplant program. And all the aluminum companies endorsed re-examining the Department's programmatic approach to supporting proprietary alumina and aluminum research.

We can only assume the Department's response is predicated on a desire not to ask for such data in order to maintain the cooperator program on a nonproprietary basis. The Bureau has the option of either redesigning the program to consider proprietary processes or getting such information outside the program through requests to firms. If the Bureau indicated a serious interest in studying, and possibly supporting, such processes, we believe the necessary information from firms could be made available through a Bureau pledge of confidentiality.

(5) The Department agreed with our recommendation for an analysis of policy options affecting domestic aluminum availability.

Office of Science and Technology Policy

The Office of Science and Technology Policy (OSTP) objected to our recommendation that it review and coordinate a special program dealing with alumina-aluminum R&D responsibilities between the Departments of Energy and Interior. The OSTP felt that the normal budget review cycle, rather than any special review, was the proper forum to deal with these issues.

We believe Bureau-level budget review will fail to coordinate the alumina-related, raw materials supply research of the Department of Interior with the aluminum-related energy conservation research efforts of the Department of Energy. It will not adequately expose incompatible approaches to proprietary research on an integrated industrial process, nor potentially conflicting major policy options confronting the two Departments. An OSTP review is the best way to focus higher level decisionmakers' attention on the consequences of incompatible research objectives.

Department of Energy

The Department of Energy had no comments on our recommendations.

AN ANALYSIS OF THE COMPETITIVE POSITION OF ALTERNATIVE PROCESSES FOR CONVERTING DOMESTIC ALUMINUM BEARING RESOURCES TO ALUMINA

BY

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Final Report

to the

United States General Accounting Office

The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies of the United States General Accounting Office or the United States Government.

January 23, 1979

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1. INTRODUCTION

At the present time, 90 percent of the primary aluminum produced in the United States is based on imported bauxite or alumina. Although international bauxite reserves are adequate to supply the world's needs for the next 200 years at current rates of consumption, there is some doubt concerning the continued availability of adequate bauxite supplies to the United States at current prices. This is partly due to increased competition with other industrialized nations for available resources, which are generally of declining grade and/or are becoming more expensive to recover because of requirements for infrastructure and transportation systems. Another factor which may influence bauxite prices is the International Bauxite Association (IBA), which controls 90 percent of the U.S. supply. Since 1970, some IBA countries--principally Jamaica--have increased the price of U.S. bauxite imports by imposing nearly 700 percent higher levies on their bauxite exports.

Since increased bauxite prices (1) add to our balance of payments deficit, (2) potentially adversely affect the competitive position of U.S. producers in the international marketplace, and (3) the threat of a supply interruption has defense-related implications, some think that it is important for the United States to develop an economically competitive process or processes for the production of aluminum from domestically available raw materials. This report is an analysis of the economic viability of alternative processes for producing alumina from domestic raw materials. The relative economic ranking of the alternative processes is first considered followed by an assessment of the potential competitive position of the most promising processes with new Bayer bauxite plants.

2. REVIEW OF RECENT PUBLICATIONS

There is no shortage of proposed alumina extraction processes utilizing domestic raw materials. The Bureau of Mines has published 20 cost evaluations of these processes between 1962 and 1974. Because of the increasing interest in advancing the technology for producing alumina from domestic raw materials, revisions of previous cost estimates and calculations of cost estimates for recently proposed processes have been reported every year since 1974. These reports, prepared by various research groups and individuals, have been unable to reach a consensus as to which proposed process is the most efficient or economically viable.

The reason for the differing cost estimates of the various processes for converting domestic raw materials to alumina can be mainly attributed to (1) non-uniform assumptions regarding the processing operations and (2) different accounting procedures for determining capital, operating and total costs. For instance, in some reports coal was assumed to be the primary energy source for a particular operation, while in other studies oil was assumed to be used for the same operation.

Comparison of alternative processes is further complicated when various reports use different criteria for calculating production costs. For instance, some reports include a specific pollution control cost while others do not; some include a charge for replacement costs, others do not; and all reports generally use different criteria for return on investment charges as well as location and size of the plant.

Of all the published reports on alternative alumina extraction processes considered, only one evaluated the sensitivity of capital and operating costs to the effect of ore quality variations. All of the other reports were based on the assumed availability of a homogeneous ore supply. An analysis of typical Georgian clays indicates that: (1) the alumina content of Georgian clay can range from 36.5% down to 29.2% on a dry clay basis, (2) the clay iron content could range from 0.86% up to 1.72%, and (3) the amount of other impurities (Ca, Mg, Na, K, and Ti salts) could range up to double the assumed level of 2.7%. The reduction in clay alumina is assumed to increase the clay silica content and subsequently increase the amount of clay and residue which must be processed. The higher iron content will require additional processing equipment for some processes which translates into increased capital and operating costs. The effect of higher levels of other impurities will mean a range of higher capital and operating costs for the various clay based processes. Kaiser Engineers report that the effect of the above variations on capital and operating costs is greater for the nitric acid process than the hydrochloric acid sparging process. Since this one comparison of only two processes is the only data available concerning the effect of clay quality variations, this factor will not be dealt with further but should not be overlooked in future quantitative studies.

In order to make the reported operating cost estimates of the various studies more comparable, the results have been adjusted where possible to reflect more uniform assumptions. The recalculated results of these studies are summarized in Table 1, which also shows the assumptions upon which these calculations are based. Tables A1-A6 of the appendix (pp. 122-127) show the changes which were made to the original date for the purpose of comparability.

Bureau of Mines

The first of these reports was prepared by the Bureau of Mines 1/ in 1974 as part of an ongoing procedure to revise and update previous Bureau alumina evaluations and to add new or modified processes not included in the original alumina series. The Bureau of Mines evaluations prepared since 1974 are updated versions of the original 1974 report. The more recent reports recalculate raw material prices, and electric power and labor rates based on 1973 values. Some changes are also made in requirements for facilities and in materials balances. The capital cost estimates presented by the Bureau of Mines are based on flowsheets and a minimum of equipment data. These estimates can be expected to be within ±30 percent of the actual costs. However, each process is evaluated by the same method, which facilitates comparison of the processes. The same argument holds for comparing the operating costs of the individual processes, although in this case the confidence limits were not specified.

The results reported by the Bureau of Mines in 1974 that are relevant to this investigation are summarized in Table 1.* These estimates are based on a 350,000 ton per year alumina facility located within trucking distance of its major ore deposit. Natural gas is assumed as the major energy source, and raw material, utility, and direct labor costs are assumed identical for each process. No geographical advantage or disadvantage is assigned to these greenfield facilities. The Bayer process is shown to be the most economical followed by the nitric acid-ion exchange, anorthosite lime-soda sinter, and hydrochloric acid-ion exchange processes in roughly that order.

Commodities Research Unit

The Commodities Research Unit Limited completed a report for the Overseas Private Investment Corporation in 1974 entitled "The Economic Effects of An Increase in Jamaican Bauxite and Alumina Export Taxes and Royalties On the Aluminum Industry." Estimates of production costs of alumina

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*The data reported in Table 1 are recalculated values of original Bureau of Mines estimates.

Table 1

Reported Operating and Capital Cost Estimates

($/AT Al_2O_3)

A--operating cost B--capital investment

Report	Bayer Bauxite		HNO_3		H_2SO_4		HCL Evaporation		HCL Sparge		Alunite		Anorthosite		Carbo-Chlorination	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
BOM (1973) 350,000 TPA	189	257	294	305	366	508	323	412	-	-	-	-	266	262	-	-
CRU (1973)	252	418	295	482	-	-	-	-	-	-	-	-	-	-	-	-
EPA (1975) 700,000 TPA	253	448	336	515	-	-	443	687	-	-	-	-	-	-	246	372
Pindyck (1976) 350,000 TPA	188	267	-	-	-	-	302	413	-	-	-	-	234	262	-	-
Kaiser (1977) Engineers 500,000 TPA	-	-	504	915	533	1138	406	753	331	629	516	928	514	992	-	-
Pullman Kellogg (1978) 750,000 TPA	277	451	-	-	-	-	-	-	-	-	-	-	-	-	226	365

Note: All costs are in 1977 dollars. Operating costs include estimates of Depreciation (5% of C.I.), Taxes and Insurance (2% of C.I.), and Return on Investment (20% of C.I. for Bayer Bauxite and 30% of C.I. for all others).

from the report are also summarized in Table 1. 2/ These estimates are for an optimal size greenfield facility for each process and include a capital or debt services charge in the operating cost. The nitric acid evaluation also includes the cost of a nitric acid plant.

While the nitric acid estimate represents 1974 values, the values reported for the Bayer process represent fourth quarter 1973 prices and do not reflect the effect of the subsequent increase in oil prices or the Jamaican tax measures, therefore underestimating current bauxite costs. CRU concluded that, given inflationary increases between 1973 and 1974 of 25 percent on capital costs, 12.5 percent on operating costs, and 100 percent on energy costs, there can be little difference in the economics of bauxite and clay processes. Taking the 1974 Jamaican taxes into account places clays in a competitive position with new bauxite plants, according to CRU.

