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GEOLOGICAL SCIENCES

MINERAL SCIENCE AN

XPLORATION

Sensing

ic Surveys

eep-Sea Drilling

eismic Prospecting

eochemical Analysis

atigraphy

PRODUCTION OF RAW MATERIALS

Surface Mining

Petroleum & Natural Gas Wells

Dredging

Quarrying

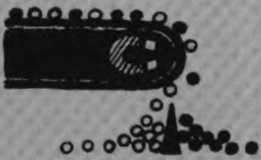
Sulfur Wells

Underg

BENEFICIATION OF RAW MATERIALS

Crushing & Grinding

Screening



Magnetic Separation

Electrostatic Separation

Hindered Settling

Flotation

EXTRA AND PROCES

Blast-Fu

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TECHNOLOGY

MATERIALS SCIENCE

ON
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Furnace

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PRODUCTION OF FINISHED MATERIALS

Light-Weight Alloys

Brick & Tile

Stone, Gravel & Sand

Fertilizers

Steel

Lubricants

PROPERTIES OF MATERIALS

Ductility

Malleability

Semi-Conduction

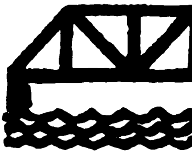
Electrical Conductivity

Optical Properties

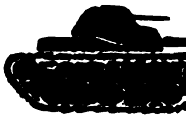
Heat Resistance

USES OF MATERIALS

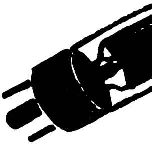
Aerospace



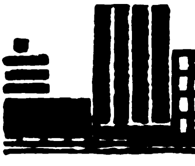
Civil Engineering



Military Materiel



Electronics



Architecture

Porcelain

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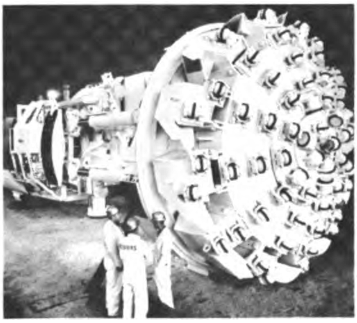

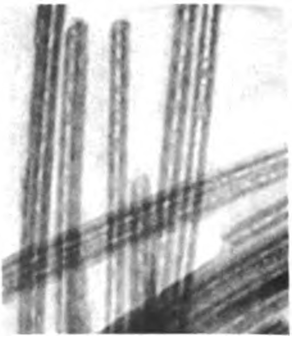

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Mineral Science and Technology

NEEDS, CHALLENGES AND OPPORTUNITIES

A REPORT BY THE

Committee on Mineral Science and Technology

NATIONAL ACADEMY OF SCIENCES
NATIONAL ACADEMY OF ENGINEERING

NATIONAL RESEARCH COUNCIL

National Academy of Sciences WASHINGTON, D.C. 1969

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FRONTISPIECE The realm of mineral science and technology. (Left to right, top to bottom.) Modern steelmaking; a giant mine-tunnel boring machine; glass fiber optics; laboratory research into the physical properties of rock; offshore drilling; on-site rock-mechanics research; blast furnaces; and asbestos fibers magnified 100,000 times, revealing the amazing tubular structure of this mineral.

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Foreword

The Committee on Mineral Science and Technology was established in 1966 by the National Academy of Sciences–National Academy of Engineering. The Committee was charged with the task of determining the state of mineral science and technology in the United States and providing information and recommendations regarding its health and effectiveness.

The Committee established six panels of experts to survey and report on the fields of mining, extractive metallurgy, production of mineral fluids, fuel science and technology, nonmetallic materials, and mineral economics and resources. Reports of these panels will appear as separate volumes; abstracts with recommendations are assembled in Appendix B of this volume.

This report is a summary of the nature and importance of the mineral science and technology fields, giving special emphasis to the present status of mineral science and engineering in universities. We are alarmed that mineral engineering programs in universities receive so little financial support, a partial consequence of which is the deteriorated state of higher education in these fields in the United States. We also find an amazing lack of coordination and support of mineral resource research by both federal and state governments as compared with the organization and funding of research on agricultural resources. We find that domestic mineral production as a percentage of the gross national product has fallen off steadily from about 4 percent a decade ago to a present level of about 3 percent, while during the same period the increase in the net value of mineral imports over exports has tripled. The country is not running out of mineral resources but out of the mineral technology

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needed for their profitable production and processing in world competition.

The United States must change this trend by invigorating mineral engineering education and research to provide the human resources and the knowledge that alone can prevent an impending serious loss in the country's competitive position in mineral technology. The U.S. Bureau of Mines must be provided with strong, stable leadership, and this Bureau along with the U.S. Geological Survey should be provided with funds to carry out needed comprehensive research programs (in cooperation with universities, state agencies, and industry) on the science and technology related to our mineral resources.

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Committee on Mineral Science and Technology

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JAMES BOYD, Copper Range Company
JOHN C. CALHOUN, JR., Texas A&M University
GERHARD J. DERGE, Carnegie-Mellon University
MARTIN A. ELLIOTT, Texas Eastern Transmission Corporation
KARL L. FETTERS, Youngstown Sheet and Tube Company
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CYRUS KLINGSBERG, National Academy of Sciences; *Executive Secretary*

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Contents

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1

Recommendations

In the body of this report are discussed the problems, needs, opportunities, and accomplishments of mineral science and technology. Despite the key role of minerals in our society and the vastly increasing worldwide demand for mineral products, mineral technology in the United States is in a declining state, and serious trouble lies ahead for the nation unless corrective actions are taken promptly. As evidence of this we find that

New developments in mineral technology are increasingly coming from abroad.

The net value of mineral imports over exports has tripled in the last decade; in 1966 imports were valued at $6.7 billion, and exports at $3.4 billion.

Support of university research and graduate programs in mineral science and engineering is far below the level needed if the United States is to maintain a pre-eminent position in mineral technology.

Mineral engineering education is in a declining state as indicated by the fact that the number of university departments of mining engineering and number of graduates are decreasing despite a continuing strong demand for mining engineers and by the fact that there are few graduate students in mining, extractive metallurgy, and petroleum engineering, and almost half of these are foreign.

Current organization and funding within the federal government for the support of mineral education and research and for the development of mineral policy do not provide the strong coherent program the country needs.

Even though many problems of mineral science and engineering can

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be handled better on the state level than on the federal level, most states do not have agencies carrying out active mineral-technology programs.

The six panel reports* that supplement this committee report present detailed discussions of the state of technology in the various subfields and present specific recommendations. We urge that industry, federal and state governments, educational institutions, and the professional societies implement in every way possible the many detailed recommendations made by our six panels and assembled in Appendix B.

We present the following general recommendations that bring to a focus the over-all concerns of the Committee.

THE FEDERAL GOVERNMENT

The federal government must have a more effective means of developing coordinated national mineral policies and of supporting, directly as well as by matching aid to the states, essential research and traineeship programs in mineral science and engineering. Further, in this era of total land use, of accompanying severe ecological problems, and of conflicts of the interests of the various users, a broad resource-management approach is long overdue. A better federal arrangement should be established for determining major needs and coordinating federal policies on all the country's natural resources in the interests of making optimum use of these resources with minimum deterioration of our environment.

In view of this, we recommend that

- *A cabinet-level Council on Mineral Resources be established at a level comparable to that of the proposed Council of Urban Affairs; that the Assistant Secretary for Mineral Resources of the Department of the Interior be established as this Council's Executive Secretary.*

- *The role of the Assistant Secretary for Mineral Resources be strengthened by administrative action on the part of the Federal Executive Offices so that the Assistant Secretary for Mineral Resources will serve as the focal point for all matters among government agencies and between government agencies and industry involving mineral science and technology.*

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* *Mineral Economics, Mineral Fluids, Mining, Non-Metallic Materials, Fuel Science and Technology,* and *Extractive Metallurgy,* to be published by the National Academy of Sciences, Washington, D.C.

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- *A National Minerals Reference Center be created within the office of the Assistant Secretary for Mineral Resources to assist him in supplying the detailed information and analyses required for sound judgment by the executive and legislative branches in the formulation and execution of national mineral policy. Since much of the information input to the Reference Center will come from the Bureau of Mines and the Geological Survey, those agencies should have adequate budgetary support to develop and apply the latest statistical and computer techniques for processing of fundamental data to give continuously current information concerning the factors affecting national and international markets and production.*

- *A program be established under the Assistant Secretary for Mineral Resources to provide continuing federally appropriated matching funds to each state in support of mineral-resources research.*

- *The Bureau of Mines develop sustaining research and educational programs in mineral science, technology, and engineering through grants, contracts, and traineeships at educational institutions.*

- *The Bureau of Mines greatly increase its fundamental research program, coordinated both with university research programs and with the research-and-development activities of the mineral industries. A vigorous program of research on underground environments is especially needed.*

- *The Secretary of the Interior provide Congress with an annual report on the state of the mineral industries, including statements on the trends in mineral science and technology and in the utilization of mineral resources, together with such recommendations for legislative programs as may be necessary to meet the mineral demands of the nation in the years to come.*

- *The Department of State increase the number of mineral attachés whose primary function is to supply basic information concerning mineral exploration and production in the international region of their assignments.*

- *The Congress provide the incentive for the private sector to enter fully into research activities by measures, such as government financing, to match industry's contribution to fundamental research.*

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STATE GOVERNMENTS

Responsibility for the wise development and utilization of the mineral resources of its particular region should be assumed by each of the states to an increasing extent. The states, in supporting research in mineral science and technology, can do a great deal for the solution of specialized problems, and, through a state agency working closely with local industry, can do much to prevent environmental deterioration and to provide for future mineral needs on a well-planned basis.

We therefore recommend that

- *Where no such agency exists, each state consider the establishment of an appropriate body, preferably in connection with a university. State funds for research in mineral science and technology must be made available to its own agencies and educational institutions on a scale commensurate with the potential importance of the mineral industries to the state's economy.*

UNIVERSITY GRADUATE AND RESEARCH PROGRAMS

The Committee has established the existence of a major deficiency in the total volume of research conducted in mineral science and engineering at universities, in the number of graduate degrees awarded in these fields, and in the amount of federal funds expended per graduate student as compared with other science and engineering fields. Present university research efforts are much too feeble to supply the backup in fundamental knowledge or the manpower that technological developments require. The present annual federal support of all university graduate and research programs in all of the fields of mineral science and engineering amounts to only some $7 million. An increase to a level of three to four times this figure in the next few years is required to place funding of present programs on an adequate level and at the same time to provide for an increase in the number of needed and expected graduate students. We believe that such action is a minimum requirement to avoid serious deterioration in the competitive position of U.S. mineral technology. The increased funds should be concentrated in those university departments where there is a present and continuing record of performance and a demonstrated ability to exercise leadership in the mineral fields.

We therefore recommend that

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- *Federal support of graduate and research programs in mining, mineral beneficiation, extractive metallurgy, production of mineral fluids, ceramics, fuel science, and mineral economics be increased over the next five years to $25 million annually.*

UNDERGRADUATE EDUCATION

The Committee foresees a continuing need for mineral engineers at the bachelor's level not only because of expanding mineral requirements, but also because of changing technology. Evidence available indicates that a tight demand situation has already developed. The number of B.S. degrees being granted annually in engineering is not increasing, and indeed since 1959 the number graduating annually in the mineral science and engineering fields has been on the decline. The problem of low enrollment in mineral science and engineering is a difficult one to correct, but must be attacked from all sides by continuing programs.

We recommend that

- *Industry and government increase present efforts in working with educational institutions to expand enrollment in undergraduate mineral engineering and two-year technician programs.*

- *Cooperative arrangements be made to provide opportunity for a resident of a state not having a curriculum in one or more of the mineral enginering fields to enroll in this curriculum in an institution in another state as, in effect, an in-state student.*

INDUSTRY

The decline in enrollments in the fields of mineral science and technology stems in part from a general lack of awareness of the opportunities and challenges in the field. There are no patent solutions to this problem, but wisely conceived activities must be established that help the general public to understand the opportunities.

In this connection we recommend that

- *Current efforts of industry, either of individual companies or cooperating through professional societies, to publicize career opportunities to prospective students and to interpret the importance of the field to the public at large be expanded and maintained at a high level.*

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- *Industry undertake an assessment of its future manpower needs for graduates (both baccalaureate and advanced degree) in all fields of mineral technology, so that the universities can have reliable statistics on which to base their educational programs in these fields.*

EDUCATIONAL AND PROFESSIONAL ORGANIZATION

Recent developments in the interdisciplinary treatment of many of the mineral sciences and technologies dictate a need for the establishment of new patterns of interaction within the university and between universities and industry. Likewise, the absence of a single professional group representing the entire field is a handicap in apprising the public and the government of problems and opportunities in the mineral-resources field.

We therefore recommend that

- *Every inducement be provided to universities to develop new structural and administrative mechanisms to facilitate multidisciplinary approaches to training and research in the fields of mineral science and engineering, and to devise new methods of cooperating with industrial and governmental research.*

- *The National Academy of Sciences–National Academy of Engineering institute a committee to examine the methods of coordinating the activities of the various professional societies and groups representing the entire field of mineral science and technology.*

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Summary

The art, science and technology utilized in the production, upgrading and reduction to primary consumer products of mineral resources is generally termed mineral science and technology. It encompasses the fields of mining, mineral beneficiation, extractive metallurgy, ceramics, mineral fluids production, fuel science and technology, and mineral economics. Together these fields comprise the inner range of a spectrum of science and engineering, dealing with the finding, winning, conversion and utilization of mineral resources, as indicated in Figure 1. The status of mineral science and technology in the United States is the subject of this report, with special attention given to the situation in universities.

Mineral resources are analogous in many respects to agricultural resources. Development of the science and technology as applied to agriculture has been on a large and broad scale for many decades, with continuous federal and state appropriations to a college of agriculture in each state, and strong, well-funded federal and state agricultural organizations. Mineral science and technology has had no such support, with consequent waste of mineral resources, widespread acid-mine-water pollution of streams from abandoned mines, continuing mine disasters, and a falling behind by the United States in the technology of extraction and primary processing of many mineral resources. The U.S. Bureau of Mines has had inadequate funding in recent decades for the task expected of it. Responsibility for federal mineral policy is fragmented. State governments support very little effort in the field; many of the companies that comprise the U.S. mineral industry are small, and few are in a position to engage in or support massive programs of research and development. In fact, only a few major oil companies and a dozen

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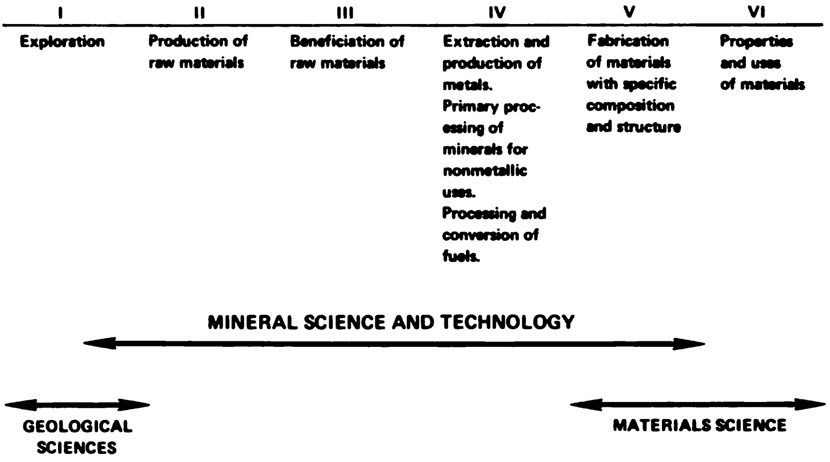

FIGURE 1 Steps in the utilization of mineral-based materials for commerce.

or so metal and ceramic companies can be singled out as major contributors to scientific and technological advances in their own major lines of endeavor.

In addition to the need for wise use of our nonrenewable mineral resources, which represent an important trust and responsibility for each generation, it should be of some concern that imports of mineral products have in recent years been rising much more rapidly than exports. This situation is not so much the result of exhaustion of the country's mineral reserves as it is of our not developing the needed technology for efficient extraction, processing, and utilization of the resources we have.

The above situation is generally known, but the United States continues to make no significant move toward reversing the trend of deterioration in mineral engineering education and research in the universities or toward developing an energetic federal and state research-and-development program in mineral science and technology. Of paramount importance at the present time are a strong governmental program directed at developing the human resources involved (i.e., personnel trained in the fields of mineral science and technology) and a simultaneous program to develop the knowledge needed for the wise development and use of the country's solid, liquid, and gaseous mineral resources. The full resources of the nation, including the many presently scattered throughout the industry, must be brought to bear on coordinated solutions of the national and international problems in the mineral field that lie ahead.

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The limited extent to which resources in men and money are being brought to bear on our mineral resources problems, and the present unsatisfactory state of mineral science and technology, can be gathered from the following summary statements on: the present U.S. resources in mineral scientists and engineers; the way the United States is organized to train men and develop the technology in the mineral fields; the funding picture for mineral science and engineering research; and conclusions regarding the status and needs of mineral science and technology in the United States.

RESOURCES IN MINERAL ENGINEERS AND SCIENTISTS

There are approximately 65,000 mineral engineers and scientists in the United States. About 80 percent of these are engaged in research, development, and production in the mineral industries, 7 percent are employed by government, 6 percent are located at educational institutions, and 7 percent have other employment. The total number is increasing about five percent per year, as indicated by membership data of the American Institute of Mining, Metallurgical and Petroleum Engineers (AIME) and the American Ceramic Society. The total graduated each year from mineral engineering and science curricula, however, is not increasing. The total number of B.S. degrees granted decreased to a minimum of 1,267 in 1963–1964 and has recovered only slightly since then, despite inclusion of "materials engineering" degrees with metallurgy in the last two years (see Table 1).

With the production of graduates in the mineral fields static and employment of engineers and scientists in the mineral industries increasing, it is evident that the industry is absorbing increasing numbers trained in other fields despite an expressed strong preference by employers for graduates of mineral engineering and science curricula.

The decrease in total bachelor's degree production during the past decade (Table 1) is alarming and presents a baffling problem to the mineral industries. That there is a relatively small number of graduates per year in mineral engineering as compared with the number of engineers and scientists working in the mineral fields is indicated by a comparison with the field of chemistry. Using figures available in a recent report,* the ratio in 1964 of professional chemists in the United States

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* *Chemistry: Opportunities and Needs,* NAS-NRC Publ. 1292, National Academy of Sciences–National Research Council, Washington, D.C., 1965.

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TABLE 1 Number of Bachelor's Degrees Granted in Mineral Science and Engineering, 1956–1966[a]

Year	Total	Mining Eng.	Petroleum Eng.	Metallurgical Eng.	Ceramic Eng.	Geological Eng.
1956–1957	1,813	231	650	577	128	227
1957–1958	1,982	240	688	670	159	225
1958–1959	2,114	239	731	724	177	243
1959–1960	1,902	242	597	682	169	212
1960–1961	1,724	220	455	720	167	162
1961–1962	1,480	193	323	679	149	136
1962–1963	1,391	180	228	721	174	88
1963–1964	1,267	144	158	686	205	74
1964–1965	1,436	146	174	851[b]	195[c]	70
1965–1966	1,351	138	133	781[b]	182[c]	117
Total	16,460	1,973	4,137	7,091	1,705	1,554

[a] Basic source of data is U.S. Office of Education.
[b] Includes materials engineering.
[c] From Ceramic Education Council of American Ceramic Society.

(125,000) to B.S. degrees in chemistry granted that year (8,500) was approximately 15. This ratio for mineral engineering is about 50, meaning that there is only one mineral engineer graduated each year for 50 professionals in the field. Inasmuch as a strong demand is said to exist for B.S.-degree chemists, an exceedingly strong demand must exist for B.S.-degree mineral engineers.

Enrollment in the mineral engineering curricula is discouragingly small at the typical educational institution, commonly a state university, having one or more of these curricula. This low enrollment has caused the demise of bachelor-degree programs in mining at nine universities in the 5-year period of 1962–1967, leaving now only 17 accredited curricula in the country.

Among mineral engineering departments at universities, the median number of upper-class majors in the fall of 1967 varied from 12 in mining to 29 in petroleum engineering. The number in the senior class is about half this number, or 6 to 14. A department having this relatively small number in a graduating class and without large enrollment in "service" courses is considered by modern state universities as being of marginal size. For many of those university departments where the number of seniors is below the median, enrollment must increase or the curriculum will be surely abandoned in the next few years. (See Chapter 6 for further details.)

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ORGANIZATION OF EDUCATION AND RESEARCH IN MINERAL SCIENCE AND TECHNOLOGY

UNIVERSITIES

Sixty-two educational institutions have undergraduate curricula in one or more of the mineral engineering fields as listed in the 1967 annual report of the Engineers' Council for Professional Development. A graduate and research program is generally also present. In distribution, size, and organizational arrangement these are notably nonuniform. For example, one university has seven separate departments with a graduate and research program as well as an undergraduate curriculum in each of: mining, mineral preparation, petroleum and natural gas engineering, metallurgy, ceramic science, fuel science, and mineral economics; in addition there is a graduate program in solid-state science which is administratively coordinated with ceramic science, metallurgy, and fuel science. On the other hand, 35 institutions have departments in only one of these fields, usually metallurgy. Not uncommonly, research in metallurgy and ceramics is done in a materials science or materials engineering department, in which case the metallurgy research is likely to be entirely physical metallurgy.

Curricula in mining, petroleum engineering, and extractive metallurgy (including process and chemical metallurgy) exist in a relatively small number of universities, typically have few students, and almost half of the graduate students in these three fields are foreign (see Tables 2 and 5, pp. 62 and 65). For example, in the fall of 1967, 17 educational institutions had accredited curricula in mining engineering. The median number of seniors was approximately six. There were at the same time 19 graduate programs in mining, the median department having eight graduate students with 48 percent of them foreign.

Ceramics and physical metallurgy curricula are in a better position both in number of students and in outside support of research and graduate work. The percentage of foreign graduate students is less—about 14 percent. These two fields are a part of the materials science and engineering wave in education funded especially by the Department of Defense in recent years but also by other federal agencies. The large materials science laboratories established at universities with federal funds almost all emphasize physical metallurgy and solid-state physics. The nonmetallic inorganic materials field (ceramics) has caught only the fringe, and extractive metallurgy has completely missed this development. Established ceramics departments where a strong background,

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interest, and competence in the field is naturally present have in general been passed over in this large funding of materials science during the past decade.

Fuel science and mineral economics are ordinarily not separate curricula. Both, however, are exceedingly important fields in the future of our economy and should be fostered and financially supported at universities. The Bureau of Mines is well known for its research in both fields and logically should become involved in support of these graduate and research programs in universities.

GOVERNMENT

The Bureau of Mines was established within the Department of the Interior by act of Congress in 1910. This Bureau was clearly intended to serve as the mineral science and technology arm of the federal government. However, there are several other agencies within the Department of Interior that also report, as does the Bureau of Mines, to the Assistant Secretary for Mineral Resources. These agencies include: the Geological Survey, the Office of Coal Research, the Office of Oil and Gas, the Office of Minerals and Solid Fuels, the Office of Water Resources Research, and the Oil Import Administration. Consequently, the Bureau of Mines is organizationally at a level where it finds difficulty in exerting major influence on national mineral policy considerations. Moreover, in recent years the Bureau of Mines has had several directors, some of whom served for relatively short periods; additionally, it has also undergone several internal reorganizations. Further, it has received grossly inadequate financial support for the job to be done.

Many other federal departments and agencies have or can have major impact on the mineral industry through regulations or support: the Tariff Commission, the Federal Power Commission, the Interstate Commerce Commission, the Department of Commerce, the Department of Health, Education, and Welfare, the Department of Transportation, the Justice Department, the Defense Department, the State Department, and the Atomic Energy Commission, to name several but by no means all.

Within every state one or more agencies have some jurisdiction over the mineral industry. Every state is concerned with taxation and safety, some are concerned with regulation of production, and many are concerned with providing adequate supplies of minerals to attract and to hold industry. Most of the effective state research programs in mineral engineering are operated by agencies affiliated with universities, and in some cases the state research is closely integrated with the state univer-

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sity program. State research in mineral science and technology is commonly directed toward problems of local interest, and in some cases directed toward the advancement of the mineral industries within the state in competition with other states. This arrangement has a particular advantage to the local industries because it allows close association between the localized industry and the research agency. In quality of personnel and facilities, the range within state agencies is from highest quality to inadequate. Also, with only a few exceptions, the level of financial support falls far short of the job that needs to be done within the state.

INDUSTRY

A few of the mineral companies have modern, well-staffed research laboratories. Laboratories of several of the major petroleum, steel, and glass companies are examples. In addition, companies in several of the industries have banded together in an organization to support research for the whole industry, for example, the American Iron and Steel Institute and the Glass Container Research Corporation, with annual expenditures, respectively, of approximately $3,000,000 and $325,000. Companies also turn for contract research to the nonprofit research organizations.

FUNDING OF MINERAL SCIENCE AND ENGINEERING RESEARCH

Research on mineral resources is similar in many respects to research in agriculture. In both cases an agency of the federal government was created with a responsibility for carrying out research—The U.S. Bureau of Mines and the U.S. Department of Agriculture. Fortunately for this country and the world, agricultural research is supported in each state by federal appropriations, a practice begun in 1887 with passage of the Hatch Act, which provided an annual appropriation for the Agricultural Experiment Station established at the land grant college in each state. Unfortunately, no such provision for support of mineral resources research at the land grant colleges or mining schools was made.

Funding of university research in mineral science and engineering is relatively small and comes from a variety of sources. Total extra-university funding of all mineral science and engineering research at universities, exclusive of physical metallurgy, was at an annual rate of only approximately $11 million in the fall of 1967 (see Table 9). The total

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outside research support of all graduate and research programs in mining departments was $681,000, of which $272,000 was from the federal government. The federal support figure for petroleum engineering is similar, and for extractive metallurgy it is about twice as much. According to a recent NSF report,* "On the average approximately $1 million in Federal funds is associated with the award of seven doctorates in science and engineering." Federal support of graduate work in mining and petroleum engineering is therefore sufficient for only two Ph.D's per year nationally in each of these fields if the programs received average federal funding per Ph.D. candidate, and for about four Ph.D's in extractive metallurgy. The NSF figure of course includes programs in physics, oceanography, astronomy and other high-cost research areas. In chemistry the cost is much less; it is estimated that not over $30,000† per Ph.D. is contributed by the federal government. In mining and petroleum where there are now granted about 20 Ph.D. degrees per year in each field, the federal contribution per degree is only about $15,000. The federal support per graduate student per year in mining, extractive metallurgy, and petroleum enginering was less than $2,000 in 1967 as compared with approximately $6,000 for chemistry graduate students in 1964.† On any basis, graduate programs in mineral science and engineering receive comparatively little federal support, and this may partly account for the lack of attractiveness of mineral engineering to graduate students.

In federal laboratories, research in mineral science and technology is largely the responsibility of the Bureau of Mines. In fiscal year 1968, approximately $36 million was spent (Table 14, p. 83). It is noteworthy that expenditures for research in the Bureau of Mines have decreased from 3 percent of the federal research-and-development budget in 1940 to 0.2 percent in 1968. The Bureau of Mines effort is concentrated in mining, extractive metallurgy, and fuel science and technology.

Comparable industrial research expenditure figures are not available. The Office of Coal Research of the Department of the Interior provided $10.7 million in fiscal year 1968 for contract research and development, largely with industrial laboratories. Funds for research and development in 1966 in four broad categories are shown in Table 19, p. 88. Funds expended for research in the mineral industries seem relatively small. Research-and-development expenditures in 1966, expressed as percent-

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* "The Dynamics of Academic Science—A Degree Profile of Academic Science and Technology and the Contributions of Federal Funds for Academic Science to Universities and Colleges." National Science Foundation Report No. 67-6.

† *Chemistry: Opportunities and Needs,* NAS-NRC Publ. 1292, National Academy of Sciences–National Research Council, Washington, D.C., 1965.

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ages of net sales, were 1.0 percent in petroleum refining and extraction; 1.7 percent in stone, clay, and glass products; and 0.8 percent in primary metals, compared, for example, to 4.0 percent in the chemicals and allied products industries.*

CONCLUSION

In past decades the United States has held the lead or has been in an excellent competitive position in virtually all aspects of mineral science and technology. Studies by our panels indicate that this is still true in petroleum production, but in several other fields the United States is losing out. The mineral resources exist. It is the technology of mineral extraction and processing that is not advancing fast enough to keep U.S. mineral production and our mineral industries at the forefront.† In addition to mineral production, tremendous opportunities exist for developing the technologies that will make possible better general use of the solid earth, and the United States should be moving on this broad front. A recent report,‡ for example, emphasizes the importance of accelerating the development of rapid-excavation technology, and earlier reports§ have shown the need for increased geological, geophysical, and geochemical research on the upper layers of the continental crust—research which will provide the long-range, basic information needed for mineral-resource evaluation and also will contribute substantially to mineral technology.

Of particular concern are the deteriorating situation of mineral engineering and science in universities and the lack of an appropriately organized and funded federal establishment for mineral science and technology. Regarding the former, the picture in mining engineering is especially serious. From 1937 until 1962 there were from 30 to 26 accredited university departments teaching mining engineering, and during those years as many as 500 first-degree mining engineers were graduated annually. The erosion since 1962 has become extremely

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* "Research and Development in Industry, 1966." National Science Foundation Report No. 68-20.

† In this connection, see: "Mineral Resources: Challenge or Threat?" by W. R. Hibbard, Jr., *Science* 160, 143–149, 1968; and "Mineral Shortages," Hearing before the Subcommittee on Minerals, Materials, and Fuels, March 21, 1968.

‡ *Rapid Excavation: Significance, Needs, Opportunities,* NAS Publ. 1690, National Academy of Sciences, Washington, D.C., 1968.

§ For example, *Solid-Earth Geophysics—Survey and Outlook,* NAS-NRC Publ. 1231, National Academy of Sciences–National Restarch Council, Washington, D.C., 1964.

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critical, with only 17 departments left in 1967 and only 138 bachelor degrees granted.

At the same time, the demand for mining engineers has remained steady. A sampling of 55 companies in 1964 indicated an estimated 10-year requirement of 162 mining engineers per year for those companies alone.

One of the reasons for low enrollment in mining is that students in approximately two thirds of the states must attend college in another state to obtain a degree in mining engineering. These students ordinarily face the handicaps of paying a higher, out-of-state tuition and of more difficult admission within an out-of-state student quota. More students would no doubt enroll in this field if arrangements were made to eliminate these penalties.

In the field of mining research, machinery manufacturers and mining companies do research directed toward meeting normal foreseeable commercial needs, but the more basic engineering research that might be done in universities is on a very small scale. Federal funds for modern research equipment and facilities and for graduate-student stipends is a pressing need at the few mining schools remaining.

In the field of nonmetallic materials (ceramics research), a study of published literature by the Panel on Non-Metallic Materials* shows that the United States is constantly falling farther behind the Soviet Union in quantity of scientific and engineering papers published in this field. In universities the problem with the nonmetallic materials program is partly one of organization and administrative concepts. The field is one where an interdisciplinary approach is highly desirable. It is a field where coupling with industry is a great advantage for support and stimulation of the university programs.

The position of extractive metallurgy is clearly unsatisfactory. Although the United States occupied a dominant position in this technology before World War II, the major significant postwar developments, with few exceptions, have originated abroad.† The competitive position of the United States relative to major foreign groups is deteriorating. This worrisome trend will not be easily reversed inasmuch as current research publications show proportionately greater activity in this field in Western Europe, the Soviet Union, and Japan. Metallurgy departments in universities may look reasonably healthy because of

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* Results of this study appear in *Non-Metallic Materials*, to be published by the National Academy of Sciences, Washington, D.C.

† A study of the source of contributions to this technology appears in *Extractive Metallurgy*, to be published by the National Academy of Sciences, Washington, D.C.

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current significant support of physical metallurgy by government agencies, but the numbers of extractive metallurgy graduates and the extent of research activity in U.S. educational centers has declined to the extent that effective continuing operation is threatened. It does not appear that current academic, industrial, and government research or student enrollments are adequate to meet the future requirements of our national goals. Federal support through traineeships and research grants to the extractive metallurgy programs still active is an immediate need.

Although the position of petroleum engineering in the universities is very similar to that of mining and extractive metallurgy, U.S. technology has maintained its pre-eminence in the field through the very extensive research carried out principally by petroleum companies. The Committee does not believe that petroleum engineering curricula should be allowed to shrink and disappear. There is, however, a need for a more interdisciplinary approach to the large problem of the extraction, movement, and storage of fluids within the earth's crust and the transmission of these fluids. Combining university work in hydrogeology and petroleum engineering, for example, could be of great benefit for both and could stimulate the development of a larger, broader group of students and faculty with more chance for support from federal and state agencies.

The role of the federal government is bound to be of major significance in the development of mineral science and technology in the United States, as it has been in the field of agriculture, but strong actions must be taken soon to avoid costly crash programs later. The important element is to plan so that we can do things in time and avoid jumping from one crisis to another. Consider the following: (a) The United States is the largest producer, consumer, and importer of minerals and fuels in the free world. (b) By 1985 the nation's mineral and fuel requirements will nearly double (see Figure 2). (c) Facilities to produce the increased supply require, on the average, about 5 to 10 years of lead time and about $100 million per venture to bring them into productivity. (d) Because foreign ores are richer and readily adaptable to proven technology, because foreign labor is cheaper, and because tax and other financial concessions are possible abroad, a substantial part of U.S. exploration and investment for facilities in the future is being made in foreign countries. (e) If present trends continue, the nation's ability to produce minerals from domestic sources will not remain static, but in some cases, will disappear.

Because of the critical problems facing the nation with respect to future shortages of minerals and the growing dependence on foreign sources of these minerals, it is in the national interest for the federal government to foster and encourage (a) the development of an eco-

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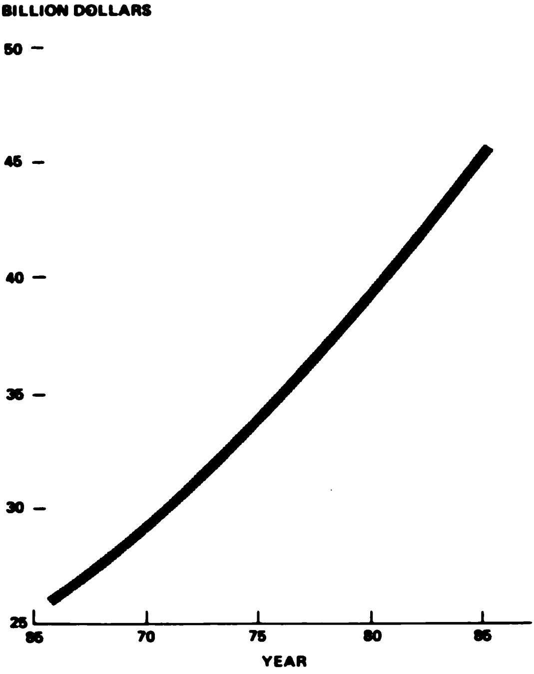

FIGURE 2 Projected U.S. consumption of minerals (in terms of constant 1966 dollars).

nomically sound and stable mining and minerals industry, (b) the orderly development of mineral resources and reserves necessary to assure satisfaction of industrial and security needs, and (c) mineral science and engineering research to promote the wise and efficient use of the nation's mineral resources.

