

Proceedings of the Raw Materials for Refractories Conference

A Collection of Papers Presented at the
Raw Materials for Refractories Conference
Sponsored by the
U.S. Department of the Interior
Bureau of Mines
Cosponsored by the
American Ceramic Society
University of Alabama College of Engineering
Alabama Mineral Resources Institute and the
University of Alabama Division of Continuing Education

February 8-9, 1982
The University of Alabama
University, Alabama

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Foreward

Raw materials for refractories are essential to the United States' economic stability and national security and play an extremely important role in our daily lives. As a nation, we are becoming increasingly dependent on foreign sources for strategic and critical materials.

Since its creation in 1910 one of the missions of the Bureau of Mines has been to help assure that the nation has an adequate supply of minerals to meet its economic and security needs. In support of this mission the Bureau of Mines sponsored a conference on "Raw Materials for Refractories" through its Tuscaloosa Research Center.

The Raw Materials for Refractories Conference provided an opportunity to discuss current developments in the availability, processing, and properties of refractory raw materials. A series of papers by leading researchers from industry and government presented an overview on refractory raw materials, focusing on materials for alumina and basic refractories as well as materials for nonoxide, carbon, and zircon refractories.

This conference was presented jointly by the University of Alabama Division of Continuing Education and the U.S. Bureau of Mines and was cosponsored by the Alabama Mineral Resources Institute, the University of Alabama College of Engineering, and the American Ceramic Society.

Particular appreciation is extended to Mr. Hendrik Heystek, Research Supervisor, and Mr. Martin Stanczyk, Research Director of the U.S. Bureau of Mines, Tuscaloosa Research Center, for their initiatives and energy in structuring an outstanding program for the minerals industry.

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The Role of the Bureau of Mines in Minerals and Materials

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Washington, DC 20241

We currently are making some changes in the Bureau of Mines that could best be characterized as ones of emphasis and commitment—commitment to helping this administration articulate a clear, coherent minerals policy based on solid analysis and up-to-date information and, more importantly, geared toward assurance of a reliable domestic mineral supply provided by a strong, productive domestic mineral industry. All of us will benefit from that strategy and so will the generations that follow us.

By assuring adequate supplies of essential minerals, we will build strength and resiliency into our economy. We will make it less vulnerable to forces that originate outside our borders.

Obviously, we cannot rearrange geology to give ourselves more mineral resources that are not naturally abundant in the U.S., but we can make more efficient use of what we do have. Technology based on sound, reliable minerals data and forecasts can provide the key.

That technology cannot be developed by any single organization. It requires the best collective efforts of government, academia, and industry, each working within its proper sphere and interfacing cooperatively with the others. We need each other, and a conference like this one helps to define the areas of our mutual interest.

Happily, cooperation with other organizations is nothing new to the Bureau of Mines. During >70 yr of existence, the Bureau has enjoyed many close and productive working relationships with industry and educational institutions. In particular, the University of Alabama has long played an important role in the advancement of mineral science and engineering, and it has consistently been a source of help and support to the Bureau of Mines.

I want to take this opportunity to thank the University and its Mineral Resources Institute for their cosponsorship of this conference, as well as for the many years of close support and assistance the University has provided. My thanks also go to the American Ceramic Society, the other cosponsor of the conference, for its help.

There is a lot of talk these days about strategic minerals. We hear concern expressed about the uncertainties attending our supplies of cobalt, chromium, or manganese. It is easy when focusing on critical supply contingencies to lose sight of some considerations that are more fundamental. True, you cannot build a jet engine without cobalt, but you cannot build a jet plane without steel. Though perhaps most people do not realize it, you cannot make steel without first having refractory linings for your furnaces.

Refractories provide the basis for much of our mineral production. They are a vital link in the mineral-production chain. We cannot afford to take them for granted.

Right now, we are importing significant amounts of refractory-grade bauxite for high Al_2O_3 refractories that are essential to the production of steel, aluminum, cement, and glass. In addition, we import FeCr_2O_4 for basic refractory products used to line copper and steel furnaces. This import dependence has raised the specter of possible shortages and has led us on a search for alternatives. Most of those alternatives will require new technology—conservation and substitution technology—that will let us do more with what we have, and new technology is the product of research and development.