Environmental Protection Agency

The results of the report prepared by Arthur D. Little, (ADL) for the U.S. Environmental Protection Agency on the alumina/aluminum industry in 1975 are also presented in Table 1. Operating and capital costs for greenfield nitric, hydrochloric acid leaching and carbo-chlorination processes are compared with a greenfield Bayer facility of equal capacity. A 20-percent pretax return on investment and a pollution control cost estimate are included in the operating cost estimate for each process. The 700,000 TPY Bayer facility evaluation was for a Texas location while both acid leaching processes were assumed to have been located in Georgia.

Some of the assumptions of the EPA report appear to be inconsistent. For instance, the EPA report assumes coal to be the major source of energy for the nitric acid process, while specifying oil or natural gas as the main energy source for both the Bayer and HCl processes. The energy requirement of the HCl process is also specified as being approximately 39.2 million BTU/ton of alumina versus 20.9 million BTU, as specified in the Kaiser Engineers' feasibility study. Substituting the coal and oil specifications of the Kaiser Engineers' study and using the coal and oil prices specified by the EPA report reduces the production cost estimate for the HCl process from $326 to $275.

The EPA study pointed out that two of the processes which were considered in their report were tested in pilot-plant operations. During the late 1960s, a non-integrated, pilot-plant operation of the nitric acid process was carried out by Arthur D. Little, Inc. Based on the chemical analysis and physical properties of the alumina produced, it was considered by an aluminum producer to be of adequate quality for use as pot feed for the Hall Heroult process cells. The Anaconda Company, during the late 1950s and early 1960s, operated a large-scale, pilot-plant operation using a hydrochloric acid leaching process. The alumina produced by this facility was actually converted to aluminum in an Anaconda aluminum smelter.

Robert S. Pindyck

In 1976, Professor R. S. Pindyck of the Massachusetts Institute of Technology reported on cartel bauxite pricing and considered alternative alumina production processes. 4/ The demand for bauxite was examined with special emphasis on (1) the evaluation of the critical price at which alternatives to bauxite become economically viable, and (2) the dependence of this price on world energy prices. Up to this critical price, the demand for bauxite remains highly inelastic. This factor allows a cartel such as the IBA to increase the price of its produce and enjoy large monopoly rents. Should the price of bauxite rise above this critical price level, the demand for bauxite would become essentially infinitely elastic in the long run, thus implying the economic advantage of alternative alumina production processes.

Pindyck's report updates the 1973 Bureau of Mines report to reflect 1976 prices. The hydrochloric acid-ion exchange process is reported as the most economical of the alternative processes over a wide range of factor input costs. The nitric acid-ion exchange process is mentioned as being close to this in cost followed by the lime-soda sinter anorthosite process. These cost estimates are compared with the Bayer process and are also presented in Figure 1.

The production of alumina from clay and anorthosite is much more energy-intensive than its production from bauxite. Since energy prices rose considerably between 1973 and 1976, Pindyck reports that the critical price at which alternatives to bauxite are economically viable increased greatly. Pindyck also assumes that the various alumina production processes have natural gas as their primary energy source. The wholesale industrial price of natural gas doubled between 1973 and 1976. Since energy requirements represent a major operating cost factor in all of the alumina production process, the economic sensitivity of each process will therefore be directly related to natural gas prices. The use of an alternative energy source, such as coal, would result in a substantial shift in the critical bauxite price calculated by Pindyck for the various market scenarios.

Kaiser Engineers

Kaiser Engineers completed a study of six alternative non-bauxite processes for the Bureau of Mines in February of 1978. The basic assumption of this study is that a 500,000 ton per year greenfield facility is assigned no geographical advantage other than being within 5 miles of the ore deposit. The resultant capital and operating cost estimates for 1977 are included in Table 1. The reported operating costs do not include charges for capital depreciation or return on investment. The inclusion of these factors--as has been done with the figures reported in Table 1--does not alter the competitive positions of the alternative processes. However, these factors do significantly increase the operating cost estimates for each process. For example, inclusion of a capital depreciation rate of 5 percent and a pretax return on investment of 30 percent of capital investment more than doubles the operating cost estimate for each process considered.

The operating cost summary prepared by Kaiser Engineers for Task I of the feasibility study assumes that oil is used to supply the heat for clay calcination. Switching to coal fired, fluid bed clay calciners, as specified in Task II, results in an operating cost savings of $5 to $6 per ton of alumina produced by the nitric and both the hydrochloric acid sparging and evaporative processes. For the sulfurous acid process the savings would be $6 to $7 per ton of product alumina. However, these savings do not result in any change in the economic ranking of the six processes.

The Kaiser Engineers ranking of the economic competitive positions of the alternative alumina processes is well documented with respect to operating and capital costs estimation. The estimates were prepared for purposes of comparison to identify the most promising process for future development. Based on heat and mass balances and equipment costing and sizing calculations, these values reflect reasonable comparative estimates of the cost of alumina production for the specified processes.

Pullman Kellogg

Pullman Kellogg 6/ completed a study of the "Toth Alumina Process" for carbo-chlorination of clays in August of 1978. The capital and operating cost estimates for the carbo-chlorination process and the Bayer process are included in Table 1. These estimates are for a 750,000 ton per year greenfield facility located in the Georgian kaolin belt. Complete offsite, powerplant, water system, and railroad facilities are included in these estimates. The cost estimates are assumed to have an accuracy of approximately ±20 percent based on domestic (Macon, Georgia) second quarter 1978 costs.

The cost estimates do not include an allowance for site preparation, land costs, or offices, warehouses, and maintenance shops. The operating cost estimate includes cost of capital and depreciation charges as a function of fixed capital costs. The fixed capital costs include subcontracts, engineering fees, field construction, freight, and insurances. Charges for sales and use taxes, licensing, and start up costs are not included.

3. EVALUATION OF NON-BAUXITIC ALUMINA PRODUCTION PROCESSES

In this section the six non-bauxitic alumina production processes evaluated by Kaiser engineers and the carbo-chlorination (Toth) process, as evaluated by Pullman Kellogg, are analyzed. First, a short discussion of the technology of each process is presented, followed by an evaluation of potential problem areas and the effects of critical uncertainties on the projected operating and capital cost estimates of each process.

The comparison of the six processes included in the Kaiser Engineers feasibility study is based on information obtained from the literature, some test work done by Kaiser Engineers, Kaiser Engineers' experience with alumina plants where applicable, and information developed by the Bureau of Mines in their mini-plant runs and elsewhere. The six process descriptions presented by Kaiser Engineers do not necessarily represent processes that have been evaluated up to the bench-test level. They do represent six processes from which it is highly probable that pot feed quality alumina can be produced.

Each of the six processes represents the current level of development as perceived by Kaiser Engineers based on the above mentioned information. As such, some of the process components may represent recent developments which have not been adequately tested to assure reliable performance. Since the operating and capital cost estimates are based on these perceived processes, they may represent only a "best case" estimate.

The analysis of the carbo-chlorination process presented in the Pullman Kellogg report is based on information obtained from the Toth Aluminum Corporation in the form of a report containing process and equipment design calculations, process block diagrams, cost estimates, and bench scale experimental data. In reviewing the process based on this information, Pullman Kellogg introduced modifications and assumptions wherever necessary.

The Pullman Kellogg report concludes that while the carbo-chlorination process for extracting alumina from kaolin is chemically feasible, additional work is required to quantify many of the mechanical process components. This is primarily due to the current level of development of the carbo-chlorination process at the bench scale stage.

3.1 Hydrochloric Acid Sparging Process

Technological Discussion

The detailed description presented by Kaiser Engineers of the alumina from clay via hydrochloric acid-extraction, hydrochloric gas-induced crystallization process is actually a composite of several older processes designed specifically to handle high quality domestic clays. As designed, this process is the most energy efficient of the six alternatives considered. This is attributed to the ease with which the motor liquor remaining after crystallization can be prepared for reuse as leach acid without distillation. Other factors include the formation of a hexahydrate rather than higher hydrate aluminum chloride crystals and the initial production of a somewhat more concentrated leach liquor using 25 to 27 percent acid. The hydrochloric acid sparging process also assumes the use of coal as the primary energy source with only small amounts of clear fuel being required. The small amount of clean fuel is needed for the thermal decomposition of the aluminum chloride hexahydrate ($AlCl_3 . 6 H_2O$) crystals, since the final stage of the process requires direct firing.

Detailed descriptions of the six individual processes will not be presented here, since they are well documented in the feasibility study prepared by Kaiser Engineers.

Potential Problem Areas

The major potential problem areas of the hydrochloric acid sparging process are discussed by Kaiser Engineers in both feasibility studies. These and other potential problem areas are identified and discussed in the following analysis.

Potentially, the most difficult of these problems * is the endothermic thermal decomposition of the $AlCl_3 . 6 H_2O$ crystals to alumina. The economic operation of the hydrochloric acid sparging process requires the production of a relatively pure hydrochloric gas by partial condensation of the HCl/H_2O vapor produced by the decomposer. This would be very difficult if the decomposer gases were diluted with combustion products. Therefore, the thermal decomposition step is specified as being carried to 90 percent completion using indirect heat. It is this indirect firing of the decomposer, with its attendant technical difficulties and costs of providing a suitable heat transfer surface in the bed, that creates a problem. No such equipment suitable for the decomposition of $AlCl_3 . 6 H_2O$ is currently commercially available.