The desired national mineral technology program should have many elements, such as federal research grant and traineeship programs at universities, a federal matching grant program with states to stimulate local mineral-technology research-and-development activities, and a far greater research effort by the Bureau of Mines on underground environments.

One of the pressing critical needs is a National Minerals Reference Center, located in the office of the Assistant Secretary for Mineral Resources. This should be a central, well-staffed information service to advise legislators and the executive branch of the government and to provide information and analytical services needed by policymakers. At present, efforts in this field are scattered among several agencies,

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principally the Bureau of Mines, the Geological Survey, the Department of Commerce, the Department of State, the Atomic Energy Commission, the Department of Defense, the Office of Emergency Planning, and the General Services Administration.

The Committee also recognizes the need for a continuing advisory group representing the mineral science and technology community to provide advice on the state and needs of mineral science and technology in the country, to aid in identifying the issues affecting the national minerals posture, and to help in resolving the problems that threaten both the adequacy and the dependability of the nation's supply of minerals and mineral fuels. This advisory group should probably be a part of the National Research Council, with recommendations channeled through normal procedures of the Council. Alternately, this advisory group might take the form of a Minerals Advisory Board appointed by the Secretary of the Interior to provide counsel to the government.

Finally, the Secretary of the Interior should provide the Congress with an annual report on the state of the mining and minerals industry, including a statement of the trend in utilization and depletion of mineral resources, together with such recommendations for legislative programs as may be necessary to meet the mineral demands of the nation in the years to come.

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CHAPTER 3

Introduction

The state of mineral technology in the United States is wretched. In universities, where the formal training of mineral scientists and engineers occurs and where a sound base of active research should be underway, the picture is indeed dismal. As an example, only 17 departments of mining engineering remain out of 26 accredited departments existing in 1962. In other words, one third of the departments disappeared in a five-year period—the latest for which data are available. On the other hand, the demand for mining engineers remains strong.

The position of the United States in mineral technology is declining. New technical developments in extractive metallurgy, mineral beneficiation, ceramics, and mining are more and more coming from abroad. The United States is losing the leadership it has had.

The role of the federal government in advancing mineral technology has been unsatisfactory. The Bureau of Mines in recent years has not been able to exercise the leadership needed in setting national goals and policies and in carrying out "scientific and technologic investigations concerning mining and the preparation, treatment and utilization of mineral substances."*

Current research on man's environment seems out of balance. Through federal funding there is now research activity on a broad front to gain greater knowledge and to make more effective use of the oceans and the atmosphere. There are no parallel new programs to learn about the earth beneath us. The upper part of the continental crust should be

* From 1913 organic act establishing "in the Department of the Interior a bureau of mining, metallurgy and mineral technology, to be designated the Bureau of Mines."

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under intensive, long-range study by various engineering, geological, geophysical and geochemical techniques.

In response to widespread concern about the state of U.S. mineral technology, and following a specific request of the Director of the Bureau of Mines, the Committee on Mineral Science and Technology was established within the National Academy of Sciences–National Academy of Engineering for the purpose of studying and reporting on the present status of the technology in the United States.

To perform this task, the Committee formed six panels representing natural subdivisions of the field of mineral science and technology. This approach seemed essential because even though there is much in common among the individual fields there are also wide divergences, and each field has a long history of development which in general is quite different from that of the others. Panels were established in mining, extractive metallurgy, production of mineral fluids (principally petroleum engineering), nonmetallic materials (principally ceramics), fuel science and technology, and mineral economics. Discussion of the field of mineral beneficiation is included in the panel report on extractive metallurgy, since this subject is generally included in metallurgy curricula in universities. This array of fields is shown schematically in Figure 1, p. 18. The geological sciences on the left and materials science on the right overlap to some extent but are not included. Thus, insofar as it has been possible to make separations, the report has not included geology on the one hand, nor physical metallurgy and the solid-state physics aspects of ceramics on the other.

The largest part of the reporting by the Committee on Mineral Science and Technology consists of these separate panel reports, which describe the present status of the technology, the trends and potential for future developments, the national situation, and the needs.

This committee report has attempted in the first two chapters to summarize the information and the principal recommendations that have been developed. In Chapter 4 is presented a general statement on the role of mineral science and technology in the economy. The general status of the technology in the various fields is discussed in Chapter 5.

In Chapter 6 the principal presentation concerns the present situation of mineral science and engineering in the universities. The most useful data were obtained from a survey of educational institutions having mineral engineering curricula, but data were also obtained from federal agencies and national societies. The survey was conducted by means of questionnaires sent in each case to a member of the faculty known by panel members, with a personal letter explaining the importance of a reply and of obtaining accurate data. For mining, extractive metallurgy,

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and petroleum engineering a very good response was obtained, and we feel the data are very reliable. In the nonmetallic materials field, the data from ceramic departments are excellent, but currently much of the research in this area is conducted in materials groups recently established in universities not having ceramic departments, and this research is not readily separated from solid-state physics, physical metallurgy, and materials science in general, which is far to the right in Figure 1 (p. 18). We have attempted to collect and use only information that we consider is truly in the mineral science and technology section of Figure 1. On the undergraduate level the figures are for ceramic departments only. The problem arises on the graduate level, where an interdisciplinary structure is developing for this field. We believe that the nonmetallic materials (ceramic) picture as presented is valid. In metallurgy the situation is somewhat the opposite, for extractive and physical metallurgists are not separated on the undergraduate level, but the university respondents were able to make a satisfactory separation at the graduate level. Fuel science and engineering is difficult to delimit and appears in different departments in different universities and commonly is in more than one. The data obtained cannot, therefore, be considered very reliable as a complete picture of the activity of universities in fuel science and technology.

Chapter 6 also discusses briefly mineral science and engineering in the federal and state governments.

As for the scale of research and development in the mineral industry, we were able to obtain only a general picture. Discussion of the type of research and an indication of the scale appear in the separate panel reports.* In a general way much is known. For example, in the ceramic field far more research is done in industrial laboratories than in university and federal laboratories combined. A single glass company spends more annually on research than all of the university ceramic research combined. In petroleum production engineering, much of the research is carried out in the field in connection with production, for each well as drilled and operated is an individual experiment from which useful scientific and engineering data are obtained applicable to a necessary furthering of our knowledge of the earth's crust and the technology of well systems. In mining the technology has been greatly advanced by research and development done by machinery and explosives manufacturers and other suppliers. The metallurgical industry has large-scale research under way, but figures for extractive metallurgy are not available. Industrial

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* *Mineral Economics, Mineral Fluids, Mining, Non-Metallic Materials, Fuel Science and Technology*, and *Extractive Metallurgy*, to be published by the National Academy of Sciences, Washington, D.C.

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fuels research is very extensive, but expenditures by type of research were not obtained.

Chapter 7 is a discussion of the supply-and-demand situation for mineral engineers and scientists. Employment figures presented were obtained principally from National Science Foundation data. There is a brief discussion, based on data obtained from several sources, on the trend in numbers of graduates in the mineral engineering fields and the demand for graduates.

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CHAPTER 4

The Importance of Mineral Science and Technology to the Economy

Man's material progress is measured by his use of minerals. Stones and shells and meteoric iron were used millions of years ago. Gold and silver were being formed by hammering and investment casting before the time of early Egypt. Copper was in use 5,000 years ago, as were metallurgical techniques for hardening copper tools. The alloying industry started in ancient times with bronze, the alloy of copper and tin. Mercury was used in ancient times to silver mirrors and as an amalgam. Extraction of iron from its ores and the manufacture of primitive steels were well known 1000 years BC. Sulfur was used as a medicine and as a weapon of war in ancient times, as were petroleum and asphalt. The extensive plumbing systems of Rome and the colonies, as at Bath, England, contained thousands of tons of lead. And everywhere in the ancient world, enduring massive structures testify to the extensive use of stone, supplemented in some cases by natural cements. Glass was known to the ancients, and ceramic articles were used in the households of the common man before the dawn of writing.

It would be impossible to catalog all the uses of minerals in an advanced economy, but a brief quantitative survey of some major uses is illustrative of the breadth and depth of the dependence of our economy upon mineral science and technology. Interestingly, on a tonnage basis, man is still making the greatest use of his oldest material—the United States annually consumes nearly one billion tons of stone per year, along with nearly one billion tons of sand and gravel. Over 70 million tons of cement, over 50 million tons of clays, nearly 40 million tons of salt, nearly 20 million tons of lime, nearly 10 million tons of gypsum, 10 million tons of sulphur, and lesser quantities of many other materials of a

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nonmetallic nature are used. In 1967 U.S. domestic production of nonmetallics was valued at $5.2 billion; these nonmetallics went into industrial and residential building, highways, water and sewer systems, and every major activity.

Minerals pervade every sector of an industrialized economy. Abundant and varied mineral supplies make possible the abundant productivity of our diversified industry. As a result, the United States has the largest gross national product and the highest standard of living in the world. Mineral raw materials are generally of relatively low value in their raw forms. And, even in the fabricated forms in which they are incorporated in most manufactured articles, they still account for only a small portion of the ultimate cost of the finished product. Yet the minerals and their fabricated forms are essential to all production. For example, the American automobile is responsible for about one out of every five jobs in the nation. It sells for about $3,000, but its 3,500 pounds of fabricated materials probably cost only about $500, and those fabricated materials in turn came from raw materials worth only about $50. The approximate composition of the car, and the raw materials necessary, are as shown in the table below.

COMPOSITION OF AN AUTOMOBILE (U.S.)

As Fabricated Materials	As Raw Materials
2,260 lb iron and steel	5,000 lb iron ore
50 lb copper	5,000 lb copper ore
50 lb lead	2,000 lb lead ore
50 lb zinc	2,000 lb zinc ore
470 lb rubber and plastics	900 lb crude oil
350 lb glass	700 lb oxides for glass
70 lb aluminum	280 lb bauxite
200 lb miscellaneous	500 lb miscellaneous
3,500 lb, worth about $500	16,380 lb, worth about $50

Man has constantly sought to ease his burdens and to do more work by harnessing new forms of energy. Undoubtedly, primitive man knew of pitch and coal. The use of mineral fuels has been steadily enlarging over the years to the point where every person in the United States has available to him the energy equivalent to the output of 260 men, and in 1966 mineral fuels provided 96.4 percent of this energy (petroleum, 39.6 percent; natural gas and natural gas liquids, 33.9 percent; coal, 22.8 percent; and nuclear energy, 0.1 percent), while water power

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provided the remaining 3.6 percent. The United States annually uses over 3½ thousand million barrels of petroleum, over 18 thousand billion cubic feet of natural gas, and over 500 million tons of coal, and these quantities of fossil fuels provide not only energy but also the raw materials for the great U.S. petrochemical and coal-tar chemicals industries. While nuclear energy derived from uranium is but a small component of the present commercial energy panorama, it is expected to grow significantly in the decades ahead. In 1967, U.S. domestic production of mineral fuels was valued as $16.3 billion, and imports, principally of crude petroleum, added additional energy and petrochemical resources.

A mere recital of annual usage of minerals, however, does not give a true picture of the role that minerals play in a developed nation such as the United States, or of their critical role in the development of underdeveloped nations, because, although fuels are consumed when burned, most other uses of minerals are long-enduring. For example, while the United States currently uses about 2 million tons of copper per year in industrial manufacturing, there are probably 40 million tons of copper previously put in place and continuing to serve important needs in the form of electrical wire, brass and bronze castings, tubing, and other applications. Therefore our actual use of minerals is far greater than the annual tonnages cited in the paragraphs above, and our society actually is dependent upon billions of tons of minerals that have been fabricated into useful buildings, structures, transportation facilities, utilities, and various articles during the past several hundred years.

Use of minerals in the United States even on just an annual basis is disproportionate to its size—with only 6 percent of the world's land area and only 6 percent of the world's population, the United States in 1966 used the following percentages of the world's total production: coal, 16 percent; petroleum, 25 percent; steel, 26 percent; copper, 35 percent; aluminum, 53 percent.

In the case of many large-bulk, low-cost items, such as stone, sand and gravel, coal, cement, and clay, where handling and transportation costs are significant, the United States is self-sufficient. In the case of a few minerals, most notably molybdenum and phosphates, production from within its own borders is sufficient to meet domestic needs plus significant exports to other nations. But, in the case of many important minerals, the United States either supplements domestic production with important imports, as in the case of copper, lead, and zinc, or is almost wholly dependent upon imports, as in the case of manganese, chrome, and tin. In recent years the United States has come to rely increasingly upon imports, and in the last decade the net value of mineral imports over

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exports has tripled, with 1966 imports valued at $6.7 billion, compared to exports valued at $3.4 billion.*

Thus far, the domestic mineral industry has done a good job in supplying the needs of the U.S. economy. While the over-all inflation of the 1967 gross national product was 117.3 (based on 1958 = 100), the 1967 wholesale price indexes (based on 1957–1959 = 100) were only 103.6 for fuels and related products and power, 104.3 for nonmetallic mineral products, and 109.5 for metals and metal products. However, domestic mineral production is gradually making a smaller contribution to the gross national product, its value falling off steadily from about 4 percent a decade ago to a present level of about 3 percent (Figure 3).

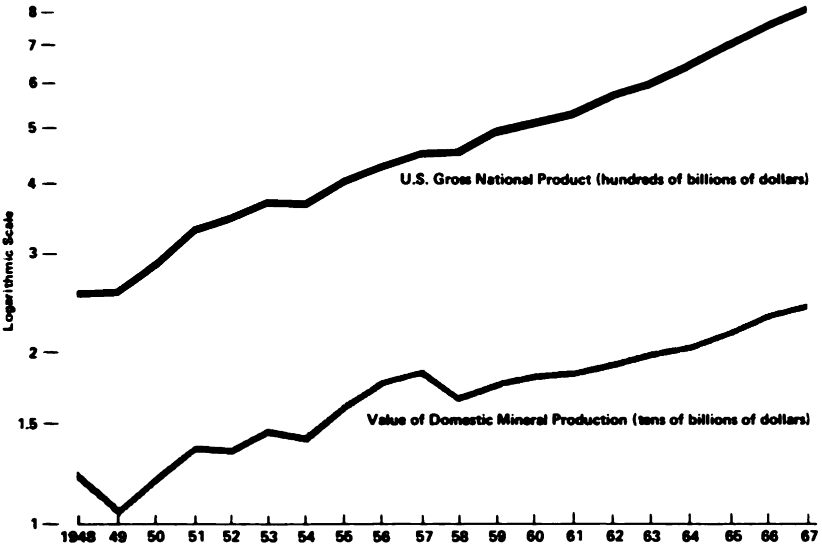

FIGURE 3 The U.S. gross national product and the value of domestic mineral production.

Wars impose special strains on the normal world mineral economy by increasing demand while also interfering with traditional sources of supplies. In World Wars I and II and in the Korean war, national security production programs required costly materials-supply expansion pro-

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* See Table 3 in *Mineral Economics*, to be published by the National Academy of Sciences, Washington, D.C.

grams; priorities for, and allocations of, materials; conservation orders and end-use limitations affecting materials; and price controls on materials and products. Thus far (December 1968), the Vietnam war needs have been met by materials "set-asides." The need for adequate supplies of materials for national security purposes has been recognized by many laws, including the National Security Act, the Defense Production Act, and the Stockpiling Act. At present, 77 materials, 63 of them metals and minerals, are stockpiled by the government, and total stockpiles are valued at more than $6 billion. Most supplies of materials in an emergency are expected to come from the on-going productive capacity of the nation and nearby dependable sources. Hence the United States must maintain an adequate domestic mineral industry mobilization base to meet the needs of any foreseeable emergency, as stockpiles are planned merely to meet the estimated deficits in supplies for a three-year conventional war. Petroleum provides a major example where reliance is placed wholly on continuity of existing industry, and the mandatory oil import controls that have been in effect since 1959 have as their primary purpose the maintenance of an adequate U.S. mobilization base. Some other vital metals and minerals are not stockpiled by the government at all, as in the case of iron ore, pig iron, or steel.

Looking ahead to the future, there is general agreement that world population, now over 3 billion, is likely to double within the next 30 to 40 years. A population increase of this magnitude will make incalculable increases in worldwide demand for minerals. At the same time, superimposed on population growth are worldwide demands for higher standards of living, which can be realized only through greatly increased per capita consumption of minerals. If the United States is already using about one quarter of the present world mineral production, how will it continue to maintain its supplies in future years, and how can the billions of other people hope to have even a modest standard of living? It is with these problems in mind that the Committee on Mineral Science and Technology makes its recommendations for greatly enhancing U.S. mineral science and technology.

We wish to enhance U.S. mineral science and technology not just to guarantee adequate supplies for our own people in future years, but also to make available to the world the technology that, along with agriculture, offers the only hope of uplifting mankind everywhere. In recent years the world has seen many examples where nations have greatly contributed to their own prosperity through the development of their own mineral resources. In the last 50 years the Soviet Union has risen to its present position as a major world power by a calculated policy of emphasizing the mineral sciences and technologies and applying them to

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the development of the vast resources once inaccessibly locked in the vast and frozen terrain of Siberia. In the last 20 years Venezuela, through intensive exploitation of its petroleum and iron ore, has reached a pre-eminent economic position in Latin America. And in just the last 5 years, Libya, once one of the poorest nations in the world, has reached a per capita gross national product of about $1,000, the highest on the African continent, through intensive exploitation of its petroleum resources. If the hundreds of millions of people living in want and misery outside the United States are to attain a reasonable standard of living, it must be done by raising their per capita consumption of every major mineral, and by increasing their consumption of energy.

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CHAPTER

5

The Fields of Mineral Science and Technology

Mineral science and technology is concerned with the extraction and primary processing of mineral materials. Involved are the fields of knowledge extending from mineral exploration to the materials sciences, portrayed schematically in Figure 1, p. 18. These fields are commonly encompassed in the term "mineral engineering." Generally recognized as distinct, though overlapping, fields are mining, mineral beneficiation, extractive metallurgy, petroleum engineering (or more broadly, "production of mineral fluids"), ceramics (or "nonmetallic materials"), fuel science and technology, and mineral economics and resources. Geological and geophysical engineering are closely associated fields and to some extent are included in this study, but are not discussed here. In this chapter, each of the fields is described with respect to its nature, present state of the technology, opportunities and needs. More detailed discussions are found in the individual panel reports.

MINING

Mining may be simply defined as a process or system, the objective of which is the separation of a mineral from its natural environment and its transportation to a point of use or transshipment for processing. Any mining system may be broken down into four major technologic elements or subsystems: rock disintegration, which may be drilling, blasting, mechanical mining, leaching, solution, etc.; materials handling, which includes but is not limited to loading and mine transportation of the

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broken mineral; ground control, which involves controlling or stabilizing the voids (and the rock surrounding them) created through gaining access to and removing the mineral from the deposit; and environmental control, which involves such things as water control and drainage and control of mine atmosphere, temperature, and humidity.

The technological problems involved in, as well as the relative importance of, each of these four elements will vary among classes of mineral deposits as their physical aspects vary. For example, ground-control subsystems applicable to thin tabular mineral deposits are not suitable in thick tabular deposits. Rockbreaking subsystems that are efficient in soft materials like coal, potash, or limestone will not work in hard taconite iron ore.

In addition, the four elements are usually interdependent: e.g., the rockbreaking subsystem will, at the very least, limit the choice of materials-handling subsystems, and in many cases will determine some of the ground-control requirements.

FIGURE 4 Modern mining machinery—A drill jumbo in use at St. Joseph Lead Company in Missouri. This unit is manufactured in the United States, based on a concept developed in Germany. The rotary-percussion drills mounted on the machine are capable of approximately twice the penetration rate of conventional pneumatic rock drills. About 500 tons of ore can be drilled per shift. (Photo courtesy John Reed.)

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During the past few years, important advances have been made in all four of these major elements of mining technology, as discussed in *Mining.** Lower-cost explosives, rapid advances in the concept of continuous mining, enormous and efficient machines for rapid tunneling, new types of conveyors of broken rock, improved roof-bolting techniques to lower cost and improve the safety of roof support, increasing use of electronic computers in mine evaluation and planning and in automation of transportation systems, and processes for decreasing acid-mine-water contamination of streams are some of the more important developments.

Many further advances are badly needed. Present tunnel-boring machines are already setting speed records while sitting idle about half the time waiting for obsolete support systems to remove the spoil and to support and line the tunnel. The solution of this systems-analysis problem alone would double our tunneling capacity with existing machines. In addition, the machines must be further developed to handle the harder rocks and to do this more efficiently, thus requiring less power and thrust. Basic research in the mechanics of rock fragmentation is needed.

The bulk of rock-breaking in mining will be by drilling and blasting for a long time to come, and greatly improved methods for drilling blast holes more rapidly and efficiently are needed. Present methods are generally very inefficient in the use of power and limited in the absolute amount of power they can transmit to the rock.

Ground control is being advanced by studies in the new field of rock mechanics. The advantages of active rock reinforcement by such means as rock bolts and pneumatically applied concrete, as compared with passive ground support by conventional shoring, are generally recognized, but new developments in techniques, materials, and equipment are badly needed. Many of the newest developments in this field are coming from abroad (Europe, South Africa, Australia, and Sweden) because little of this research and development is done in the United States.

Environmental control of groundwater, ventilation, and heat are greatly complicated at depth. Mines are rapidly going deeper in the search for new ore, and various nonmining excavations are also probing beneath our mountains and cities to an ever-increasing extent where environmental control becomes more critical. Again, little research is being done on these problems in the United States, and the most advanced technology and research in the world is found abroad, notably

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* To be published by the National Academy of Sciences, Washington, D.C.

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in South Africa, where mining is carried on at a vertical depth of two miles, the deepest in the world.

In at least three of these subsystems, the newest, best, and, sometimes, only equipment available in the United States is developed and manufactured abroad, and there is not even a competitive product made in this country.

Active research-and-development programs on the basic aspects of these subsystems should be going on at those university mining departments remaining in existence in the United States, but present support is barely sufficient to maintain undergraduate instruction, much less to finance significant research. The Bureau of Mines should develop an adequately funded national program of support of university research and graduate work in the basic science and engineering aspects of mining technology. The present annual federal support per graduate student in mining of approximately $2,000 (see p. 78) should be increased to at least the $6,000 level existing for the average graduate student in chemistry. The Bureau of Mines in its own laboratories and field stations should greatly increase its research in mining enigneering, coordinated with university programs on the one hand and with the research-and-development programs of mining companies on the other. The recurrence of mine disaster emphasizes the need for more intensive research in mine safety. A national effort in rapid excavation* is another example of a program that needs coordination as well as federal funding.

MINERAL BENEFICIATION

Mineral beneficiation involves the segregating and concentrating of the values in an ore into a product of smaller bulk. Many unit processes are used and our knowledge of them ranges from that associated with the practice of an art to that of a technology. Research in this field is directed at: (a) improving understanding of unit processes; (b) determining the optimal ranges of the operating process variables; (c) devising new processes to yield improved results; (d) making equipment and machinery improvements; (e) improving mill design; (f) increasing automatic control of mill operation; and (g) developing a systems approach to the over-all problem of beneficiation. Research on unit processes may be conducted at two levels: first, a general level at which

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* *Rapid Excavation: Significance, Needs, Opportunities,* NAS Publ. 1690, National Academy of Sciences, Washington, D.C., 1968.

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the physicochemical principles common to all applications of the process are probed and, second, a level at which the specifics of the particular ore to which the process is being applied are investigated.

Over the past quarter century the flotation process (Figure 5) has received the greatest research attention. In this separation process, reagents are used to render certain mineral surfaces hydrophobic and others hydrophilic. The physicochemical bases of this process have been intensively studied. While no single unifying theory of flotation exists,

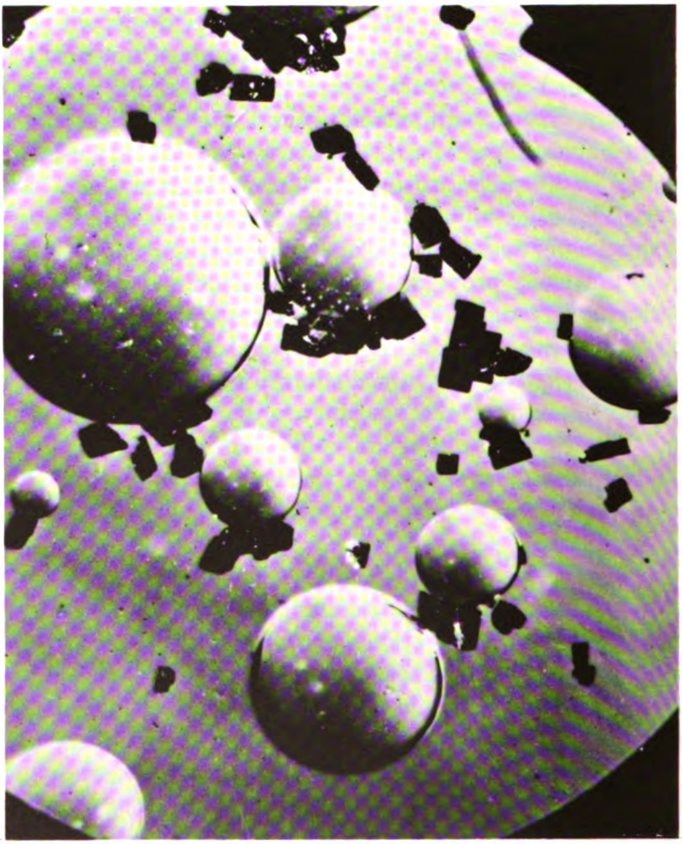

FIGURE 5 One of the principal means of mineral beneficiation is the flotation process illustrated in this photograph. Galena (PbS) particles preferentially attach themselves to bubbles in ethyl xanthate solution and are carried to the surface, separated from particles of different composition. Magnification about 45×. (Photo courtesy H. R. Spedden.)

our understanding has nevertheless increased to the point where almost every mineral can be separated today by anionic or cationic flotation.

Perhaps the most promising process investigated is leaching and its associate developments of solvent extraction and ion exchange. As our ores become leaner, more complex, and more finely disseminated, the need for a beneficiation process operating at the molecular level increases. The impetus for resurgent interest in this process stemmed largely from uranium-ore beneficiation; currently leaching and ion exchange are also being applied to the separation of the rare earths. The leaching of copper dumps accounts for a significant percentage of the copper produced today, and this percentage is increasing very rapidly.

Except for natural sands, virtually all ores must be comminuted to liberate the valuable minerals from the host rock prior to concentration. Fracture studies, testing of theoretical and empirical equations relating energy consumption to size reduction, and rock characteristics are only a few of the research activities in this field.

Virtually all separation processes are under continuing study. Electrostatic separation has been subjected to analysis of the dielectric and coulombic forces which come into play. Similarly, the heterogeneous fields of high-intensity magnetic separators have been studied and this application extended in consequence. The problem of the viscosity of the medium of a heavy-media separator has been investigated as to its effect on separation rates. Studies on liquid–solid separators, e.g., cyclones, thickeners, and filters, have led to more efficient use and, in some cases, improved designs. Pelletizing, which is a relatively new process growing out of the needs of the steel industry, has received considerable attention; it is also of interest in the ceramic, fertilizer, and manganese fields.

Automation and mill control lag behind the advances made in other industries. While computer control is still far in the future, it is encouraging to note that instrument manufacturers have made considerable advances in improving on-line sensing instruments.

Basic research in mineral benefication is done largely in universities, in some of the laboratories of the Bureau of Mines, and occasionally in the research institutes that undertake projects for industry on a contract basis. Application and testing research is done largely by industry and to some degree by contracting research institutes.

As judged by volume of output of research results, the Soviet Union leads any other country by an order of magnitude. In terms of quality and degree of sophistication, U.S. research in mineral beneficiation is either first or second, compared to the Soviet Union. The quality of

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work done in England, Australia, Canada, and Japan is also extremely high.

EXTRACTIVE METALLURGY

Extractive metallurgy is an activity which correlates all aspects of mineral science and technology. The extractive metallurgist uses the ores, fuels, and fluxes provided by mining, usually upgraded by mineral beneficiation, and converts the ore to useful metals. The critical equipment for these chemical reduction and refining processes is highly dependent on the refractories of the ceramist and the energy is dependent on fuels (solid, liquid, or gas) used directly or converted to electricity. How effective this coordination is for any particular metal or situation determines in part the mineral economics for this system. Amplification of the status of extractive metallurgy follows.

The field of extractive metallurgy comprises the processes and technology by which raw materials from the earth's crust (ore) are treated to recover their metal content. In addition to this virgin metal, other secondary sources such as scrap are utilized to varying, and often significant, degrees. In most cases no material produces either a pure metal or useful alloy composition without further refining by selective chemical reactions. The processes commonly employed are in three traditional categories:

Pyrometallurgy (also called smelting or thermal processing) is both the most ancient and the predominant method in use today. Temperatures typically fall in the range of 800°–2,000°C, permitting the design of processes with large production rates per unit volume using inexpensive reagents such as carbon, but representing a higher temperature range than is characteristic of ordinary industrial chemical processes and imposing a high premium on the specialized combination of scientific and engineering skills required. The iron blast furnace epitomizes these processes. Modern units in Japan produce 4,000 tons of metal per day, with advances in both economy of fuel and production rates continuing at a rapid pace.

Hydrometallurgy consists of chemical reactions carried out in solutions whereby ores or concentrates are selectively dissolved (leached) and the metal values selectively extracted from the solution. Historically this has been accomplished predominantly in aqueous systems and originated with the solution of copper oxide in sulfuric acid, followed by precipitation of Cu on metallic iron. More recently, the versatility of

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FIGURE 6 (a) Primitive metal smelting (Agricola: "De Re Metallica"); (b) modern blast furnace; (c) computer control room for blast furnace.

these methods has been enhanced by the use of pressure and high temperatures and solvent extraction and ion exchange. Recent advances provide a potential to eliminate the actual mining in some ore bodies. There appears to be great promise in the future development of this branch.

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Electrometallurgy employs electrolysis to extract or refine metals from aqueous solutions, as in the recovery of silver from copper bullion, or in the electrolysis of fused salts, as in the Hall process for aluminum. The latter has many advantages for the production of reactive metals that have only recently become commercial, such as the rare earths. The possibilities for future development are extensive.

The importance of extractive metallurgy to societies and nations throughout history has led to its unusually high development through empirical methods and knowledge. This inheritance from previous centuries, and the economic factors associated with high investments in production facilities, has produced a conservative technology that has been relatively slow to take advantage of the possibilities of modern science and engineering. Nonetheless, there have been continuous changes and improvements, and the United States maintained a competitive position, even one of leadership, in many areas of research and production in the first half of the twentieth century. This position has deteriorated seriously since World War II, and important advances in both ferrous and nonferrous metallurgy (basic-oxygen steelmaking, and the zinc–lead blast furnace) have originated elsewhere. (See the report of the Panel on Extractive Metallurgy* for data and discussion of the relative position of the United States.)

Present trends indicate that traditional batch operations will become automated and continuous and that increasingly rigorous chemical specifications must be met despite the fact that more complex and difficult raw materials will be treated, if future requirements of the economy are to be satisfied. The basic science and engineering developments needed for such progress will require a considerable research effort and highly trained technical manpower. Existing educational facilities do not appear adequate for this effort.

At the present time, research and specialized training in extractive metallurgy is conducted in no more than 25 schools, and in many of these on a marginal basis. The metallurgical industries have expanded their organizational and physical (plant) research facilities in recent years but these efforts will not realize their potential without trained personnel. Government research in extractive metallurgy is almost exclusively in the Bureau of Mines, where it prospered for a number of years, but recently it has suffered for lack of adequate stimulation.

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* *Extractive Metallurgy,* to be published by the National Academy of Sciences, Washington, D.C.

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Immediate action is needed to re-establish an adequate level of education and research in extractive metallurgy, and several specific recommendations listed in Appendix B center upon the fiscal support of the authorized responsibilities of the Bureau of Mines to meet these needs.

PRODUCTION OF MINERAL FLUIDS

There are two fundamentally different methods of carrying out activities within the crust of the earth. The first of these is mining, in which men and machines physically remove rock either at the surface or through shafts or pits dug into the earth. The second involves recovery of fluids from the earth, introduction of fluids into the earth, and control of movement of fluids within the earth through the use of wells. Mineral fluid technology is primarily an American development reaching its greatest sophistication in the recovery of petroleum and natural gas but being used also in groundwater recovery, underground storage of fluids, sulfur production, underground disposal of waste fluids, recovery of mineralized water, and geothermal development. Potential uses of the technology include gasification of coal underground, fluidization of ore bodies, *in situ* retorting of oil shale, underground chemical reactions, and alleviation of earthquake stresses.

The technology of handling fluids in the earth is the composite of many technologies: fluid movement in pourous rocks; drilling, completion, and stimulation of wells; evaluation of underground formations; selection of surface and underground equipment for the handling of fluids; use of multiple well systems for control of fluid movement in the earth; and provision of an adequate base for operations, e.g., offshore. Within these broader classifications there are many technical specialties and variations that depend upon the commodity involved, economic incentive, and historical development.

The history of research and development for mineral fluid production has been a very gratifying one. Not only has this technology enabled a nation to have ample supplies of petroleum to fuel and lubricate a steadily expanding economy and a military operation through two world wars, but it has been able to do this through a long period of inflation in which petroleum products are among the few commodities which have not experienced spiraling prices. This impressive result has been accomplished by research and development financed almost wholly by private enterprise and disseminated freely and widely through professional and trade literature. It has provided the base for worldwide

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FIGURE 7 New concept in offshore oil storage. Artist's sketch of a 500,000-barrel oil tank to be located about 65 miles off the coast of the Sheikdom of Dubai for storage of oil produced in the Arabian Gulf. (Courtesy Chicago Bridge & Iron Company.)

operations of the petroleum industry and as such is undoubtedly one of the United States' major technological exports.

An idea of the growth of technology in the oil industry can be gained

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by reviewing a few of the major landmarks. Those developments which have led to most significant improvements in efficiency or capability are rotary drilling, reservoir analysis and control, waterflooding, and hydraulic fracturing.

ROTARY DRILLING

The dawn of the rotary-drilling era with the famous Lucas gusher in 1901 is considered a major landmark. This technique proved more susceptible to modification and improvement than the cable tool technique, and hence rotary drilling is now used almost exclusively.

Essentially, the rotary technique involves turning a metal bit on the bottom of the hole. The bit is screwed on the bottom of hollow pipe which serves to weight the bit down and to circulate drilling fluid. Drilling fluid circulated down the pipe and up the annulus serves to cool and lubricate the bit, to prevent high-pressure fluids from entering the well, and to lift rock cuttings from the hole. As the bit wears and becomes dull or if bearings fail, the drill pipe must be pulled from the hole to replace the bit. Obviously, as greater depths are reached, the size of the surface equipment needed to turn and hoist the added weight of drill pipe is increased.

RESERVOIR EVALUATION AND ENGINEERING

Early evaluation of producing formations was primarily based on production testing. It was possible, however, in using cable tool wells, to examine rock cuttings bailed from the well as the hole was cleaned every few feet. In 1870, diamond-core drilling machines based on the work of the French engineer Leschot came into use in the Pennsylvania coal fields. Diamond-cut cores are still a primary source of data in evaluating the quality of a producing formation, although other methods of cutting cores are in use. Reservoir permeability, porosity, and fluid saturations can be determined from analyses of cores. Another method of formation evaluation consists of running traverses or logs of wells to measure electrical or radioactive signals. The first electric log run by Schlumberger in 1927 measured the electrical resistivity of the formation as a function of depth. Modern electric logging includes measurement of spontaneous potentials generated by current flow between sand and shale members because of differences between ion contents of waters in the formation and in the hole, in addition to measurement of electric resistivities. Other types of logs are gamma-ray logs (1937), which measure natural

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radioactivity, neutron logs (1938), which reflect absorption of neutrons, and velocity or sonic logs (1949), which measure the rate at which sound waves travel through rock. Through proper interpretation of several types of logs, porous intervals can be located and a qualitative measure of the porosity and fluid saturation can be ascertained. Another method of evaluating underground formations is through well tests from which calculations can be made of formation transmissibility around single wells and between interfering wells.