For many years, the Bureau has had a substantial interest in ceramics, including refractories. Ceramic educator Edward Orton, Jr., was one of our early supporters, taking an active role in encouraging Congress to establish the Bureau in 1910. We wasted no time getting involved with ceramics. Only 1 yr later, our first ceramics research program was started in Columbus, OH. In 1918, a cooperative research program on nonmetallic minerals was launched at what was then called the Northwest Experiment Station on the University of Washington campus in Seattle. The Bureau's Southern Experiment Station was started in 1920 in cooperation with the State of Alabama in Tuscaloosa and was the forerunner of today's Research Center. A former president of the National Institute of Ceramic Engineers, T. A. Klinefelter, initiated the Bureau's clay research program in Tuscaloosa in 1939, and it continues today in cooperation with >30 states. Most recently in 1971, Elburt Osborn, Bureau director and former American Ceramic Society president, created a centralized ceramic research program for the Bureau in Tuscaloosa, making ceramics research a prominent part of the Bureau's mission. That research continues today.

A milestone in minerals research was reached with passage of the National Materials and Minerals Policy, Research, and Development Act in 1980. That Act set the stage for much of the Bureau's current work, but most importantly, the 1980 Act emphasized the vital part that minerals and materials play in the security and economic well-being of the U. S. The Act calls for the development of a national materials policy aimed at strengthening the nation's mineral research, development, and production capability.

This is certainly not the first time that a law has called for strengthening our mineral capabilities, but it is the first time in quite a while that an administration has been as serious about implementing a minerals law as the present administration is. I can assure you that the Bureau intends to play an active part in that implementation process.

In response to the 1980 Act, federal agencies are taking several steps. The Department of Commerce, in conjunction with other agencies, is currently assessing the material needs of the aerospace industry. This is just the first in a series of studies to find out exactly what the critical material needs are in industries crucial to our national security.

The administration as a whole is improving its coordination of mineral activities through the President's Cabinet Council for Natural Resources and the Environment which is chaired by Secretary James Watt. The mineral issues under consideration by that council are being developed by a subcommittee—the Strategic Minerals Policy Subcommittee—with Deputy Assistant Secretary of the Interior W. Perry Pendley as its chairman.

Mineral issues are now receiving attention at an extremely high level of government—much higher than at any time in the recent past.

In the Bureau, we have made a number of program changes to reflect the intent of the 1980 Act. We are beefing up our information-gathering functions. For years, the Bureau has been a primary source of statistical information on minerals. Bureau publications, especially the Minerals Yearbook, have become standard sources of data for business and academia alike. Recently, we have made a concerted effort to get the Minerals Yearbook out more promptly, and the issuance in early January 1982 of Volume I of the 1980 edition—presenting statistical coverage of domestic mineral production—was the fastest it has been done in many years. Volume II, presenting 1980 data by states, and Volume III, our international volume, were scheduled for publication in late April 1982. We intend to do an even better job in the future, especially in the area of foreign data collection, and we are already taking the steps to make it possible.

We are also strengthening our ability to analyze the data we collect and to forecast future mineral developments. We are working to develop an “early-warning” system to spot potential trouble spots in mineral supply. Such a system is essential if government is to develop and carry out a comprehensive minerals policy. Moreover, the long lead time needed for research and development and for commercial adoption of the new technology that results makes it vital that we forecast future problems as soon as possible before those problems actually confront us.

Finally, but perhaps most importantly, we have significantly increased our research on strategic and critical minerals. This has included not only a changed emphasis among programs but a change in the budget as well. Research in our Mineral Resources Technology Program, which concentrates primarily on strategic and critical minerals, will receive ≈\$31 million in funding this year, up 28% from Fiscal Year 1981.

Bureau research can be characterized as “high risk, high gain.” In general, we conduct research that cannot be done by private or other public organizations, either because they lack the Bureau’s research capabilities or because the problems are not yet of such immediate economic concern to companies to justify private research efforts. Yet, the problems are of enough concern to the nation as a whole to justify Bureau action. Industry’s research, quite naturally, is profit driven and that of the universities has instruction as its basic purpose. Research and development in the Bureau is aimed at meeting national needs.