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*Discussed by Kaiser Engineers in Phase I (pp. 4-3-4 and 4-3-9) and Phase II (pp. 4-2-14 and 4-2-15).

Information required for the engineering design of an indirectly fired decomposer must be developed before the design of a demonstration plant can be completed.

The second major problem * associated with the hydrochloric acid sparging process is the optimization of production conditions with respect to tradeoffs between allowable impurity concentrations and bleed stream processing costs, percent recovery of product, and optimum production rate based on operating conditions. The solution to these and related problems is the essence of process optimization and is essential to the proper sizing and costing of processing equipment in capital cost calculations.

Kaiser Engineers has estimated the hydrochloric acid makeup requirement to be 190 pounds/ton of alumina. This appears to be somewhat optimistic, since clay feed impurities alone may account for 25 percent of this loss. The clay feed, on a dry basis, contains 0.082 percent magnesium oxide and 0.042 percent calcium oxide, both of which may consume hydrochloric acid to form very stable chlorides. Recovery of this chloride value would be very difficult at any reasonable temperature. If the total magnesium and calcium content of the clay feed were to form chlorides, up to 47 pounds of 31.5 percent hydrochloric acid would be consumed per ton of alumina produced. **

There is some question as to the efficiency of HCl gas-induced crystallization. The solubilities of calcium and magnesium chlorides are depressed by the addition of HCl to the liquor while other metallic chlorides tend to increase in solubility. Insufficient data exist to explain the solubility relationships of the complex liquors involved. Also, very little quantitative data is available concerning acceptable concentration levels of various impurity metal chlorides in the mother liquor entering the crystallizer. Such data are necessary for the efficient operation of the crystallizers and the production of acceptable quality crystals. The crystallizer unit has, however, been operated successfully on a small pilot scale as part of the miniplant program.

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*Discussed by Kaiser Engineers in Phase II (pp. 4-2-4).

**The 47 pounds of hydrochloric acid represents 25% of the estimated total HCl makeup requirement. These numbers serve to underscore the possibility that the makeup requirement may have been underestimated by Kaiser Engineers.

According to Kaiser Engineers' Table 2-1 Task II, the energy requirement for the HCl acid sparging process is 20.9 million BTU/ton of alumina produced. This assumes the employment of fluidized solids techniques for clay calcination and indirect firing of the thermal decomposition process as discussed earlier. The major problem concerning the use of fluid-bed clay calciners is whether the physical properties of the clay will result in the generation of excessive amounts of fines with an attendant uncertain degree of calcination. The fluid-bed clay calciner offers an energy savings of 0.63 million BTU/ton of alumina as well as other positive features. However, the process will require further testing to substantiate its effectiveness.

The Economic Sensitivity of Potential Problems

The potential problem areas discussed in the preceding section will each have an effect on the economics of the process. The extent of this influence could alter the competitive positions of the processes. Therefore, it is very important to identify these potential problem areas--some of which are the result of unsubstantiated assumptions--and to examine the possible economic impact of changes in critical uncertainties.

For example, if the indirect-fired thermal decomposition process were unable to be operated as efficiently as specified in the feasibility study, it would have a significant effect on the process economics. As specified, the indirect-fired decomposition unit supplies 2,149 tons of HCl acid to the system. If the indirect fired decomposition process is carried to only 80 percent of completion, 10 percent of the recycled HCl acid would be lost. * This HCl acid loss would add .215 tons to the HCl acid makeup requirement per ton of alumina produced, resulting in an addition to the operating cost estimate of approximately $20. If additional HCl acid were recovered from the 20-percent direct-fired portion of the process, a portion of this additional $20

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* It should be noted that indirect-fired decomposition and the production of HCl for recycling are directly related as seen by the following reaction:

$$2Al_2Cl_3 \,.\, 6H_2O \quad Al_2O_3 + 6HCl \quad + 9H_2O \,.$$

The indirect-fired decomposition of $2Al_2Cl_3 \,.\, 6H_2O$ generates HCl/H2O free of combustion products. The HCl/H_2O can then be easily handled to produce recycled HCl acid. If the above reaction could be carried to only 80 percent, rather than 90 percent, completion by the indirect-fired process, it is assumed that a corresponding loss of recycled HCl would result.

cost may be saved. Based on the current level of development of this indirect-fired thermal decomposition unit, careful consideration must be given to the stated assumptions because of the sensitivity to the operating cost estimate.

The second major technical problem associated with the HCl acid sparging process involves the optimization of the production process with respect to operating condition tradeoffs. It is only after the process has been optimized and the process flows established, that accurate sizing and costing of the equipment can be accomplished. The final selection of the materials of construction is also dependent on the final, optimal processing conditions. In conversations with Reynolds Metals Company, these and other concerns about the ability of certain process steps to perform as assumed were raised. According to spokesmen for Reynolds, these factors could affect the capital cost requirements by as much as 10 percent, adding as much as $60/annual ton.

The HCl acid make-up requirements, as outlined in the previous section, could also affect the operating cost estimate. The 47 pounds of HCl acid assumed to be consumed by magnesium and calcium components of the ore represent an additional operating cost of only about $0.70/ton of alumina. If the 190 pound HCl acid make-up requirement were to be overly optimistic, it could represent an error of a few percent in the operating cost estimate. For instance, doubling the HCl acid make-up requirement would add approximately $3 to the operating cost.

Concern over the accuracy of the specified crystallizer efficiency has also been expressed by Reynolds Metals Co. Sufficient process steps to guarantee the purity of the product may not have been specified. The addition of extra process steps could become necessary if the unit is unable to perform as assumed. This additional equipment would have a small but measureable effect on both the total capital and operating cost estimates.

With respect to energy costs, the fluid-bed clay calcination unit conserves 0.63 million BTU/ton of alumina which represents $0.75 in coal costs. Therefore, the use of the fluid-bed clay calciner, while it may offer other advantages, has only a minimal effect on the energy economics.

On the other hand, if the indirect-direct thermal decomposition unit can operate only up to 80 percent of completion, the added energy costs could be significant. Under the original assumption that the indirect-fired thermal decomposition unit operates up to 90 percent of completion, the final 10 percent of the thermal decomposition in the direct-fired decomposition unit accounts for 28 percent of the total decomposition energy requirement. This is due to the high operating temperature (1800 F) of the final stage and the corresponding heat content of the existing streams. If the original assumption is off by 10 percent and the thermal decomposition process can be carried to only 80 percent completion in the indirect-fired unit, an additional 10 percent of the thermal decomposition process will have to be performed by the direct-fired process. If it is assumed that this additional 10 percent of direct-fired thermal decomposition requires only half of the energy required by the original 10 percent of direct-fired thermal decomposition (due to the decreasing temperature requirement), or 2.0 million BTU/ton of alumina produced, the additional operating cost due to the extra fuel requirement will be nearly $2. This sensitivity of the operating cost to the indirect-fired thermal decomposition operating efficiency assumptions warrants close examination.

Many of the process steps described in the HCl acid sparging process description specifically state the need for additional information and data to optimize either the overall system or a specific process component. Such research and development efforts will necessitate additional capital expenditures which may be difficult to estimate accurately. These costs must also be reflected in the capital cost estimate for the process and will probably be significant.

The demonstrated economic sensitivity of the basic process assumptions clearly illustrates the importance of identifying and quantifying their effects. Only with this information can the accuracy of the capital and operating cost estimate be clearly stated and expressed in terms of possible contingencies.

3.2 Nitric Acid Extraction Process

Technical Discussion

The detailed description of the nitric acid extraction of alumina from clay presented by Kaiser Engineers is based on information supplied by the Bureau of Mines, Arthur D. Little, Co., and the Idaho National Engineering Laboratory (INEL). This process is more energy intensive (28.4 million BTU/ton of alumina) than the HCL acid sparging process, principally because of the difference in the hydrated crystals, i.e., aluminum nitrate nonahydrate versus aluminum chloride hexahydrate. In addition to this, the crystallization of $AlCl_3 \cdot 6H_2O$ is induced by HCl gas whereas all of the nitrate recovered must be evaporated. However, as specified in the feasibility study, the nitric acid process uses only 0.6 million BTU/ton of alumina in the form of clean fuel versus 2.2 million BTU/ton of alumina for the HCl acid sparging process. Clean and dirty fuel refer to oil and coal, respectively, in the KACC feasibility study and are assumed to have a price ratio of 1.7/1.0.

The nitric acid process utilizes ammonia in the production of its nitric acid requirements. The conversion to coal from natural gas as the feed stock in the manufacture of ammonia could lead to increases in production costs. The makeup requirements of nitric acid are also larger than for the HCl process because of unavoidable losses of nitrate by decomposition to the lower oxides of nitrogen and to elemental nitrogen gas.