The heart of the petroleum industry lies in proper development and control of the reservoir. When the rule of capture prevailed, the goal was to get as many wells as possible into the ground and to produce oil from those wells as fast as possible without regard for control of reservoir pressure or fluid distribution. Under this policy, most reservoirs were produced by the relatively inefficient dissolved gas drive where the force driving oil into the well was expansion of gas released from solution. The era of the rule of capture lasted until about 1930. The advent of conservation and research into the mechanics of reservoir drives early in the 1930's led to adoption of control, where possible, of rates and production by more efficient means.

WATERFLOODING

A third major factor in oil industry technology has been the advent of waterflooding. The technique of injecting water into pressure-depleted sands to get a second crop of oil flow grew from early work in the Bradford field in Pennsylvania, where increases in production caused by water injection began in 1907 and peaked in 1937. The technology grew rapidly in the 1950's when large-scale waterflooding began in the southwestern United States. The term waterflooding is applied to injection of water into a pressure depleted field when production rates by primary dissolved gas drive or gas cap drive approach uneconomic levels. Waterflooding is distinguished from pressure maintenance by water, a process in which water is injected while reservoir pressure and production rates are still near their original values.

HYDRAULIC FRACTURING

The development of hydraulic fracturing is the fourth major landmark that has greatly extended the efficiency and capability of the petroleum industry. Fracturing or parting of the earth by fluids injected into it under pressure was done accidentally and often unknowingly in early

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days during drilling, acidizing, or even in waterflooding in the Bradford field. The technique developed in 1949 by Pan American (then Stanolind Oil and Gas) engineers consisted of injecting high-viscosity fluids at high rates into a well to part the target formation and then to inject sand-laden fluid into the fracture to prop it open once injection ceased. Early success with the method led to its rapid adoption, and many improvements ensued. Today, methods are available for estimating the width, length, and conductivity of a fracture. Most fractures are thought to be vertical or near-vertical, extending for as much as several hundred feet from the well. Typically, several-fold increases in production rates are achieved in well-engineered fracture treatments where attention is given to the viscosity and fluid loss properties of the fracturing fluid and to the strength and concentration of the propping particles.

Hydraulic fracturing has had a profound effect on the industry. Fracturing has made production from many low-permeability formations commercially feasible and has extended the life of many low-productivity wells. It is estimated that fracturing has added 7 billion barrels of oil to U.S. reserves. It is difficult to estimate the effect of fracturing on the productive capacity of U.S. wells, but the volume probably exceeds 1 million barrels per day.

CONCLUSION

Research pertaining to mineral fluid technology needs to be increased in proportion to the potentials that can be seen for its use. This potential indicates that research activity should be broadened in scope as well. The bulk of research done on underground fluid processes has been done by the oil and gas industries. Primarily because of research, these industries have been able to supply the nation's increasing energy demands despite the depletion of the resource involved. There has been little research on underground fluid processes outside the petroleum and natural gas industries, and this has been done by government agencies or universities. In the universities, the research has been mostly related to oil recovery, natural gas, and groundwater, but the level of university research in these fields is not as great as it should be. In comparison with other fields, it is inadequate to support the graduate students involved.

As requirements for mineral recovery have advanced and as uses of the earth's crust have developed, it has been recognized that there is a continuing need for fundamental research related to subsurface rocks and the fluids within them. Some of the better university work has been done in these areas. Also, as science advances, and as more is learned

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about the atmosphere and ocean, we realize that there are also many basic facts about the earth's crust that are unknown, even though man has been producing minerals from it for thousands of years.

At one time in its history, the Bureau of Mines was at the forefront of research activity in underground fluid recovery. In recent decades, this has not been so, and much of the Bureau's activity has been directed toward development, often duplicating and sometimes lagging behind similar efforts in industry. There is much fundamental work that needs to be done, and the Bureau should recapture its previous role of basic data gathering. Broad-gauge reconnaisance research, investigations of insufficient commercial interest to be pursued by a single company or industry, and long-range studies which industry cannot justify but which are in the public interest are other areas to which the Bureau should attend.

In spite of the advanced state-of-the-art which this technology has achieved, there are outstanding problem areas to which greater fundamental research effort should be directed. Many of these lie in the area of understanding the subsurface environment and its behavior. Some of the more obvious fields of research, such as improving drilling methods, are also some of the more difficult fields, on which considerable research money has already been spent. Nevertheless, significant advances in these difficult areas would encourage effective and economic use of the technology. Many of the fields where advances might be made are of the fundamental type from which broad-scale benefit to the public could result and which therefore ought to qualify for public funds.

The Bureau of Mines should be engaged in a vigorous program of research on underground environments and on the behavior of fluids in the various types of underground situations. This research should be broadly based and should concentrate on fundamentals rather than on development. It should seek to provide the basic knowledge necessary for subsurface environmental evaluation and the basic understanding of underground fluid processes which are common to all applications that require the handling of fluids within the earth.

The Bureau of Mines should create a clear-cut long-range national plan to gain more scientific facts from the earth. This plan should include the drillings of wells for research purposes with public research funds where definite scientific reasons can be enumerated. The plan might include a system whereby wells on public lands are not abandoned or plugged until the appropriate government agencies have been given an opportunity to consider using the wells for scientific purposes. All permits for wells on public land should contain stipulations for the acqui-

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sition and dissemination of geological and engineering information.

The Bureau of Mines should encourage increased basic research in underground fluid technology in the universities and should be a distributing agency for federal funds to be used in stimulating such research.

NONMETALLIC MATERIALS

Essentially the entire solid surface of the earth consists of nonmetallic materials. The first steps in the utilization of these inorganic raw materials are encompassed by the science and technology of mining and mineral beneficiation. Beyond these early stages, the partly processed nonmetallic resources are divided into those which become the raw materials for products which emerge finally as metallic phases, and those which lead to other technological products which in final form are inorganic nonmetallic materials. The latter may be grouped rather naturally into five types of materials: glass; "synthetic minerals," such as graphite, silicon carbide, oxide whiskers, and nuclear fuels; electronic materials; traditional ceramics, including refractories, whitewares, and ceramic coatings; and building materials, including cement, brick, asbestos products, and wall tile.

GLASS

The glass industry in the United States is a healthy one in both growth and technical achievement, having gradually changed from the high-labor, small-plant industry of fifty years ago to one that is highly automated. The development of high-speed automated machines for producing glass envelopes for incandescent light bulbs is a good example of this change. Over one and a half billion light bulbs were produced in the United States in 1966. These were made at a rate exceeding 2,000 per minute for some sizes on "ribbon machines" operated by one man; this compares with the production rate of from 100 to 150 bulbs per hour produced by a four-man hand shop in 1925. At this hand-shop rate, the glass bulb alone would cost almost as much as the retail price of the finished lamp does today.

Flat glass has also proceeded through a major evolution of technical development. The quality of drawn window glass has been improved so that it can be used in side and rear windows of automobiles. Ground and polished plate glass is being produced in a continuous ribbon where both sides are simultaneously ground before cutting. This polished plate

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glass is now being supplanted in part by "float glass," the new process developed in England for making plate-glass quality without the need to grind and polish. The molten glass ribbon is floated on a bath of molten metal as it is cooled, and a flat fire-polished surface on both sides results.

High-production units have been developed for making fiber glass. A large effort in research and development is continuing in the study of resin coatings and laminates. Better resin–glass coupling agents have been developed. Many systems of fiber and cloth with resins have been studied to obtain the optimum in strength. Higher-temperature resins are being investigated to increase the heat resistance of fiber-glass–resin composites.

Some of the most important advances in glass technology of the last decade resulted in the development of crystallized glasses (called glass-ceramics) and the new systems of enhancing strength of glass and glass-ceramics. Glass-ceramics are a family of new materials obtained by heat-treating a glass of the proper composition, first to nucleate and then to grow the desired crystals to obtain an almost fully crystallized fine-grained material with unique properties. Missile nosecones, tableware, cooking ware, electrical appliances, telescope mirror blanks, electrical and electronic components, and structural wall panels are now being produced commercially of glass-ceramics. Other strong glass products are being marketed with transverse strengths exceeding 50,000 psi, compared with thermally quenched glass at 20,000 psi and annealed glass about 6,000 psi. These strengths are being achieved with high-compressive surface layers produced by chemical diffusion at elevated temperatures. Rear windows of convertible automobiles, strong chemical-laboratory ware, and safety glasses are present products.

The new developments of glass-ceramics, strong glass, and the numerous other vitreous materials with new controlled properties will greatly extend the uses of glass and glass-ceramics. The full significance of chemically strengthened glasses and glass-ceramics is still to be determined. They are now stronger than most metals, and no yield, before failure, has been detected. Their ability to withstand high stress for long periods and their low density are creating great interest in their use for deep-submergence vehicles. Further studies on structure and mechanisms of failure will extend present capabilities.

SYNTHETIC MINERALS

The most important materials in this category are: carbides, borides and nitrides; graphite, carbon, and diamond; synthetic gems and single

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FIGURE 8 Synthetic quartz crystals grown at high pressure.

crystals; and nonglassy fibers. All are of great and increasing importance in the growth of the economy. In general, research activity in industrial and government laboratories has grown sharply in recent years. The level of university research and student training in these areas, on the other hand, has been low. Major advances in the technology of all of these matrials, especially in single-crystal technology, have been made in the United States. U.S. industry supplied the vast majority of physicists all over the world with single crystals of the alkali halides on which the experimental foundation of solid-state physics was laid, and brought synthetic quartz (see Figure 8), as well as commercial synthetic diamonds, into genuine industrial production in the early fifties. However, our lead in this field is quickly slipping away. The traditional strength in inorganic chemistry in the Soviet Union and Europe is now being turned toward the preparation of sophisticated single-crystal material on a scale which dwarfs our enterprises. Likewise, the Japanese effort is now bearing fruit. Hence, whereas hardly a decade ago the United States was the acknowledged leader in the field, new materials (e.g., ultrapure large SiC

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and CdS crystals) have become available in the Soviet Union, making possible new devices that cannot be planned in the United States for lack of material.

The need for research and training activity in this area is great. It is needed at two levels and in two different contexts. A major increase in the research by chemistry and chemical engineering departments on the synthesis and growth of new materials is essential. Equally essential is the establishment of a few adequately staffed centers where major national research efforts on crystal preparation (including characterization) can be carried out to provide, hopefully, the material for the "transistor" of the next generation.

ELECTRONIC MATERIALS

Included in this group are semiconductor materials, integrated circuits, phosphors, ferrites, and ferroelectrics. Two important aspects of this field, its interdisciplinary nature and its increasing impact on daily life, are illustrated by the history of the transistor and of one of the major applications of this invention, the electronic digital computer.

The basic research that opened up the field of solid-state electronics was carried out in Europe by physicists and chemists studying the control of the electrical properties of solids, and particularly semiconductors, through the dissolution of minute amounts of impurities in their crystalline lattices. Extensive following work on silicon single crystals at both Purdue and the Bell Telephone Laboratories finally led to the invention of the transistor in 1948 at Bell by a team of chemists and physicists. It has been the transistor, and now increasingly the integrated circuit, that has made possible the extremely-high-speed electronic digital systems of today.

In the semiconductor and electronic composites field it appears that silicon planar technology and, in particular, silicon integrated circuits will dominate the electronic components industry. This will have an increasingly adverse effect on the usage of discrete devices, both active and passive, in the 1970's. The materials field will continue to be dominated by silicon, although germanium may find new life as a material for very-high-speed logic circuits and increasing use of intermetallic compounds, such as gallium arsenide and gallium phosphide, will be found in such applications as optical electronics and in bulk-effect devices.

Turning to ferroelectrics and ferromagnetic materials, higher-purity, higher-density, and more closely controlled parameters are to be expected, along with increased understanding of degradation mechanisms in ceramic capacitors. However, increased use of stacked ceramic con-

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figurations and ceramic loaded polymer films, especially for energy storage applications, may well be offset by replacement of ceramic capacitors in many applications by low-cost solid tantalums, and by the gradual displacement of passive components in general by integrated circuits.

The story is much the same with ferromagnetics: A large increase due to their use in new consumer products (for example, electric knives and electric toothbrushes) will be compensated for by a peaking in the ferrite memory core volume in 1970. However, application of modern solid-state techniques to the fabrication of pulse transformers will continue to make this an attractive growth area.

Trends in piezoelectric materials are harder to evaluate. An intriguing multiplicity of new uses is seen in laser modulators for such applications as communications and photography, as well as in ultrasonic and microwave transducers. Nevertheless, it would appear that dollar sales will remain dominated by quartz crystals.

Particularly in the semiconductor and electronic composites aspects of electronic materials, industry has a large lead on the universities in trained personnel, in equipment, and in support (internal as well as federal). Therefore it is evident that industry is in an excellent position to help train personnel for this field.

REFRACTORIES, WHITEWARES, AND CERAMIC COATINGS

The traditional fields of refractories, whitewares, and ceramic coatings have become important elements in our rapidly advancing technology. For example, refractories for the aerospace and the nuclear-energy industries have become the objects of major development programs.

Further development of the nuclear-energy industry is dependent on materials development and characterization in a category very close to traditional refractory technology. There is at present a technological scrambling for ceramic engineers and scientists for this growing nuclear-power industry. This shortage will become even more critical as the advanced breeder reactor and fast neutron reactors appear (after 1980).

The refractory industry in general is one whose major problem areas are material characterization, process development, and material utilization. Probably few new materials will appear in the near future. Rather, the breakthroughs will come at all levels of improved characterization with emphasis on synthetic mineral production and controlled microstructure. This is all being done in an economic climate in which an expenditure for research of 2–3 percent of sales would be high and in which there has been relatively little government funding.

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BUILDING MATERIALS

In the projected vast urban development programs, building materials will play an important role, and the major opportunities for research and development are in the mineral products field, where materials are needed that are more fire-resistant, that are more vandal-proof, that facilitate "componentization," and that are more gratifying to the human senses.

CONCLUSION

The science and engineering of nonmetallic materials has emerged from the era of an empirical technology aimed at producing inexpensive products in large volume into an era in which the principles of modern solid-state chemistry and solid-state physics must pay a crucial role in further advances. Radically new technologies have been developed that add enormous value, via novel processing methods, to ceramic materials; these have led to a diverse set of new materials, including synthetic diamonds, ceramic armor, crystallized glasses, and miniature integrated circuits. Yet the potential exists that with the right support the world of inorganic materials will make an advance that would correspond to the transition in the organic world from the rayon era to the nylon–polyethylene age.

This branch of technology is characterized by a very low ratio of government to industrial research and development money, and also by a low figure for research and development as a percentage of sales. These and other factors have led to three serious imbalances in the field: The applied research and development (conducted mainly in industrial laboratories) outweighs the necessary supporting basic work performed in industry and universities; the students trained within the discipline do not match the needs of the employers either in numbers or in nature of training; the chemical sciences of synthesizing, preparing, and characterizing ceramics have been neglected in favor of property-oriented research.*

The Committee recommends the development of several major centers of excellence at universities to provide for both basic research and training of personnel. Doubling of the total federal support of research and development, which would include tripling of support of basic research at universities, can be achieved effectively within a decade.

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* *Characterization of Materials,* MAB-229-M, Materials Advisory Board, National Research Council, National Academy of Sciences, Washington, D.C., 1967.

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FUEL SCIENCE AND TECHNOLOGY

Fuel science and technology embraces basic and applied research as well as commercial developments associated with the analysis, properties, reactions, processing, distribution, and ultimate use of primary and processed fuels. Included are: combustion of fuels, conversion of fuels to other forms of energy, use of fuels in metallurgical and reduction processes, and conversion to non-fuel uses (chemicals, food, etc.). Only fossil fuels and their commercial application are considered here. Nuclear fuels and fuels for rocket propulsion are outside the scope of the report.

COMBUSTION

Basic and applied research on the combustion of solid, liquid, and gaseous fuels has contributed to the advanced state of development of large central station boilers, jet engines, and reciprocating internal combustion engines. Nevertheless, there is still need for improved understanding of: combustion aerodynamics (mixing, turbulence, swirl, and recirculation) and radiation; and flame stabilization and high-intensity combustion. The development of such information is the most pressing requirement for the advancement of combustion technology.

Throughout the history of combustion research, attention has been directed to the solution of problems involving air pollutants emitted with the products of combustion. The intensive use of fossil fuels now and projected for the future emphasizes the need for expanded research efforts in this field, including the acquisition of more detailed knowledge of the chemistry of combustion.

Fire research in which the basic principles of fuel science and technology are applied to control and prevent destructive fires has been receiving increased attention in the recent past. Because of the importance of this area in conservation of resources and in reduction of property losses, it is important that this area of research be continued and expanded.

CONVERSION OF RAW FUELS

Conversion of raw fuels to useful forms includes refining of crude petroleum and conversion of solid fuels to gases and liquid fuels. The refining of crude petroleum is highly advanced, and only minor refinements can be anticipated in this technology. In the conversion of solid fuels,

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essentially coal, to marketable gases and liquids, the development of new technology to improve the economics of such processes is now in progress in the United States.

Significant contributions of future research and development to advance fuel science and technology can be made by

- Development of economical processes for converting coal, oil shale, and tar sands to gases and liquids. Such developments would not only ensure the supply of fuel in the desired form but would also contribute significantly to the solution of air pollution problems involving particulate and sulfur emissions.
- Increased efficiency of conversion of fuels to electricity.
- Increased efficiency of utilization of fuels, specifically in the area of developing convenient mass transportation systems that would eliminate the inefficiency and congestion resulting from the "one man–one car" system now extant.
- Improvement in the reliability and reduction in cost of distributing electricity.

METALLURGICAL USES OF FUELS

Primary metal production involves a use of fossil fuels that is of major national importance and is an area in which the fuel technologist has made great contributions. In looking at opportunities for future research, iron must take first priority by sheer magnitude of the quantity produced. Opportunities exist in the following areas

- Direct reduction (non-blast-furnace processes)
- Reduction in the cost and sulfur content of metallurgical coke and production of a coke of uniform size and regular geometric shape
- Development of improved technology for injecting natural gas, petroleum products, and coal into the bottom of the blast furnace
- Development of technology for the direct utilization of natural gas in the production of aluminum and magnesium
- Development of methods for reduction and elimination of pollution problems in primary metal production

NON-FUEL USES

Coal, petroleum, and natural gas are the raw materials used in the production of organic chemicals and ammonia.

Research and development on the production of organic chemicals

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from fossil fuels has been done almost entirely by industry. Because of the value added to the raw materials, there has been adequate economic incentive for private enterprise to undertake and continue research in this area, and federal support is unnecessary.

The production of protein for food using fossil fuels as raw materials is a relatively new area receiving increased research attention. At present this research is being done principally by industry and some independent research organizations, and the Committee sees no need for federal involvement at this time.

MINERAL ECONOMICS AND RESOURCES

Mineral economics involves studies of past, present, and future supplies of, and requirements for, minerals and mineral products, along with costs and profitability. Mineral economics is intimately involved in the practical application of the six basic mineral science and technology fields described in the preceding pages. However, in addition to purely scientific and technical information, mineral economics also considers the politicoeconomic factors affecting minerals in every nation that is an actual or potential producer or consumer.

Mineral economics studies vary in breadth and depth, depending on the ultimate purposes. Every firm in the mineral industry must use mineral economics both in day-to-day operations and in long-range planning. In a free economy, mineral economics provides the analyses which determine profitability—the common denominator governing the ultimate application of all science and technology. Some large firms have special mineral economics staffs. Banks involved in the financing of mineral ventures make extensive economics studies. Labor unions engaged in contract considerations must consider mineral economics. Additionally, consulting firms, technical societies, trade associations, foundations, and universities make mineral economics and resources studies. A significant role is played by the many publications that report, and sometimes analyze, items of mineral economics news.*

Some mineral economics and resources studies are supranational or international: for example, those by or for the European Coal and Steel Community, the International Lead-Zinc Study Group, the International Tin Council, the International Monetary Fund, various agencies of the United Nations, and many other groups. In almost every country, free

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* See appendix of *Mineral Economics*, to be published by the National Academy of Sciences, Washington, D.C.

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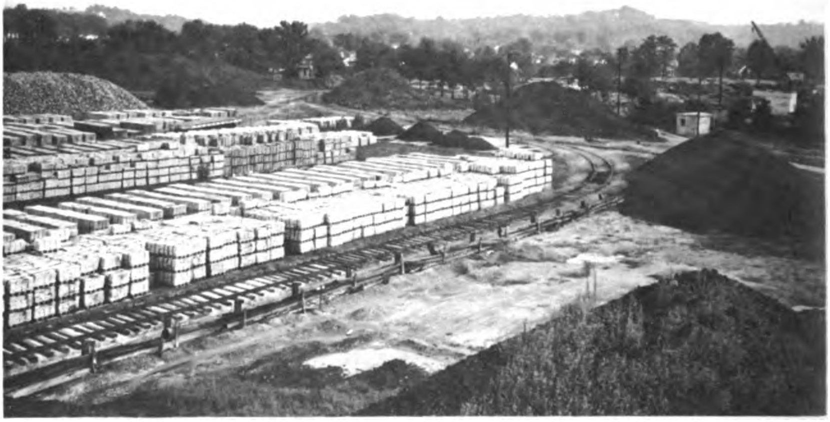

FIGURE 9 Open storage of several different metals and ores at one of the national stockpile depots. Materials are stored as close as possible to consumers to aid continuity of production despite disruption of transportation facilities in wartime. Note that provision is made for ready access by both truck and rail. As much as 1 million tons of ore may be stored in one pile, or in some cases, as little as 20 tons. (Photo courtesy U.S. Bureau of Mines, U.S. Department of the Interior.)

or totalitarian, governmental studies seek to discover resources that can be developed and to set forth policies and programs that will lead to the proper use of these resources in the service of man. In free countries, such as the United States, mineral economics plays a prominent role in many agencies of the federal government* in connection with matters of national security, such as oil import regulation, stockpiling 63 strategic and critical minerals (see Figure 9), and maintenance of an adequate mobilization base, while everyday peacetime considerations revolve around trade policy, monetary policy, taxation, antitrust, patents, public lands, stimulation of the economy, research and development, conservation, and environmental enhancement. In totalitarian countries, mineral

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* See appendix of *Mineral Economics*, to be published by the National Academy of Sciences, Washington, D.C.

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economics lays the groundwork for national goals; for example, the expansion and dispersion of the Soviet steel industry many years ago, or the more recent decision of the Soviet Union to enter the petroleum markets of Western Europe. In the United States, at the regional level, many studies are made of the problems peculiar, for example, to Appalachia, or to the continental shelf, or to the megalopolis of the East. In each state, one or more agencies are concerned with various aspects of mineral economics.* And at the local level many studies involve, for example, the adequacy of materials for construction; or environmental enhancement involving local streams, estuaries, land usage, or atmospheric problems.

The "total energy" concept, the need to meet materials performance specifications, the desirability of utilizing all possible by-products, the increasing investment needed to assure high productivity, the increasing desirability of transportation and power systems that cross national boundaries, the increasing involvement of governments, and the increasing complexity of all advanced economies are all accelerating the trend toward rationalization of the U.S., and the world, mineral industries. Rationalization is marked by mergers, and by horizontal and vertical integration. Rationalized industries will have greater need for mineral economics than did the relatively simple business units that concentrated on one or two basic products that sold in substantially the same form for generation upon generation. Governments, too, need more and better mineral economics and resources information.

Fortunately, the United States has a good start in the relatively new field of mineral economics. One university already has an established Department of Mineral Economics, and several others have given degrees and/or sponsored studies in the field. One foundation and many companies have sponsored studies. Interest in mineral economics and resource studies is on the increase in a number of important agencies of the government. But much more needs to be done, and it must be done in conjunction with the six basic fields of mineral science and technology whose trained personnel in turn need to know more of the worldwide politicoeconomic environment. Industry, professional societies, government, and education are all in a position to make significant inputs into the field of mineral economics. And, as is true for any field, the greater and the better the inputs, the better and more useful should be the outputs. Needed all along the line is more information—information about

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* See appendix of *Mineral Economics*, to be published by the National Academy of Sciences, Washington, D.C.

reserves, technological processes, productivity, costs, profits, markets, detailed applications and uses, and national and international politico-economics. As one important step in fulfilling this need, we urge that the Director of the Bureau of Mines institute timely studies on a continuing basis, using the most advanced techniques for economic and technologic forecasting and analysis, and for data handling, storage, retrieval, and display, all aimed at keeping readily available for use an up-to-date knowledge of the forces affecting mineral production, supply, demand, and consumption in the United States and the world.

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6

Organization and Financing of Research and Education in Mineral Science and Technology

The number of mineral scientists and engineers in the United States is approximately 65,000. They belong to several different technical societies which serve the important functions of providing national forums for the presentation and discussion of technical papers and of publishing journals for dissemination of research results and other information of professional use. Three of the societies are grouped within the American Institute of Mining, Metallurgical and Petroleum Engineers (AIME): the Society of Mining Engineers (about 15,000 members), the Metallurgical Society (about 13,000 members), and the Society of Petroleum Engineers (about 17,000 members). Mineral economists and some fuel scientists and engineers are also active participants in the AIME. The American Ceramic Society, with a membership of approximately 7,000 scientists and engineers, is the principal organization for technical people dealing with nonmetallic, inorganic materials. Engineers and scientists engaged in research in fuel science and technology number about 10,000 and are variously affiliated with the American Society of Mechanical Engineers, the AIME, the Fuel Chemistry Section of the American Chemical Society, the Society of Automotive Engineers, and other organizations. Based on data provided by the AIME and the American Ceramic Society, approximately 80 percent are employed by industry, 7 percent are employed by government, 6 percent are located at educational institutions either as employees or as student members of the AIME or the American Ceramic Society, 4 percent are self-employed, and 3 percent have other employment.

That the field of mineral science and technology does not represent

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a homogeneous discipline is illustrated by the dispersal of its practitioners among many societies, and also by the variety of organizational arrangements in universities and in state mining bureaus. In the federal government the fields are largely grouped within a single agency, the Bureau of Mines, but related programs and mineral policymaking groups are dispersed throughout many parts of the government.

The following sections briefly describe the organization and financing of mineral science and technology in universities, government, and industry, and present suggestions regarding desirable future developments.

UNIVERSITIES

The following statement by the well-known mining engineer, Herbert Hoover, is of interest as an introduction to a discussion of university programs in the mineral fields.*

> In the year 1556 the first systematic treatise upon engineering, chemistry, law and something on medicine in relation to mining was published under the title "De Re Metallica," by Georgius Agricola. Agricola called his exposition a discussion of the "many arts and sciences of which the miner must not be ignorant." The book was in Latin. But translated into many languages, it became the center around which innumerable groups were taught over two centuries the beginnings of these sciences. Chained to the altars of the churches in the days of the Spanish Conquest, it was translated and expounded by the priests of the first Spanish miners. Here, perhaps, first began technical education.
>
> Indeed, a large part of early engineering and chemistry had its origins in the mines. The beginnings of systematic engineering training began with the Old World mining schools established during the eighteenth century. These schools were largely to train minor officials for the state-controlled or state-owned mines. Engineering as a profession received its real establishment in the New World. Socially, officially, and economically, the builders of cathedrals, the operators of mines, the makers of bridges and ships were regarded as artisans until well within the nineteenth century.
>
> My own impression is that it was not until the American universities embraced engineering as a full part of their work that engineering took upon the full dignity of a profession. The major demarcation between an artisan and an engineer is not alone the actual technical knowledge. It is the recognition of the qualifications of broad education and obedience to a code of ethics. Anyway, the British universities refused to incorporate engineering into their curricula until much later than the Americans. In the meantime, the American engineers—especially the mining engineers—flooded the British Empire.

Degree programs in mineral engineering were established in the United States beginning in the mid-nineteenth century, coincident with

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* Foreword *in The Development of Mineral Industries Education in the United States,* by T. T. Reed, AIME publication, 1941.

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the founding of the land-grant colleges and the great surge toward the development of practical higher education. Mineral industries education had been developing in Europe for over a century before the first mining degrees were granted in the United States. The Polytechnic College of the State of Pennsylvania was the first American institution to grant mining degrees. It was founded in 1853, and it is known certainly that two bachelor of mine engineering degrees were awarded on June 26, 1862. Columbia and the University of Michigan granted 13 and 2 E.M. degrees, respectively, in 1867. Massachusetts Institute of Technology, Yale, Lafayette College, Washington College (Washington and Lee), Lehigh University, and Rensselaer Polytechnic all began offering a curriculum in mining and/or metallurgical engineering in the 1860's. In the latter part of the nineteenth century, separate schools of mines were established in the western states. Curricula in petroleum production engineering were established at several institutions during the first two decades of the twentieth century. The first curriculum in ceramic engineering was established in 1894 at Ohio State University. Subsequent departments of ceramic engineering were established at other state institutions throughout the country during the next half century. Curricula in fuel technology and in mineral economics were established at The Pennsylvania State University in 1932 and 1947, respectively.

Since World War II, the number of mining departments in universities in the United States has decreased, and mining schools have enlarged their offerings to become more broadly engineering colleges. Insufficient undergraduate enrollment has been the cause of the demise of some of the older mining schools such as those at Lafayette College and Lehigh University. At others, the undergraduate curriculum has disappeared, but the graduate curriculum has been retained, as the number of graduate students in mining as well as in the other engineering fields has recently increased. Many of the institutions having one or more of the mineral engineering curricula have for the past decade or more faced the serious question of whether the need for mineral engineers in the state or region served by the institution can justify the maintenance of curricula that attract so few students and thus represent high-cost education; another problem is that of obtaining first-rate faculty members for a department with a questionable future. Proponents of maintaining these departments despite the present low enrollment argue that the country must train people in these fields and must make every effort to encourage students to enter them so that the United States can maintain its position in the production and extraction of mineral resources. It is felt that, compared with some other fields, the mineral engineering fields may not have received the badly needed support since World War II that would have helped them maintain their competitive position with those

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other fields that have received large-scale financial support from the federal government. The following sections present summaries of data obtained on the present status of the mineral science and engineering curricula in universities, obtained largely from a survey of schools having one or more of the mineral curricula.

THE NATURE OF MINERAL ENGINEERING* CURRICULA IN EDUCATIONAL INSTITUTIONS

There are in the United States a total of 62 educational institutions having undergraduate curricula in one or more of mining, metallurgical, petroleum, and ceramic engineering as listed in the 1967 annual report of the Engineers' Council for Professional Development (ECPD). Forty or fifty other schools have programs in one or more of the fields of geological engineering, mineral economics, fuels engineering, and materials engineering where work in ceramics or extractive metallurgy is included. A questionnaire (see Appendix C) was sent to 98 of these institutions—all of those from whom it was believed that information might be obtained which would be helpful in this study. The response was excellent, for although only 71 of the 98 replied, the respondents included virtually all of the schools having accredited curricula in the fields of present interest. For example, replies were received from every one of the 17 mining departments plus an additional four engineering departments which have a mining program but not an ECPD-accredited curriculum in this field. Similarly, replies were received from every one of the 13 institutions having an accredited undergraduate curriculum in ceramics (or ceramic engineering or ceramic science) plus an additional four institutions which have an undergraduate ceramics option or major but not an accredited curriculum. In petroleum engineering, 13 of the 19 departments having accredited curricula replied. Obtaining meaningful data on extractive metallurgy is a problem, for even on the graduate level, separation from physical metallurgy is not sharp at schools offering both, and furthermore, physical metallurgy merges into or may be absorbed in a materials science or engineering curriculum. Data on metallurgy curricula were provided by 42 institutions, including 25 of the 32 departments in the United States having the largest number of juniors and seniors.

Fifty-nine of the institutions replying to the questionnaire reported

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* Although the terms science and technology are used in the title of this report and apply broadly to the subject, curricula representing the mineral fields in universities are most commonly classed among the engineering fields. Therefore, and in the interests of simplification, the curricula will be referred to as engineering in this section.

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graduate programs and 54 reported undergraduate programs in mineral science or engineering.

We believe that the data obtained give a reliable picture of the status of mineral engineering in the universities in 1967–1968, providing current data on the size of mineral engineering departments, the nature of support of graduate and research programs, and the needs of these departments. Tables 2 through 11 summarize the data.

Table 2 summarizes information obtained on undergraduate enrollment in the upper classes in the fall of 1967. The figures therefore represent the total number of students in these curricula in the last two years of a four-year program or last three years of a five-year program. Figures for the freshmen and sophomore years were not requested for several reasons, the principal one being simply that in many schools freshmen are not differentiated by curriculum. Especially noteworthy is the extreme spread among schools in number of upper-class students in a particular curriculum. For example, in mining the median number of upper-class students in the fall of 1967 was 12, but in one school there were 120 and in another there were only two. The classification "other mineral science and technology" is principally geological engineering, but also includes mineral economics and engineering geoscience.

Tables 3 to 5 show the graduate enrollment. Among the institutions reporting, there were 152 M.S. programs and 119 Ph.D. programs as compared with 103 B.S. programs (Table 2). The graduate programs of particular interest in this table for purposes of this study are those in mining, extractive metallurgy, nonmetallic materials, and petroleum engineering. Physical metallurgy is considered generally outside the scope of this study, and the data were obtained on this field only incidentally (and are not complete) while seeking information on extractive metallurgy. Fuel science and "other mineral science and technology" are important components of this study but are impossible to define in such a way as to obtain very useful data from a questionnaire. For Ph.D. programs in mining and petroleum engineering, the median number of graduate students per department is 5, and for extractive metallurgy the median is 7, and almost half of these students are foreign. Inasmuch as about five years are spent in graduate school for a Ph.D. degree, we judge that only about one Ph.D. degree is awarded in the median department per year in these fields, and every other year it is awarded to a foreign student.

The small size of the full-time faculties, averaging 3.5 in mining, extractive metallurgy, and petroleum engineering and 6 for nonmetallic materials, is apparent from Table 6, and is to be expected from the small student enrollment.

Table 7 provides data on graduate student stipend and tuition support.

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TABLE 2 Upper-class Undergraduate Enrollment, Fall 1967[a]

Field	Number of Departments Reporting	Number of Students						
		Total	Min.–Max.	Average Number	Median Number	Number Foreign	Percent Foreign	Percent of Total
Mining	21	392	2–120	19	12	13	3	13
Metals engineering	36	1,199	3–156	33	28	31	3	39
Ceramics & ceramic engineering	17	579	4–154	34	24	13	2	19
Petroleum engineering	13	412	8–73	31	29	74	19	12
Fuel science	3	20	1–11	7	8	7	35	1
Other mineral science and technology	13	510	2–326	39	15	25	5	16
Total	103	3,112				163	5	100

[a] The number of institutions reporting was 54, and the average number of upper-class mineral science and engineering undergraduates enrolled per institution was 57.