Right now, the U. S. has access to adequate supplies of critical and strategic materials. In the case of refractories, Guyana and the People’s Republic of China supply most of the refractory-grade bauxite we need. The Philippines and South Africa supply the FeCr_2O_4 used in refractories. But someday, because of political unrest, disruption of shipping, or some other contingency, we might find that supplies are cut off. Then, we will need a viable technology that can supply our requirements from domestic resources.

The research that the Bureau of Mines is doing today is designed to provide that kind of technology. Let me give a few examples.

We are looking for ways to develop domestic substitutes for imported refractory-grade bauxite. Our dependence on other countries for that material concerns the Federal Emergency Management Agency—which maintains the national mineral stockpile—and other agencies for a couple of reasons. For one thing, maintaining a stockpile is costly. For another, a cutoff in the supply of

refractory-grade bauxite could jeopardize our steel industry.

The Bureau is investigating the possibility of producing a refractory-grade substitute from high Al_2O_3 domestic sources such as the saprolites in Alabama, Virginia, and North Carolina, or from the gibbsite sands along the Gulf Coast. We are looking, too, at kaolin clays from Georgia and high Al_2O_3 wastes from secondary aluminum processing as possible substitute materials.

We are also exploring the possibility of upgrading some low grade Al_2O_3 refractories by impregnating them with various oxides, and we are working on methods for reducing the amount of FeCr_2O_4 used in MgO refractories by substituting domestic dolomites or seawater periclase.

Other research efforts are dictated by changes in processing technology. With the increasing emphasis on hydrometallurgy, liner materials for leach vessels are being exposed to an ever wider variety of chemical reagents. By analyzing the behavior of refractories in such environments, we may be able to find ways to extend the life of the refractory, thus conserving vital minerals.

In addition, we are experimenting with the use of refractories in special applications such as conversion of coal to CH_4 and gasification of low energy fossil fuels.

Our materials research does not stop there. We are working on other critical mineral problems in addition to those affecting refractories. We are developing methods to conserve, recycle, and substitute for imported chromium, platinum, nickel, manganese, cobalt, and tungsten.

In all of this research, the Bureau works closely with industry to ensure that newly developed technology is put into practice as soon as possible. To prevent overlaps and to make certain that our efforts are keyed closely to national needs, we also maintain close contact with other federal agencies. Recently, we cooperated with the Department of Energy on developing materials for valves and catalysts, as well as for refractories, for use in coal-gasification plants. We joined the National Bureau of Standards in a search for ways to reduce the deterioration of materials due to corrosion and with the Department of Transportation's Federal Highway Administration on the use of sulfur in asphalt and concrete pavements. The Bureau has had a number of projects with the Department of Defense, including one to develop metal-matrix composites as substitutes for chromium alloys and another to develop technology for recycling electronic wastes.

Our objectives in this work may seem modest. We do not expect to eliminate our dependence on foreign sources of minerals. The U. S. will continue to rely on South Africa and the Philippines for chrome, on Guyana and other countries for bauxite, and on Zaire for cobalt. The Bureau's aim is to minimize the vulnerability that accompanies such dependence. We are developing technology that can provide a hedge against any sudden disruption in supply. Materials are called strategic or critical because the nation has to have them no matter what the cost. In a world that is functioning normally, Bureau technology may never come off the shelf, but we intend that it will be there if and when it is needed.

One might look at the Bureau's research as insurance and program costs as the premiums the nation pays. As with insurance, we will be better off if we never have to collect on the policy.

Success in the Bureau's programs depends heavily on the quality of our relationships with all the relative segments of the scientific and engineering community—in industry, in the universities, and at all levels of government. We look to you for guidance in developing our programs and for cooperation and

assistance in carrying them out. I promise that the Bureau will continue, as in the past, to give as good as it gets.

Refractories Are Critical Materials

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It was suggested that in addition to our strategic metals—chromium, cobalt, manganese, molybdenum, and nickel—one very important aspect of the production of these materials has not been given proper, if any, attention. It has been assumed that the refractory materials required for their processing can be considered as “off-the-shelf” items and suggested that refractory products, in all categories, must be considered as strategic materials not only from the standpoint of their need in the processing of strategic metals but also based on our dependence on imported raw materials in many cases, plus increasing competition for what in the past have been considered “bountiful” raw materials.