The development of the liquid ion exchange technology for the separation of iron from aluminum has made it possible to abandon the pressurized leaching of the clay while improving the product alumina quality as well as yields of alumina from the clay. It is this process step more than any other factor that has contributed the most to the economic viability of the acid extraction processes.

Potential Problem Areas

The operation of the thermal decomposition-acid recovery process steps * represents a serious potential problem to the nitric acid process. Methods of thermal decomposition employed by INEL and ADL incurred economically significant losses of nitrate by decomposition to nitrogen. While INEL has successfully produced quality alumina at the pilot-plant scale, they were not concerned with the recovery of nitrate. The development of a decomposer-acid recovery design capable of producing reduction-grade alumina with an acceptable recovery of nitrate is essential before a nitric acid extraction demonstration plant can be built. The feasibility study specifies a loss of up to 14 percent of the nitrate fed to a decomposer operating at 750 F.

The second potential problem involves the treatment and disposal of large volumes of waste $FeSO_4$ sludge and chloride-bearing wash waste from the solvent extraction system. * Since these wastes cannot be expelled into the environment, the reprocessing/utilization of the waste streams is a problem which must be solved before the nitric acid process can be considered commercially viable.

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*Discussed by Kaiser Engineers in Phase II (p. 4-1-3).

Additional information concerning the trade-off between crystal growth rate per unit crystallizer volume, crystal volume, number of crystallizers, and size of the bleed stream is required to design properly the demonstration plant crystallizer system. All of these factors are essential to the efficient operation of the system.

The clay calcination step is essentially the same for the nitric acid process as for the HCl sparging process. If the fluid-bed clay calcination process is employed, the problems of excessive fines * generation and degree of calcination result, as discussed for the HCl sparging process.

The development of the liquid ion exchange technology for the extraction of iron from the leach liquor greatly improved the efficiency of the acid alumina extraction processes. However, this technology creates a serious secondary problem of its own for the nitric acid process. For the nitric acid process, this step requires that HCl acid be used to strip the iron from the organic solvent. The organic solvent can then be recycled to the system. However, great care must be taken that no chloride is carried with this solvent back into the nitric acid system. If an operational upset should occur and the chlorides become mixed with the nitric acid, severe metallic corrosion problems would result.

The nitric acid process requires a net energy supply of 28.4 million BTU/ton of alumina. Only 0.6 million BTU/ton of alumina need to be supplied as a clean fuel other than coal. This compares to 2.2 million BTU/ton of alumina as clean fuel for the HCl sparging process. In summary, the nitric acid process requires 1.6 million BTU/ton less in clean fuel that the HCl sparging process, but requires 7.5 million BTU/ton more than the HCl sparging process on an overall energy consumption basis.

The Economic Sensitivity of Potential Problems

The Kaiser Engineers' feasibility study has specified a certain level of efficiency for the thermal decomposition acid recovery process steps. This estimate is based on information obtained from actual decomposition data and separate data concerning nitrate losses based on decomposer nitrogen balance calculations. The loss of 3 percent of the nitrate fed to the indirect fired thermal decomposition step represents a $14.70 operating cost factor. It is assumed

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*The term fines refers to clay with an extremely small particle size.

that this 3 percent nitrate loss represents 60 percent of the total HNO_3 acid makeup requirement as implied by the process assumptions of the Kaiser Engineers Phase II report. Unfortunately, accurate estimates of the nitrate losses of the thermal decomposition process are not available. It is known that the nitrate losses are critically dependent upon the actual operating temperature. Nitrate losses of 14 percent and 7.4 percent have been reported by the Idaho National Engineering Laboratory for thermal decomposition operating temperatures of 750 F and 400 F respectively. However, 400 F is the minimum practical temperature for industrial scale decomposition while 1800 F is the temperature required to destroy the last traces of nitrate in the product alumina. Kaiser Engineers specify that the decomposition process will be carried out in stages with the solids being subject to increasing temperatures until the decomposition is carried to completion.

If the actual thermal decomposition acid recovery process fails to meet the specified operational assumptions, a significant additional operating cost penalty will be incurred. Because of the lack of accurate data and of the sensitivity of the total operating cost estimate to the nitric acid make-up requirements, careful consideration should be given to all assumptions concerning nitrate losses.

Solutions to the potential disposal problem of $FeSO_4$ sludge and chloride-bearing waste water created by the solvent extraction process, and nitrogen oxide recovery from combustion product streams are still being sought. Energy and capital requirements for the mode of treatment that is finally chosen must be added to the process totals. Accurate data concerning the geographic location of the alumina facility and the mode of treatment are essential to the calculation of these costs. Since these costs significantly influence the total process costs, an assumption concerning these factors must be carefully considered.

The liquid ion exchange solvent extraction technology specified for iron removal from the leach liquor presents a serious potential corrosion hazard. Should an operational mishap cause the chloride to be carried into the nitric acid system, serious corrosion problems would result. This event or the slow leakage of even small quantities of chloride into the nitric acid stream could add significantly to the repair and maintenance labor and materials costs, which represent 18 percent of the total operating cost estimate.

As stated in the previous section, the nitric acid process suffers from a 7.5 million BTU/ton of alumina energy disadvantage when compared to the HCl acid process, which requires an additional 1.6 million BTU/ton of alumina in clean fuel. This energy requirement difference is unlikely to be offset by differences in the price of coal versus oil/natural gas alone. However, these energy requirements are based on numerous assumptions of operational efficiency for various process steps. The 25 percent difference in total energy requirements could be shifted significantly by actual operating conditions. Since energy costs account for a large portion of the operating cost for both processes, the assumptions determining energy requirements should be carefully analyzed. For example, the actual total energy requirement for the nitric acid process may be only 25.0 million BTU/ton of alumina produced, as suggested by Reynolds Metals. Also, the indirect-fired thermal decomposition process of the HCl sparging process may only operate to 80 percent of completion as discussed in an earlier section of this report. This would result in an extra 2.03 million BTU/ton of alumina clean fuel energy requirement. The net result is that the nitric acid process requires 4.1 million BTU/ton in excess of the HCl sparging process, while the HCl sparging process requires 3.63 million BTU/ton more clean fuel.

	HNO_3	HCl Sparging
Oil	0.6	4.2
Coal	24.4	16.7
Total	25.0	20.9

Given these operating conditions and the fuel prices assumed in the KACC feasibility study, the difference in total energy costs for the 2 processes is less than $2.

Optimization of the nitric acid process with operating condition tradeoffs and process equipment requirements can be expected to affect significantly the capital and operating costs as estimated by the Kaiser Engineers feasibility study. As with the HCl sparging process, the nitric acid process as specified is heavily reliant on processing assumptions based on incomplete test results. The current nitric acid process represents only an initial attempt at optimization and could benefit greatly from further study. Only after further development can accurate equipment costing and sizing estimates be determined. This is particularly true with regard to estimates for the materials of construction.

The processing capital and operating cost estimates presented in the Kaiser Engineers' feasibility study represent the best estimates presently available. However, these estimates are based on limited information about actual capital and operating costs, most of which is impossible to verify at this time. Experience has shown that capital costs, in particular, tend to be underestimated for new processes. Therefore, the economic sensitivity of the assumptions assigned to each process becomes critically important to the comparative analysis of the Kaiser Engineers' feasibility study.

3.3 Hydrochlorid Acid Extraction-Evaporative Crystallization Process

The HCl evaporative process differs from the HCl sparging process in two major areas. The HCl evaporative process, as its name implies, produces the $AlCl_3 \cdot 6H_2O$ crystals by evaporation of all of the mother liquor associated with the crystals. Secondly, the evaporative process is specified with a direct-fired thermal decomposition unit. This unit requires 14.5 million BTU/ton of alumina as clean fuel.

The HCl evaporative process has been tested by Anaconda up to the pilot-plant level. However, not all of the process component innovations specified in the Kaiser Engineers' feasibility study for the HCl sparging process were included in this pilot-plant study, including the indirect-fired decomposition process.

The evaporative process utilizes a 20-percent HCl acid concentration in its leaching operation. Increasing this to 25 to 27 percent, as is used in the HCl sparging process, should present no real problem and result in significant operating cost reductions. The leaching, solid-separation and other unit operations would require further study to optimize the overall process. However, in the final evaporative process design, the operation cost differential between the HCl evaporative and sparging processes should be minimal for all process steps except for the crystallization process. The impression formed from conversations with industry is that whatever is done to improve the sparging process can also be done with the evaporative process and vice versa.

It appears that the "Feasibility Study" HCl evaporative process estimates are based on operating conditions as outlined in earlier studies. No attempt has been made to incorporate the innovations of the HCl sparging process into this technology. Only the new anionic chloride, iron separation, solvent extraction technology has been included as a possible improvement to the evaporative process. Therefore, the true competitive position of the HCl evaporative process is understated.

If the direct-fired decomposition unit is replaced by an indirect-fired decomposition process, the required 14.5 million BTU/ton of alumina could be primarily supplied as coal. If the energy requirements for this process are assumed to be similar to those specified for the HCl sparging process, an energy cost saving of nearly $11/ton of alumina is obtained. The operating cost saving may be partially offset by additional capital costs associated with the more expensive indirect-fired unit. However, this operation will also increase the recovery rate of HCl which will also tend to lower the operating cost and help to offset any additional capital cost requirements.