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TABLE 3 Enrollment in M.S. Degree Programs, Fall 1967

Field[a]	Number of M.S. Programs Reported	Number of Students						Percent of Total
		Total	Min.–Max.	Average Number	Median Number	Number Foreign	Percent Foreign	
Mining	19	117	1–20	6	5	56	48	8
Extractive metallurgy	25	140	1–18	6	4	58	41	9
Physical metallurgy	38	498	1–55	13	11	81	16	33
Nonmetallic materials	32	333	1–33	10	8	63	19	22
Petroleum engineering	15	210	1–45	15	6	85	41	14
Fuel science	5	29	1–16	6	4	16	55	2
Other mineral science and technology	18	179	1–91	10	5	17	10	12
Total	152	1,506				376	25	100

[a] Fifty-nine institutions reported M.S. degree programs in one or more of these fields.

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TABLE 6 Number of Faculty and Other Professional Members of Staff, Fall 1967[a]

Field	Number of Departments Reporting	Regular Faculty (Professional Ranks)		Other Professional Personnel, Not Degree Candidates[b]	Total	Percent of Total
		Full Time	Part Time			
Mining	21	81	21	2	104	10
Extractive metallurgy	28	90	10	14	114	11
Physical metallurgy	44	228	31	55	314	31
Nonmetallic materials	35	206	13	56	275	27
Petroleum engineering	16	55	24	1	80	8
Fuel science	7	26	2	9	37	3
Other mineral science and technology	21	76	16	9	101	10
Total	172	762	117	146	1,025	100

[a] The number of institutions reporting was 59.

[b] Visiting professors, postdoctoral fellows, etc.

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TABLE 7 Support of Graduate Students by Fellowships, Assistantships, Traineeships, Fall 1967[a]

Field	Number of Departments Reporting	Number of Students						Financial Support of Students ($ Thousands)			
		Scholarships, Fellowships, Traineeships		Research Assistantships		Teaching Assistantships		Annual Support over and above Tuition		Annual Tuition Support	
		Total	Median	Total	Median	Total	Median	Total	Median	Total	Median
Mining	17	41	3	98	7	12	1	327	17	71	6
Extractive metallurgy	18	99	4	152	4	29	1	799	25	208	4
Physical metallurgy	32	215	5	380	9	74	2	2,107	42	792	7
Nonmetallic materials	25	148	3	220	3	40	2	1,515	32	355	6
Petroleum engineering	11	28	2	47	4	17	3	229	15	26	3
Fuel science	9	40	3	34	1	3	1	241	10	58	3
Other mineral science and technology	17	115	4	198	7	59	2	1,007	38	235	7
Total	129	686		1,129		234		6,225		1,745	

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[a] The number of institutions reporting was 59.

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Table 8 summarizes data on the annual rate of funding of graduate and research programs by organizations other than the institutions themselves. The figures include fellowships and traineeships as well as research grants and contracts. The figures are for contracts and grants in effect in the fall of 1967 and are those reported by the institutions having the 159 graduate programs of Tables 3–5. If physical metallurgy is omitted, the total is $10.8 million. Support of the graduate and research program in many departments is indeed very small for an experimental science or engineering program.

The sources of the funds reported in Table 8 are indicated in Table 9. About three-fourths of the funds are from the federal government, with largest amounts coming from the Department of Defense, the Atomic Energy Commission, the National Science Foundation, and the National Aeronautics and Space Administration.

Funds for support of the graduate and research programs by field are shown in Table 8. In Tables 10 and 11, the distribution by resource and by activity, respectively, is indicated. Regarding resource, about three-fourths of all funds are expended for programs concerned with metals and nonmetallic materials. Each of the other resources received 6 per-

TABLE 8 Distribution by Fields of Funding of University Graduate and Research Programs by Outside Agencies, Fall 1967[a]

Field	No. of Departments with Graduate-Research Programs Reporting	$ (thousands)	Percent of Total	Percent of Total less Physical Metallurgy
Mining	19	681	4	6
Extractive metallurgy	25	1,744	10	16
Physical metallurgy	38	6,704	38	
Nonmetallic materials	32	4,734	27	44
Petroleum engineering	15	745	4	6.5
Fuel science	6	595	4	5.5
Other mineral science and technology	18	2,323	13	22
Total	153	17,526	100	100
Total less physical metallurgy	115	10,822		

[a] The number of institutions reporting was 53; two institutions reported only physical metallurgy on this questionnaire.

TABLE 9 Distribution by Field and by Agency of Funding of University Graduate and Research Programs by Outside Agencies, Fall 1967 (thousands of dollars[a])

Field	NSF	DOD	NASA	USBM	NDEA	AEC	Other Federal Agencies	Total Federal	State Agencies	Industry	Endowments and Other	Total	Percent of Total
Mining	82	1	0	40	19	0	130	(272)	195	101	113	681	4
Extractive metallurgy	234	75	2	138	41	26	90	(606)	222	775	141	1,744	10
Physical metallurgy	1,117	2,260	498	20	73	1,272	372	(5,612)	74	928	90	6,704	38
Nonmetallic materials	761	1,609	466	19	66	751	186	(3,858)	298	547	31	4,734	27
Petroleum engineering	5	0	22	10	6	140	162	(345)	109	245	46	745	4
Fuel science	156	39	27	35	0	0	87	(344)	89	157	5	595	4
Other mineral science and technology	523	166	184	6	61	15	693	(1,648)	483	121	71	2,323	13
Total	2,878	4,150	1,199	268	266	2,204	1,720	(12,685)	1,470	2,874	497	17,526	
Percent of total	16	24	7	2	2	12	10	73	8	16	3		100
Total less physical metallurgy	1,761	1,890	701	248	193	932	1,348	(7,073)	1,396	1,946	407	10,822	
Percent of total	16	17	7	2	2	9	12	65	13	18	4		100

[a] Figures rounded off to nearest thousand.

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cent or less. Inasmuch as the bulk of the funds are in physical metallurgy and ceramics, the largest percent of funding falls in the "other" category of Table 11.

Mining Engineering Undergraduate programs leading to an ECPD-accredited degree in mining engineering exist now in only 17 schools, all of which responded to the questionnaire. In addition, four other institutions having mining engineering programs or options in an engineering department also responded, giving a total of 21 departments, as shown in Table 2. The significant number for undergraduates is the number of upper-class majors, excluding freshmen and sophomores. This number is 19 in the average department, 12 in the median, and varying from two students in the smallest to 120 in the largest department. This means that there are about nine or ten students in each of the junior and senior classes in the average department, and only about six in the median. Of the total of 392 students, 13, or 3 percent, are foreign.

In the graduate program in mining, 19 schools reported M.S. programs, and nine reported Ph.D. programs. In the M.S. program, an average of six students was reported, a mean of five with a variation of from one to 20. The eight Ph.D. programs average seven students, with a

TABLE 10 Distribution by Resource of Funding of University Mineral Science and Technology Graduate and Research Programs by Outside Agencies, Fall 1967

Resource	Number of Departments Reporting	$ (thousands)	Average $	Median $	High $	Low $	Percent of Total
Coal	10	634.3	63.4	28.4	358.2	4.8	4
Petroleum	12	644.2	58.6	30.1	203.6	17.9	4
Natural gas	8	349.9	43.7	20.1	174.5	5.9	2
Oil shale	6	120.5	20.1	18.7	35.0	6.7	1
Industrial minerals and rocks	15	967.8	64.5	31.7	334.5	1.7	5
Metals	40	7,575.8	189.4	138.4	1,251.7	2.2	43
Nonmetallic materials	35	5,082.9	145.2	82.0	1,330.6	2.1	29
Water	13	998.4	76.8	40.0	336.9	4.8	6
Other	10	1,111.6	111.2	87.3	329.0	10.0	6
Total	149	17,485.4					100

TABLE 11 Distribution by Activity of Funding of University Mineral Science and Technology Graduate and Research Programs by Outside Agencies, Fall 1967

Activity	Number of Departments Reporting	$ (thousands)	Average $	Median $	High $	Low $	Percent of Total
Production of raw materials	24	1,745.9	72.7	28.9	698.1	3.0	10
Beneficiation of raw materials	17	832.2	49.0	16.0	255.9	2.1	5
Extraction and primary processing of metals	23	1,509.6	65.6	45.2	208.5	3.9	9
Processing minerals for nonmetallic uses	19	2,223.6	117.0	36.4	1,381.8	2.1	13
Fuels research and development	9	607.0	67.4	28.4	358.2	13.9	3
Environmental improvement	13	1,526.9	117.5	62.7	423.0	9.3	9
Underground storage	6	286.0	47.7	25.6	175.5	5.9	2
Nonmineral applications of mining technology	5	174.4	34.9	25.1	95.2	5.3	1
Transportation of mineral materials	2	27.7	13.8	15.0	15.0	12.7	0
Safety and health	4	51.3	12.8	14.3	19.3	5.0	0
Other	41	8,500.8	212.5	137.0	1,573.6	9.1	48
Total	163	17,485.4					100

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median of five and a spread of from one to 17. In contrast with the undergraduate program, approximately half of the students in the graduate program are foreign—56 of 117 M.S. candidates and 33 of 67 Ph.D. candidates. In the 19 departments reporting graduate students, the average total number of students is ten and the median is eight.

The faculties in mining departments are small, as suggested from Table 6, where only 81 full-time faculty are listed for 21 departments, an average of about four per department.

Financial support of the graduate and research program in mining is astonishingly small when considered as a country-wide total. The total in outside funds in support of all of the graduate and research programs in mining reported in the questionnaire (Table 8) is $681,000 on an annual basis for 19 departments reporting, for an average of only approximately $36,000 each. This is to maintain an average of 10 graduate students per department!

Metallurgy The undergraduate curriculum in metallurgy is taught under various departmental labels: metallurgical engineering, metallurgy, metallurgy and materials science, materials engineering, and materials science. The ECPD listing includes 48 accredited curricula. The questionnaire was returned from 38 of these and from four other institutions having a metallurgy program. Thirty-six departments reported upper-class undergraduate enrollment. The coverage of metallurgy departments was not as complete as for mining, but was nevertheless very good, as indicated by the fact that of the 32 departments in the country having the largest number of juniors and seniors, questionnaires were returned from 25. Extractive and physical metallurgy are not separated on the undergraduate level, but on the basis of the ratio of graduate students in the two fields, about 40 percent of the 1,199 upper-class students (about 480) will have primary interest in extractive metallurgy, the field of principal concern in this study. The average department has 33 majors, and the median number is 28. If approximately 40 percent of these have primary interest in extractive metallurgy, then there are fewer (about 13) upper-class undergraduates in extractive metallurgy than in mining in the average curriculum.

On the graduate level, a reasonably good separation can be made between students and programs in extractive metallurgy from those in physical metallurgy. The physical metallurgy reported is substantially only that being done in metallurgy departments and does not include the bulk of graduate and research work in this field being done in graduate materials science groups throughout the country. Our principal concern here is in extractive metallurgy. This field in universities closely re-

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sembles mining in its historical development and in its decline in the United States during the past two or three decades. Comparing the M.S. programs of mining and extractive metallurgy (Table 3), the respective numbers are 19 and 25 departments reporting, identical number of students (six) in the average department, with a minimum and maximum number of one and 20 and one and 18, and 48 and 41 percent of the students are foreign. Twice as many Ph.D. programs were reported in extractive metallurgy as in mining (18 versus 9), but the minimum and maximum numbers of students are identical (one and 17), the average number of students is the same (seven), and the percentage of foreign students is 41 in extractive metallurgy versus 49 in mining.

The size of the faculty in extractive metallurgy is similar to that in mining—about three full-time members per department.

Total funds from outside sources in support of extractive metallurgy graduate and research programs as reported from the 25 departments were $1.744 million on an annual basis in the fall of 1967, for an average of $70,000 each, to support an average of 11 graduate students. This is at a higher rate than for mining, but less than we consider adequate to provide competitive stipends and modern research equipment.

Ceramics There are 13 undergraduate curricula in ceramics (or ceramic engineering or ceramic science) in the 1967 ECPD listing. All of these departments responded to the questionnaire, and, in addition, response from the questionnaire was received regarding four other undergraduate ceramic programs, for a total of 17.

It will be noted from Table 2 that there are fewer than half as many ceramic as metallurgy undergraduate departments, and that the number of majors in the average department is almost identical in the two cases. In ceramics there is no breakdown between the extractive or process or chemical ceramics on the one hand and physical ceramics on the other, corresponding to these divisions in metallurgy. This is because there is no "extractive ceramics" in the sense of "extractive metallurgy." There are process ceramics, chemical ceramics, and physical ceramics, but these are inseparable on both the undergraduate and graduate levels, and hence ceramic departments on both levels compare approximately with combined extractive and physical metallurgy in type of subject and scope and, as it turns out, also in average number of students in a curriculum and in amount of outside financial support.

In the M.S. program in ceramics, or nonmetallic materials of Table 3, the total number of degree candidates and the average and median per department is between that of extractive metallurgy and physical metallurgy. Comparing the nonmetallic materials M.S. program, which in-

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cludes all aspects of ceramics, with the total metallurgy programs, the average number of M.S. candidates is identical, i.e., ten in each case.

In the Ph.D. program (Table 4) the ceramics groups (nonmetallic materials) compare much more closely to physical metallurgy than to extractive metallurgy. Thus, in the Ph.D. program, the number of candidates is approximately 15 in the average ceramics or physical metallurgy group, and this compares with seven in the average extractive metallurgy or mining group. The percentage of foreign students is comparable in ceramics and physical metallurgy, and much smaller than in mining and extractive metallurgy. In combined number of M.S. and Ph.D. candidates, ceramics and physical metallurgy are the same at 24. There are 11 students in the average extractive metallurgy program, and 10 in the average mining program.

In the funding of graduate and research work in ceramics (nonmetallic materials of Table 8), the figures are comparable to those for physical metallurgy, with an average per department of about $150,000 to $175,000 on an annual basis in the fall of 1967.

Petroleum Engineering The number of undergraduate programs in petroleum and in natural gas engineering on the ECPD list is 19. Thirteen of these, and all of the larger groups, responded. The number of upper-class majors in the average department is 31, similar to the figure for metallurgy and ceramics. Not surprisingly, the percentage of foreign students is much higher—19 percent of the total. On the graduate level, the profile of petroleum engineering departments resembles mining and extractive metallurgy rather than ceramics and physical metallurgy. Referring to Table 4, the Ph.D. program is characterized by a small number of students, about seven in the average department, and by a high percentage of foreign students (38 percent), as in mining and extractive metallurgy.

The total outside support of graduate and research programs in petroleum engineering was approximately $700,000 on an annual basis in the fall of 1967, or an average of $50,000 per department.

Fuel Science Very active and sizable research programs exist in the field of fuel science in universities, and undergraduates in several departments, e.g., mechanical engineering, chemical engineering, and extractive metallurgy, receive instruction in this field. There is, however, only one department of fuel science in the country, and it grants B.S. as well as M.S. and Ph.D. degrees in this field. Fuels research, however, has been and remains a very important field of activity of the Bureau of Mines and of the newer Office of Coal Research, and even though dis-

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persed among several departments in universities, this is a mineral engineering field worthy of serious consideration in this study. It was not possible by use of this questionnaire to separate out from university statistics the data we would like to have. In the tables we show what information was obtained and recognize it as being very incomplete.

Other Mineral Fields Under the heading of "other mineral science and technology" in the tables are included geological engineering, where the respondent felt that emphasis in the curriculum is on extractive mineral engineering rather than on exploration; mineral economics; and water treatment and air pollution engineering programs closely related to mineral engineering. The ECPD lists 15 curricula in geological engineering. In addition, there is one department of mineral economics and a department of engineering geoscience. Thirteen undergraduate programs were reported with a total of 510 upper-class students—more than in either mining or petroleum engineering. On the M.S. level, 18 reported a total of 179 students, and on the Ph.D. level, 15 reported a total of 143 students. We believe this rather large group of students, principally geological engineers, should be included as mineral engineers. Support of the program in this field is shown as $2.3 million on an annual basis in the fall of 1967.

GENERAL COMMENTS AND CONCLUSIONS REGARDING MINERAL ENGINEERING IN EDUCATIONAL INSTITUTIONS

Arrangement of Mineral Engineering Curricula in Universities. A striking feature of mineral industries education is the very irregular arrangement in the distribution of mineral engineering curricula both among and within institutions. One university has all of mining, mineral preparation, petroleum and natural gas engineering, metallurgy, fuel science, and mineral economics as separate B.S.-, M.S.-, and Ph.D.-granting curricula. At the other extreme are 35 institutions having only one of these, most commonly metallurgy. The curricula are usually in an engineering college, but may be grouped within a separate college or school, or may be separated, for example, where mining may be a part of a mineral science school and ceramics is part of a new materials science unit located in a different part of the institution. The advantage of placing these curricula in the engineering college is to provide association with other engineering curricula in the development of a common approach to the subjects that are inherently similar. On the other hand, from a subject-matter standpoint, grouping these fields with the geosciences is beneficial because of the interplay possible between the basic geological sciences and these mineral engineering fields. For instance, hydrogeology, a rapidly developing field, has much in common with petroleum engineering, and in fact these fields are now using similar approaches and are cooperating in research in at least one institution where the combined program is becoming one dealing with the broad problem of fluid occurrence within the earth's crust, its properties, and extraction. Similarly, mineralogy and geochemistry are closely allied with ceramics in subject matter, types of equipment used in research, and so on, and should be as closely associated as possible. In one institution, mineralogy is in the engineering school, located physically next to ceramics to provide maximum opportunity for interplay.

Mining, Extractive Metallurgy, and Petroleum Engineering. Curricula in mining, extractive metallurgy, and petroleum engineering typically have few students and a relatively low level of funding from the federal government. Almost half of the graduate students in these three fields are foreign. This high proportion of foreign students on the graduate level reflects both the recognition by developing countries of the great need for specialists to accelerate the development of mineral resources and the general lack of interest in the United States in maintaining leadership in the technology of mineral extraction. Inasmuch as mineral-extraction technology is basic to the country's maintaining a competitive position in mineral production, this indicates that the United States will continue to decline as a mineral producer.

Even though a proportion of these foreign graduate students in the extractive mineral fields remain in this country for a few years, and some permanently, our data indicate that most return to their native countries. This training of these mineral specialists is a major contribution of the United States and a counterbalance to the "brain drain." By this activity, however, the United States is building up its future competition and should be making every effort to encourage U.S. students to work in this field to avoid becoming largely dependent on foreign processes, equipment, and techniques in such fields as mining, steel-making, and petroleum production.

In mining and extractive metallurgy, the median number in the senior class is only five or six. Especially with the increasing enrollment in most other curricula and the pressure for greater economies in higher education, the question of continuing low-enrollment curricula is ever present. Half of the departments in these fields have fewer than six in the senior class, and the outlook for continuation may be very cloudy. As uncertainty develops regarding the future of a department, it is more difficult than ever to obtain high-caliber faculty-members, new equipment,

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research funds, and needed facilities. In some cases, the undergraduate curriculum has been eliminated, but graduate work has been continued as foreign students are available to fill out the group to a reasonable number and as the emphasis on graduate work in engineering fields increases. Elimination of the B.S. degree would be a severe blow to extractive mineral technology, however, in two respects: B.S. engineers are critically needed for research-and-development programs as well as for production; and the B.S. engineers are needed to feed into the M.S. and Ph.D. programs.

How do we build up the undergraduate enrollment in these extractive mineral fields and in petroleum and ceramic engineering as well? There is a general consensus among educators in these fields that the tarnished public image of the mineral industries is at the root of the problem. In many areas of the country, continuing and aggressive programs are being carried out to tell the story of the importance and attractiveness of careers in these fields. Without such programs by ceramics groups, several undergraduate ceramic curricula in the country would undoubtedly have been eliminated during the last 15 years. The great demand for ceramists with a B.S. degree does not seem to be an important factor in attracting undergraduate students into the field, for there has been a demand for engineers in all fields. Popularity of the mineral fields needs improving.

Another deterrent to undergraduate enrollment is the small number of university departments in these fields. Over half of the states do not provide undergraduate education in mining, ceramics, or petroleum engineering. These fields thus tend not to be known by parents, high-school counselors, and college students. In addition, a student in a state not providing this education is discouraged from enrolling in a school in another state by higher out-of-state tuition and restrictions on numbers of out-of-state students enrolling in state universities. It is at these state institutions that most mining, ceramic, and petroleum engineering curricula are located. Arrangements among states to provide special admissions procedures to alleviate this problem would no doubt encourage enrollment in the mineral engineering and science fields.

The three extractive mineral engineering fields are notable for their relatively low level of funding of the graduate and research programs. The total of outside agency support in each of these fields is less than $2 million a year, and in fact is only approximately $700,000 each for mining and petroleum engineering, according to our survey. As shown in Table 9, the total federal support of graduate and research programs reported for mining, extractive metallurgy, and petroleum engineering was only $1.2 million a year in the fall of 1967. In these programs there was a total of 261 Ph.D. candidates and 467 M.S. candidates. The federal

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support of graduate students in these fields is thus less than $2,000 per student per year. This compares with $6,000 of federal support per graduate student per year in chemistry.* Perhaps as important as the amount of funding per student is the small total amount, which hinders increasing the number of graduate students in these fields.

These three extractive mineral fields are at the heart of the Bureau of Mines program. Their low degree of support of graduate and research programs reflects the traditional absence of a policy on the part of the Bureau of Mines to finance these programs in universities.

Ceramics and Physical Metallurgy. Ceramics and physical metallurgy are, in general, more robust curricula, both in number of students and in outside support of research and graduate work. These fields are a part of the materials science and engineering wave in education, funded on a large scale by the Department of Defense (especially the Advanced Research Projects Agency) in recent years and by other federal agencies. However, the large materials science laboratories established at universities with federal funds almost all emphasize physical metallurgy and solid-state physics. The nonmetallic inorganic materials (ceramics) have caught only the fringe. Further, established ceramics departments where a strong background, interest, and competence in the field is naturally present have been almost entirely passed over in this large funding of materials science during the past decade. Other agencies have provided some support to ceramic department programs, but the Bureau of Mines has provided none.

Fuel Science and Mineral Economics. Fuel science and mineral economics are ordinarily not separate curricula. Both, however, are exceedingly important fields in the future of our economy and should be fostered and financially supported at universities. The Bureau of Mines is well known for its research in both fields, and logically should become involved in support of graduate and research programs in universities.

Financial Support of Mineral Engineering in Universities. Tables 10 and 11 were developed to show the distribution of university research funding of mineral engineering by type of resource and type of activity. The relatively trivial amount of funding of research on the nation's great natural resources of coal, petroleum, and industrial minerals and rocks is apparent and alarming. The United States unquestionably is wasting

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* *Chemistry: Opportunities and Needs*, NAS-NRC Publication 1292, National Academy of Sciences–National Research Council, Washington, D.C., 1965, p. 168.

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part of its heritage of irreplaceable minerals by remaining ignorant of them. The larger funding shown for metals is mostly for physical metallurgy, and that for nonmetals is well to the right in Figure 1, p. 18, i.e., in the materials science field.

The university graduate and research programs in the mineral engineering fields have been to some extent casualties of federal organization and evolution. The three fields of mining, petroleum production, and extractive metallurgy are basic to the mission of the Bureau of Mines. Although they might have been supported as are the agriculture resources fields, they are receiving incredibly small funding. As a result, little basic research in these fields is coming out of the universities, and there is a discouragingly small group of trained specialists to man the positions in the Bureau of Mines and industry. The Bureau of Mines at long last (1966) has the authority to make research contracts and grants to universities but lacks funds.

All of the engineering fields have had relatively small funding from the National Science Foundation. Perhaps properly, the NSF, though it has an engineering division, puts most of its funds into the science programs. But engineering increasingly is the discipline needed to attack and solve the great and increasing problems of our modern culture. What the NSF has done for science, perhaps a new National Engineering Foundation should do for engineering.

The analysis of the growth and decline of university departments dealing with the mineral science and technology fields points up two very significant generalizations:

The number of private institutions with research or training programs in mineral engineering and science fields, which was once nearly equal to the number of public institutions, is now small. Thus, nearly the entire burden for such education is placed on the public educational facilities.

These institutions are spread thinly over the country in only about one third of the states. Hence, without special arrangements, two thirds of the population is kept away from this field by the absence of low-cost higher education in the home state. Adequate recognition should be given to the fact that higher education in these fields clearly is more of a federal responsibility than in the typical engineering field. Thus more direct federal aid may be required as well as state-level legislation for special admissions arrangements among states.

Opinions from Universities. In the questionnaire sent to universities (see Appendix C), opinions were requested on the greatest needs for the development of the research and graduate program in the mineral engi-

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neering fields and on what would stimulate undergraduate and graduate enrollment. The following responses are representative:

> Greater interest within the industrial organizations that produce metals of the role that modern science and technology should play in the field. An improved public image of the metal producers and their technical interests. More competence and breadth of vision by those who control the technical activities in government agencies and industrial firms.
>
> Collectively, the field is held in low esteem by young people as they consider technical or scientific careers. Two problems have to be faced, (a) the level of research effort and the quality of that effort in the colleges and universities must be improved. This requires an increase in direct support of research and of facilities for research, (b) the field, academia, government agencies, and industry, must make it evident to young men entering college and those working in the field that modern technology *is* important to the field.
>
> Better career guidance.
>
> A greater public recognition of the importance of these fields (especially fuel science, a sadly neglected field).
>
> Funds for graduate students and equipment. Closer industry–university relations.
>
> More federal support. Increased public awareness of field. The professional societies and major industries concerned should sponsor career advertising on a broad national basis.

THE FEDERAL GOVERNMENT

Many agencies of the federal government are concerned with mineral resources or have regulatory or other authority which in one way or another affects production of minerals in the United States and abroad and hence the health of the U.S. mineral industry. The principal responsibility for minerals, however, lies with the U.S. Geological Survey and the U.S. Bureau of Mines. The very fine basic and applied research of the former provides us with information helpful in mineral exploration. The Geological Survey is backed up by 85 university geology departments with Ph.D. programs, an additional 63 with M.S. programs, and 126 other universities and colleges with B.S. programs. In addition, there are several very good state geological surveys. The Bureau of Mines complements the Geological Survey. The Bureau's mission is to provide the needed basic and applied research having to do with mineral extraction, i.e., mining, metallurgy, mineral preparation, fuel science and technology, etc. Its backup in universities has been the departments of mining, mineral preparation, metallurgy, petroleum and natural gas engineering, ceramics, fuel

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science and engineering, and mineral economics—the mineral science and technology fields. But these departments have been disappearing rather than expanding. Lafayette, Lehigh, Pittsburgh, Ohio State, Illinois, the University of California, and others have eliminated their mining engineering departments in recent years. Relatively little research and graduate training is going on in the universities in these mineral fields.

The Bureau of Mines was established within the Department of the Interior by act of Congress in 1910. As stated in its charter, the province and duty of the Bureau of Mines is

> to conduct inquiries and scientific and technologic investigations concerning mining, and the preparation, treatment, and utilization of mineral substances with a view to improving health conditions, and increasing safety, efficiency, economic development, and conserving resources through the prevention of waste in the mining, quarrying, metallurgical, and other mineral industries; to inquire into the economic conditions affecting these industries; to investigate explosives and peat; and on behalf of the Government to investigate the mineral fuels and unfinished mineral products belonging to, or for the use of the United States, with a view to their most efficient mining, preparation treatment and use; and to disseminate information concerning these subjects in such manner as will best carry out the purposes of this Act.

From its inception, the research program of the Bureau of Mines has been highly significant. Its research on mine safety, mining methods, fuel technology, petroleum production, and allied areas has been very important to the development of our mineral resources and the mineral industries. Prior to World War II, the Bureau of Mines research-and-development program was relatively large. Its research budget in 1940 constituted 3 percent of the total government research-and-development funds. This compares with about 0.2 percent in 1968.

From the beginning, the Bureau of Mines has worked with university groups, placing practically all of the ten research stations established between 1910 and 1930 on university campuses. At these locations, close cooperation in research has existed between the Bureau of Mines personnel and members of the faculty in the extractive mineral fields. The Bureau of Mines, however, has not supported university research and graduate programs, as have the Department of Agriculture and many other agencies. It was not until 1966 that the Bureau received specific authorization to enter into contracts and to make grants in support of university research and graduate programs. Unfortunately, the Act carried no additional money with its authority and the program has been very slow in getting under way. On the other hand, at about the same time funds were made available for solid waste grants and contracts, and these funds represent the current source for the several grants and contracts for research and graduate work at universities.

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During the fiscal year 1967–1968, the Bureau of Mines expended approximately $36 million on its research-and-development programs. Table 12 shows expenditures by activity. The two major efforts during this year, each using almost one third of the budgeted funds, were in the extraction and primary processing of metals and in fuels research and development. The production of raw materials was third, with 19 percent of the expenditures.

It is clear from Table 13 that the resources being concentrated on during 1967–1968 were metals at 45 percent and coal at 35 percent. Research on the engineering phases of water recovery and use was negligible.

Divided among the fields as shown in Table 14, the budget supported in almost equal amounts the three principal fields of research in mining, extractive metallurgy, and fuel science and technology.

Additionally, the Bureau of Mines annually spends about $10 million on mineral resources statistics and studies, $10 million on mine safety, and utilizes an additional $15-million borrowing authority for the operation of its helium facilities. Within the Department of the Interior, the Office of Coal Research spends another $11 million annually on coal.

Regrettably, the Bureau of Mines is at a rather low level in the government hierarchy, and in the past 20 years it has suffered at least four changes of directors, often with periods of acting directors between changes. During this time the Bureau of Mines has not been able to exert significant national leadership in the mineral field.

The Department of the Interior has an Assistant Secretary for

TABLE 12 U.S. Bureau of Mines Research-and-Development Expenditures by Activity, Fiscal Year 1968

Activity	$ (thousands)	Percent
Production of raw materials	6,750	19
Beneficiation of raw materials	1,350	4
Extraction and primary processing of metals	10,938	30
Processing minerals for nonmetallic uses	300	1
Fuels research and development	11,778	32
Environmental improvement	1,600	4
Underground storage	120	0.3
Nonmineral applications of mining technology	—	—
Transportation of mineral materials	240	0.7
Safety and health	1,826	5
Explosives and explosions	1,470	4
Total	36,372	100.0

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TABLE 13 U.S. Bureau of Mines Research-and-Development Expenditures by Resource, Fiscal Year 1968

Resource	$ (thousands)	Percent
Coal	12,624	35
Petroleum Natural gas	3,360	9
Oil shale	1,620	4
Industrial minerals and rocks	1,126	3
Metals	16,328	45
Nonmetallic materials	300	1
Water	—	—
Helium	1,014	3
Total	36,372	100

Minerals Resources, but in recent years his office has been burdened with serious problems arising from the oil import regulation program, and his office has been unable to give much steady over-all direction to the broad questions of national mineral policies that should be the concern of the national government. Of great benefit to the country's mineral program would be a National Minerals Advisory Center, established within his office, for supplying the information required by the legislative and executive branches of the government for mineral-policy formulation and needed by an informed public as well as the industrial sector to assure an adequate, dependable, and timely flow of minerals and mineral fuels within the economy.

It seems apparent to the Committee that the Bureau of Mines must

TABLE 14 U.S. Bureau of Mines Research-and-Development Expenditures by Field of Science or Engineering, Fiscal Year 1968

Field	$ (thousands)	Percent
Mining	10,286	28
Extractive metallurgy (including mineral beneficiation)	10,838	30
Physical metallurgy	1,100	3
Nonmetallic materials	300	1
Petroleum and natural gas engineering	1,850	5
Fuel science and technology	10,398	29
Other	1,600	4
Total	36,372	100

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play a more significant role in developing the country's mineral technology if the United States is to maintain a competitive position with other major nations in the extraction and primary processing of minerals, and if at the same time our knowledge of the solid earth is to be advanced as needed for safe underground storage, excavation construction, and other uses. The Director of the Bureau of Mines should institute timely studies on a continuing basis, using the most advanced techniques for economic and technologic forecasting and analysis and for data-handling, storage, retrieval, and display, all aimed at keeping readily available for use an up-to-date knowledge of the forces affecting mineral production, supply, demand, and consumption in the United States and the world.

STATE GOVERNMENTS

Traditionally, state governments have accepted at least some measure of responsibility for support of the mineral industries within their borders. Although in some states this responsibility has been only in the areas of regulation, safety controls, and exploration, half of the states support some mineral engineering research. The total level of this support in research and development is listed in Tables 15–17 in parallel form to the data for the U.S. Bureau of Mines.

TABLE 15 State Research-and-Development Expenditures by Activity, Fiscal Year 1968[a]

Field	$ (thousands)	Percent
Production of raw materials	276	12
Beneficiation of raw materials	630	28
Extraction and primary processing of metals	98	4
Processing minerals for nonmetallic uses	213	10
Fuels research and development	413	19
Environmental improvement	125	5
Underground storage	100	4
Nonmineral applications of mining technology	15	7
Transportation of mineral materials	4	—
Safety and health	68	3
Other	183	8
Total	2,125	100

[a] In-house research only.

TABLE 16 State Research-and-Development Expenditures by Resource, Fiscal Year 1968[a]

Field	$ (thousands)	Percent
Coal	260	12
Petroleum	250	11
Natural gas	115	5
Oil shale	7	3
Industrial minerals and rocks	370	17
Metals	520	24
Nonmetallic materials	120	6
Water	443	20
Other	40	2
Total	2,125	100

[a] In-house research only.

The figures of these tables represent estimates based on a survey of state agency expenditures carried out by the Committee in the spring of 1968. They do not include funds expended in water engineering fields and in general are considered no better than a rough approximation. Most of the effective state research programs are operated by agencies affiliated with universities, and in some cases the state research program

TABLE 17 State Research-and-Development Expenditures by Field of Science or Engineering, Fiscal Year 1968[a]

Field	$ (thousands)	Percent
Mining	160	8
Extractive metallurgy (including mineral beneficiation)	615	29
Physical metallurgy	25	1
Nonmetallic materials[b]	323	15
Petroleum engineering[c] (including natural gas engineering)	340	16
Fuel science and technology	302	14
Other[d]	360	17
Total	2,125	100

[a] In-house research only.
[b] Ordinarily, but not limited to, ceramic science or engineering, materials science, or solid-state science programs.
[c] Including production of other mineral fluids, e.g., natural water and sulfur.
[d] Such as mineral economics, geoengineering, and water-treatment and air-pollution technology related to mineral science and technology.

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in mineral science and technology is closely integrated with the university program.

State programs in this area are commonly directed toward problems of local interest and in some cases are directed toward the advancement of the mineral industries within the state in competition with those in other states. A particular advantage of this arrangement to the local industries is the close association that develops between the industry and the research agency.

In some of the states the agency charged with regulatory, health, and safety responsibilities also carries on the research activities. In other states, generally those with the more extensive research programs, these functions are separated. This is usually the case where the research agency is closely affiliated with a university.

In quality of personnel and facilities the range within state agencies is from highest quality to inadequate. Also, with only a few exceptions, the level of financial support falls far short of the job that needs to be done within the state.

Responsibility for the wise development and utilization of the mineral resources of its particular region should be assumed by the states to an increasing extent. The states, in supporting research in mineral science and technology, can do a great deal for the solution of specialized problems, and through state agencies working closely with local industry, they can do much to prevent environmental deterioration and to provide for future mineral needs on a well-planned basis. Where no agency exists, each state should consider the establishment of an appropriate body, preferably in connection with the state university or land-grant institution. State funds for research in mineral science and technology should be made available to its own agencies and educational institutions on a scale commensurate with the importance of the mineral industries to the state's economy.