A historical review was given relative to how the cutoff of imported chemical porcelains, high grade optical glass, and refractory glass pots during World War I was solved when our industry, with government support in some cases, rose to the occasion, and by 1919, we were completely independent of foreign imports of these products.

A similar situation was resolved during World War II when our domestic sources of bauxite were rapidly becoming depleted as the war-time requirements for aluminum metal were increased. The manufacturers of high Al_2O_3 refractories still had the disapore pits of central Missouri, but by 1944, it was apparent that substitutes for these would have to be found in the not-too-distant future. The Bureau of Mines, in conjunction with the private sector, initiated a program to develop means of extracting Al_2O_3 from clays. This effort was supported by the federal and state geological surveys in locating potentially usable deposits throughout the country. By the war's end, pilot plants were in operation which proved the feasibility of several processes, although their costs would hardly permit them to be competitive in a peace-time economy.

The refractory industry would have considerable competition for the clay as a source of Al_2O_3 . This would obviously come from the aluminum-metal industry, but competition also would come from the requirements for paper, abrasives, and electronics. Other refractory materials are in similar situations.

The refractories industry has kept pace with the population growth in this country as shown in Fig. 1. According to the 1977 Census of Manufacturers,¹ the value of blast-furnace and steel-mill production was $\approx$ \$39.4 billion, compared with the refractories industry's \$1.27 billion. This steel group employed 529 200 persons, while only 20 400 were employed in refractory production. It is interesting to note, however, that the value of product per employee was relatively close—\$74 and \$63, respectively.

Some efforts should be discussed as to how to improve our visibility. This will require planning and cooperation by all interested parties. The importance of refractory raw materials and products should be identified in a manner that is crystal clear to those in Congress and the executive branch who are responsible for the adoption of a national materials policy. The American Ceramic Society is in

a position to assist in this matter. Our Society has a long history of cooperative efforts with the Bureau of Mines, the Geological Survey, and the Bureau of Standards. The Refractories Division is our Society's largest, and many of its members were participants at the conference. Our committees on ceramic minerals and government relations are two which have substantial interest in this area, and the chairmen of both attended the conference.

It was suggested that the results of this meeting should be not just a published proceedings but should include the initiation of a sustaining effort to focus the attention of our government policy-makers on this currently low profile but highly significant industry. They should be made to understand that the refractory industry must compete with currently recognized strategic-material industries for common raw materials and for the energy required for their processing. Present at the conference were persons who represent all the components which have a substantial interest in such an effort. It was suggested that some time be taken to develop a plan for immediate implementation prior to another crisis.

Reference

¹Census of Manufacturing. Bureau of Census, U. S. Dept. of Commerce, Washington, DC, 1977.

Editor's Note: The complete text of this paper may be found in the *American Ceramic Society Bulletin*, **61** [7] 754 (1982).