The only necessary difference between the sparging and evaporative processes is in the crystallization process steps, where it is necessary in the evaporative process to evaporate the mother liquor completely. This carries with it an added energy requirement over the sparging process. Use of the indirect versus direct-fired thermal decomposition unit will be determined by the optimum operating conditions, i.e., additional capital requirements versus energy and HCl acid make-up costs. Since these two factors represent the only differences between the evaporative and sparging processes, their effects should be accurately quantified as part of the comparative analysis.

3.4 Anorthosite via Lime Sinter Process

The anorthosite process evaluated within the Kaiser Engineers' feasibility study is constructed from information derived from Bureau of Mines reports, current BOM miniplant data, published literature and Kaiser Engineers' experience. The process evaluated by Kaiser Engineers is somewhat different from previous studies, in that it is an anorthosite/limestone sinter process with no addition of soda to the sintering process step.

This process, as described, has two potential problem areas. Gelation in the leaching section is potentially the most serious technical problem. Even under carefully controlled operating conditions, gelation will probably remain as a major operating problem.

The second potential problem is in the environmental area. Because of the quantity of waste leach residue, its disposal will be a serious problem. The residue amounts to 10 tons/ton of alumina produced.

The anorthosite process, as described in the feasibility study, has a net thermal energy requirement of 61.9 million BTU/ton of alumina. If this estimate is correct, the energy costs alone make this process uneconomical. The large quantities of ore required (16 tons/ton of alumina) also represent a large operating cost factor. The combination of these factors places the anorthosite process, as described by Kaiser Engineers, in a very poor economic competitive position.

Information concerning a modified anorthosite process that may be economically competitive has been obtained in conversations with representatives of Alcoa. Alcoa currently holds two patents on this process which they claim to be competitive with the HCl acid sparging process.

The proposed process would require only one half of the limestone specified in the anorthosite process as described in the feasibility study. The anorthosite raw material requirement has also been reduced. This reduction in raw material requirements will result in substantial energy savings due to the reduced sintering requirement. The reduced raw material requirement will also reduce the volume requirements of other process components per ton of alumina produced. Taken together, these processing improvements represent substantial capital and operating cost savings and warrant careful analysis for comparison with the six processes included in the Kaiser Engineers' feasibility study. Alcoa appears to be willing to sell information necessary to perform this analysis, and to supply the necessary data for pilot-plant sizing.

3.5 Alunite Process

Information concerning the alunite process, upon which the feasibility study is based, was obtained primarily from the Bureau of Mines in the form of a draft environmental impact statement prepared by the Bureau of Land Management describing proposed actions of Alumet.

As described by Kaiser Engineers, the most significant potential problems of the alunite process are tied to the removal of potassium and sulfate, which enter the system as major ore constituents. In an attempt to recover the capital and energy investment required for their removal, these ore constituents are converted to 1.0 and 0.73 tons of sulfuric acid and potassium sulfate respectively, per ton of alumina. However, this solution is not as simple as it seems. In the reducing roast step for sulfate removal, the degree of sulfate removal increases with increasing roast temperature. Unfortunately, the alumina is converted to a caustic-insoluble form with increasing roast temperature. The optimum obtainable result is 80 percent sulfate removal and 80 percent of the alumina remaining in the soluble form. Potassium hydroxide or ammonia equivalent to the unreduced sulfate content is required in a subsequent process to complete the sulfate removal. No significant technical improvements in the removal process are foreseen in the near future. Although this is an efficient method of sulfate removal, its primary disadvantage is that the cost of the KOH used far outweighs the value of the resulting K2SO4 by-product.

The 365,000 tons/year of K_2SO_4 produced by a 500,000 ton/year alumina plant would represent a 50 percent increase in the current K_2SO_4 supply. K_2SO_4, as a fertilizer, is preferred to KCl and could probably expand to replace some of the KCl market. An optimistic price of $72/ton has been suggested by Kaiser Engineers for this expanded K_2SO_4 market.

The alumina plant would also produce 500,000 tons/year of by-product sulfuric acid. Based on past market and transportation conditions, Kaiser Engineers assumes that this acid could be sold on the Gulf Coast at a net profit of $10/ton.

If these two by-product markets were available, they would lower the operating cost of the alunite process to a competitive level. However, two problems persist. First, the capital costs remain very high, partly due to the required handling of large tonnages of material necessitated by the low alumina content of the alunite ore. Secondly, the value of the two by-products would represent a large portion, if not all, of the profit margin of the alumina facility. The loss of either or part of these two by-product markets could seriously jeopardize the profitability of the alunite process. Therefore, any discussion of the economic feasibility of the alunite process will require a detailed analysis of the by-product markets. Only when this information is available can an accurate comparison with other processes be made.

3.6 Sulfurous Acid Extraction Process

The technical description of the sulfurous acid process is based on a Bureau of Mines study of published German investigations and patent literature, a Kaiser Engineers' review of published German investigations, and private conversations with one of the original German investigators. No recent published work exists that suggests major potential improvements in this process. It is concluded by Kaiser Engineers that the sulfurous acid process, as it exists today, is approaching the maximum state of development.

The operating cost estimate for the sulfurous acid process compares favorably with the HCl and HNO_3 processes. This could be improved slightly if the coal fired, fluid bed clay calciner discussed earlier proved to be operable. This potential savings would be $6 to $7/ton of alumina. However, it is not sufficient to change the competitive positions of any of the processes.

The major problem associated with the sulfurous acid process is the environmental control of sulfur dioxide gas emissions. In a pressurized system such as this, control of the SO_2 gas emissions will be very difficult. These sulfur losses will cause both air and water pollution problems which will be not only difficult but also costly to control.

The capital cost estimate for this process is the highest of the six processes considered. This factor by itself is nearly prohibitive. Combining the potential pollution problem and the lack of any potential technological advancement places the sulfurous acid process in a very poor competitive position.

3.7 Carbo-Chlorination Process

The carbo-chlorination process for the production of alumina and/or aluminum chloride from domestic kaolin clays, as developed by the Toth Aluminum Corporation, was analyzed in detail by Pellman Kellogg 6/ in a report issued in August 1978. The results of this report indicate that the carbo-chlorination process may be more competitive with the Bayer process than the six processes discussed in the Kaiser Engineers' study. For this reason, the carbo-chlorination process is included as part of the current analysis.

The original process contained three major barriers to the successful carbo-chlorination of kaolin clays: (1) a slow alumina chlorination rate (2) excessive costs associated with the simultaneous chlorination of silica with the aluminum, and (3) inefficient separation of iron chloride from aluminum chloride.

The difficulty associated with the slow alumina chlorination rate has been eliminated with the use of a new catalyst. This catalyst permits chlorination of the alumina content of the clay to take place in 2-3 minutes at a temperature as low as 750 C.

The use of a boron chloride catalyst suppresses the chlorination of the silica content of the clay to 25 percent while permitting the chlorination of 75 percent of the alumina content of the clay. This development results in both a capital cost savings in the process section handling $SiCl_4$ and an operating cost savings through reduced chlorine requirements.

Four different economical solutions to the iron-aluminum separation problem have been developed. In one process the aluminum and iron chlorides are dissolved in a fused salt solution from which pure aluminum chloride is rectified under pressure.

The carbo-chlorination process also generates a saleable $TiCl_4$ by-product. The $TiCl_4$ can either be sold as such or oxidized first to produce pigment. This by-product credit reduces the total operating cost of the process by more than 10 percent.

Estimates of the operating and capital cost requirements for the carbo-chlorination process (shown in Table 1) are lower than similar estimates for a new Bayer alumina facility in both the EPA and the Pullman Kellogg reports. The authors of this study find the assumptions and calculations of both these publications--particularly that of Pullman Kellogg, which developed detailed capital and production cost estimates based on process flowsheets, equipment loadsheets, plant layouts, piping take-offs and construction specifications--to be reasonable, with few exceptions. However, those few areas where we do disagree with the findings of the Pullman Kellogg report do not have a significant effect on the total cost estimates. For instance, our very cautious analysis of the carbo-chlorination process suggests that the energy requirements, the chlorine makeup requirements, and the amount of the solid waste streams may be underestimated in the Pullman Kellogg report. Doubling the requirements for each of these factors adds approximately $36/ton to the production cost estimates. These are the only areas of disagreement which lead to higher cost estimates than those reported by Pullman Kellogg. Moreover, even with the imposition of these conservative requirements, the carbo-chlorination process remains competitive with the Bayer alumina process on an operating cost basis. The revised cost estimate for the carbo-chlorination process (i.e., adding $36/ton) is included in the summary Table 3 on page 39 of this report.

The carbo-chlorination process has the added advantage that it utilizes coal as its sole source of energy and can be completely independent of off-site power sources. Additionally, this process offers the possibility of producing either alumina for use by the Hall process or aluminum chloride for use in the new Alcoa aluminum chloride process.