Because of the great need for a better understanding of the engineering problems of the solid earth from which we must obtain our solid, liquid, and gaseous mineral materials as efficiently as possible, on which we must build larger and more numerous stable structures, through which we must do more and more tunneling, and into which we are injecting more and more solid, liquid, and gaseous materials, studies on local as well as regional and national levels should be encouraged. In the whole field of mineral science and technology, certain problems can be better attacked on the state level. The Committee feels that it would be highly desirable to establish a program of federal funding, on a matching basis, in support of state centers for research in mineral science and technology, similar to the program of the recently established Office

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of Water Resources Research in the Department of the Interior. For those states that have a good on-going program, this would be very helpful, and for states not now engaged in mineral resources research this would undoubtedly stimulate research highly desirable to industry and to the community at large.

THE MINERAL INDUSTRY

Despite the dreary current picture of research in the mineral fields in universities and the small-scale effort in mineral science and technology in the federal government as compared, for example, with agricultural science and technology, there are indications that the level of mineral technology in the United States has been high. One such indication is the fact that while the over-all inflation in the 1967 gross national product was 117.3 (based on 1958 = 100), the 1967 wholesale price indexes (based on 1957–1959 = 100) were only 103.6 for fuels and related products and power, 104.3 for nonmetallic mineral products, and 109.5 for metals and metal products. Despite poorer ores and steadily increasing labor costs, the prices of many mineral commodities have dropped, often dramatically, as shown in Table 18. Furthermore, through application of new technology, productivity in the mineral industry continues to increase. In the giant steel industry, for example, the number of man-hours per ton of finished steel has decreased steadily from 15.3 in 1961 to 12.3 in 1966.*

TABLE 18 Comparison of Price of Key Mineral Commodities—1890–1966[a] (in Constant 1954 Dollars)

Commodity	1890	1957	1966
Aluminum, lb	1.16	0.26	0.19
Copper, lb	0.53	0.28	0.28
Pig iron, ton	58.07	61.80	49.60
Bituminous coal, ton	3.38	4.80	3.58
Petroleum, bbl	2.63	2.92	2.26
Sulfur, ton	69.90	23.07	20.44
Cement, bbl	1.98	3.03	2.47

[a] Data from hearings before the Committee on Interior and Insular Affairs, House of Representatives, Ninetieth Congress, Briefing Session with Director of Bureau of Mines and Staff, February 7, 1967, p. 154.

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* C. A. Lovgren, "Forces of Economic Change—Steel U.S.A.," *J. Met.* 20, 17–21, 1968.

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TABLE 19[a] Industrial Research-and-Development Expenditures in 1966 (in millions of dollars)

Primary metals	228
Stone, clay, and glass products	131
Petroleum refining and extraction	441
Chemicals and allied products	1,515

[a] Adapted from "Research and Development in Industry, 1966," National Science Foundation Report No. 68-20.

The figures are impressive, but can the present U.S. effort maintain a sufficiently high level of technology to retain the favorable competitive position of the past few decades? The unsatisfactory state of decreasing enrollment and low-level support of research in university mineral engineering programs suggests trouble ahead. Reports of both the Extractive Metallurgy and Non-Metallic Materials panels provide the discouraging picture of a serious decline in the U.S. position relative to other major countries in the number of contributions being made to advance the technology in these fields. In this connection, we may note, for example, that the increased productivity in the manufacture of steel cited above may result to a large extent from new technologies developed abroad, one example being the basic oxygen furnace. The $3-billion gap in the mineral import–export balance is far from reassuring, and the gap is still increasing.

Expenditures for research in the mineral industries are not impressive. Funds devoted to research and development in 1966, expressed as percent of net sales, were only 1.0 percent in petroleum refining and extraction, 1.7 percent in stone, clay, and glass products, and 0.8 percent in primary metals, compared, for example, to 4.0 percent in chemicals and allied products* and the average 4.2 percent for all manufacturing companies performing research and development.

Funds for research and development in 1966 in four broad categories are shown in Table 19.

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* "Research and Development in Industry, 1966," National Science Foundation Report No. 68-20.

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The Outlook for Manpower Resources and Needs

The national supply-and-demand picture for scientists and engineers has been discussed extensively. The general conclusion is that the supply will be insufficient for the predicted demand of the next few years. This situation will require stretching the supply thin, resulting in less efficient industrial operations, lower-quality research, and a lower level of competence in university faculties than should be expected in the United States. As pointed out earlier in this report, we can see a definite decline under way in this country's position in research and in innovations in several areas of mineral science and technology. This decline is expected to spread if present trends continue, resulting in, among other things, a lowering of the competitive position of U.S. industry. The picture in the universities is especially discouraging. In the mining engineering and extractive metallurgy curricula for example, the number of graduate students is very small, and almost half of them are foreign.

Figures for supply and demand are somewhat uncertain because of the flexibility inherent in both and a lack of good data, especially with respect to future demand. Some figures are available, however, giving a general picture, and these are discussed briefly below.

THE NUMBER OF MINERAL SCIENTISTS AND ENGINEERS

In the preceding chapter the number of scientists and engineers in mineral science and technology was estimated at 65,000. This was based on professional-society membership and excluded in general the geologists,

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located on the left end of the chart in Figure 1, p. 18, and the materials scientists at the right end of this figure.

From employment data a comparable but somewhat higher total can be obtained. The number of scientists and engineers employed in the mineral industries can be judged from figures compiled for 1962 by the NSF (Table 20).

TABLE 20 Scientists and Engineers by Industry Classification, 1962[a]

Industry	Scientists and Engineers
Stone, clay, and glass products	9,100
Blast furnaces and basic steel products	20,200
Other primary metal industries	11,800
Metal mining	3,400
Coal mining	3,100
Crude petroleum and natural gas	16,400
Quarrying and nonmetallic mining	1,800
	65,800

[a] Adapted from "Scientific and Technical Manpower Resources," National Science Foundation Report No. 64-28, p. 22.

The total of 65,800 includes several thousand whom we do not classify for purposes of this report as being in the area of mineral science and technology, and for this reason the figure is high. The principal group involved is the 6,500 geologists and geophysicists included within the 16,400 figure for "crude petroleum and natural gas." Most of the geoscientists are not directly involved in the extractive part of the industry. On the other hand, the total figure does not include an unknown number, probably several thousand fuel scientists and engineers in other U.S. industries, and this may approximately balance in number the geoscientist group.

The number of mineral scientists and engineers in federal and state agencies cannot be directly obtained from employment classification data. The total of professional employees with the Bureau of Mines was 1,349 in 1967. This probably represents the majority of all those employed by government, again excluding geoscientists engaged in geological research and "materials scientists."

On the basis of our questionnaire, we believe the number employed by universities as faculty members in mineral engineering fields to be about 1,200.

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THE PRODUCTION OF MINERAL SCIENTISTS AND ENGINEERS

The annual supply of new professional people in mineral science and technology is drawn from three groups of graduates: (1) the mineral engineering fields of mining, petroleum engineering, metallurgy and ceramics; (2) other engineering fields; and (3) the sciences, especially geology and chemistry.

The number of graduates in all engineering fields is indicated by the curves of Figure 10. The postwar surge in numbers of B.S. degrees granted reached a peak of 52,000 in 1950 and was followed by a strong recession, dropping to a minimum of 22,000 in 1954. A secondary maximum of 38,000 was attained in 1959 and 1960, and the number of degrees now appears to be leveling off at about 36,000 annually.

As shown in Figure 11, the number of B.S. degrees in mineral engineering had maxima at approximately the same times as for all engineering, but since 1959 the number of degrees granted annually has been dropping sharply. The production of B.S.-degree graduates has thus been shrinking, but the supply available to employers has been decreasing at an even faster rate because of the increase in number of these graduates going on to graduate school. It will be noted in Figure 11 that the numbers of M.S. and Ph.D. degrees granted has recently shown a large annual increase at the same time that the rate of production of B.S. degrees has been decreasing. Desirable as the increase in number of advanced degrees is, these graduates do not all represent new additions

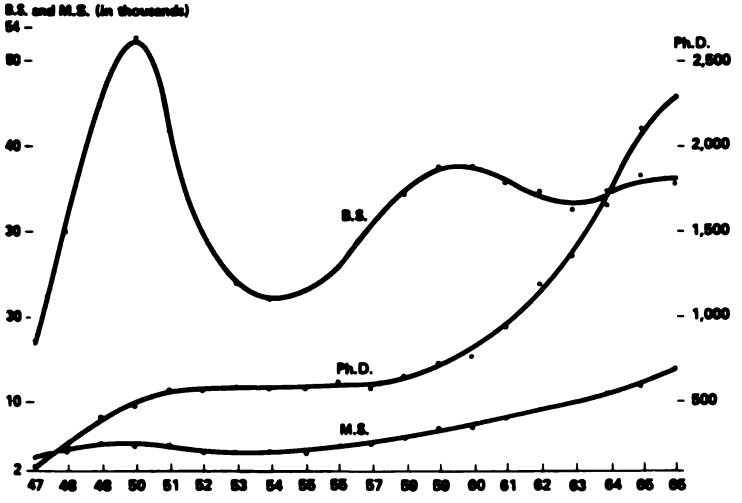

FIGURE 10 Engineering degrees granted, 1947–1966.

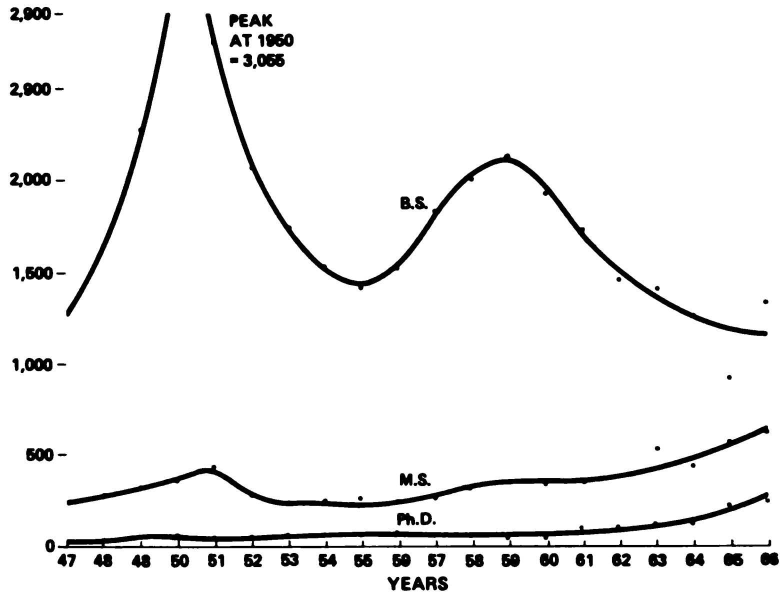

FIGURE 11 Degrees in mineral science and technology granted, 1947–1966.

to the labor market, for significant numbers of them have completed the graduate program after employment.

We find, therefore, that the annual production of new engineering graduates is not increasing, and this is especially true in the mineral engineering fields. The third source of supply, geology and chemistry, should not be reassuring to mineral science and technology employers. In the first place, graduates of these fields are more likely to be attracted to jobs in their chosen fields, and second, the number of chemistry graduates being produced is insufficient to meet the needs of chemistry.* The picture in geology is probably similar.

THE DEMAND FOR MINERAL SCIENTISTS AND ENGINEERS

The demand for engineers has been thoroughly discussed recently in two reports, one by the Engineers Joint Council in 1966† and the other by the

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* *Chemistry: Opportunities and Needs,* NAS-NRC Publ. 1292, National Academy of Sciences–National Research Council, Washington, D.C., 1965.

† "Demand for Engineers and Technicians—1966," A report conducted by the Engineering Manpower Commission of the Engineering Joint Council, November, 1966.

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American Society for Engineering Education in 1968.* Defining demand and determining future demand are both very difficult. Recognizing this, the Engineers Joint Council report (p. 9) nevertheless includes the following general statement:

> Since 1951, the Engineering Manpower Commission has been conducting surveys of the demand for engineers. Other agencies, notably the National Science Foundation, have also made large-scale projections of supply and demand. As might be expected, each survey has produced different estimates of how much manpower will be needed and in which areas of technology the need will be greatest. One feature has stood out in all of these surveys, however, namely that the demand appears to be greatly in excess of the projected supply of formally educated engineers, scientists and technicians. In the arguments back and forth over methodology, many have lost sight of the fact that the differences are ones of degree but not of directions. The important thing is that the projected supply of college graduates will be insufficient to meet any of the demand figures projected in recent years.

Unquestionably, the supply–demand situation is especially tight in mineral engineering. The number of baccalaureate graduates is decreasing at a faster rate than for engineering as a whole, and yet the demand seems as great or greater than for the average engineering field. Mining engineering can be taken as an example. The number of B.S.-degree graduates in mining has decreased steadily from 242 in 1960 to 138 in 1966, as the number of accredited departments of mining has decreased from 26 in 1962 to 17 in 1967. On the other hand, the number of new employees needed by U.S. companies for positions that should be filled by mining graduates is increasing. A survey made in the fall of 1964 involved answers from 55 U.S. mining companies regarding their estimated needs for new mining engineers 5 and 10 years in the future.† The results from just those 55 companies indicated a need for 147 mining engineers per year over the next 5 years, or 162 per year over the next 10 years.

A similar survey of 26 employers in 1967 indicated a need for 153 mining engineers that year for those companies alone (Table 21).

Another approach to the question of comparative supply and demand by field is on the basis of number employed to number of B.S.-degree graduates per year. We can make a comparison on this basis between chemistry, where a strong demand for graduate exists,‡ and the mineral

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* "Final Report: Goals of Engineering Education," *J. Eng. Ed.* 58, 367–446, January 1968.

† George T. Bator and John J. Reed, "Mining Engineering Employment Market," *Mines Mag.* 55, 30, March 1965.

‡ *Chemistry: Opportunities and Needs*, NAS-NRC Publ. 1292, National Academy of Sciences–National Research Council, Washington, D.C., 1965.

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TABLE 21 Requirements for Mining Engineers, 1963–1967 (Survey of 26 Companies Interviewing at The Colorado School of Mines)

Year	Vacancies	Job Offers	Engineers Hired	Offers/ Vacancies	Hirings/ Vacancies	Demand Index-Vacancies per Company
1963	22	30	13	136%	59%	2.4
1964	25	29	19	116%	76%	2.8
1965	50	83	39	166%	78%	4.3
1966	95	140	50	147%	53%	5.1
1967	153	201	56	131%	37%	5.9

science and engineering fields, where we believe the demand is even more urgent. In chemistry the ratio of number of professional chemists to B.S. degrees granted in 1964 was 125,000 : 8,500 or approximately 15. In mineral science and engineering the ratio is 65,000 : 1,350, or approximately 50. For engineering as a whole this ratio is about 25. On this basis the demand for graduates to fill positions in the mineral science and engineering fields is about three times as great as for chemists to fill chemistry positions, and approximately twice as great as for all engineering averaged. The picture, of course, is not this simple, for chemists and chemical, mechanical, and other engineers are recruited for some of the mineral science and engineering positions, but the great bulk of such positions are best served by graduates of the mineral science and engineering curricula.

There is a need for better data. The Committee suggests that industry undertake an assessment of its future manpower needs for graduates in all fields of mineral technology, both undergraduate and graduate, so that the universities can have reliable statistics on which to plan their educational programs in these fields.

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APPENDIXES

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APPENDIX A

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APPENDIX B

Panel Abstracts and Recommendations

PANEL ON MINING

ABSTRACT

This study covers the importance of the mining industry, its needs and opportunities to fulfill the nation's needs, and the consequences if these needs are not met.

Mining is the production of the solid-mineral raw materials upon which our industrial strength is based. Mining technology is also essential in rock excavation and support as in tunnels, highway cuts, subways, underground chambers, and similar civil-engineering projects.

The needs of our industrial economy require that our mineral production be doubled in the next few decades, and that thousands of miles of tunnels be driven. To accomplish this we must increase mining engineering education and research several fold.

During the 25 years prior to 1962, the mining engineering departments in the nation numbered from 26 to 30, and produced up to 500 engineers annually. Since 1962, this total has dropped to only 17 departments which produced 138 engineers in 1966.

The mining research effort is badly understaffed, underfinanced, and far behind our needs. Mining is a predominant contributor of technical knowledge in such important areas as rock excavation and support, rock mechanics, bulk haulage, and underground ventilation. Mining is also an important contributor to control of noxious gases and dusts and to the study of heat tolerance. Although the U.S. mining industry has made commendable progress in research recently to meet rising costs

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and foreign competition, many immediate and future needs are still not being met. At the same time the shortage of technical manpower is critical.

RECOMMENDATIONS

Therefore, the Panel recommends that:

1. *Strongly increased continuing industrial support for mining engineering education and research, with supplementary long-term federal assistance, be concentrated in institutions with an established record of superior performance.*

2. *The Assistant Secretary for Mineral Resources of the Department of the Interior promptly assume a much larger and more effective coordinating role with respect to the bureaus and offices within his authority and other agencies dealing with minerals policy.*

3. *Full educational cooperation between states be instituted to make a mining education available to residents of every state at in-state tuition rates subsidized by the resident state.*

4. *The public be made increasingly aware of the role of the mining industry through:*

   a. *Public displays, television programs, popular magazine articles, and literature for school distribution.*

   b. *Emphasis on the benefits of the mining industry in all relevant government publications.*

   c. *Short orientation courses for high-school teachers and counselors.*

   d. *Summer "involvement" work in the mineral industry for high-school and junior-college teachers.*

   e. *U.S. postage stamps depicting the mineral industry.*

5. *The* AIME *expand its current efforts in producing texts, reference books, and* Mining Abstracts, *with the cooperation of the mining schools and some federal funding.*

6. *The United States educate more foreign mining students, but with full actual costs met by funds from home or from the U.S. Government if in the national interest.*

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PANEL ON EXTRACTIVE METALLURGY

ABSTRACT

A careful review of all aspects of extractive metallurgy, including ore preparation, establishes a close correlation between educational activity, research accomplishments, and industrial proficiency. The competitive position of the United States relative to major foreign groups is deteriorating. National defense, economic well-being, environmental improvement, and conservation of natural resources are all dependent upon an adequate number of trained scientists and engineers with special competence in extractive metallurgy. It does not appear that current academic, industrial, and government research or student enrollments are adequate to meet the future requirements of our national goals. An undue proportion of the existing graduate programs is now involved with foreign students.

Immediate action is needed to re-establish an adequate level of education and research in extractive metallurgy, and several specific recommendations center upon the fiscal support of the authorized responsibilities of the U.S. Bureau of Mines to meet these needs. They include the coordination of all government interests in extractive metallurgy under the administration of the Assistant Secretary for Mineral Resources of the Department of the Interior.

CONCLUSIONS AND RECOMMENDATIONS

Improvement in the educational program in extractive metallurgy is necessary. In order to provide the immediate trained research-and-development manpower needs in the government, industrial, and academic areas in the field of extractive metallurgy, it is recommended that:

1. Congress designate budgetary support of at least $5 million per year for ten years to implement the newly authorized function of the Bureau of Mines to contract research in extractive metallurgy.

2. These funds be concentrated in departments with an established and continuing record of performance and a demonstrated capacity for professional leadership.

3. An additional sum of at least $1.5 million per year be directed to a coordinated program to provide educational support for backward

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nations to improve their economy and provide the mineral raw materials for our national welfare.

4. Other research-sponsoring agencies both within and outside the federal sphere be made aware of the critical importance of research in extractive metallurgy.

Government planning procedures should be improved to include essential support technology. To this end it is recommended that:

1. Related extractive metallurgy research be included with each end-product program.

2. Public programs of conservation and environmental control include and be coordinated with the raw-material and process-development requirements of the metal-producing industry.

The image and stature of extractive metallurgy should be strengthened. In order to attract the quality and quantity of manpower required for national needs it is recommended that:

1. All extractive-metallurgy-oriented research which is now thinly and sporadically scattered through the various defense, space, welfare, commerce, and other agencies of the government be concentrated under and administered by the Assistant Secretary for Mineral Resources of the Department of the Interior, thus providing a strong center that will be generally recognized for its essential role.

2. The cooperation of industry and education in solving public problems related to extractive metallurgy be made effective by organization of joint projects by the Assistant Secretary for Mineral Resources.

3. Industry and universities independently arrange for mutually advantageous programs involving long-range research planning and exchange of personnel.

The extractive metallurgy program of the nation must operate in the public interest. To this end it is recommended that:

The NSF *organize a civilian commission of high-level professional personnel. The commission would hold regular meetings to establish policies governing research and educational programs in extractive metallurgy.*

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PANEL ON MINERAL FLUIDS

ABSTRACT

More than seventy percent of the energy requirements of the United States is derived from fluids produced through wells, and in 1966, over three fourths of the sulfur used in this country was produced through wells. Natural-gas storage capacity underground, possible through well systems, now exceeds 4 trillion cubic feet. Underground disposal of industrial waste liquids, brines, and radioactive material takes place through more than 10,000 wells ranging in depth to 12,000 feet. Geothermal waters for energy production, brines for recovery of chemicals, helium extracted from natural gas, underground storage of refinery gases, and the production of groundwater also involve wells and the technology of underground fluid control through wells.

As a result of these activities, but principally because of the growth in oil and natural gas production, the nation has a viable technology for handling and controlling fluids from and within the earth. The technology is not widely known, however, and is not used to a high degree of sophistication except in oil and gas production. Among new applications that have been proposed and are being examined are the use of nuclear devices in wells, reservoir analysis for the development of geothermal reservoirs, gasification of coal in place, *in situ* burning of sulfur, quantitative development of groundwater resources, solution mining, and control of salt-water intrusion into freshwater aquifers.

Research pertaining to this technology is below the average level of research in other technological areas, and the amount of research support in universities is small. This fact appears to be coupled with low university enrollments in this field. However, there has been little attempt to draw the facets of this technology together into a cohesive academic program, and this deficiency in the academic world may be partly responsible for low enrollments. There is little federal support for the technology through university programs. No federal agency has taken a lead to develop the field. In this respect, the Bureau of Mines is a key agency and is a focus from which federal stimulus for the technology could emanate.

There is much basic research that needs to be done in this field, particularly in measuring the environment, in petrofabrics, in fluid–rock relationships, and in understanding the dynamics of the many processes that take place when fluids are moved through porous strata. The role of federal agencies in this field of research should be examined critically.

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It is apparent that development of the technology is intimately tied to policies for leasing public lands, for conservation, and for regulating mineral fluid production. These policies should be examined with a view toward maximizing the relationship between developing the technology and efficiently developing our natural resources.

RECOMMENDATIONS

1. *There should be a public program to stimulate the application of mineral fluids technology to new situations, using public funds through appropriate agencies such as the Bureau of Mines and the Geological Survey.* Some of the priority areas toward which applications should be directed are:

a. The possible control of salt-water intrusion into freshwater aquifers along coastlines by the appropriate placement of wells and use of recharge systems.

b. The storage and disposal of fluid wastes underground.

c. The utilization of geothermal resources.

d. The development of mineral exploration techniques making use of what is known about subsurface rocks and fluids in mineral-recovery technology.

e. The possible use of underground fluid injection to relieve earth stresses and correct subsidence.

2. *The role of the Bureau of Mines in this area should be re-examined and strengthened through appropriate action by the Congress, the Department of the Interior, or the Bureau, and such actions should include the following:*

a. The Bureau should be renamed to reflect more accurately its activities and its role as the leading government agency for government involvement in development of programs for mineral resources and other uses of the subsurface. (A more appropriate name would be the Bureau of Mineral and Underground Resources.)

b. The Bureau mission and program should be restated in a manner that will convey national recognition of the Bureau's responsibility for focusing the nation's concerns related to the effective use of underground fluid processes regardless of what applications or mineral commodities may be involved.

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c. For those areas of subsurface applications which may not be mineral recovery, such as geothermal development, groundwater recovery, and waste disposal, the Bureau should be given a clear responsibility to identify the needs for, and to stimulate the development of, the appropriate technology.

d. Where there is an absence of private-enterprise support, such as in groundwater recovery, the program of the Bureau should seek to stimulate the use of the most advanced state of the art through demonstration programs or other appropriate methods.

e. The Bureau should establish a clear organizational focus for all aspects of the technology related to underground fluid processes, with particular attention to the common principles and problems associated with gas and oil recovery, groundwater recovery, underground waste disposal, geothermal wells, sulfur production through wells, and other earth processes that involve wells and the movement of fluids. It might do this by reorganizing its petroleum division.

3. *The* NSF *and other government manpower survey and reporting groups should identify and report this area of technology as a separate listing under a title such as Mineral Fluids Engineering.*

4. *The* NSF, NAS-NAE, *Bureau of Mines, or some professional society such as* AIME *should convene a working group of professionals from among the various societies or associations concerned with mineral fluids technology in order to stimulate a professional unity for the technology.*

5. *The Bureau of Mines or* NSF *should consider funding programs for the preparation of basic monographs on the unifying principles of this technology.*

6. *The* NSF *should be encouraged to allocate institutional development funds to selected universities that are prepared to accept leadership in developing academic programs that will unify the several academic fields concerned with mineral fluids technology.* A program name such as Mineral Fluids Engineering should be sought to take the place of and to supersede such program names as Petroleum Engineering and Groundwater Hydrology.

7. *The Bureau of Mines should encourage increased basic research in underground fluid technology in the universities and should be a dis-*

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tributing agency for federal funds to be used in stimulating such research and in supporting graduate activities in the universities.

8. *The Bureau of Mines should consider financing year-long leaves of absence for the preparation of critical state-of-the-art reviews by industry or university personnel.*

9. *The Bureau of Mines should be given funds for a program to develop resident research advisors.* These advisors would be eminent fluid technologists invited to spend a period of time with the Bureau in order to originate and conduct fundamental research within the province of the Bureau, and to assist in the in-house development of Bureau of Mines staff.

10. *The Bureau of Mines should initiate a continuing education program for its own employees, particularly new employees,* so that it will be assured of a continuing staff of high-quality mineral fluid engineers. The Bureau should probably contract with universities and industry for the operation of this program.

11. *The Bureau of Mines' and the Geological Survey's research programs related to mineral fluids technology should emphasize the nature of underground environments and the quantitative behavior of fluids in the various types of underground situations. This research should be broadly based and should concentrate on fundamentals rather than on development. It should seek to provide the basic knowledge necessary for subsurface environmental evaluation and the basic understanding of underground fluid processes that are common to all applications that require the handling of fluids within the earth.* Some of the priority areas are:

a. The petrofabrics of porous media constituting subsurface fluid reservoirs. Such research should encompass both micro and macro pore structure and distribution, including the influences of such factors as environments of deposition, depth, temperature, and diagenetic processes.

b. The distribution of fluids in and their movements through porous earth materials. These investigations must include the solid–fluid interactions and the interaction of multiple fluid phases in these complex porous systems.

c. The transport processes within the earth (mass, heat, sound,

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etc.) and the influence of factors such as normal and abnormal structures, unconformities, and petrofabric variations on these processes.

d. The phase and thermodynamic behavior of the commonly encountered fluids and fluid mixtures under conditions encountered in the earth.

e. The role of capillary forces in reservoir control and their use for increased production.

f. Drilling methods and increased effectiveness of drilling.

g. Recharging of groundwater aquifers and the process of filling any porous material at depth.

h. Fluid replacement and fluid dispersion processes in geologic environments.

12. *The Assistant Secretary for Minerals, Department of the Interior, should create a clear-cut, long-range national plan, including steps for its implementation, to gain more scientific facts from the earth.* This plan should include programs for the drilling of wells for research purposes with public research funds where definitive scientific reasons can be enumerated. The plan might include proposed procedures whereby wells on public lands would not be abandoned or plugged until the appropriate government agencies had been given an opportunity to consider using the wells for scientific purposes. It could also require that permits for wells on public land contain stipulations for the acquisition and eventual dissemination of geological and engineering information. It may be that the plan to gain scientific facts from the earth should include creation of privately managed groups, financed by public and/or private funds, to consider scientific requests from individual scientists and to organize and oversee research into these areas.

13. *The Bureau of Mines regional laboratories for mineral fluid production should be examined critically for effectiveness, particularly with the possibility of increasing the quality of the research output by concentrating all available resources at this time into a single National Center for Mineral Fluids Technology.*

14. *The Bureau of Mines should be charged with maintaining a continuing review of federal policies, practices, and regulations with respect to mineral fluids and of federal leasing and conservation procedures in*

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order to stimulate improvements resulting from technology and technological innovations.

15. *The Bureau of Mines should be strengthened by an administrative acknowledgment on the part of the federal executive offices to the effect that the Bureau of Mines will be used in an advisory role in all matters between government agencies and industry pertaining to underground fluids technology and the use of the earth through well systems.*

16. *Federal agencies concerned with the administration of minerals on public lands or with regulations and conservation practices pertaining to underground fluids should encourage the employment of professionals from industry on a one- or two-year leave-of-absence basis in order to establish better liaison and communication between federal agencies and industry with respect to mineral fluids technology and its capabilities.*

PANEL ON FUEL SCIENCE AND TECHNOLOGY

ABSTRACT

The field of fuel science and technology has provided the foundation on which all of the fossil-fuel-energy industries are based. In the broadest technological sense, fuel science and technology deals principally with the conversion of the energy in fossil fuels into useful forms desired by the ultimate consumer. In this context, conversion encompasses combustion either for the generation of process or comfort heat or for addition of heat to a working fluid used in the generation of shaft horsepower or electricity; processing of raw liquid and gaseous fuels to other marketable fuels and products; and production of liquid and gaseous fuels from coal, oil shale, and tar sands. In addition to these conversions of fossil fuels *per se*, the field has contributed significantly to the conversion of ores into primary metals.

Since our effective use of energy is so basic to our continued economic well-being, it is evident that fuel science and technology must be concerned with reliability of supply, continuity of economic supplies in the form desired by the ultimate consumer, and efficient utilization of all sources of supply to conserve our energy resources and to minimize contamination of our environment.

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RECOMMENDATIONS

These recommendations concern only the possible role of the federal government in fossil-fuels research, development, and manpower, with the exception of one which concerns nuclear fuels. The basic premise is that the federal government should assume an active role only when, in the opinion of an impartial advisory board established by the federal government, the efforts of private industry are inadequate.

1. Major problems in fuel science and technology will have to be solved if we are to supply the increasing demand for energy in the form desired by the ultimate consumer. This will require an intensification in research and development in this field, by both private industry and government. Projected government expenditures on fossil-fuel research *per se* for fiscal 1968 were $28 million as compared with about $1 billion for basic and applied research on nuclear energy.

Therefore, the Panel recommends that *the federal government seriously consider the disproportionate expenditures on atomic energy in relation to fossil fuels and consider increasing support in the areas mentioned below.*

2. The need for intensifying research on fossil fuels implies an increased need for manpower. Experience has shown that it is difficult to recruit and retain individuals from conventional engineering disciplines for work in the fuel industries. This results from a lack of knowledge of the industry and a consequent poor industry image. This is not the case with individuals trained in fuel science and technology who have acquired a knowledge of the field.

Therefore, the Panel recommends that *study of and research on fossil fuels, combustion, and energy conversion be encouraged through creation of graduate-level "centers of excellence" at several universities in this country. The funding should include provision for staff, facilities, and a basis for continuing support of research.*

3. The predominant role of fluid fuels, liquids, and gases in supplying our energy requirements, coupled with the need for supplying this obvious preference from domestic fossil fuels, points up the importance of converting solid fossil fuels to fluid fuels. This implies the transition from a fuel economy based predominantly on fluid fossil fuels to one based on solid fossil fuels that will be processed to yield fluid fuels.

Therefore, the Panel recommends that *strong support for research and development on the conversion of solid fuels to liquids and gases continue at a greatly increased level.*

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4. The ever-increasing demand for energy, which will continue to be supplied by fossil fuels for many years, points up the urgency for making sure that this energy will be supplied without contaminating our environment.

Therefore, the Panel recommends that *support of research on all forms of pollution and on the safe disposal of radioactive wastes be increased through the cooperative efforts of the federal government and private industry.*

5. Our fossil-fuel reserves are large but finite. The continuity of supply of energy is essential to the functioning of our society.

Therefore, the Panel recommends that *increased attention be given to problems of more efficient power generation and more reliable power distribution.*

6. Fuel scientists and technologists are in an excellent position to contribute to the advancement of knowledge in the prevention, control, and extinction of fires and consequently help in conserving resources and reducing property losses.

Therefore, the Panel recommends that *the support of fire research be increased.*

7. No one can foresee the demands that will be placed upon fuel science and technology in the future. As in the case of all areas of science and technology, it is essential to continually increase resources of basic knowledge.

Therefore, the Panel recommends that *long-range fundamental research on fossil fuels be actively supported.*

PANEL ON NON-METALLIC MATERIALS

ABSTRACT

The science and engineering of nonmetallic materials has been of substantial economic importance to the nation. Now, in 1968, it stands at a crossroads. It has emerged from the era of an empirical technology aimed at producing large-volume, inexpensive products into an era in which the principles of modern solid-state chemistry and solid-state physics must play a crucial role in further advances. Radically new technologies have been developed which add enormous value via novel processing methods to ceramic materials; these have led to a diverse set of new mate-

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rials, including synthetic diamonds, ceramic armor, crystallized glasses, and miniature integrated circuits. Yet the potential exists that with the right support the world of inorganic materials will make an advance that would correspond to the transition in the organic world from the rayon era to the nylon–polyethylene age.

This branch of technology is characterized by a very low ratio of government to industrial research-and-development money and also by a low figure for research and development as a percentage of sales. These and other factors have led to three serious imbalances in the field: The applied research and development (conducted mainly in industrial laboratories) outweighs the necessary supporting basic work performed in industry and universities; the students trained within the discipline do not match the needs of the employers either in numbers or in nature of training; the chemical sciences of synthesizing, preparing, and characterizing ceramics have been neglected in favor of property-oriented research. The field is also notable for its diversity, and traditional approaches to the solution of its current problems must be altered in favor of interdisciplinary mechanisms. It poses an example of a more general problem of national scientific management in the United States—namely, what role the National Academies and/or the National Science Foundation should play in encouraging or sustaining (via policy and fiscal decisions) the growth of "emerging" fields judged to be in the national interest.

RECOMMENDATIONS

Administrative and Procedural

1. It is of the greatest importance that the area of nonmetallic- or ceramic-materials research not be permitted to fall into the cracks between physics, chemistry, metallurgy, and earth science programs in universities and government agencies. *Identified funding structures with clearly defined objectives administered by personnel trained in the field appear to be an essential first step.*

2. Since the nature of the field has the essential characteristics of cutting across established departments and disciplines and demanding new interdisciplinary mechanisms and a "group science" level of coherency of effort, the Panel recommends that *encouragement and incentive be provided to universities which devise and execute imaginative and effective solutions for developing graduate training and research in*

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interdisciplinary fields in the areas of nonmetallic materials science and engineering. Present creation of new institutions of several kinds provides the government with a special opportunity for more direct impact on educational patterns.

3. From the viewpoint of developing manpower and simultaneously getting high-caliber university research performed, *a program should be initiated to interest, especially, more chemistry and chemical engineering departments in this field.* This requires not only an educational program via the appropriate technical societies, the university communities, and the National Academies but also the availability of special funds for support of ceramic materials preparation and characterization in chemistry and chemical engineering departments.