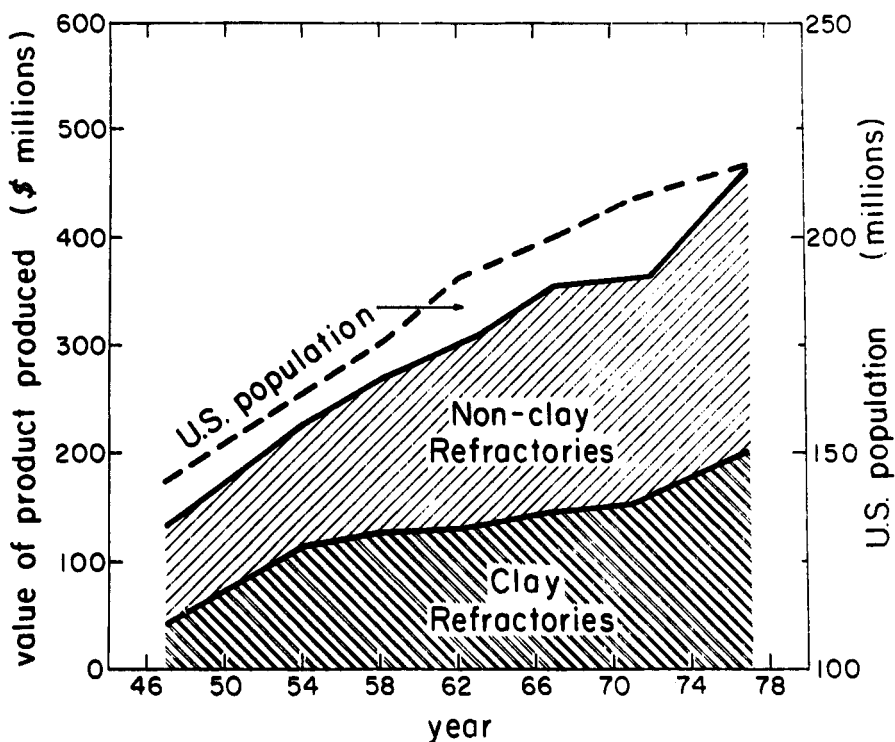


Fig. 1. Value of refractories manufactured during 1947-1977 adjusted to 1947 dollars based on the U.S. Department of Labor's Consumer Price Index (Ref. 1).

Chinese Refractory-Grade Bauxite and Other Refractory Raw Materials from China

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The People's Republic of China is rich in refractory raw-material resources. Refractory bauxite is mined in at least four provinces with proven reserves of ≈ 1 billion tonnes (≈ 1.1 billion tons), $\leq 50\%$ of which contains $\leq 85\%$ Al_2O_3 on a calcined basis. Bauxite occurs in massive beds > 7.6 m (> 25.0 ft) thick and is detrital in origin. Present production is conservatively estimated at ≈ 1.5 million tonnes/yr (≈ 1.7 million tons/yr) of all qualities of bauxite, with $\approx 750\,000$ tonnes representing 85% Al_2O_3 on a calcined basis. Low iron-content MgO is also mined in several provinces, but far and away the largest deposit occurs in Liaoning Province in the northeast section of China. This deposit ranks with the largest in the world and has proven reserves of > 3 billion tonnes (> 3.3 billion tons), with the limits still undefined. At least 50% of this total contains $\leq 95\%$ MgO on a calcined basis. The MgO occurs in steeply dipping beds in which the base limit has not been determined although it has been drilled to a total of ≤ 300 m (≤ 980 ft). Present production of dead-burned MgO from three open-pit mines on this deposit is conservatively estimated 750 000 tonnes/yr (830 000 tons/yr). Natural flake graphite is mined in four provinces, with proven reserves of > 10 million tonnes (> 11 million tons). At least 50% of the graphite has a carbon content of $> 80\%$. The graphite occurs in thick beds and is flotation beneficiated. In addition to the above, China has reserves of refractory FeCr_2O_4 which has future potential. However, production is presently limited due to a lack of infrastructure and remoteness of the location of the deposits. Large amounts of calcined flint clay, fire clay, and dolomite are also produced in China, primarily for internal consumption.

Introduction

China is the third-largest country in the world in area, ranking behind the U. S. S. R., which is first, and Canada, which is second. It has an area of 9.6 million km^2 (3.7 million mi^2) and is slightly larger than the U. S.

Geographically, China is bounded on the north by the Siberian Steppes, by tropical jungles to the south, and by desert and high plateau to the west. To the east is the Pacific Ocean, providing China with ≤ 4000 km (≤ 2500 mi) of coastline and several adequate deep-water ports.

Geologically, China is quite complex with a long and varied history of deposition, mountain building, and erosion. The geological history and tectonic history of China has been described, compiled, and detailed by the Institute of Geology of the Chinese Academy of Geological Sciences.

In general, the mountain ranges trend northeast-southwest with the principal drainage eastward along the three major river systems. The complex and varied geologic history has provided China with many rich mineral deposits which today provide a source of raw-material resources to China and to the world.

Chinese Refractory-Grade Bauxite

Geology

Chinese refractory-bauxite deposits are found in the provinces of Guizhou, Henan, Shanxi, Shaanxi, Hebei, Guangxi, and Sichuan. The bauxite occurs as massive beds >7.6 m (>25.0 ft) thick within a thick sequence of thinly bedded shales. The bauxite is carboniferous in age, and the deposition is most typically cyclothemic.