Carbo-Chlorination--ALCOA Smelting Process

Integration of the carbo-chlorination process with the new ALCOA smelting process could result in significant cost savings by eliminating the final aluminum chloride oxidation and densification steps in the carbo-chlorination process and the alumina chlorination step in the new ALCOA smelting process.

The new ALCOA smelting process--which is presently undergoing testing in a 30,000 tons per year pilot plant in Palestine, Texas--produces aluminum metal by electrolysis of aluminum chloride in a molten salt bath, producing molten aluminum at the cathodes and chlorine gas at the anodes. The aluminum chloride feed for this process is obtained by chlorinating pure Bayer alumina using pure carbon reductant produced on site by pyrolysis of petroluem products. In addition to the direct capital and operating cost savings resulting from the elimination of capital equipment at the tail end of the carbo-chlorination plant and at the front end of the ALCOA plant, there would also be indirect economies resulting from the combination of the two processes. For instance, the chlorine liberated at the anodes of the ALCOA process could be collected and recycled to the chlorination reactors of the carbo-chlorination process.

Detailed estimates of the relative economics of aluminum production via the Bayer-Hall, Bayer-ALCOA and Carbo-Chlorination-ALCOA processes are not included here because of the unavailability of detailed cost estimates for the new ALCOA process. However, it does appear at this time that a combined carbo-chlorination operation could offer cost savings on the order of 20% over both the new Bayer-Hall and Bayer-ALCOA processes. It should be emphasized that this estimate is tentative and not meant to be taken as a definitive number. However, regardless of the economics of integrating the carbo-chlorination process with the new ALCOA smelting process, the carbo-chlorination process appears to be potentially competitive with new Bayer processes on its own merits as a means of producing alumina.

Table 2
Operating Cost Calculation for Domestic Bayer Bauxite Process

	Unit Cost	Usage	Operating Cost
Major Materials:			
Bauxite	$ 21.50/T	2.550T/T	$ 54.83
Limestone	1.25/T	0.145T/T	0.18
Soda Ash	60.50/T	0.075T/T	4.54
Starch	143.00/T	0.006T/T	0.86
Utilities:			
Fuel Oil	$ 2.13/MMBTU	257 lb/T	$ 10.33
Steam, 300 PSIG, as Coal	1.25/MMBTU	0.413 T/T	12.38
Electric Power	0.02/KWH	72.2 KWH/T	1.42
Water, Cooling	0.04/MGal	2.76 MGal/T	0.11
Water, Process	0.20/MGal	2.0 MGal/T	0.40
Labor:			
Operating Labor	$ 20 K/MY	169 Men	$ 9.66
Admin. & Supervision	30 K/MY	154 Men	13.20
R & M Labor	22 K/MY	1.9% DC	9.72
Supplies & Miscellaneous:			
R & M Materials		2.5% DC	12.78
Operating Supplies	20% Oper. Lab.		1.93
Taxes, Ins., & Other		2.0% CI	13.17
Depreciation		5.0% CI	32.91
Return on Investment		20.0% CI	131.65
Total			310.07

Capacity: 350,000 TPA

Capital Investment: $230,400,000

Source: G. B. Kenney and J. P. Clark

4. COMPARISON OF ALTERNATIVE PROCESSES WITH THE BAYER BAUXITE PROCESS

Estimates of the 1977 operating and capital costs for the domestic Bayer bauxite process are shown in Table 2 for comparison with the equivalent costs for the alternative alumina processes. This evaluation, conducted by the authors of this report, is made using process requirements reported by the Bureau of Mines and cost data used by Kaiser Engineers.

It is also assumed that bauxite is supplied at $21.50 per ton, coal is the source of steam heat and electrical power, and fuel oil or natural gas satisfies the remaining energy requirement.

The data shown in Table 2 imply that the more cost efficient alternative alumina production processes utilizing domestically available raw materials are economically competitive with new Bayer bauxite facilities. Specifically, the capital and operating cost data of the HCl sparging process, as determined by Kaiser Engineers, are comparable (i.e., less than 10% higher) to the cost estimates prepared by the authors for the Bayer bauxite process. However, the cost estimates for the carbo-chlorination process (Pullman Kellogg) are lower than those of the most recent Bayer bauxite estimates. However, the data presented in Tables 1 and 2 have not been normalized with respect to project size or location; capital cost estimate input factors and assumptions have not been standardized. The effect of these inconsistencies are discussed in Section 5.

It should be noted that all of the alternative alumina production processes require larger quantities of energy than the Bayer bauxite process. However, only small portions and in some cases none of these energy needs will specifically require oil or natural gas. The major portion of the energy required can be supplied as coal. For example, the Bayer process has a total energy requirement of approximately 15.5 billion BTU/ton of alumina, 4.84 million BTUs of which are required as a clean fuel such as oil. The nitric acid process requires a total 28.4 million BTU/ton of alumina and only 0.6 million BTUs as clean fuel. However, the most energy efficient of the six alternative processes, the HCl acid sparging process, requires only 20.9 million BTU/ton of alumina and only 2.2 million BTUs as clean fuel.* This means that the HCl acid sparging process uses 5.4 million more BTU/ton of alumina than the Bayer process in the form of coal while conserving 2.64 million BTUs in the form of oil. If the price of oil then exceeds the price of coal by a factor of two on a BTU basis, the energy costs of the two processes will be identical. Preliminary estimates for the carbo-chlorination process indicated a net energy requirement of 16.3 million BTU/ton. However, this total energy requirement can be supplied as coal. This is a

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* Note: There appears to be some discrepancy as to the fuel oil requirement of the HCl sparging process as reported in Table 2-1 of the Task II feasibility study and the Unit Cost and Usage table prepared by Kaiser Engineers.

particularly strong competitive advantage in the United States, where oil and particularly natural gas are in short supply. This has led to a heavy dependence on foreign supplies of energy with the subsequent national balance of payments burden. Therefore, it could be in the national interest to promote processes which conserve scarce domestic natural resources while utilizing more abundant materials. This factor should be carefully considered with respect to the economics and the competitive positions of the various processes.

5. DISCUSSION OF CAPITAL COST ESTIMATION

Capital investment cost estimates are usually stated with assigned confidence levels. A confidence interval of ± 20% is generally established by a preliminary capital cost estimate before work on the project is initiated. The accuracy of the confidence interval is directly related to the current level of development of the technology under consideration. For this reason contingency funding allowances are usually assigned to reflect the specific level of risk associated with new projects. Contingency allowances reduce the overall financial risk of the project by anticipating project unknowns such as factors that are overlooked, forgotten, underestimated, and miscalculated. Projects introducing new and/or untested commercial processes may require substantially higher contingency funding allowances than the normal 25% of fixed capital for proven technologies.

A complete capital investment cost estimate includes the following factors: (1) physical plant costs, (2) engineering costs, (3) offsite costs, (4) contractor's fees, (5) contingency allowances, (6) land acquisition costs and, (7) working capital requirements. An estimate based on the above factors will also vary with the location and size of the proposed facility due to the geographical variation of cost factors and the economics of scale associated with construction costs. Inconsistencies in the size, location, and cost factors used by the various investigators is primarily responsible for the variations in the capital cost estimates of the eight processes presented in Table 1.

The data presented in Table 1 can be normalized with respect to the assumed size of the project using the six-tenths rule. This technique is ideally suited to extrapolating capital cost estimates for similar projects in similar locations. The normalized data of Table 1 is presented in Table 3 with a confidence interval of ± 30%. (Since this technique cannot be applied to operating cost estimates, these values are omitted from Table 3).

Table 3

Size-Normalized Capital Cost Estimates
($/AT Al_2O_3)

Report	Bayer Bauxite	HNO_3	H_2SO_4	HCL Evaporation	HCL Sparge	Alunite	Anorthosite	Carbo-Chlorination
BOM (1973) 500,000 TPA	223	264	440	357	-	-	227	-
CRU (1973)	418*	482*	-	-	-	-	-	-
EPA (1975) 500,000 TPA	513	589	-	786	-	-	-	426
Pindyck (1976) 500,000 TPA	231	-	-	358	-	-	227	-
Kaiser (1977) Engineers 500,000 TPA	-	915	1138	753	629	928	992	-
Pullman Kellogg (1978) 500,000 TPA	530	-	-	-	-	-	-	429
Kenney-Clark (1978) 500,000 TPA	572	-	-	-	-	-	-	-

Note: All costs are in 1977 dollars. Confidence level is ±30%.

*CRU estimates are unchanged since no plant capacity is given.

The consistency of the Bureau of Mines and Pindyck data presented in Table 3 is due to the fact that the Pindyck cost estimates are extrapolations of the Bureau of Mines cost calculations. This is also true of the Environmental Protection Agency (EPA) and Pullman Kellogg data for the Bayer bauxite process. The two capital cost estimates presented for the carbo-chlorination process by EPA and Pullman Kellogg appear to be independently calculated values.

The overall inconsistency of the capital cost estimates presented in Table 3 is due to three primary factors. The first concerns the method used to escalate the estimated capital cost values of the different investigations to 1977 dollars. The Chemical Engineering Plant Cost Index is used in this investigation as the best available escalation factor. However, this factor only approximates the real escalation factor for alumina plant capital costs and thereby introduces an error term.