4. To help reach our manpower objectives, *a part of the program of research support should be made available for smaller college science departments for research in materials-oriented projects. In most cases, this could also involve undergraduate participation in the research.*

5. The modern ceramic industry can benefit substantially from the introduction of two-year vocational and technical school curricula into appropriate institutions. *The Panel believes that an incentive program placed in the many new two-year institutions being created would produce large dividends in useful plant and technician manpower.*

6. The national research-and-development activity in nonmetallic materials has been maintained at its present level largely by the efforts of U.S. industry. As increased federal participation strengthens the university segment, it will be important that adequate mechanisms be devised to enhance university–industry cooperation. The Advanced Research Projects Agency of the DOD has made a modest beginning in this area with its "coupled contracts." Further, the State Technical Service Act enables the Department of Commerce to support many innovative approaches to interaction between universities and industry at the information and education level. We recommend that *further exploration and innovation be encouraged in patterns of joint research efforts by university–industry–research-institute teams via bilateral or multilateral arrangements.* Financial structures to provide for two-way communication are essential. This would enable, for instance, a more widespread use of the Ford Foundation's "practicing engineer" concept for professors to spend time in industry, and periodic retreading of

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postdoctoral industrial personnel in universities. *New programs for university–industry coupling specifically for advanced training purposes should be supported.*

Funding

7. It is proposed that *immediate steps be taken by the agencies of the U.S. Government to improve the low proportion of federal support of research and graduate training in the nonmetallic field. More specifically, the total annual support in universities, which now amounts to roughly $5 million, should be trebled in the next decade. Total federal dollar support of basic research, if doubled during the same period, would provide for an attainable and not wasteful growth rate, since this increase could be distributed over the several related disciplines.*

8. Recognizing that the nature of materials research falls in the category of "group science," requiring certain minimum-sized facilities and super-critical-size faculties, it is strongly suggested that careful planning be done in the distribution of funds. Attempts to disperse the limited research activity in this area over dozens of campuses would be disastrous; the small-college program alluded to above is basically a manpower solution. It is recommended that *for the next decade the nation develop and support perhaps six to eight major effective centers specializing in the preparation and characterization of the nonmetallic materials.*

9. At present, basic research in this area is supported by many agencies. However, besides the NSF, which supports a relatively small portion of the total research, the mission-oriented agencies (e.g., DOD, NASA, AEC) are heavily biased towards particular physical-property research—the nominal respective payoffs for their agencies. We therefore recommend that *a civilian agency (such as the U.S. Bureau of Mines) institute an appropriate capability or expand greatly its contracting capability with universities. Funding from such a lead agency should be directed much more toward the fundamentals of preparation of new and improved ceramic materials as the end product of the mining process and hence, hopefully, would emphasize the chemical (synthetic and preparative) aspects of the field.*

10. This recommendation calls for both additional funds and new administrative practice concerning the relationship between the govern-

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ment and the industry association laboratory. In virtually all other highly developed economies (Europe and Japan) there is some kind of coalition between the public and private sectors in the matter of research, especially for the smaller industries. The developmental research required to improve the competitive position of the United States is within the province of the Bureau of Mines. An in-house effort alone is unlikely to get the industry acceptance and support that would be essential for the program to be effective. Federal and state programs that provide information and continuing-education services fill an important need for the smaller industries and should be continued. We recommend *a study to determine how research for groups of small industries may best be conducted: by federal funds provided to nonprofit research institutes on a matching basis with industry funds, by direct subsidy of trade-association laboratories (and protection from antitrust action), or by other means.*

11. The role of materials-based industries in connection with the relation of the United States to the underdeveloped countries is of special interest. Such ceramic industries do not require massive investments or a large amount of highly trained labor; they are largely concerned with consumer and civilian demands and are often conditioned by raw-material availability. Developing economies need a variety of such industries. U.S. industry has already demonstrated the ability to make a contribution at this point in low-risk countries. All that may be called for here is encouragement, by way of some guarantee against expropriation, to enter the same market in many other countries. It is recommended that the *role of the federal government in providing training, information services, and continuing education in the home country be expanded first.*

Subject-Matter Areas for Support

12. The Panel recommends that *the concentration of federal research support, especially in the universities, be directed toward the fundamental chemistry and physics of nonmetallic materials.* The reason for this is twofold. First, it is in the basic area that the United States is weak. Second, the applied research effort in industry and certain government laboratories, as has been noted, is vigorous and healthy and could quickly absorb and apply the results and personnel produced by an expanded basic research program. At a time when support for applied and mission-oriented research and development is on the increase

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(at least relatively) it is important to develop the basic aspects of this field in order to maintain a technically optimized balance.

13. Care must *be taken to support the development of a healthy balance between the physics and chemistry and between the science and engineering of nonmetallic materials by increasing the emphasis on chemistry.* The study of physical phenomena and properties of such materials is, we find, relatively well-supported by existing programs. Less well supported are the chemical aspects, such as preparation, i.e., systematic and innovative syntheses, thermodynamics and reaction mechanisms, the growth of single crystals, and the purification and preparation of desired forms, including multiphase and composite structures; and characterization appropriate for the task, which has as its objective the analysis of the elements present and their distribution and analysis of "structure" (arrangement of the atoms in space by application of a combination of methods).

14. The Panel finds that considerable work on specific item-by-item recommendations has been carried out in three exhaustive recent studies by the Materials Advisory Board of the National Academy of Sciences, "Processing of Ceramic Materials," MAB Report 195-M, 1965; "Characterization of Materials," MAB Report 229-M, 1967; and *Ceramic Processing,* NAS Publ. 1576, National Academy of Sciences, Washington, D.C., 1968. These reports provide a wealth of detail on programs in the nonmetallic materials field. The Panel recommends that *all government agency administrations utilize their thoughtful and detailed guidelines to aid in maximixing the effectiveness of increased funding.*

PANEL ON MINERAL ECONOMICS

ABSTRACT

Mineral economics is the study of supplies of and requirements for minerals and mineral products. Past and present data are used to make projections into the future, taking into account technological trends. Where possible, cost data are developed, looking to the ultimate calculation of profitability. Studies may cover individual mineral deposits, company operations, regional areas, national problems, or international matters. Along with purely technological considerations, studies consider such politicoeconomic matters as tariffs, taxes, regulations, and

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customs, both in the nation furnishing capital for development and in the host country where the mineral venture is planned.

Mineral economics studies are made by companies, consultants, banks, universities, foundations, one or more agencies in each of the 50 states, upwards of 30 major agencies in the U.S. Government, and many international and supranational agencies. Thus far only one university—Pennsylvania State University—offers a degree-granting program in both undergraduate and graduate mineral economics.

Minerals are absolutely essential to modern industralized civilization. Rising populations coupled with demands for higher standards of living are resulting in greatly increasing requirements for minerals and mineral products. Viewing the total effort in all quarters, the United States is a leader in mineral economics, but more must be done to meet future needs.

RECOMMENDATIONS

Accordingly, the Panel recommends:

1. *That government act only after adequate study and interagency and industry consultation so that a sound and integrated national mineral policy is developed.*

2. *That programs related to national security be frequently reviewed to assure maintenance of an adequate mobilization base.*

3. *That careful assessment of the role of foreign operations be made when economic or security matters are considered.*

4. *That continuous quantitative cost–benefit analyses of alternative routes to environmental enhancement be undertaken.*

5. *That the Assistant Secretary for Minerals (Department of the Interior) be designated as the primary point of contact for interagency and industry consultation on matters of national mineral policy.*

6. *That the activities of the Bureau of Mines relating to the collection and dissemination of mineral economics information be expanded.*

7. *That the Department of State make increased use of minerals attachés.*

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8. That industry, professional societies, and government all exert more effort to collect, publish, disseminate, and analyze information important to mineral economics.

9. That the Public Land Law Review Commission consider fully modern science and technology.

10. That research in mineral economics be expanded commensurate with other mineral fields.

11. That formal training of persons for positions of responsibility in the industry include mineral economics.

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APPENDIX

C

Mineral Science and Technology Questionnaire to Universities

The following questionnaire was sent to 98 educational institutions, of which 62 have undergraduate curricula in one or more of the fields of mining, metallurgical, petroleum, and ceramic engineering, as listed in the 1967 annual report of the Engineers' Council for Professional Development, and the remaining 36 schools have programs in one or more of the fields of geological engineering, mineral economics, fuels engineering, and materials engineering where work in ceramics or extractive metallurgy is included. The response was excellent, for although only 71 of 98 replied, the respondents included virtually all of the schools having accredited curricula in the fields of present interest. For example, replies were received from every one of the 17 mining departments plus an additional four engineering departments that have mining programs but no ECPD-accredited curriculum in this field. Similarly, replies were received for every one of the 13 institutions having an accredited undergraduate curriculum in ceramics (or ceramic engineering or ceramic science) plus an additional four institutions that have undergraduate ceramics options or major but not an accredited curriculum. In petroleum engineering, 13 of the 19 departments having accredited curricula replied. Obtaining meaningful data on extractive metallurgy is a problem, for even on the graduate level, separation from physical metallurgy is not sharp at schools having both, and, furthermore, physical metallurgy merges into or may be absorbed in a materials science or engineering curriculum. Data on metallurgy curricula were provided by 42 institutions, including 25 of the 32 departments in the United States having the largest number of juniors and seniors.

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The following institutions responded to the questionnaire:

University of Alabama
University of Alaska
University of Arizona
Alfred University
Brigham Young University
California Institute of Technology
University of California, Berkeley
University of California, Los Angeles
University of California, Santa Barbara
University of California, San Diego
Carnegie-Mellon University
Case-Western Reserve University
University of Cincinnati
Clemson University
Colorado School of Mines
Columbia University
University of Connecticut
Cornell University
University of Denver
Drexel Institute of Technology
Georgia Institute of Technology
Harvard University
University of Houston
University of Idaho
Illinois Institute of Technology
University of Illinois
Institute of Gas Technology, IIT
Iowa State University
University of Kentucky
Lafayette College
Lehigh University
Marquette University
Massachusetts Institute of Technology
University of Massachusetts
Michigan Technological University
University of Michigan
University of Minnesota
Mississippi State University
University of Missouri, Rolla
University of Nevada
City University of New York, City College
State University of New York at Buffalo
State University of New York at Stony Brook
New York University
North Carolina State University
Northwestern University
Ohio State University
University of Oklahoma

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The Pennsylvania State University
Princeton University
Purdue University
Rensselaer Polytechnic Institute
Rutgers University
San Jose State College
South Dakota School of Mines
University of Southern California
Southern Illinois University
Stanford University
University of Texas
University of Tulsa
University of Utah
Virginia Polytechnic Institute
University of Virginia
Vanderbilt University
Washington State University
University of Washington
West Virginia University
University of Wisconsin
Worcester Polytechnic Institute
University of Wyoming
Yale University

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UNIVERSITY QUESTIONNAIRE*

Committee on Mineral Science and Technology (MST)
of the NAS–NAE–NRC

November 30, 1967

Name of Institution (will not be reported by Committee)

Signature of Respondent

I. Please indicate in Table 1A and in Table 1B your institution's current enrollment (1967–68) in mineral science, mineral engineering or mineral technology. Following this number, place in parentheses the number of those students who are foreign. (Ex.: 40 (12) means that of a total of 40 students in a curriculum, 12 are foreign).

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TABLE 1A Upper-class Undergraduate Enrollment, Fall 1967

Curriculum	**Upper-class Undergraduate Enrollment (excluding Freshmen and Sophomores, Fall 1967)**
A. Mining	
B. Metallurgical Engineering	
C. Ceramics and Ceramic Engineering[1]	
D. Petroleum Engineering (include Natural Gas Engineering)[2]	
E. Fuel Science and Technology	
F. Other MST-related fields[3]	
G. MST fields located within other curricula (please specify)	

[1] Include materials science or solid state science programs that are primarily concerned with ceramic materials.
[2] Including production of other mineral fluids, e.g., natural water and sulfur.
[3] Such as mineral economics, geo-engineering, water treatment and air pollution technology related to Mineral Science and Technology.

*Please return Questionnaire to Dr. Cyrus Klingsberg, National Academy of Sciences, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

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TABLE 1B Graduate Enrollment, Fall 1967

Degree candidates primarily in the field of: (irrespective of title of curriculum)	MS Program Enrollment	Ph.D. Program Enrollment
A. Mining		
B1. Extractive Metallurgy (including mineral beneficiation)		
B2. Physical Metallurgy		
C. Non-Metallic Materials[1]		
D. Petroleum Engineering[2] (include Natural Gas Engineering)		
E. Fuel Science and Technology		
F. Other MST-related fields[3]		

[1] Ordinarily, but not limited to, ceramic science or engineering, materials science, or solid state science programs.

[2] Including production of other mineral fluids, e.g., natural water and sulfur.

[3] Such as mineral economics, geo-engineering, water treatment and air pollution technology related to Mineral Science and Technology.

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II. Please indicate in Table 2 the number of Faculty and other Professionals in Research and/or Instruction in MST fields, Fall 1967

TABLE 2 Number of Faculty and Other Professionals, Fall 1967

Field (irrespective of title of curriculum)	**Regular Faculty (i.e., assistant, associate, or full professor)**						**Other Professional Personnel, *Not* Degree Candidates**
	Full-time			**Part-time**			
	Teach Only	**Research Only**	**Teach & Research**	**Teach Only**	**Research Only**	**Teach & Research**	
A. Mining							
B1. Extractive Metallurgy (including mineral beneficiation)							
B2. Physical Metallurgy							
C. Non-Metallic Materials							
D. Petroleum Production Engineering							
E. Fuel Science and Technology							
F. Other MST-related fields							

[1] Such as: visiting professors and postdoctorals. Please indicate number of each.

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III. Please List Support of Graduate Students by Fellowships, Assistantships, Traineeships, Fall 1967. (Do not list students where total support is less than $500 per year.)

TABLE 3 Support of Graduate Students, Fall 1967)

Field (irrespective of title of curriculum)	Number of Students			Financial Support of Students	
	Scholarships, Fellowships, Traineeships	Research Assistantships	Teaching Assistantships	Total Annual Student Support Over and Above Tuition	Total Annual Tuition Support
A. Mining					
B1. Extractive Metallurgy (including mineral beneficiation)					
B2. Physical Metallurgy					
C. Non-Metallic Materials					
D. Petroleum Engineering					
E. Fuel Science and Technology					
F. Other MST-related fields					

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IV. Please list the Annual Rate of Funding of Research Programs by Outside Agencies at the time of Fall 1967.

TABLE 4 Annual Rate of R&D Funding by Outside Agencies, Fall 1967[1]

Field (irrespective of curriculum)	NSF	DOD	NASA	USBM	NDEA	AEC	Other Federal Agencies	State Agencies	Industry	Endowments & Other	Total Number	Total $
A. Mining No. of Grants or Contracts											#	
Total Expenditures												$
B1. Extractive Metallurgy (including mineral beneficiation) No. of Grants or Contracts											#	
Total Expenditures												$
B2. Physical Metallurgy No. of Grants or Contracts											#	
Total Expenditures												$
C. Non-Metallic Materials No. of Grants or Contracts											#	
Total Expenditures												$
D. Petroleum Engineering No. of Grants or Contracts											#	
Total Expenditures												$
E. Fuel Science & Technology No. of Grants or Contracts											#	
Total Expenditures												$
F. Other MST-related fields No. of Grants or Contracts											#	
Total Expenditures												$

Grand Total #________

Grand Total $________

---

[1] Include Fellowships and Traineeships even though they are also included in Table 3.

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V. Please list the Distribution of Total R&D Funds from Outside Agencies According to the Commodity Principally Involved and the Goal or Activity. Estimate Distribution of Total R&D Funds from Table 4 in percent.

DISTRIBUTION OF RESEARCH AND GRADUATE FUNDS

Table 5a By Resource

Resource	%
Coal	
Petroleum	
Natural Gas	
Oil Shale	
Industrial Minerals and Rocks	
Metals	
Non-Metallic Materials	
Water	
Other	

Table 5b By Goal or Activity

Activity	%
Production of Raw Materials	
Beneficiation of Raw Materials	
Extraction and Primary Processing of Metals	
Processing Minerals for Non-Metallic Uses	
Fuels Research and Development	
Environmental Improvement	
Underground Storage	
Non-Mineral Applications of Mining Technology	
Transportation of Mineral Materials	
Safety and Health	
Other	

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VI. Questions:

1. What are the greatest needs for the development of the research and graduate program in these fields in your university?

   A. Mining:

   B. Extractive Metallurgy (including mineral beneficiation):

   C. Non-Metallic Materials:

   D. Petroleum Production Engineering:

   E. Fuel Science and Technology:

   F. Other MST-related fields:

2. In your opinion what would stimulate enrollment in the fields of Mineral Science and Technology (undergraduate and graduate)?

3. Approximately what percentage of foreign students in Mineral Science and Technology graduating from your university remain in the U.S. for *employment* after completing their formal education?

   1 year maximum ____________________, 5 years maximum ____________________, 10 years or more ____________________

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Mineral Science and Technology

MINING

Report of the
Panel on Mining
of the
Committee on Mineral Science and Technology
Division of Engineering, National Research Council

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National Academy of Sciences
2101 Constitution Avenue
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PANEL ON MINING

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FREDRICK C. KRUGER, Stanford University
STANLEY D. MICHAELSON, Kennecott Copper Corporation
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CYRUS KLINGSBERG, National Academy of Sciences–National Research Council, Executive Secretary

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Abstract

Mining refers to the production of solid mineral raw materials, common and uncommon, metallic and nonmetallic. This includes all the diverse needs of our industries such as iron, coal, copper, silver, salt, talc, asbestos, sand, gravel, lime, common clay, and many others. In addition, the application of specific mining technology such as rock excavation and the use of rock as a structural material is rapidly becoming a critical need of our society in such civil engineering projects as highway cuts, tunnels, subways, dams, and underground chambers for storage, powerhouses, and defense.

Present U.S. mineral production, both in value and tonnage, absolutely must be doubled and trebled in the next few decades if our society is to continue at its present growth rate. In general, the necessary natural concentration of valuable minerals required to render an occurrence economically recoverable is, by its very nature, very unusual. Once mined, an ore deposit is nonrenewable within the lifetime of mankind. Therefore, if needed by man it must be mined where it is, and not where the operation would be more convenient. When present deposits are exhausted, new ones must be discovered and mined. These will be of lower grade and less accessible than those currently being mined, and because of lower grade ores and increasing needs, the new mines must inevitably be larger and more numerous. Faced with these natural conditions, the nation has only two alternatives: (1) continue to use present practices and technology and increase the price of mineral raw materials to the consumer (the nation); or (2) develop new technology and environmental practice which can reduce costs or at least maintain stable costs.

It is the purpose of this study to state the fundamental importance of the mining industry to the nation's development, defense, and economic well-being. In this context, it is appropriate to consider the industry's contribution to our society in the past, its present status

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and contribution, and most important, what it can contribute in the future if properly directed.

The future of the mineral industry depends upon the research and development of greatly improved equipment and techniques, and the education and training of adequate numbers of people to do this and to apply the results. One of the most critical problems facing the industry and the nation is the present status of mining engineering education and research.

During 25 years prior to 1962 the mining engineering departments in the nation numbered from 26 to 30, and produced up to 500 engineers annually. In the following 5 years this total dropped to only 17 departments, by 1966 producing only 138 engineers, as seen in the following:

Year	B.S. Mining	M.S. Mining	Ph.D. Mining
1960	242	35	3
1961	220	33	2
1962	193	49	6
1963	180	65	3
1964	144	43	4
1965	146	85	25
1966	138	80	27

At the same time, the demand for mining engineers has never been greater, as shown in the following tabulation of recruiting experience at the Colorado School of Mines (4).

Year	Vacancies	Job Offers	Engineers Hired	Offers/ Vacancies	Hirings/ Vacancies	Vacancies per Company
1963	22	30	13	136%	59%	2.4
1964	25	29	19	116%	76%	2.8
1965	50	83	39	166%	78%	4.3
1966	95	140	50	147%	53%	5.1
1967	153	201	56	131%	37%	5.9

Mining engineers are the only engineers specifically trained for the rapidly expanding field of rock excavation and the use of rock in place as a structural material. Thus in the face of greatly increased needs for mining engineers, in new fields as well as in the traditional ones, we have today the lowest production of mining engineers in the past 25 years, and the trend continues downward. Even the rapid increase in advanced degrees granted in mining is a cause for concern when compared with the concurrent decrease in first degrees. Research and development is certainly needed, but so is the operation of the industry.

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CHAPTER 1

Summary and Recommendations

The mining industry must continue to be a powerful and vital force in the development of the country, the growth of the economy, and the maintenance of our national defense and well-being.

Growth and improvement in technology have been rapid, but not rapid enough to prevent rises in prices and increased imports of some products (the only notable exception being coal).

Mining technology has contributed predominantly to related disciplines such as tunneling (see Figure 1) underground storage, rock mechanics, explosives development, and bulk haulage.

This technology has been almost the sole support for some key areas of endeavor, such as rock excavation.

Mining engineering has developed almost the entire area of knowledge concerned with underground ventilation and the detection and control of explosive gases such as methane and other undesirable gases and atmospheric dusts. In addition, the control of excessively hot working environments, and the physiology of human heat tolerance have been highly developed in connection with deep mining, especially in South Africa. All of this technology is and will be badly needed in the future in deeper mines as well as in tunnels and other underground chambers for various nonmining purposes.

The mining industry has been and still is a prime factor in the economic growth of many of the underdeveloped countries.

Present federal support for education and research, such as that from NSF, HEW, etc., tends to lump mineral engineering with engineering in general, and because its representation is then small the discipline does not receive the support it needs and deserves as an essential basic industry.

Mining engineering education is concentrated in only a few universities (all but one are state supported), and almost invariably has the

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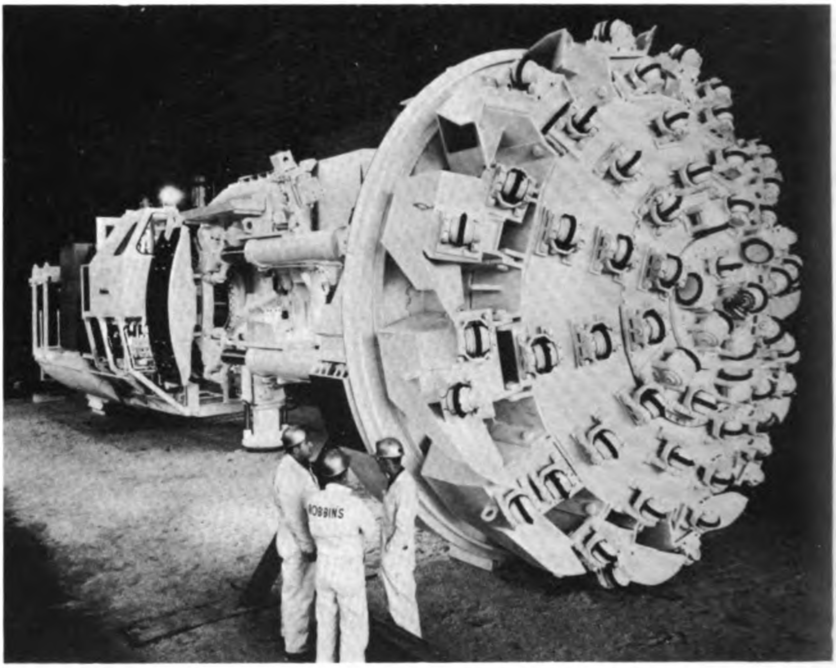

FIGURE 1 Tunnel boring machine.

status of a relatively small specialized group within a much larger educational organization. Under these special conditions, and with the present extreme demands on higher education in general, it is inevitable for mining departments to suffer in the competition for staff and funds, and for their plight to become rapidly and progressively worse.

The panel offers the following recommendations:

1. Mining engineering education and academic research must have greatly increased financial support to supply our urgent manpower needs, present and future. This effort should be concentrated in centers of excellence for mining education where adequately sized faculties and student enrollments can be assured. Only industry can react quickly and decisively to meet this emergency, and strong federal support can assist on a long-term basis. Primary emphasis should be on quality staff and facilities.

- Therefore, the panel recommends strongly increased continuing industrial support for mining engineering education and

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research, with supplementary long term federal assistance, to be concentrated in institutions with an established record of superior performance.

2. Within the Department of the Interior there are many bureaus and offices dealing with mineral policies and programs. Such multiple responsibility requires much coordination to achieve prompt and efficient results to meet the national mineral needs.

- Therefore, the panel recommends that the Assistant Secretary for Mineral Resources of the Department of the Interior should promptly assume a much larger and more effective coordinating role with the bureaus and offices in his charge, and with other agencies dealing with minerals policy.

3. Mining engineering is a national and international industry and its product an absolute necessity. Yet because 16 of the 17 mining schools are state supported they are forced to charge higher tuition to out-of-state students and thereby discourage enrollment from students in at least 34 states.

- Therefore, the panel recommends full educational cooperation between states to make mining education available to residents of every state at in-state tuition rates supplemented by appropriate financing from the state of residence.

4. The production of minerals for our society, and the application of mining technology to society's needs, are as basic and essential as agriculture, and there is an urgent need to stimulate governmental and public appreciation of the contributions of the mining industry to our economy and society.

- Therefore, the panel recommends increasing public awareness of the role of the mining industry through: (a) public displays, television programs, popular magazine articles, and literature for school distribution; (b) emphasis in all relevant government publications on the benefits of the mining industry; (c) short orientation courses for high school teachers and counselors; (d) summer "involvement" work in the mineral industry for high school and junior college teachers; (e) U.S. postage stamps on the mineral industry.

5. The supply of modern mining texts and reference books is very limited, and new publications face obstacles of high costs and limited

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circulation. Inexpensive and flexible systems with frequent updating, which include a "mining abstracts," should be created.

- Therefore, the panel recommends that the AIME expand its current efforts in producing texts, reference books, and a "mining abstracts," with the cooperation of the mining schools and publishers, and with some federal funding.

6. American exploration and mining technology, exported to the developing countries, contributes strongly to the rapid development of mineral industries and the economic growth based on them. While we are not fully supplying our own manpower needs now, we are currently educating many foreign students in our methods.

- Therefore, the panel recommends the U.S. education of more foreign mining students, but with full costs met by funds from their homelands, or from the U.S. government if in our national interest.

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CHAPTER 2

Introduction

DEFINITIONS

Mining in its broadest historical sense is the winning from the earth and sea of any mineral material, solid, liquid, or even gaseous, for the benefit of man. Specialization within this broad concept has grown through the years, until now mining is understood to refer only to the production of solid minerals. However, the layman may still not realize that this may include the mining of such common materials as sand, gravel, and stone for aggregate and roads, salt evaporated from the sea, salt and sulfur from deep wells, and many other nonmetallics such as talc, asbestos, and common clay. Another definition of mining that is often overlooked is the application of mining technology to construction or civil engineering projects where the production of a valuable mineral product is usually not involved, or is at most secondary to the creation of a useful highway cut, tunnel, or underground chamber for storage, a powerhouse, or defense. It may be in this latter area that mining will make contributions most visible to the layman in the next few decades, although the behind-the-scenes production of tremendously increased tonnages of the mineral products needed by all branches of our economy and civilization are in fact far more essential.

IMPORTANCE OF MINING

The only two truly basic industries are mining and agriculture. Only these two produce the raw materials and new wealth from which all the others fabricate and service our industrialized way of life.

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Our complicated economic machine works with the products of these two basic industries, or serves the people who do. The whole system would come to a halt without the essential input of new wealth and material provided by mining and agriculture. Furthermore, unless we are to sacrifice our national economic and defense posture, we must continue to mine the necessary materials, and at an ever-increasing rate.

The following paragraphs from "Mineral Facts and Problems," USBM Bull. 630, 1965 edition (44) help illustrate these facts:

> Structures, roads, and machines are built largely of mineral products; the energy to heat the structures and to power the machines is derived mostly from minerals. Agricultural output is sustained with the aid of mineral fertilizers; and the Nation's economic and military security both are founded ultimately on its ability to obtain and utilize essential metals, nonmetals, and mineral fuels.
>
> To assure a future supply of minerals, the facts about minerals must be ascertained. The mineral problems of today must be identified, and those of tomorrow anticipated. Preparation must be made to attack any impediment to meeting the Nation's mineral requirements—by prospecting for new ore bodies, by research to find improved extractive, processing, and utilization methods, and by making abundant resources substitute effectively for those that are scarce. In short, all available knowledge, foresight, energy, and wisdom must be enlisted to assure the present generation, and those that are to follow, a mineral-resource base on which the United States can continue to build.

The present total U.S. mineral production is about $24 billion annually, and this total, both in value and absolute tonnages of mineral, absolutely must be doubled and tripled in the decades ahead if our society is to continue at its present growth rate. Paradoxically, however, because of the "value added" effect of this essential mineral input, while the total economy expands phenomenally, the percentage contribution of raw mineral production to the gross national product is constantly shrinking and is presently well under 5 percent.

The layman has little appreciation of the fundamental nature of an economic mineral deposit and its efficient exploitation for the public benefit. As a result, the mining industry is often censured as a public nuisance, partly because of past bad practices long abandoned or corrected, but in a larger sense because of misunderstanding.

In general, an economic mineral deposit is a freak of nature. In the case of the rarer elements such as copper, lead, zinc, gold, and silver, the natural concentration of the minerals to render the deposit an economically recoverable "ore" is a very unusual occurrence. With this type of ore body, its location relative to access,

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supplies, and markets is important, but not necessarily critical to its minability. In the case of the more common mineral products such as limestone, sand and gravel, industrial salt, coal and iron ore, proximity to market (or low cost high tonnage transportation) is very often the controlling factor which decides whether one has an ore body or just a specific mineral occurrence. If the mineral is to be made available for man's use, it must be mined where it is and not where it might be more convenient or less of a nuisance. Furthermore, it requires capital investment to find and delimit such a deposit by geologic exploration, and once found it contains only a finite, limited, and irreplaceable mineral content. When it has been completely mined it has no salvage value, and unlike old farm land, it cannot be rejuvenated by the judicious use of crop rotation and soil conditioners. Hopefully, with advanced mining and reclamation technology, the site of the terminated mining operation may be made at least socially tolerable to its neighbors, and often actually more desirable than before mining began due to new recreational or agricultural benefits. Meanwhile, the mining industry must reinvest its capital to find a new deposit to replace the old one, and move or replace its entire operating facility in order to assure its corporate continuity and a constant mineral supply to society.

It is a common misconception to judge the health of the mineral industry in terms of a specific mineral such as gold, silver, lead, zinc, etc., or with a particular type of mining or a local region in mind. This is to completely ignore the fundamentally limited characteristics of mineral deposits as they exist in fact, not as we should like to find them.

The mining industry must be flexible enough, astute enough, and willing to accept the challenge to produce what is needed, where it is needed, with the manpower and resources available.

STUDY OBJECTIVES

The purpose of this study of mining is to describe the fundamental importance of this industry to the nation's development, defense, and economic well-being. In this context it is important to outline the development of the industry in terms of what it has contributed in the past, its present state and current contribution to our society, and most important, what it should contribute in the future if properly directed.

This study has been limited in general to technological matters involving the mining industry, and by agreement with the other panels of the Committee on Mineral Science and Technology, the Mining Panel has confined its attention to the production of mineral solids.

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CHAPTER 3

History of Mining

EARLY BEGINNINGS

Mining is one of the earliest forms of directed human endeavor. Early man, in his struggle for survival, recognized the special characteristics of certain rock materials for weapons and domestic implements. Carbon-dated artifacts place the use of some stone materials at the dawn of human history. Since that early beginning, mining has had a most profound effect on world history. Prehistoric man mined flint, obsidian, and native metals for tools, weapons, and ornaments. Various other minerals served for colors and perhaps even for medicinal purposes.

As the stone age was succeeded by the bronze, so was the bronze by the iron age. Manufacture of iron has been dated as far back as 1500 BC in western Asia, while in China the first known record is 122 BC. China was also producing castings as early as 900 AD. By Roman times the mining, smelting, and fabrication of iron and steel tools and weapons was well advanced (33).

Many ancient wars and extensions of empire have been based primarily on an emerging civilization's need for mineral resources. The early Egyptians and Phoenicians developed stone quarries and ranged far in their search for gold and copper, while the later Romans mined all around the Mediterranean and as far as Britain. They needed the tin of Cornwall to alloy with copper from Cyprus to make bronze implements and utensils. Good iron ore sources were also avidly sought to make weapons and tools that gave such a decided superiority over peoples still in the bronze age or with inadequate reserves of ore and techniques of manufacturing iron (33).

After the Romans, the development of the rich ores of Sweden

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helped give the Scandinavians a mastery of northern Europe for centuries. This influence also extended into Russia, the Ottoman Empire, and North Africa. It might also be mentioned that it was this growing iron industry that led to the formation of the first stock companies in the world.

It is thus evident that all through ancient and medieval times, those peoples and those countries with access to readily mined mineral reserves, and who developed the necessary techniques to mine and refine minerals, were always those who gained ascendency and made the most progress in civilization.

This brings us to the New World where the Indians were still in the stone age when Columbus arrived. They mined flint, obsidian, and worked other stones to make tools and weapons. There is evidence of mining to obtain native copper on Isle Royal in Lake Superior as far back as 5000 BC. There is also evidence of a little mining by Indians to obtain materials for coloring, and even a slight use of coal. The Incas and Aztecs mined native copper, gold, and silver.

After the discovery of America, the first emphasis was largely to find gold and silver. In this the Spanish were eminently successful when they conquered the Aztec and Inca empires. While adept at quarrying, building, and carving in stone, such gold, silver, and copper that the latter possessed came from findings of native metal deposited in stream beds or easily mined from outcroppings. After their conquests, the Spanish pushed the mining of these metals and instituted wide searches for more deposits.

Other European explorers and settlers, such as the Portuguese, French, and English, were first attracted by the possibility of finding precious metals, and only secondarily by furs, fishing, and agricultural products. They failed in their search for metals, so their settlements and developments came later and at a slower pace than those of Spain.

The first permanent English colony was Jamestown, Virginia. Here Captain John Smith led unsuccessful expeditions to find gold, but he did find iron ore, and as early as 1608 a shipment of 35 tons of ore from Jamestown to Bristol, England, was smelted into a good grade of iron. This was followed by the establishment of an iron works in the colony in 1620 to manufacture the tools so badly needed by the settlers (33).

Similarly, iron mining was begun in 1657 near New Haven, Connecticut. While George Washington was president, every one of the 13 states was mining and producing iron (12).

U.S. gold mining began in North Carolina, which produced the entire U.S. output from 1793 to 1828, although the Spanish may have had a little production in the Southwest. This early production spread

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to both Carolinas, Georgia, and Virginia. The first U.S. mints were established at Dahlonega, Georgia, Charlotte, North Carolina, and New Orleans, although the latter did not operate until the later California discoveries. This early gold production was relatively unimportant, but did serve to prepare miners with techniques for the bigger developments in the West (33).

Lead was first discovered by the French in the Mississippi Valley, and first produced in 1690 at Galena, Illinois. By 1782, lead mining had spread to other states. One of the main uses of this lead was for ammunition on the frontier (33).

Copper was apparently first mined at Simsbury, Connecticut, in 1709. Other early ventures were at Hanover, New Jersey, in 1719, and at Brunswick, New Jersey, in 1750. Although copper was known to exist in the Lake Superior district, the first company organized to develop its deposits was created in 1844. In the Southwest, the Spaniards attempted the mining of copper in New Mexico in 1598 at Santa Rita, but continued only sporadically until the latter 1700's. The first copper mining by an American firm was in 1854 at Ajo (33).