The Basal member of the cyclothem is an Ordovician limestone with an eroded unconformity developed on its surface. The limestone is ≈ 90 m (≈ 300 ft) thick. Ancient bog iron-ore deposits ranging in thickness from 0 to 6 m (0 to 20 ft) were deposited on this eroded surface in many localities. Thinly bedded shales >6 m (>20 ft) thick overlay the bog iron ore. The shale in turn is overlain by massive bauxite beds >7.6 m (>25.0 ft) thick. The bauxite is overlain by thinly bedded shales >4.6 m (>15.0 ft) thick. In many localities, the shale is overlain by coal.

The above geologic sequence was typical all over the world during the carboniferous period of the Paleozoic Era. It suggests deposition in a lagoonal or mud-flat environment with periods of transgression and regression and the chemical environment alternating between oxidizing and reducing.

Mining and Calcining

The bauxite is mined by open-pit methods consisting of removal of overburden, drilling, blasting, and loading by power shovels. The material is transported by trucks or, in one case, by an aerial tramway to the calcining plants. Presized material is then fed to either shaft kilns or rotary kilns for calcining at temperatures between 1650° and 1700°C (3000° and 3100°F).

In the shaft-kiln operations, uniformly sized and screened pieces of bauxite ≈ 10 cm (≈ 4 in) in diameter are charged to the kiln with coal in a ratio of 7:1. The kilns hold ≈ 750 tonnes (≈ 830 tons) with a total residence time in the kiln of ≈ 4 days. Material is continuously charged and discharged every 2 h. After discharge from the kiln, the material is hand-sorted according to quality-assurance standards. Any underburned material is sequestered for recycling or is sold on the world market for further calcining. The finished product, meeting preset quality standards, is then crushed to specific customer standards and shipped by rail to the seaports.

In the rotary-kiln operations, uniformly presized pieces of bauxite 0.65 to 5.1 cm (0.25 to 2.0 in) are charged to the rotary kilns. Except for one rotary-kiln operation fueled by oil, the rotary kilns are fueled with powdered coal. The bauxite fed to the kilns is calcined at a temperature of $\approx 1700^{\circ}\text{C}$ ($\approx 3100^{\circ}\text{F}$) and has a residence time in the kiln of ≈ 2.5 to 3 h.

The cooled material is conveyed under a magnet and screened to customer specification of ≈ 0.2 to 5.0 cm (≈ 0.1 to 2.0 in). After passing quality-assurance tests, the material is stored in bins and then shipped via rail to the seaport.

Reserves and Production

Reliable statistics on production and reserves of Chinese bauxite are unavailable on a routine basis such as we have in the U. S. However, it can be conservatively estimated that there are proven reserves of at <1.0 billion tonnes (<1.1 billion tons) of Chinese refractory bauxite with $<50\%$ of that total containing $<85\%$ Al_2O_3 on a calcined basis.

Annual production exceeds 1.5 million tonnes (1.7 million tons), with $\leq 750\,000$ tonnes ($\leq 830\,000$ tons) containing $>85\%$ Al_2O_3 on a calcined basis.

Mineralogy

Chinese bauxite is composed mainly of the mineral diasporite, an alumina monohydrate (AlOOH). The raw Chinese bauxite is tan, very hard and lumpy, and does not produce many fines. Microscopically, the raw Chinese bauxite has a matrix of finely crystalline diasporite crystals with a few large-size crystals of kaolinite, rutile, anatase, biotite, and some amorphous iron oxides and hydroxides. Oolites are quite ubiquitous in the Chinese material and show a high degree of deformation and/or elongation. These relict structures of the original host rock suggest a detrital origin and deposition in a mildly high energy environment. The reddish-brown, amorphous, iron-rich material surrounds the oolites and some of the other mineral inclusions.

The Chinese bauxite calcined at temperatures between 1650° and 1700°C (3000° and 3100°F) exhibits a uniform texture with very little porosity. Corundum of uniform grain size and shape is found evenly distributed in a vitreous phase.