The second factor refers to the inconsistency of the Bureau of Mines (and therefore Pindyck), Environmental Protection Agency and Kaiser Engineers data. Since these investigations lag each other by two successive years, and since technological research and development together with financial conditions are functions of time, these three research groups perceived three distinctly different operating conditions. Consequently, the differing assumptions made by three independent investigations regarding the construction and operation of the various processes result in differing operating and capital cost calculations.

The third factor which leads to differences in the estimates reported in Table 3 is the inconsistency of the cost factors included in the capital cost algorithms used by the various investigations. For example, the Pullman Kellogg values listed in Table 3 of this investigation include a 19% contingency funding allowance while this factor is not included in the Kaiser Engineers estimates.

To summarize the preceding points, it is necessary that the location and the assumptions regarding the components of the capital cost algorithms be normalized for each separate process before any direct comparisons of the capital cost estimates of these processes can be made. Any statement of capital cost estimates without associated confidence intervals is incomplete. Of the values listed in Table 3 only 2 sets have been assigned confidence levels by the investigators. The Bureau of Mines presents study estimate values with an assigned confidence interval of ±30%. Pullman Kellogg, in presenting preliminary estimate values, has assigned a ±20% confidence interval.

In an attempt to establish the accuracy of the capital cost estimates of Pullman Kellogg and Kaiser Engineers, this investigation has assigned a ±20% confidence interval to the Kaiser Engineers' investigation while recognizing the very high probability of a nonuniform real confidence interval distribution for these processes. The varying degrees of financial risk or uncertainty represented by the real confidence levels associated with these processes can be theoretically reduced to a common ±20% confidence level through the assignment of suitably adjusted contingency funding allowances. The contingency allowance assigned to each process reflects the level of technical and/or financial uncertainty associated with that process and thereby reduces the risk (capital cost confidence interval) to a common level.

The capital cost estimates of Kaiser Engineers, Pullman Kellogg, and this investigation are presented in Table 4 with assigned contingency allowance, confidence interval and size normalization accuracy distributions. The intent of Table 4 is to present a coherent listing of the estimated capital costs of the 8 alumina processes under consideration. Size normalization capital cost adjustments are not assigned to the Kaiser Engineers estimates because these values are reported by Kaiser Engineers in 1977 dollars at the normalized plant size of 500,000 TPA. To reflect the relative certainty associated with the sulfurous acid and alunite technologies, the capital cost estimates of these processes are assigned contingency funding allowances of 35%. The other four processes reported by Kaiser Engineers are assigned 50% contingency allowances which reflect the limited data base and technical assumptions made regarding each process. A 50% contingency funding allowance is a conservative estimate when being applied to a project introducing a new and/or untested commercial scale process.

Pullman Kellogg's capital cost estimate for the carbochlorination process includes a 19% contingency funding allowance. This has been adjusted upward to 50% in this investigation to more accurately represent the technical uncertainties and limited data base available. A 30% size normalization adjustment is also assigned to the carbochlorination process to account for the six-tenths rule discussed earlier.

The results of Table 4 illustrate the potential cost of the current uncertainty associated with the seven alternative alumina production processes. It should also be noted that 37% of any capital cost increase associated with these processes must be added directly to the operating cost estimate as part of the Depreciation, Taxes and Insurance, and Return

Table 4

Capital Cost Estimates with Assigned Levels of Accuracy (1977b dollars per annual ton of Al_2O_3 Capacity)

REPORT		KAISER ENGINEERS (1977) 500,000 TPA	PULLMAN KELLOGG (1978) 500,000 TPA	KENNEY-CLARK (1978) 500,000 TPA
Bayer Bauxite	base		530	572
	confidential interval		+30%	± 25%
	size normalization		±30%	
	range		260 - 896	429 - 715
HNO_3	base	915		
	contingency funding	+50%		
	confidence interval	±20%		
	range	1098 - 1647		
H_2SO_4	base	1138		
	contingency funding	+35%		
	confidence interval	±20%		
	range	1229 - 1884		
HCl Evaporation	base	735		
	contingency funding	+50%		
	confidence interval	±20%		
	range	904 - 1355		
HCl Sparge	base	629		
	contingency funding	+50%		
	confidence interval	±20%		
	range	755 - 1132		
Alunite	base	928		
	contingency funding	+35%		
	confidence interval	±20%		
	range	1002 - 1503		
Anorthosite	base	992		
	contingency funding	+50%		
	confidence interval	±20%		
	range	1190 - 1786		
Carbo-Chlorination	base		429	
	contingency funding		+31%	
	confidence interval		±20%	
	size normalization		±30%	
	range		313 - 875	

on Investment factors. Revised operating cost estimates are not presented here because operating cost estimates cannot be normalized with acceptable confidence limits.

Based on the data presented in Tables 3 and 4 and probable operating cost estimates, the total costs of new Bayer bauxite and carbo-chlorination processes are roughly comparable and have the lowest estimated costs at both the upper and lower end of the range. Behind these two processes the competitive ranking of the other processes is as follows: the hydrochloric acid sparging, hydrochloric acid evaporative, alunite, nitric acid, anorthosite, and sulfurous acid processes in that order. This economic ranking is based on a current capital investment cost of $625 per annual ton of alumina capacity for the Bayer bauxite process.

6. SUMMARY AND CONCLUSIONS

The "Alumina Process Feasibility Study," as presented in Tasks I and II by Kaiser Engineers, represents a competent study of the six alternative processes considered based on the information available to them. This investigation supports the conclusion of Kaiser Engineers that, of the six alternative processes evaluated, the HCl sparging process has the lowest relative cost given the specified operating assumptions. However, insufficient quantitative data are currently available to substantiate the accuracy of the reported production cost figures within ±30%. Capital cost estimates are less reliable because of the limited scale of engineering development of the various processes and the lack of contingency funding allowances. Also, the lack of an analysis of the Bayer process by Kaiser Engineers detracts from the investigation's usefulness in that the six processes considered are not directly compared to the commercial standard.

As discussed in the previous sections and as reported by Kaiser Engineers in both Tasks I and II, many of the components of the various processes are based on assumptions concerning both feasibility and efficiency. Although the flow diagrams do represent practicable processes, they do not represent optimal processes, because sufficient data are not available for an engineering design of such a plant. Therefore, the operating costs of all six processes, with the possible exception of the sulfurous acid process, can be expected to decline with time due to the learning curve phenomenon. Specifically, operational experience will result in improvements in the efficiency of the various process operations and an overall trend towards process optimization. On the other hand, capital and initial operating cost estimates based on flow sheet data are usually underestimated.

The absolute capital costs of the processes are expected to be significantly higher than those estimated because of the usual omission of significant factors such as unforeseen start-up costs associated with inaccurate operating assumptions, process component incompatibilities, inaccurate sizing and costing of equipment, and inappropriate materials of construction. Contingency funding allowances designed to account for these factors for projects utilizing established technologies are usually set at 25% of fixed capital cost. Contingency allowances for projects introducing new or innovative technologies should be adjusted upward from 25% to reflect the level of overall risk or uncertainty involved. For these reasons, the capital cost estimates presented in the Kaiser Engineers study should not be misinterpreted as representing and actual costs of final plant construction and start-up.

The six processes considered by the feasibility study represent the current level of development of each as perceived by Kaiser Engineers based on information available to them. Additional information, which was not available to Kaiser Engineers, suggests that a modified anorthosite process may be economically competitive with the HCl acid sparging process. The necessary information needed to evaluate this alternative process can and should be obtained from ALCOA.

It should be noted that in the Kaiser Engineers' feasibility study some of the assumptions are common to several of the processes. In a comparative analysis, assumptions of this type detract only slightly from the accuracy of the analysis. Specifically, any penalty associated with a deviation from assumed performance of this common component will have essentially the same impact on each process. For example, powdered coal, direct-fired, fluid-bed clay calcination is assumed for both the nitric and hydrochloric acid processes of Task II. Since both processes have essentially the same clay feed requirements, any penalty in performance efficiency will result in similar operating cost penalties to each process. Since the penalties are identical to both processes, no change in the relative competitive positions of these processes will result.

In its analysis, Kaiser Engineers has compared the six alternative processes based on data available for each individual process. Innovations developed for a particular process were not prescribed for alternate processes which might have also benefited from its application. This is particularly apparent in the comparison of the HCl sparging and evaporative processes as discussed in Section 3.3. The result in this case could be a drastic reduction in the gap between the capital and operating cost estimates of the two processes.

Pullman Kellogg's analysis of the carbo-chlorination process is considered by this investigation because of its purported competitiveness with the Bayer process. Although this process had been evaluated earlier in the Environmental Protection Agency study, it was not considered as part of the Kaiser Engineers investigation. This was probably due to the three major technical difficulties with the process (See Section 3.7 of this investigation). According to Pullman Kellogg's analysis, these problems have been solved, thereby moving the carbo-chlorination process into a strong competitive position.