While the French and English explorers early discovered coal, its first recorded use was in 1702 when a French settler in Virginia was granted permission to use coal for his forge. Earliest recorded commercial mining was from the James River field near Richmond, Virginia about 1750, with shipments to Philadelphia, New York, and Boston, as well as for local consumption. Most of this coal was used to manufacture iron, and this proved so important to make shot and shells during the Revolution that the British sent an expedition to destroy the works in 1781 (12).

Coal consumption in America had an extremely show start, and its use for heating, smelting, and coke was at least a century behind Britain. Much of this was because the abundant forests supplied nearly all needed fuel, while charcoal manufacture and use was cheaper and better known than coke. For these reasons total coal production was only 108,000 tons in 1800. From this point consumption gradually increased until it superseded wood for the first time in 1840, after which wood's importance as a fuel rapidly declined (12).

It must be realized that smelting and any type of manufacture in the colonies was curtailed by the British, who had a policy of restricting the colonies to the production of raw materials, with manufactured products coming only from Britain. Consequently, early mining, smelting, and manufacture were held back. This curtailment was one of the grievances leading to the Revolution. After independence, the early beginnings described above set the stage for a surge of mineral discovery and mining development. This was of major importance in settling the United States and making it the leading industrial nation of the world.

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MAJOR ACCOMPLISHMENTS

The list of basic industrial developments that were first conceived and applied to mining purposes is impressive. The first steam engines were developed to pump water from mines. The first rail transport was for mining operations, the first steam locomotive was for mining, and the first electric locomotive (1883) was developed for mines in Germany.

The invention of gunpowder is credited to the Chinese, and its first application was probably for entertainment. However, it was later adopted for mining and other rock excavation purposes, where it supplanted the age-old system of fire-setting. The development by Nobel in 1864 of modern high explosives and the means to detonate them was primarily for mining and construction purposes (5).

Conventional commercial and military explosives developed rapidly until about World War I, after which little was developed until during and just after World War II. In the past 20 years, however, the whole science of commercial explosives has been revolutionized with the advent of sophisticated plastic and molded explosives, cheap ammonium-nitrate-fuel oil bulk explosives, and ammonium-nitrate slurries. The last two are even manufactured on site in large open-pit mines by special mix trucks at the blast hole, and the formulation is varied to meet each specific need (see Figure 2).

By virtue of Project Plowshare, the basic technology of nuclear explosives for peaceful purposes is now quite well known, and is being demonstrated commercially in underground applications in such projects as "Gasbuggy" and "Sloop," (36, 39). However, surface uses of commercial nuclear explosives must await better techniques of controlling contamination and better international understanding and agreement.

Two fundamental developments in mineral processing about the turn of the century led directly to the concept of mining low-grade ore in extremely large tonnage operations. The development of cyanidation for gold recovery was first applied on a large scale about 1890 on the Witwatersrand in South Africa. The flotation process for concentrating sulfide ores was developed about 1905, and one of the early extensive applications was for lead at Broken Hill, Australia (33).

D. C. Jackling in the United States began to develop a truly revolutionary idea in mining operations about 1910, and the flotation process made it eminently successful. Jackling conceived the idea that the copper deposits of the porphyry type, long considered economically unminable, could be made economic if mined on a very large scale so as to greatly decrease unit costs. He started several operations with a minimum capacity of about 5,000 tons of ore per day, which was considered to be a very large mine in those days. The

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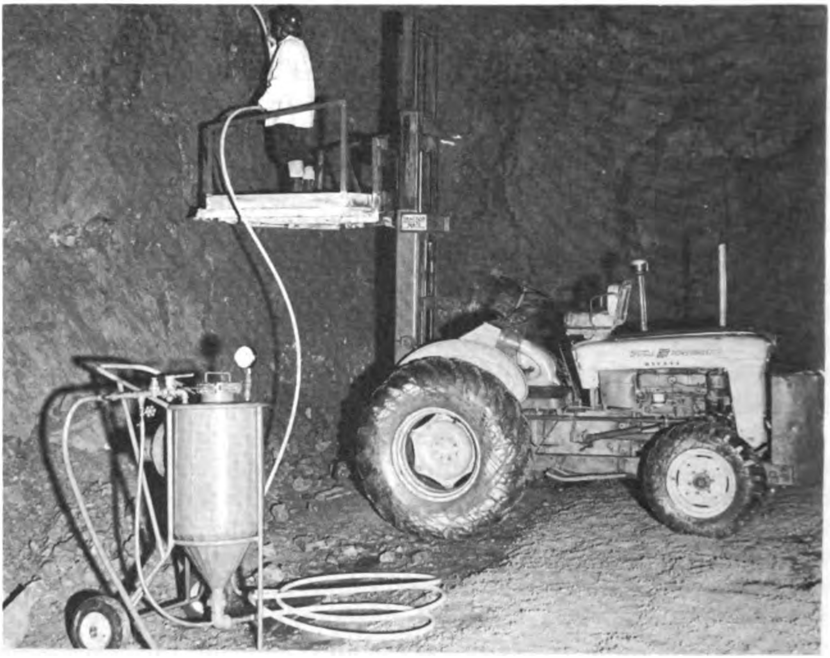

FIGURE 2 Modern bulk methods for charging ammonium-nitrate-fuel oil explosives into drill holes.

Utah Copper Company now mines about 100,000 tons of ore plus 200,000 tons of waste daily, and many large surface mines process 10–40,000 tons per day. Although the early bulk mining attempts were surface or open-pit mines, when the principle was seen to be valid, new underground bulk mining methods were developed, notably block caving, and now 20–40,000 tons per day underground mines are operating successfully.

An early event of major importance in finding new ore bodies was the development of the diamond drill about 1880. This drill uses diamonds as the cutting medium, and permits the recovery of a perfect rock core from depths as great as 2 miles. It is still the most essential tool in proving subsurface geology, and finds wide use in the construction industry as well.

Several developments just after World War II have profoundly affected coal and metal mining practice as well as the construction industry. Tungsten carbide bits are now an essential part of hard rock drilling, continuous coal miners, and tunnel, shaft, and raise borers, and have made things commonplace which were literally

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impossible with ordinary hardened steel bits. Yielding hydraulic props for coal mines were first set individually by hand, and have now developed to self-advancing multiple units, with experimentation toward a remotely controlled, completely automated, longwall coal face. Rock bolts are used to reinforce rock so as to support itself, and have to a large degree eliminated conventional timber and steel shoring.

Continuous full face boring of tunnels and shafts is presently revolutionizing our concepts in underground excavation (20, 21, 31).

The great iron ranges of the Lake Superior district began to be developed in 1844. A canal around the rapids of Sault Ste. Marie, between Lake Superior and Lake Huron, linked the Lake Superior ores with excellent coking coals in the East. The steel industry areas of Pittsburgh and the lower lakes area are the result (12).

In the late 1880's, Thomas Alva Edison developed the basic technology of magnetic concentration of a low grade taconite-like rock in New Jersey. The fine iron concentrate was pressed into briquettes and dried in a furnace. In 1914, D. C. Jackling began experimenting with this idea on the Mesabi taconites, and eventually built a concentrator near Babbitt, Minnesota. This project was abandoned in 1924, largely because of excessive mining costs and extremely difficult blast hole drilling. Finally the jet piercing drill solved this latter problem in the 1950's, and this long sequence of efforts led to the present successful taconite industry in Minnesota, assuring abundant new supplies of high grade iron ore.

Once coal consumption exceeded that of wood in 1840, the development of railroads, steel mills, and other large consumers of fuel was such that coal mining became increasingly more important. In one century and principally after the Civil War when industrial development grew so rapidly, coal consumption jumped until it was close to 200,000,000 tons annually by 1900 and 500,000,000 tons by 1910 (12).

Following World War I, oil and gas began to provide a higher proportion of the total energy used. The convenience of these fuels for domestic and small industry use caused coal to gradually lose these markets until now they are negligible. Likewise, the widespread introduction of diesel locomotives after World War II resulted in a total loss of what has been the coal industry's largest sales. Fortunately, these losses began to be offset by the growth in electrical power generation which is now coal's most important use, amounting to about half of total production, a proportion that is increasing annually.

Since World War I, coal production has generally fluctuated around 500,000,000 tons annually with more during boom periods, such as during and following World War II when a peak of 630,000,000 tons was reached in 1947. For the past 7 years growth has been steady with 550,000,000 tons being produced in 1967.

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Coal deposits of the United States are fairly well distributed over the country (see Figure 3). However, 90 percent of consumption is east of the Mississippi River whereas the bulk of reserves are in the Rocky Mountains and adjoining states (42).

Figure 4 shows recent coal consumption and its projection through 1980. It indicates that 50 percent of total consumption for electric power generation in 1966 will become 64 percent by 1980, and this estimate is based mainly upon commitments already made. Total consumption will thus jump from 550,000,000 tons actual in 1967 to 701,000,000 in 1980, the increase being almost entirely due to sales to electric generating stations.

Natural gas and oil have largely ceased to be very competitive with coal in electric power generation. Figure 5 shows the projected proportion of fuels used in electric generation to 1980 in tons of coal equivalent. Need for more electricity is so strong that both coal and nuclear fuels will be needed in greatly increased amounts during the period shown (15, 16).

Regardless of nuclear energy, coal has a strong competitive position where transportation charges are not too high. Coal is almost certain to be very important for the balance of this century. What happens after that will probably depend upon the economics of gasoline and pipeline gas from coal, soon to be indicated by several pilot plants.

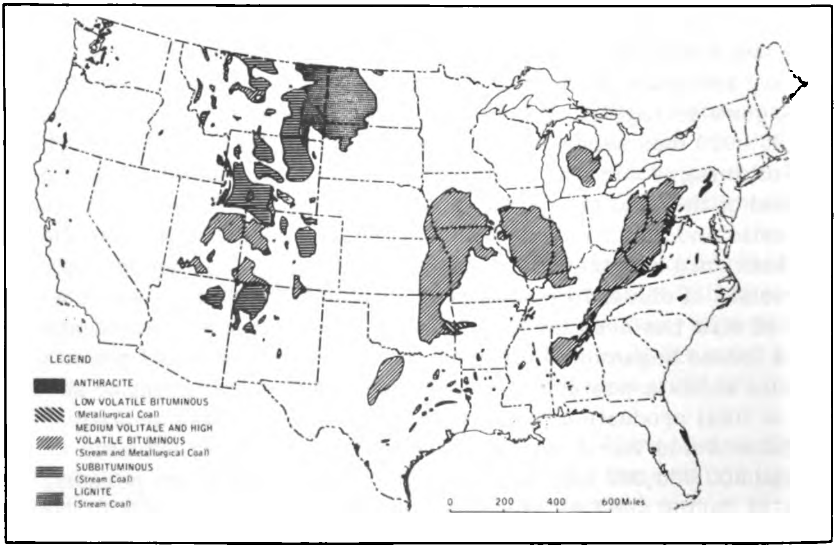

FIGURE 3 Coal reserves in the United States.

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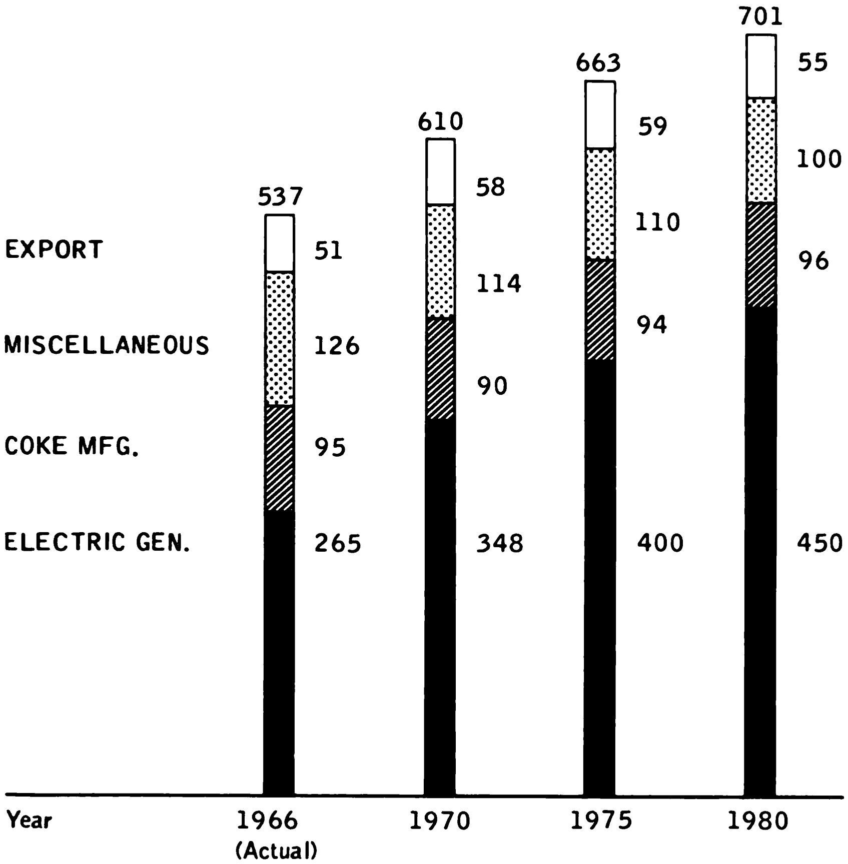

FIGURE 4 Projected U.S. bituminous coal consumption and exports. (Millions of Tons)

Reserves of all fossil fuels are limited, but the United States has more reserves in coal than in oil, gas, oil shale, and tar sands combined, as shown in Table 1 (43).

Even if coal reserves are overestimated, as some in the industry believe, the relative dominance compared to other fossil fuels is apparent. Reserves of all fossil fuels are finite, so for the long pull the world is fortunate in having nuclear energy. The long-term future will probably see all fossil fuels conserved for higher uses than boiler fuel, for example: petrochemicals, lubricants, gasoline, chemicals, etc.

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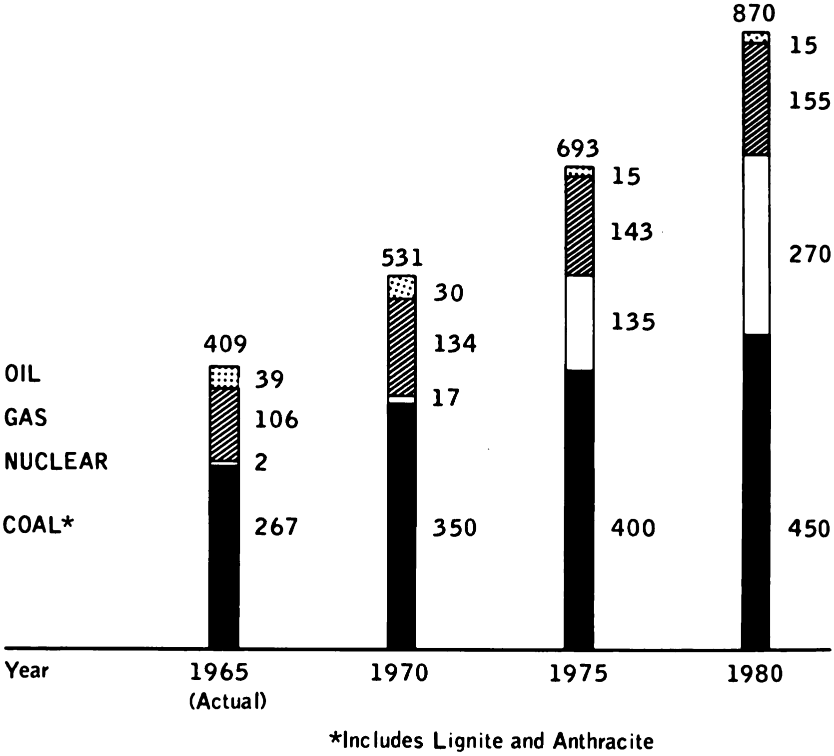

FIGURE 5 Projected U.S. energy consumption for electric generation. (In Millions of Coal Tons Equivalent)

TABLE 1 U.S. Reserves of Fossil Fuels Expressed in Heat Value

Reserves	Quadrillions of Btu
Coal	17,307
Oil	2,373
Natural gas	1,906
Tar sands	7
Oil shale	4,060
Total	25,653

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An outstanding feature of the coal industry has been its level and even declining price per ton at the mine despite very large and continuous increases in costs of labor, materials, machinery, and other items of expense. This is explained by higher productivity, new and better mining techniques, vastly improved machinery, and better management resulting from the constant drive to stay competitive. These cost and price trends are shown in Figure 6. Relative prices of natural gas, petroleum products, and coal are shown in Figure 7 (47).

GENERAL STATE OF MINING

The U.S. mineral industry produces over $10 billion annually in solid mineral raw materials (see Table 2), employs over 400,000 people (see Table 3), and provides an impressive variety of mineral products (see Table 4). As its product is the raw material from which so many manufacturing industries make their products, mining's total impact on our economic society is much greater than these figures alone would indicate (48, 49).

As early as 1910, Herbert C. Hoover found that productivity of American labor in mining led the world (19). This was the result of the improved machinery and techniques developed by the U.S. mining industry following the Civil War when Americans began to discard

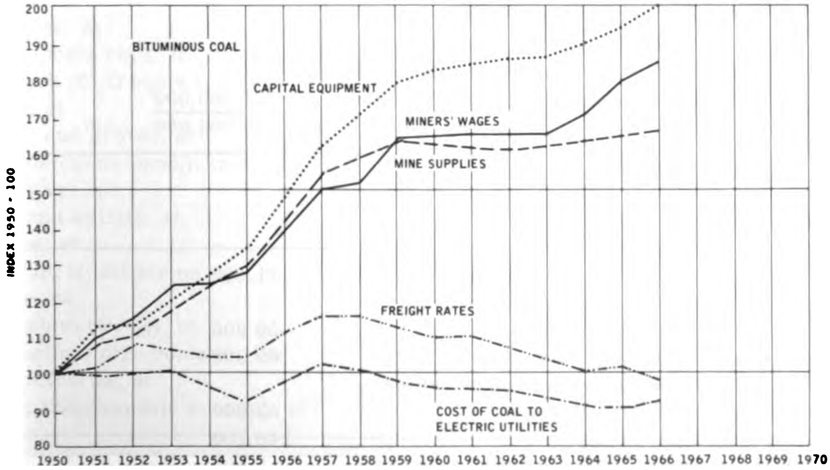

FIGURE 6 U.S. bituminous coal prices and principal price components.

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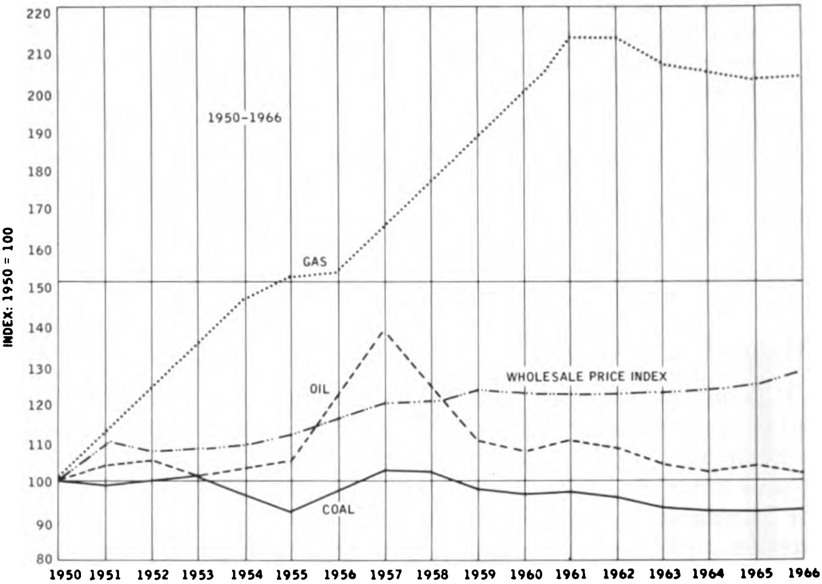

FIGURE 7 Fuel costs in power generation.

TABLE 2 Value of Solid Mineral Production in the United States during 1966 (excludes Petroleum and Gas)

Metals	$ 2,621,000,000
Nonmetals	5,177,000,000
Mineral fuels; including bituminous coal, anthracite coal, lignite, peat, asphalt, and related bitumens but excluding natural gas and petroleum	2,537,000,000
Total value	$10,335,000,000

TABLE 3 Number of Men Working Daily–1966

Metal mining and mills	71,600
Nonmetallic mines and mills, excluding stone	50,900
Stone mines and mills	89,300
Primary nonferrous reduction and refining plants	42,600
Coal, all types	146,200
Other, approximately	1,000
Total	401,600

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TABLE 4 Production During 1966 in the United States for Selected Mineral Products

	1966
Aluminum, primary st (short ton)	2,954,000
Antimony, st	900
Asbestos (sales), st	138,000
Barite, st	947,000
Bauxite, lt (long ton)	1,700,000
Boron minerals, st	861,000
Cement (Portland and other), bbl (barrels)	393,137,000
Coal (bituminous and lignite), st	532,000,000
Coal (anthracite), st	13,000,000
Copper (recoverable content), st	1,415,000
Feldspar, lt	643,000
Fluorspar, st	247,000
Gold, troy oz.	1,810,000
Gypsum, st	10,090,000
Ilmenite (concentrate), st	950,000
Iron ore, lt	92,200,000
Lead (recoverable content), st	321,000
Lime, st	17,917,000
Magnesium (primary), st	79,000
Mercury, 76-lb flasks	21,700
Mica, st	125,000
Molybdenum, lbs contained molybdenum	89,000,000
Nickel (recoverable content), st	14,771
Perlite, st	500,000
Phosphate rock, lt	30,900,000
Potash (K_2O equiv.), st	3,334,000
Salt, st	36,331,000
Sand and gravel, st	894,000,000
Silver (mine prod.), troy oz.	42,200,000
Soda ash, st	1,744,000
Sodium sulfate, st	666,000
Stone, st	777,000,000
Sulfur, lt, all forms	9,082,000
Talc, st	897,000
Uranium (U_3O_8), st	9,500,000
Vanadium (ore content), lbs	12,524,000
Vermiculite, st	250,000
Zinc (recoverable content), st	585,000

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the European methods they had inherited. The result is that for years American productivity per man has led the world on any kind of a comparable basis.

U.S. coal mine productivity figures are based on salable cleaned coal. Total material mined usually ranges from 5 to 40 percent higher. Some underground mines are obtaining a productivity of 40 to 60 tons per man-shift while some strip mines are achieving as high as 75 to 100. Increase in productivity has been averaging 5 to 6 percent per year for the industry as a whole. Compared to these figures the rest of the world is far lower, as shown in Table 5 (51).

This comparison shows why the U.S. coal industry could deliver coal to most parts of the world cheaper than indigenous supplies if it were not for restrictions and protective tariffs.

While American mining productivity continues to lead the world, in many cases this is more the result of constantly improving existing methods and equipment than of really new breakthroughs in mining science. Indeed, as will be seen, many of the new developments in the recent past and present are coming from abroad. Pertinent examples are in areas of controlled blasting (Sweden), ground control in tunneling (Europe), rotary-percussion drilling (Germany), tungsten carbide (Europe), ventilation, heat, rock mechanics, shaft sinking (South Africa), and rock reinforcement (Australia).

Not only is much of the higher quality mining research being done abroad, but we are constantly facing the reality that the newer and richer ore deposits are being found and developed overseas. If the U.S. mining industry is to remain in the forefront of world mining, we must drastically accelerate our efforts in research and development. The alternative is to become dependent on foreign sources of minerals, and this is not only economically intolerable, but disastrous in time of military emergency.

TABLE 5 Productivity, Tons of Coal per Man-day, Selected Countries (1966)

United States	18.52
Australia	9.07
United Kingdom	2.87
Belgium	2.16
West Germany	3.23
Poland	2.47
France	2.32
Netherlands	2.47
Japan	1.50 estimated
U.S.S.R.	2 to 3 estimated

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CHAPTER

4

Specific State of Mining

NEW MINE DEVELOPMENT

Introduction

The development of new mines can provide the opportunity for new or improved mining technology, but often the situation is that of the absolute necessity to devise new and effective means of ore extraction in the face of new or changed conditions. For the purpose of this discussion, "new mine development" includes extension of existing mines into ore materials of different character, requiring changes in mining method or equipment or beneficiation processes.

There must be an end point in the exploitation of any mineral resource. In underground mining this point is reached at an extraction short of 100 percent, owing to pillars left for roof or ground support, materials lost in retreat mining or abandoned due to caving, hazardous conditions or flooding, or dilution by waste rock. Mine organizations are working with rock mechanics techniques to determine stress limits for the benefit of mine planning toward optimum support, extraction, and safer terminal operations.

In open-pit mining, waste rock which covers the ore must be removed, as well as large amounts on the sides in order to achieve stable pit slopes. The ratio of the total waste rock moved to the ore recovered is called the stripping ratio. As a pit deepens in following the ore, the stripping ratio must increase until finally it becomes economically intolerable and a switch to underground mining must be considered. Meanwhile, improved drilling and blasting, and the development of larger loading and hauling equipment, tend to increase the limiting ratio.

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The termination of one mine may give life to another through the transplanting of an entire mine organization, or the organization may be split up and distributed among other mines of a company. The modern, effective mine organization is a responsible team. The influence of unrelated technologies for the betterment of mining is much more effective today than a generation ago, but there is progress still to be made in this area. For implementation of progressive ideas the team still needs effective leadership, stimulated by an appreciation of the necessity for change.

Deterioration of ore quality can force cessation of mining and search for replacement elsewhere, or it may force a new development into much lower grade materials, using new excavation and beneficiation technology. The development of taconite mining in Minnesota and Michigan is representative of the latter condition. The survival of an iron mining industry in those states, faced with approaching exhaustion of natural ores and heavy competition elsewhere in the world, depended heavily on research programs, largely private, but with significant contributions by state programs. Another significant factor was a change in the tax law to encourage investment leading to taxable production, instead of discourage it.

For reasons of capturing or retaining markets, consumers of mineral raw materials may take the bold step of relocating major smelting and refining facilities close to large concentrations of population, often on tidewater. This often results in violent dislocation of raw materials suppliers, who are faced with unassailable competition unless they adjust by locating ore deposits in which they can operate competitively. Whole mining districts have thus been isolated, and searches for substitute supplies have culminated, in some instances, in establishment of operations on foreign shores. Such new developments in underdeveloped countries have fostered significant technological progress due to the fact that planning encompassed whole operations from the mine to tidewater, unfettered by ties to existing transportation systems, labor contracts, or historical practice.

The customer for a mineral raw material is seldom completely satisfied. In a given market, an improvement of quality through advanced technology (or simply owing to better crude ore) forces higher quality standards. Thus where market requirements can be met, new developments are born.

Domestic Versus Foreign Development

Much of the iron ore mining done around the world is an extension of U.S. technology, or U.S.-adopted technology, simply because U.S.

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companies have been instrumental in the development of those deposits, particularly during the past 15 years. A significant design advantage abroad, in many cases, is the necessity to design operations from mine to vessel at tidewater. While such complete development represents high capital investment, it affords opportunities for modern high-efficiency design, whereas developments within the United States are often tied to existing transport systems with built-in limitations. A current example is found in Tasmania, where a 52-mile pipeline will carry iron concentrates from the mine to a pelletizing plant at the shipping port. Present U.S. mines tie into existing conventional transport systems, but successful operation of the Tasmanian pipeline will lead to consideration of pipeline transport of taconite concentrates direct from mine to steel-making centers.

Developments in remote areas abroad often require establishment of residential and business communities to minimize labor turnover, as well as complete public utilities systems involving railways, roads, airports, water supply, etc. On the other hand, they are much less restricted by land availability and environmental controls, and they are more likely to be encouraged by incentive tax structures aimed at developing new industry.

The recent availability of vast iron ore reserves in Australia has promoted a number of major developments there. Aside from excellent mining conditions, the nature of these developments is bound to exert considerable influence in world iron ore markets. While Japanese markets, some 3,500 nautical miles distant, occasioned most of the development to date, the developers, conscious of relative isolation from western world markets, have been "thinking big." New ore export facilities have the capability of loading 100,000 ton freighters, and may ultimately service even larger vessels which could competitively deliver iron ore to European ports over 11,000 nautical miles distant, and to United States ports from 12,000 to 13,000 nautical miles from Australian ports.

All these incentives exert a strong pull on capital from the United States and many other nations seeking mineral raw materials and more attractive investment environments. The establishment of mining developments in many underdeveloped countries, thus encouraged, influences comparative technologies in this manner:

1. Engineers of such projects are encouraged to devise new or better means of mining, beneficiating, and transporting ores to shipping points.
2. Engineers at domestic sources must engage in creative thinking toward improvement of methods and facilities to maintain competitive position.

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3. Owing to the involvements of U.S. companies abroad, there is an internal feedback of information growing out of relatively uninhibited planning and design which tends to broaden engineering thinking toward bold application of new or improved technologies at home.

Transportation

The shipment of mineral products to their point of use is generally a major factor in their final cost. This is especially true of high tonnage items such as coal and iron, and low value items such as sand, gravel, and limestone. During the last decade, therefore, with rising costs and relatively stable commodity prices, management has focused its inventiveness on various facets of the transportation problem in trying to maintain a competitive position.

Marine shipping has probably reached the point of diminishing returns in going to jumbo sizes, and real advances have been made in loading and unloading innovations that reduce demurrage and turnaround time. Now thoughts are turned to improving the utilization factor, from 50 percent upward, by seeking two-way hauls.

The transportation of energy in one form or another is a major problem. Potentially, the cost of energy transmission in gaseous form is the cheapest known, with the liquid form a close second, and both far ahead of shipping in a solid or electrical form. This is a major reason for the present drive to convert coal to synthetic gas and liquid fuel forms. Meanwhile, the effort to ship coal more economically from mine to power plant resulted in the successful operation of the first coal slurry pipeline over 6 years, shipping 1,250,000 tons annually a distance of 110 miles. The first pipeline in Ohio is no longer operating, but is maintained in standby condition to insure railroad performance.

Another pressure on the railroads was the perfection of very high voltage electrical transmission lines which gave lower costs for large blocks of power from mine-based generating stations, thereby eliminating the shipment of coal.

The railroad's answer to these pressures was unit-trains of up to 10,000 tons capacity, employing cars of up to 110 tons, and operating from one mine loading point to one power plant. These trains move as an unbroken unit, frequently with no changing of locomotives. The best rates are secured when cars of at least 100-ton capacity are used with facilities capable of loading and unloading up to 3,500 tons per hour.

Pipeline transport of solid minerals in suspension has many attractive advantages such as minimal requirements as to right-of-way or space, safety, nuisance, maintenance, operating labor, power, etc. Four major examples are seen in Table 6.

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TABLE 6 Major Slurry Pipelines

Length, miles	Diameter, inches	Mineral	Capacity, tons/year	Location
72	6	Gilsonite	0.4 million	Colorado
108	10	Coal	1.3 million	Ohio
52	9 5/8	Iron ore	2 million	Tasmania
273	16	Coal	5.5 million	Arizona

Pipeline transport is also being developed for hoisting minerals vertically from deep mines and for spoil removal from tunnel boring machines.

Environment

In today's world of expanding populations and a very strong public concern for the maintenance of a healthful and aesthetic total environment, there is no place for any operation, mining or otherwise, which despoils the environment unnecessarily and disregards the long-term consequences for the sake of a short-term profit. Fortunately, the majority of mining companies have recognized this principle for some years, and modern plants are a far cry from those erected just a few years ago.

In seeking quick solutions to problems in our total environmental system, we must be careful that the alternatives do not create worse problems of their own. Coal-fired steam generating plants present air pollution problems, but oil, gas, and nuclear energy sources have their problems of pollution, contamination, and waste disposal, too, and we must be careful not to simply trade a well-understood problem for another less well known and perhaps even more serious one. Electric cars emit no exhaust, but they have batteries which need charging, which means more power generation, and we are back to air pollution, happily somewhat easier to control at a central source.

It is singularly unfortunate that the word pollution is generally applied to all conditions of change, from simple discoloration by chemically inert and harmless substances to noxious contaminants harmful to health. Both the air and water have the ability not only to disperse but to destroy pollutants that are injected into them. Thus, air and water quality begins to deteriorate only when the contaminants exceed these abilities.

Pollution of air and water is everybody's problem, to which every man contributes in some measure. The degree to which our burgeoning population may be allowed to pollute its environment will be determined by laws, regulations, and standards now being formulated.

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The practicality of regulations and standards is everybody's business. The imposition of unreasonable standards on any business endeavor may result in higher consumer prices or, in the extreme, business failure. The formulation of reasonable, attainable standards for air and water quality, in the interest of public health and general welfare, including recreation—standards that take into account variables such as population density, topographic and climatic characteristics, and existing or projected land use and economic development—will assure the cooperation of industry and the populace for the common good.

The mining industry is highly vulnerable to criticism. Public concern has been widely expressed regarding acid mine waters and dump leaching; turbidity in mine drainage, tailings basins, runoff from spoil banks; windblown dusts from mines, tailings piles, ore preparation plants, kilns; and mill and smelter stack gases and smoke. By and large, the mining industry is conscious of its responsibility in these matters. It has been active in experimentation and installation of pollution control measures and has complied, or is moving toward compliance, with state and local laws and regulations. In many cases, forward-looking managements have exceeded the requirements established by codes or laws in the states and the federal government, and have expended huge sums of money on controls to demonstrate their willingness to cooperate.

Various neutralizing schemes have been tried at mines yielding acid water. Effective retention and neutralization of huge volumes of water at tolerable cost is a difficult problem, and one for which research and experimentation continue in many organizations such as Bituminous Coal Research and the Battelle Memorial Institute, with results as yet undetermined. Recently some coal mines have installed practical plants to treat their acid discharge water effectively at bearable cost.

Enlightened administration of laws and regulations, and an understanding and cooperative mining industry, together brought about an effective control of an undesirable condition in Minnesota's iron country—i.e., iron oxide discoloration of streams and lakes, known as red water. Old water supply and tailings disposal systems were changed over to closed circuit systems, and mine pumping for drainage was led into settling ponds designed to provide adequate retention time. New installations are subject to advance approval, generally concurrent with approvals for appropriation of water. Such means of turbidity control are also applied effectively to the taconite industry, although the slimes from taconite concentration in Minnesota generally color water gray rather than red.

Control of dusts from tailings basins has posed a problem to the mining industry, and has encouraged much experimental work by the

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mining industry and governmental agencies toward adequate tailings stabilization. Experimentation runs the gamut from the use of emulsified oils and latexes to many varieties of vegetation common to the areas involved, but no solution as yet has been completely resolved. Acid spoil banks often require a blanket of soil capable of supporting vegetation. Some pines are surprisingly tolerant to acid conditions, and thrive in mineral soil, providing a wind break as well as a crop.

Responsible mining companies have extensive land reclamation programs, and in many localities more land is being reclaimed annually than is being mined over, so that there is a net gain in restored land. In many areas the value of the restored land is actually higher than that of the original surface. As in many situations, the irresponsible behavior of a small minority may engender a general denunciation of those making true progress, but much improvement has been made and more must come. Once current operations are carried on in an acceptable manner—restoring land and safeguarding streams, etc., as they go—the old mined areas can be reclaimed gradually, but the nation cannot afford to simply prohibit modern well-planned operations in emotional retaliation for the mistakes and poor judgment of 50 to 150 years ago.