Chemistry and Phase Relationships

The typical chemical composition as determined by a wet chemical analysis of the Chinese bauxite is shown in Table I. There is very little interaction between the phases of diasporite, anatase, mica, and kaolinite below 1000°C (1800°F). The diasporite begins dehydrating at $\approx 550^\circ\text{C}$ ($\approx 1020^\circ\text{F}$) with a total weight loss of $\approx 13.5\%$ after heating to 1450°C (2640°F). There does not appear to be any formation of transient aluminum oxides. Corundum forms directly from the diasporite beginning at $\approx 550^\circ\text{C}$ ($\approx 1020^\circ\text{F}$). The curve depicting corundum formation climbs steeply to a value of ≈ 80 wt% at $\approx 1300^\circ\text{C}$ ($\approx 2400^\circ\text{F}$) and drops slightly at $\approx 1550^\circ\text{C}$ ($\approx 2820^\circ\text{F}$). At $>1000^\circ\text{C}$ ($>1800^\circ\text{F}$), the grains of corundum have grown to a relatively large size, thus impeding any reaction with the liquid to form mullite. However, the slight alkalinity is probably more significant in precluding the formation of mullite in favor of corundum and a liquid phase.

On cooling, the liquid phase rich in SiO_2 and Al_2O_3 with some alkali forms a glass matrix in which the corundum grains are embedded. The latter is responsible for the hardness and good abrasion resistance of the calcined Chinese bauxite.

Refractory Products

Since the spring of 1979 when the first large shipload—16 500 tonnes (18 200 tons)—of Chinese refractory-grade bauxite arrived in the U. S. to relieve a major shortage, $>500\,000$ tonnes ($>550\,000$ tons) have been imported to the U. S. and Mexico.

Chinese refractory-grade bauxite has become a standard raw material for the refractories industry. The U. S. government, acknowledging the support of the Chinese refractory-grade bauxite by the U. S. refractories industry, revised its national defense strategic stockpile-acquisition specifications and recently purchased 25 000 tonnes (28 000 tons) of Chinese refractory-grade bauxite for the stockpile. At the present time, Chinese refractory-grade bauxite is used throughout the product lines of most refractory producers in varying percentages up to 100%. Service results have been excellent as attested to by continuously growing demand for this raw material by the refractory producers.

Initially, as with any new refractory raw material, there were a few technical problems. These problems related mostly to the hardness of the Chinese material

and the mineralogy of diaspore as opposed to gibbsite. Through the cooperation of the U. S. and other international refractory manufacturers and the Chinese producers, these problems were overcome.

The hardness problem has been resolved in two ways: 1) the refractory producers have installed new crushing equipment such as jaw crushers and gyro-disk crushers, and 2) the Chinese producers now offer several different sizes such as <10 cm (<4 in), <5 cm (<2 in), and <2.5 cm (<1.0 in). The original hardness problem has also provided several benefits such as developing essentially no fines on crushing and permitting the use and blending of excess fines developed from the use of other raw materials. The angularity of the crushed size fractions allows for better packing density in the brick, resulting in very little breakage in the green state and excellent dimensional integrity.

The diaspore mineralogy and the different phase relationships of corundum vs mullite, both excellent refractory minerals, have been resolved by various research teams of the refractory producers. Products containing Chinese refractory bauxite have higher green strength and higher hot strength at $>1100^{\circ}\text{C}$ ($>2000^{\circ}\text{F}$) than gibbsite-based refractory products. Furthermore, Chinese refractory-grade bauxite-containing products have less reheat expansion and, therefore, less porosity. In summary, most of the original technical problems have been resolved, and Chinese refractory-grade bauxite is now a standard raw material for the refractories industry.

Chinese Magnesite

Low iron-content magnesite is mined in several provinces, but far and away the largest deposit occurs in Liaoning Province in the northeast section of China. This deposit ranks with the largest in the world and has proven reserves of >3.0 billion tonnes (>3.3 billion tons), with the limits still undefined. At least 50% of this total contains 95% MgO on a calcined basis. The magnesite occurs in steeply dipping beds in which the base limit has not been determined, although it has been drilled to a total <300 m (<1000 ft).

The ore body is <100 km (<60 mi) long along the strike, but, at present, only three mines are being worked and they occur within a distance of 35 km (22 mi). The three mines are worked by the open-pit method, utilizing blasting, power shovels, and trucks.