The reported cost estimates for the carbo-chlorination process, as developed by Pullman Kellogg, are also expected to be higher than those listed in Table 1 because of similar uncertainties in the estimates. However, even upon doubling the energy requirements, chlorine make-up requirements, and solid waste streams--adding a cost of $36 per ton--the operating cost estimates are still competitive with those for new Bayer bauxite plants. Table 5 compares total production cost estimates for Bayer bauxite plants with those for the two most economically attractive processes reviewed by Kaiser Engineers--HCl Sparging and Nitric Acid--and with the Toth process. As can be seen from Table 5, even with upward adjusted operating cost estimates the Toth process is the alternative alumina production process which compares most favorably with the Bayer bauxite process.

Table 5
Estimated Total Fixed and Variable Costs of Alumina Production Processes per Ton of Alumina

Process	Total Cost
Bayer Bauxite	$310 1/
HCl Sparge	$331 2/
HNO_3 3/	$504 2/
Carbo-Chlorination	$262 3/

1/Source: Table 2 (Kenney and Clark)

2/Source: Table 1 (Kaiser Engineers as modified by Kenney and Clark)

3/Source: Table 1 (Pullman-Kellogg data as modified by Kenney and Clark)

The other six processes are not assigned adjusted operating cost estimates associated with technical difficulties because of the lack of empirical data to confirm such adjustments with acceptable confidence levels. The carbo-chlorination operation cost adjustments are presented to highlight the competitiveness of this process.

Even though the reported capital cost estimates for the non-bauxitic processes are understated, it is felt that the potential benefits of incorporating the Toth process with the new ALCOA chloride (smelting) process offer potentially large enough cost savings to make the Toth process an economically feasible alternative in the mid to late 1980s.

It is the conclusion of this investigation based on the data (or lack thereof) presented that no single alternative alumina production process can be identified as being superior to all others and also competitive with the Bayer process. The ordinary ranking of the six processes considered by Kaiser Engineers cannot be confirmed due to the lack of contingency funding allowances and consistent confidence intervals. Also, these six processes cannot be directly compared to the Bayer process and/or the carbo-chlorination process because the analyses of the eight processes were not part of one integrated and standardized investigation.

7. RECOMMENDATIONS FOR FURTHER WORK

While recognizing the operational uncertainties of many of the technical assumptions of the seven processes considered, this investigation does not dispute the potential feasibility of the processes. However, in order to determine accurately the relative competitive position of the alternative processes versus the Bayer Bauxite process, additional work is required to quantify the probable distribution of the operational efficiency of the processes and of each process component of the processes considered. This particular type of analysis could be accomplished using Monte Carlo techniques.

Based on the conclusions of this investigation, the following recommendations are made. First, because of the uncertainties associated with the basic operating assumptions of the various processes, further economic feasibility work is warranted in the analysis of their relative economic competitive positions with respect to the Bayer bauxite process. It is recommended that this further study be conducted in the form of a Monte Carlo simulation analysis. Using this multi-equation simulation technique, a probability distribution would be assigned to each estimated coefficient of each equation. The probability distribution assigned to each coefficient would correspond to the uncertainty associated with a particular processing assumption. Specifically, the Monte Carlo simulation model would identify the critical assumptions and associated uncertainties of the various processes by quantifying the operating and capital cost sensitivity of each. For example, this would include the assumptions concerning materials of construction, direct versus indirect-fired thermal decomposition completion levels, fluid bed clay calcination product quality, overall operational efficiency and trade-offs, etc.

It is recommended that the Monte Carlo study be completed before any final evaluation of the relative economic competitive positions of the alternative alumina production processes versus the Bayer bauxite process is made. It is therefore recommended that the pilot-plant phase be initiated after the Monte Carlo study has been completed.

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6. "Toth Alumina Process," prepared by Pullman Kellogg for the Toth Aluminum Corporation, Report No. RD-78-1398, August 1978.

Table A-1
Bureau of Mines' estimated operating costs in 1977 dollars

	Bayer Bauxite	HNO_3	H_2SO_4	HCl Evaporative	Anorthosite
Direct Cost:					
Raw Materials	61.02	28.13	26.18	29.93	24.34
Utilities	29.97	104.58	77.55	86.05	110.67
Direct Labor	11.11	12.48	34.52	9.46	9.85
Plant Maintenance	8.01	14.47	13.84	21.18	9.24
Payroll Overhead		7.41		7.13	5.93
Operating Supplies		2.89	2.08	4.24	1.85
Indirect Cost (50% Direct Labor)	9.56	10.78	24.18	12.26	7.64
Fixed Cost:					
Taxes & Insurance (2% of CI)	5.13	6.10	10.15	8.25	5.24
Depreciation (5% of CI)	12.83	15.24	25.38	20.62	13.09
Return on Investment (30% of CI: Other 20% of CI: Bayer)	51.33	91.46	152.30	123.71	78.56
Total Operating Cost	188.96	293.54	366.18	322.83	266.41

Table A-2
Commodities Research Unit's estimated operating costs in 1977 dollars

	Bayer Bauxite	HNO_3
Direct Cost:		
Raw Materials	56.25	28.35
Utilities	36.02	37.45
Direct Labor	19.23	19.23
Plant Maintenance	11.93	14.45
Payroll Overhead (50% of DL & PM)	15.58	16.84
Fixed Cost:		
Taxes & Insurance (2% of CI)	8.36	9.63
Depreciation (5% of CI)	20.89	24.08
Return on Investment (20% of CI: Bayer, (30% of CI: Other)	83.57	144.47
Total Operating Cost:	251.83	294.50

Table A-3
EPA's estimated operating costs in 1977 dollars

	Bayer Bauxite	HNO_3	HCl
Direct Cost:			
Raw Materials	56.31	32.44	28.39
Utilities	30.80	39.19	86.05
Direct Labor	18.58	21.12	25.99
Maintenance Mat'ls & Supplies	6.71	10.29	13.75
Payroll Overhead (32% of Wages)	5.95	6.76	8.32
Miscellaneous	0.86	1.18	5.29
Fixed Costs:			
Plant Overhead (60% of Wages)	11.15	12.67	15.59
Taxes & Insurance (2% of CI)	8.95	10.29	13.75
Depreciation (5% of CI)	22.38	25.74	34.37
Return on Investment (20% of CI: Bayer, 30% of CI: Other)	89.52	154.43	206.21
Pollution Control	1.59	21.61	5.69
Total Operating Cost:	252.80	335.72	443.40

Table A-4
Pindyck's estimated operating costs in 1977 dollars

	Bayer Bauxite	HCl	Anorthosite
Direct Cost:			
Raw Materials	61.09	30.03	23.79
Utilities	28.36	68.19	74.31
Direct Labor	11.10	9.46	9.85
Plant Maintenance	6.13	19.24	11.86
Payroll Overhead (35% of Payroll		7.13	5.94
Operating Supplies (15% of P.M.)	0.92	3.85	2.37
Indirect Cost: (50% of DL and P.M.)	8.62	11.48	8.68
Fixed Cost:			
Taxes & Insurance (2% of CI)	5.35	8.26	5.25
Depreciation (5% of CI)	13.37	20.66	13.12
Return on Investment (20% of CI: Bayer, 30% of CI: Other)	53.48	123.95	78.74
Total Operating Cost:	188.42	302.25	233.91

Table A-5
Kaiser Engineer's estimated operating costs in 1977 dollars

	HNO_3	H_2SO_4	HCl Evaporation	HCl Sparge	Alunite	Anorthosite
Direct Cost:						
Raw Materials	46.15	22.73	18.48	16.99	87.05	21.43
Utilities	70.87	64.21	68.42	44.83	47.85	90.93
Direct Labor	29.12	28.74	25.20	23.32	26.43	24.11
R & M Materials	18.16	14.74	14.50	12.05	9.62	9.48
Operating Supplies (20% of Operating Labor)	1.22	1.38	1.12	1.15	1.57	1.38
Fixed Costs:						
Taxes & Insurance (2% of CI)	18.30	22.76	15.07	12.58	18.56	19.84
Depreciation (5% of CI)	45.75	56.90	37.67	31.44	46.41	49.60
Return on Investment (30% of CI)	274.49	341.39	226.02	188.67	278.48	297.59
Total Operating Cost:	504.06	552.85	406.48	331.03	515.97	514.36

Table A-6
Pullman Kellogg's estimated operating costs in 1977 dollars

	Bayer Bauxite	Toth
Direct Cost:		
Raw Materials	57.16	49.51
Utilities	30.80	15.41
Direct Labor	9.66	7.93
Plant Maintenance	22.62	17.16
Payroll Overhead (30% of DL)	6.87	5.27
Plant Operating Supplies (15% of Operating Labor)	1.26	1.03
Plant Overhead (80% of DL)	18.31	14.05
Indirect Overhead (5% of Total Production Cost)	7.41	5.52
Fixed Costs:		
Taxes & Insurance (2% of CI)	9.03	7.30
Depreciation (5% of CI)	22.56	18.25
Return on Investment (20% of CI: Bayer, 30% of CI: Other)	90.25	109.50
Credits (Electric Power: @$.015/KWH TiCl : 0.182 Ton)		-25.10
Pollution Control	1.47	
Total Operating Cost:	277.40	225.83

Table A-7
Technical Advisers on the Clark and Kenney Paper

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