Before the material is mined, drill holes are placed every 3 to 4 m (10 to 13 ft), and the material is analyzed in order to keep quality standards high. After mining, the material is presized and moved by truck to several calcining plants for further processing. The finished product is then stored in silos and shipped via rail to the seaport.

In order to give some idea of the size of this operation, all three mines annually produce $\approx 700\,000$ tonnes ($\approx 770\,000$ tons) of dead-burned magnesite, $\approx 300\,000$ tonnes ($\approx 330\,000$ tons) of dead-burned dolomite, and several hundred thousand tonnes of light-burned magnesite. In all, the three operations move >50 million tonnes (>55 million tons) of ore and waste rock annually. Table II lists typical analyses of material presently available.

At the present time, the major factor holding back the full development of this operation and its major impact on the world magnesite market is the lack of high temperature calcining facilities. However, I can assure you that in the not-too-distant future this hurdle will be overcome.

Presently, shaft kilns and rotary kilns are used for dead-burning the magnesite prior to export or domestic use.

There are >30 modern shaft kilns, all equipped with electronic controls. The kilns vary in size and produce from 40 to 80 tonnes (44 to 88 tons) per day of dead-burned magnesite. The kilns are fed automatically with magnesite and coke in a ratio of 5:1. Residence time in the kilns averages ≈ 8 h, and the calcining temperature is $\approx 1600^\circ$ to 1700°C ($\approx 2900^\circ$ to 3100°F), depending on the quality of the product being produced. After production, the material is hand-sorted to assure uniform quality.

Two rotary kilns ≈ 60 m (≈ 200 ft) long and 4 m (12 ft) in diameter, are also used for dead-burning. The rotary kilns use oil as a fuel and have a temperature capability of 1730° to 1790°C (3150° to 3250°F). Each kiln produces ≈ 200 tonnes (≈ 220 tons) per day, and 6 h is the approximate process time. A doughnut-shaped calcimatic kiln was in evidence and is used to produce light-burned material.

There are at least two electric-arc furnaces in operation producing fused magnesite. These furnaces produce 5.0 to 8.0 tonnes (5.5 to 8.8 tons) per day, with an annual capacity of >2000 tonnes/yr (>2200 tons/yr).

There is also under construction a small, modern, high temperature shaft kiln which will have a temperature capability of 2000°C (3600°F) and will produce 30 to 35 tonnes (33 to 39 tons) per day. It is envisioned that this kiln, together with the high quality magnesite, will produce a world-class product with MgO content of >97%, and a BSG in the 3.40 g/cm^3 range.

Chinese Natural Flake Graphite

Natural flake graphite is mined in four provinces of China. They are Shandong, Heilongjian, Inner Mongolia, and Hebei. Shandong has the largest production, and Hebei, the smallest production. Estimated annual production from all of the provinces is >50 000 tonnes/yr (>55 000 tons/yr). Because of the remoteness of several of the operations, it is difficult to obtain accurate reserve estimates for the flake graphite, but, conservatively, it appears there are >10 million tonnes (>11 million tons). The graphite occurs in beds up to several hundred feet thick interlayered with marble. Geologically, the deposits appear to be ancient lagoonal deposits with the original coal and limestone metamorphosed to graphite and marble. The deposits are mined by open-pit and underground methods. The raw ore with $\geq 34\%$ fixed carbon is hand-sorted. The ore is then crushed and beneficiated by flotation to a carbon content of 80% to 99%. The finished product is sized to customer specifications, bagged, and shipped via rail to the seaports.

Chinese Refractory-Grade Chrome Ore

Chinese refractory-grade chrome ore occurs in three provinces—Tibet, Xinjiang, and Inner Mongolia. No accurate estimates of the reserves are presently available, but the largest reserves and highest quality material are in Tibet. The chrome ore is characterized by low iron content (14%), high Al_2O_3 content (10%), and low SiO_2 content (5%). The ore closely resembles Philippine chrome ore.

At the present time, only small quantities—10 000 to 20 000 tonnes (≈ 11 000 to 22 000 tons)—are produced annually due to the remoteness of the areas and inadequate infrastructure. The future potential of this raw-material resource is large but will take several years to develop.