A pollution problem that bears directly on a segment of the mining industry producing and smelting sulfide ores, and indirectly but significantly on the coal mining industry, is sulfur dioxide in stack gases. Higher and higher stacks are being built for high altitude dilution and dispersal of stack gases, and are proving very effective at heights over 800 feet. Some being built will be over 1,200 feet high. However, as a result of air stagnation caused by calms and atmospheric thermal and subsident inversions, air pollutants emitted from normal height stacks designed only for combustion efficiency continue to accumulate, much to the discomfort of inhabitants of the affected areas. Research is in order to remove the sulfur dioxide from the stack gases and recover it as a valuable by-product as well. In developed coal areas, research is being pursued vigorously toward more effective reduction of sulfur content, but mechanical means are limited to elimination of inorganic sulfur; organic sulfur largely remains. However, according to the National Coal Institute, reduction of sulfur from stack emissions is about 5 years away.

There is abundant opportunity for research in techniques of air and water pollution control. It is important, however, for researchers and the mining industry to have some idea of practical and reasonable objectives, requiring parallel objective research and effective coordination by others outside the industry, as in the public health area.

Pollution is everybody's concern, to the point that there should be articulate participation by the mining industry in determination of

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pollution control standards by which it will be governed. Public education as to the principal causes of air and water pollution, proportions assessable to industry and others, and the appreciation of pollution control efforts and problems of the mining industry should be the job of all mining men, in industry, education, and government service.

Markets and By-Products

Mill and market specifications have a profound effect on mining operations, and as they can sometimes change rapidly, they may even disrupt or revolutionize a mining operation. A particularly striking example of this is the recent phenomenal development of the iron ore pellet.

The advantages of beneficiated blast furnace burdens have long been appreciated. Chemical quality improvement has been given first consideration over the past several decades. More recently, advantages of improvement of structure of the burden materials, particularly the iron ore, are being given increasing recognition.

By fortuitous circumstance, taconite pellets have proved themselves a superior raw material in blast furnace burdening, principally due to their shape and size. The practical necessity of agglomerating flour-fine taconite concentrates for blast furnace use was obvious; the development of a high-volume, continuous agglomerating process was an economic necessity; the development of the balling drum and various means of indurating the balls or pellets (not without many technical problems) was the most practical solution, and the most successful venture in the effort merely to form this extremely fine material into a form acceptable for use. By what might be called a happy accident, the pelletized agglomerates have become generally acknowledged as a superior form of blast furnace feed. Witness the astounding growth of iron ore pellet production in North America, from 1,000,000 gross tons in 1955 to 49,000,000 gross tons in 1966, and an increase in the rated annual capacity in 1967 to 73,000,000 gross tons. Here is a case in which one segment of a broad research effort in taconite beneficiation produced a result far beyond expectations.

The ultimate effect of using pellets as blast furnace feed has been to greatly increase the capacity of existing furnaces with no further capital investment. Understandably, under these conditions iron ore is no longer a premium product, but pellets are, and mines must radically modify their operation or be forced out of competition.

An outstanding feature of new coal mine development in recent years is that no new mines are started now without long-term com-

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mitments from the consumer, frequently with dedication of an individual mine's entire reserves to the buyer. This means contracts of 15 to 35 years' duration before any major investment is made. Most of the new developments are for power plants, but some are for coking coals for steel mills, and some for export.

There has been considerable development in the use of fly ash from boiler stacks as an ingredient of concrete and as a road or foundation base. Fly ash adds desirable properties to concrete strength and workability. Although its application has been fought by the cement manufacturers because it partly displaces cement, its advantages are becoming better known, and its use is spreading. This relieves the power companies of a major disposal problem, and has the advantage of a by-product sales credit against the cost of coal.

Many chemicals and drugs are made from coal, and many more could be so derived, but even if they all were in effect, the added coal production would be negligible, on a tonnage basis. In the distant future, when other power sources become available and conversion processes are highly developed, it is likely that coal consumption will be reserved for these higher uses, and much less will go as simple boiler fuel.

SURFACE MINING

Introduction

Mining metalliferous ores by surface mining methods is commonly designated as open-pit mining as distinguished from strip mining of coal and quarrying of limestone, gravel, and certain other nonmetallics. The principles in each case are similar, involving the exposure of the valuable ore, the preparation of the material for removal, the installation of a method of removal, and ultimately an orderly mining sequence.

The term quarrying originated from the Latin word for "squared stone" and has since evolved to cover the mining of many nonmetallic minerals where much of the preparation of the material for its ultimate consumption is accomplished as part of the mining process.

Strip mining of coal, as the name implies, involves the orderly stripping of successive layers of overburden and coal from relatively shallow dipping carbonaceous formations. The rapid growth of strip mining was made possible by the general geology of the coal fields. Most bituminous and lignite coal beds are fairly flat. Thus, a combination of surface topography and coal beds frequently presented sizable areas along the outcrop that had light overburden over the coal

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FIGURE 8 A large stripping shovel removing blasted overburden with a 130 cubic yard bucket. Coal loading shovel is in left foreground. Note relative size of cars in center on top of coal seam. Overburden in this case is only medium thick.

and could be more cheaply mined by stripping than by underground methods (see Figure 8).

In the Appalachian fields many coal seams outcrop on the side of the hills or mountains. In such cases only one or two cuts can be made before the overburden becomes too high to handle. This limits the width of stripping but is offset by, literally, thousands of miles of outcrop in various seams at different locations. This condition requires mobility, so the shovels and draglines are relatively small. Output of each mine is generally low, but the number of such mines is large.

In Ohio, the Midwest, and the Rocky Mountain states the surface where coal exists is gently rolling or nearly flat so that area stripping, as contrasted to contour stripping, is feasible. Under such conditions, many successive cuts can be taken before the cover becomes too great. This condition promotes large output mines with sizable shovels, draglines, trucks, drills, and other auxiliary equipment.

The open-pit mining method is applicable to ore bodies at or near the surface. Initially, the method involves stripping of overburden.

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As mining proceeds, the excavation generally proceeds from the center of the deposit outward and from the surface downward in a series of benches with material blasted from steep faces, loaded by shovels, and removed by truck or rail transportation.

The choice between open-pit and underground mining of a given ore body is primarily a matter of extraction cost, and is based on such factors as size, shape, and depth; dilution of ore with waste; percentage extraction; topography and surface improvements; climate; available labor skills; continuity of operation; political considerations; and availability of capital. In all cases, open-pit mining cost includes the cost of removing overburden and waste in the pit slopes, and the ratio of waste to ore is therefore a controlling factor in comparing the economics of open-pit and underground mining.

There are predominant advantages inherent in the open-pit method. Open-pit mining is flexible, allowing for relatively large increases or decreases in production on short notice, without rapid deterioration of the workings. Shutdown expenses are relatively small, and there is greater opportunity for selective mining for blending purposes. Grade control can be accomplished easily by leaving lean ore sections temporarily, or by wasting leaner materials.

While open-pit mining offers greater opportunity for selectivity than underground mining, at the same time it offers the opportunity, at low variable cost, to mine leaner materials for beneficiation or concentration by various means. In the orderly development of an open-pit mine, some lean materials must be lifted and hauled from the pit. Because most metal mines today are coupled with beneficiation facilities to meet grade demands of mills or smelters, the consignment of lifted lean materials to the plant or waste dump is an economic decision based on a comparison of concentration with waste disposal costs. In this regard, computers are being effectively employed in making such decisions in advance of operations, given adequate sampling data. Similarly, market specifications are most significant in nonmetallic mining, and a careful coordination of the mining plan and treatment costs is required.

Larger equipment can be used in surface mining than in underground mining with resultant higher productivity per employee. Lastly, open-pit mining is not subject to some of the hazards inherent in underground mining such as the failure of natural or mechanical supports or loose material directly overhead; the possibility of fire, flood, or explosion in confined areas; and the comparative difficulty of constant supervision of safe practices.

Disadvantages of open-pit mining include a high outlay of capital for equipment, which is often nonproductive during the initial stripping period. Disposal of the waste from stripping operations may be

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a serious problem, especially where there is little topographic relief or where land is expensive. Also, climatic conditions may necessitate limiting operations during certain times of the year.

One other surface mining method is dredging. Phosphate deposits and placers, sediments or gravels containing mineral values, are mined by dredging or with draglines. Draglines reach out with a long boom and bucket to excavate unconsolidated material and convey it by buckets to trucks, railcars, or conveyor belts. With the dredge, wet sediment is either dug by a "bucket ladder" or loosened by a cutting head and pumped to a separation plant.

Mining usually begins in the richest and most accessible of known deposits, and when these are exhausted, continues with leaner or less accessible ores. The increasing difficulties of extraction and depletion of the reserves are offset by improvements in extraction technology, improved transportation, and exploration for new deposits. Because the trend in surface mining has been toward the utilization of lower grade ore and more complex and refractory ores, large-scale mass mining method improvements have been the dominant trend in technology. The major changes in surface mining have been largely in equipment for loading and transporting material, types of energy used, and in techniques, equipment, and materials for breaking rock. Great progress was made in loading when the steam shovel, traveling on railroad tracks, was replaced by the more mobile, crawler-mounted, revolving shovel using electric power. Improvements in transportation resulted by changing from steam to electric trains, and more recently by changing to diesel or diesel-electric-driven equipment of large capacities. Improvements in drilling equipment, explosives, and mechanical breakage methods have helped to overcome increasing physical difficulties of operation.

Surface Coal Mining

In coal mining, there is seemingly no technical limit, so far, in size and capacity of shovels, draglines, overburden drills, and haulage trucks. Shovels and draglines of 180 to 220 cubic-yard bucket capacity, and trucks hauling 240 tons are now in successful use, with larger equipment projected. Important improvements have been and are being made in ammonium nitrate type explosives and overburden drilling machinery and techniques, and articulated end-loaders are being used increasingly to replace conventional power shovels.

Auger mining is the recovery of additional coal from the wall of an open cut by means of horizontal auger drills (see Figure 9). The machinery for this method has been steadily improved in capacity and flexibility during the past 25 years of substantial use. Places

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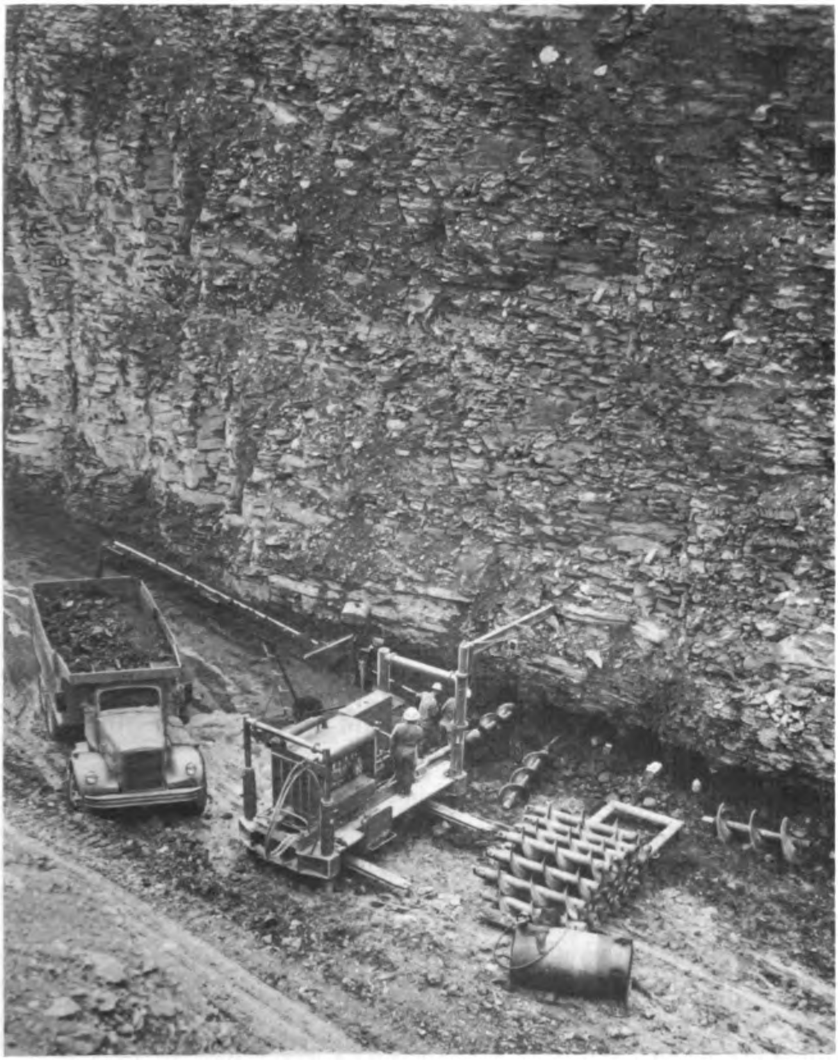

FIGURE 9 Auger mining to obtain additional recovery after strip mining is completed due to depth of cover.

where it can be used are limited, average coal recovery is only 35 percent at best, length of holes drilled is seldom beyond 150 or 200 feet, and production per day is low. Its principal advantage is to recover another 100 to 200 feet of coal after stripping has ended due to heavy overburden, or along an outcrop where stripping is not fea-

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sible. In proper applications, auger mining can be done at low cost, but its production growth is limited and may even decline. There are many operators who believe that better and lower cost extraction can be done by a series of small conventional mines using regular underground mining equipment.

Figure 10 shows the proportion of coal mining by various methods. Since 1940, strip production has increased from 10 percent of the total to about 35 percent in 1966. In the eastern and midwestern coal fields of the United States, the bulk of remaining strippable coal is being mined or is under commitment to consumers as reserves when present mines are depleted. For this reason, it is difficult to see the possibility of much increase in strip production. In the West most new production will be strip coal to supply electric generating plants. Some of the largest coal companies in the eastern and midwestern United States, with a high proportion of strip to total production, are now faced with the urgent need to develop underground mines to supply new contract commitments as well as to replace strip mines which have no more strippable reserves.

Surface Metal Mining

Four types of drills are in use at surface metal mines: percussion, down-the-hole percussion, rotary, and jet piercing—with the use of the latter primarily in taconites. In certain softer or nonspalling iron

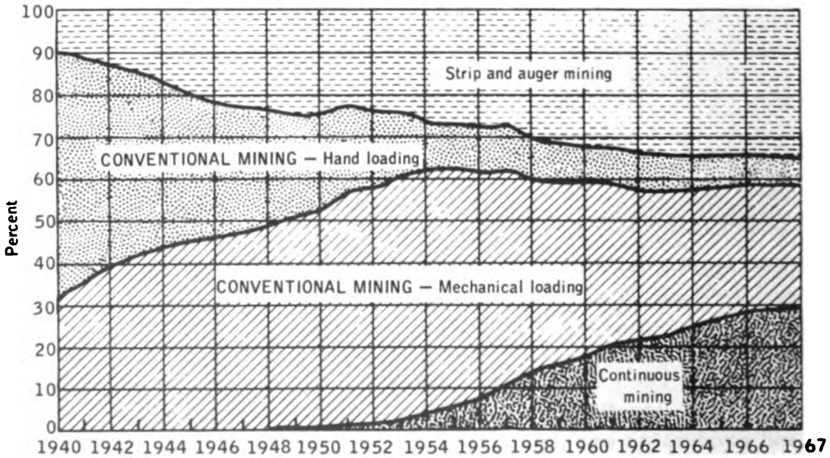

FIGURE 10 Percentage of total U.S. production of bituminous coal and lignite by type of mining.

formations, and in magnetite and hematites, rotary and down-the-hole types have found favor. The copper mining industry now relies almost exclusively on rotary drilling, with percussion drills ordinarily used only for drilling of holes in the bench toe to allow blasting to control the floor elevation. Concerning rotary drilling practice, a wide range of bit pressures and rotation speeds are used. It is believed that the optimum pressure-rotation speed combination with given drilling equipment is usually established by production drilling, rather than through controlled experimentation, and some research in this area would be of value.

Great strides have been made in explosives technology since World War II, and this is especially evident in open-pit blasting. The older nitroglycerine-based explosives have been replaced by ammonium-nitrate-fuel oil mixtures (AN-FO), and ammonium nitrate slurry explosives. The cost of AN-FO is but a fraction of dynamite costs, and slurry explosives are flexible in their applications and have very high energy characteristics. These new explosives are commonly delivered to the blast hole site in bulk haulage trucks with mixer equipment attached, and the explosive is actually tailor-made on site to meet specific conditions.

One of the keys to the increasing productivity that has been maintained over the last 20 years has been the improvements in drilling and blasting. The size distribution of the broken ore determines production capabilities of mine equipment, the crushing plant, and in some instances, the mill. Shovels digging finely fragmented material can produce three or four times the output of shovels digging poorly fragmented rock. Truck or rail haulage production is correspondingly increased because loading time is reduced, crusher capacity is increased and, on occasion, mill capacity has been increased by simple grinding circuit adjustments. At the same time, wear on equipment is reduced. When one taconite operation improved its fragmentation through heavier blasting, shovel buckets lasted four times longer and shovel teeth six times as long.

In terms of quality control, most problems occur near the mining face. As a result, there has been a trend in the shallow taconite pits, where working area and oxidation of broken ore are not problems, toward larger multiple row blasts. Another technique whose effects have been theorized and debated, but which is the exception rather than the rule in practice, is angle hole drilling. Where this technique has been employed it is reported that fragmentation has improved, "toe-problems" have been eliminated, explosive costs have decreased, drilling patterns have increased in size, and damage to the subsequent bench below is reduced.

A review of drilling and blasting practice in the copper surface

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mining industry based on a recent survey of major producers is typical of surface mining practice. The majority of open-pit copper mine production drilling is performed by rotary drills. Hole diameters vary from 6 inches to 12 inches, with 9-inch holes being most common, and penetration rates vary from 35 feet to 60 feet per hour.

Single row blasting is practiced at rail-haulage pits, but is not uncommon at truck-haulage pits. Bench heights are generally 40 to 50 feet, but vary from 30 to 79 feet. Several operations are considering increased bench height for stripping where fragmentation is not critical and the use of larger equipment is economically desirable. Subgrade drilling is common, and increased subgrade drilling was mentioned as a means to improve the bench floor. Air decking (leaving air space in the explosive charge) is practiced only on an experimental basis.

During the last few years there has been less change in the capacity of large off-highway haulage trucks, with most of the emphasis being placed on the development of higher horsepower engines and better tires. A long life, lightweight engine of over 1,000 horsepower has not appeared as was hoped for. Both diesel and gas turbine engines are being tested without conclusive result.

One type of haulage equipment is approaching the truck-train concept and is being examined closely, and a tandem axle, 30-yard, aluminum body truck that can pull as many identical sized wagons as grade permits is being manufactured.

Radio dispatching of trucks is becoming a necessity in large haulage fleets, providing close control of production and a fast on-site maintenance and repair service.

Open-pit railroad users have adopted control techniques that reduce labor costs and result in efficient haulage systems. Railroad scales with automatic electronic car number reading, weighing, deduction of tare, and recording of weights, have been placed in service for the determination of crude weights to plants and the division of crude ore by properties. Also, aluminum bodies have found application in unit trains.

The use of conveyors has increased dramatically. At a bauxite mine in Jamaica, a 42-inch wide conveyor system, 6.5 miles long, is being installed to transport bauxite from the mining area to a port. A new concept in bulk transportation appears to be a competitor to conveyor belt operation. This system will haul material on horizontal, vertical, and/or inclined slopes. The system consists of unmanned A.C. motor-propelled 16-cubic-foot capacity modules, automatically operated singly or coupled in flights, running on specially shaped tracks in an enclosed tubular roadway. The design allows modules to travel in an upright or inverted position, and a pilot

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system has operated in a 1,600-foot continuous loop operation at speeds in excess of 30 miles per hour. This principle may answer the dilemma that some pits will reach as they get deeper—how long will spiraling out of a pit with haulage trucks be economical? Large modules on this new principle could propel themselves up a 45° pit slope, thus shortening the haul distance.

The use of scrapers in open-pit mining has increased. For example, at Anaconda's Twin Buttes operation, a work record of 345,000 tons per day of overburden has been moved by scraper. One new scraper being used in highway construction has an overall length of 200 feet and has three bowls capable of hauling 120 tons each. The use of rippers has enabled scrapers to tackle jobs hitherto thought to be possible only by blasting and shoveling.

A 180-cubic-yard shovel is stripping coal, and predictions are that there are no obstacles to building 300-cubic-yard shovels. These shovels only move the overburden to a new position, and do not load trucks. It is significant that this type of equipment is operated by one man. Advances in shovel sizes in iron and nonferrous surface mines has temporarily halted at the 15-cubic-yard shovel awaiting the higher powered engines and larger tires that will make available haulage trucks of 150 to 200-ton capacity.

The bucket wheel excavators are being proved in more and tougher digging operations, and are fast approaching the stage of development where, combined with blasting, they may edge into metal mining pits to give a great improvement in loading speed. In the future, we may well see 8,000 tons per hour or larger machines feeding a mobile crusher conveying system or loading larger trucks. Wheeled front-end loaders are gaining on small shovels because they require less initial investment and have greater versatility.

In truck pit operation, the trend is toward larger haulage vehicles. Currently however, the development of truck engines with sufficient power for 100-ton trucks operating over steep grades is lagging. Various operations reportedly are testing 100-ton side-dump and rear-dump trucks utilizing diesel and gas-turbine engines. Several pits are considering installing trolley lines on main haulage roads and pantagraphs on large electric wheel trucks to provide more efficient and economic operation.

Mining Methods and Men

Fairly recently, a new approach to the design of open-pits has been brought about by the development of computers that can perform a large simulation of unit operations in fractions of seconds. Variables in mine design and operation in numbers that cannot be satisfactorily

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handled by manual means can now be incorporated into a model that a computer can handle. Practical experience in mine operations incorporated with computer planning techniques is adding greatly to the science of mine planning.

Mine planning and other operations research techniques and economic evaluations, which have become increasingly complex as pit size and equipment size have become larger, and as metallurgical considerations (blending, by-products recovery, etc.) have become more complex, can be readily adapted to computer programming.

Research on systems analysis for truck and shovel selection is improving the mining engineer's capability of evaluating possible combinations of shovels, trucks, and haul road layouts in light of production goals to achieve minimum costs.

In modern large tonnage operations, an accurate form of production scheduling is an absolute necessity. The use of computers in taconite mine production scheduling, and the development of linear programming systems for both production scheduling and product distribution, are examples of advancements in the field. Also, the use of computerized cost and maintenance control systems provides mine managers with much useful information for controlling operations and pinpointing areas where cost reductions may be effected.

An old art that is evolving into an important science in the copper mining industry is the leaching and recovery of copper from waste dumps. Improved methods for controlling the leaching environment and for precipitating copper from pregnant solutions are emphasized by the fact that a major copper mining company is now producing about 25 percent of its total copper from leaching. After extensive research, Kennecott developed a sophisticated cone-precipitation leaching system which allows for efficient copper recovery and large volumetric capacity.

One Arizona operation has converted from open-pit mining to ripping, scraping, and heap leaching. The system there has allowed the production of copper from an otherwise unprofitable open-pit mining operation.

Most open-pit operators will agree with the thesis that maintenance is the most important single function in any successful mechanized mining plan. The need for a good maintenance organization has led not only to the investment of substantial sums in mine plant maintenance facilities, but also to the recognition that well-trained maintenance personnel do not become skilled simply by manning an organization chart. Supervised training programs employing sophisticated training aids have been developed. Also, comprehensive record keeping systems have been instituted as a tool in preventive

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maintenance, and maintenance check lists and service records are becoming standardized.

The major problem that faces not only surface mining, but all mining, is the overall one of producing more efficiently. As labor and material costs go up, the engineer and the researchers are the people management will look to for that added efficiency. This is made all the more necessary because we will have to mine lower and lower grades of ore that are, in many instances, less and less accessible. As our problems and challenges increase in intensity, it will be industry's responsibility to employ more engineers, and more highly skilled ones.

Furthermore, industry and academic institutions must recognize the importance, and develop the techniques, of training and developing some engineers for production operations as well as others for management and research. All are essential, and all must be rewarded financially and have equal opportunities for advancement to the top of the organization.

UNDERGROUND MINING

Introduction

During the past 30 or 40 years, underground mining of high-grade ore deposits has tended toward less predominance compared to surface mining. This was due to rapidly rising efficiency in open-pit mining made possible by the development of very large and efficient drills, shovels, trucks, earth movers, etc. These have made it possible to move huge tonnages of very low grade material at very low unit costs.

However, for several important reasons this trend is now beginning to reverse toward increased underground mining. As surface mines are depleted and known ore bodies mined, the new ore found is bound to be increasingly at depth. As we pay increasing attention to the maintenance of our environment, underground mines become increasingly desirable because they disrupt the least. Lastly, while the development of underground mining equipment lagged behind surface equipment for many years, this is changing rapidly now. Mechanized drills, greatly improved blasting technology, mechanical shaft, raise, and tunnel borers, continuous miners, powered self-advancing supports, and large capacity, trackless loading and haulage equipment have all come into general use within the past 10 years (see Figures 11, 12, and 13).

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FIGURE 11 Diesel powered underground loading and haulage units.

As the result of all these developments, underground mining as well as underground construction is destined to undergo unprecedented advancement and expansion in the next two decades, but a great amount of research and development is needed to make this occur as rapidly as possible.

Present Status

Productivity of both manpower and machines varies from mine to mine. Increasing costs and more difficult mining conditions require an increased productivity to maintain a satisfactory cost-price relationship. Worker output is often restricted by more or less primitive equipment, established methods and procedures and, in some cases, by "worker-set" production limits. Mechanization of some mining procedures—for example, mechanical loading and drilling—has helped to improve the production potential and contributed to a reduction in the human effort required to extract ore. Often, however, human failings or inept direction and work pacing preclude

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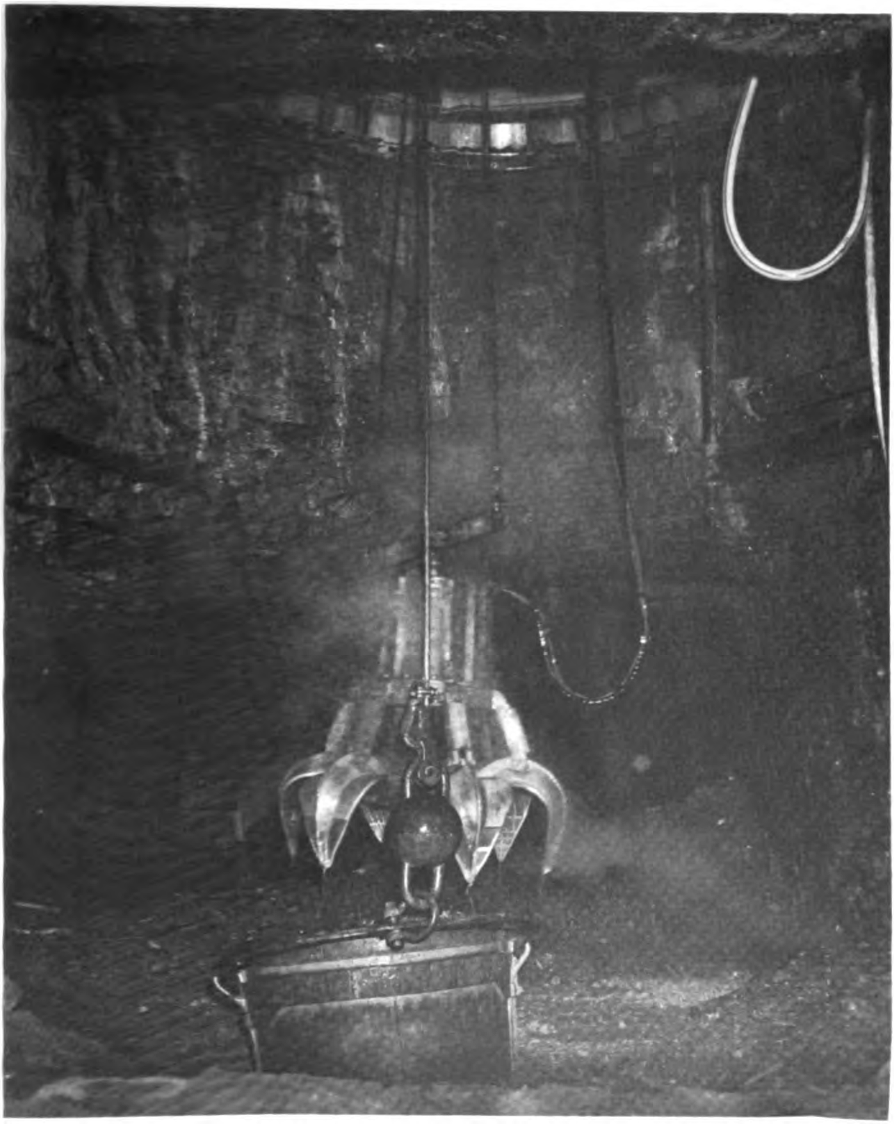

FIGURE 12 A "cactus grab" for loading rock in a shaft.

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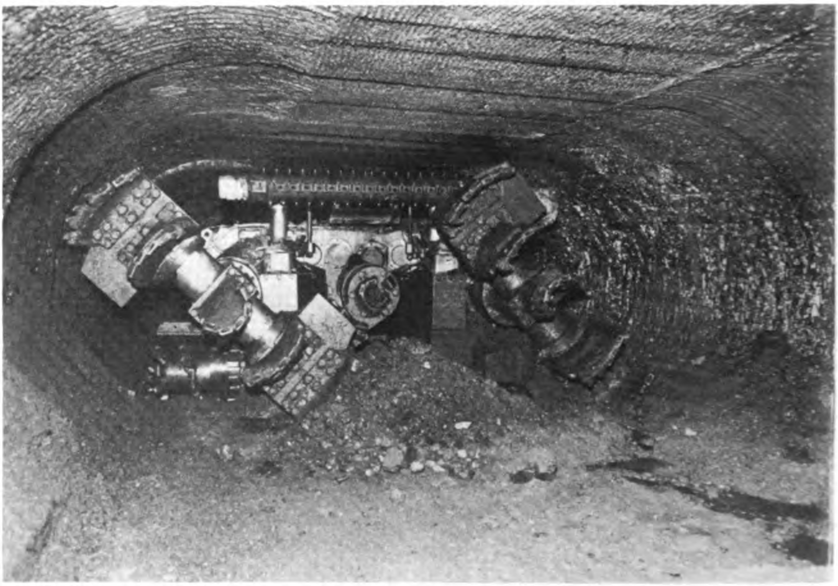

FIGURE 13 Boring type continuous miner trammed back from the coal face to show cutting tools.

attainment of the full capability of machine units, to the detriment of productivity.

Mining methods, in general, constitute an area of challenge to the minerals industry. Few changes or innovations have been made in extraction techniques, and those methods employed by early miners, and exemplified as standards in some mining schools, remain little changed and without contemporary replacements. A notable exception exists in underground coal mining where continued growth in mechanized loading has all but eliminated hand loading, and the development and application of "continuous miners" now accounts for about half of deep coal production.

Methods and procedures of mineral extraction relate directly to productivity and costs as well as to the nature of the ore body. With the need to increase production efficiency and reduce costs to compensate for less available mineral reserves, the development of new or improved methods of extraction must be considered in the same category as updating mining equipment.

Concurrently with problems of archaic mining methods, inadequate productivity, and limitations on reserves, underground mining is faced with the need to improve ground support, ventilation, and scheduling of interrelated mining activities. Each of these areas,

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treated in many mining operations as integral with normal planning, has assumed the significance of a major problem and must be considered as such.

Ground support is always a demanding element of the extraction procedure. Some support methods which were adequate for higher grade, more available deposits are not practically or economically applicable under conditions now existing. For example, square-set timbers, used to support large openings in some types of stope mining (see Figure 14), cannot be economically used today except in exceptionally high-grade ore bodies. In addition to the more complex and variable technical problems in ground support systems for modern mechanized mining, cost increases in materials greatly restrict the techniques capable of economic utilization.

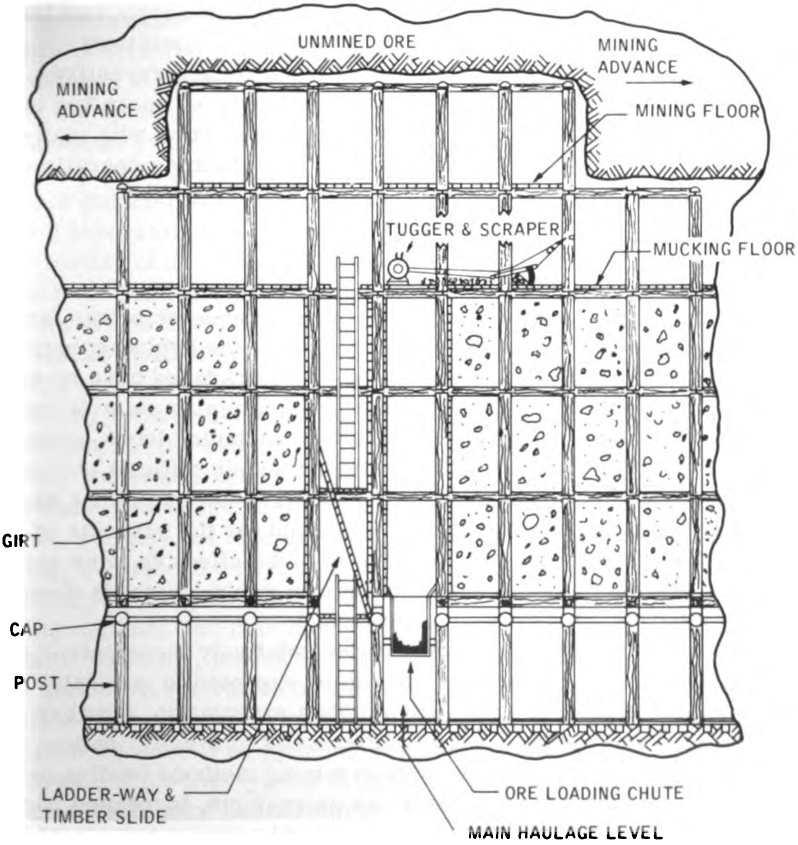

FIGURE 14 Typical longitudinal section through square-set stope.

Ventilation of underground openings has been accomplished in the past within the limits of relatively simple basic rules satisfying the limited operational demands of traditional mining methods. Due to increasing power and equipment costs, more definitive health and safety rulings, and the need to provide air to greater depths and over larger areas, ventilation looms as a major problem in future mining. For example, the adaptation of diesel-powered machines in some mining operations greatly increases the demands on ventilation systems.

Another area generally receiving rather informal attention is the scheduling of functions which support mining activities. Supporting activities for some mine operations, by virtue of their simplicity or of repetitive experience, can be managed, operated, and maintained without resort to formalized control systems. Other more complex or developing mine organizations recognize the great value of scheduling supporting activities within the framework of short- and long-range plans and standards, to the improvement of operations, productivity, and costs. Programs which emphasize preventive maintenance of equipment have successfully reduced operating and capital costs. Detailed extraction plans, in conjunction with manpower and expenditure scheduling, bring order to mine operations and insure maximum utilization of resources.

Future Needs

To the studious observer, it is apparent that unique problems face the underground mining industry. By reason of the depleting nature of the reserves involved in mining, the problems faced have no close counterpart in other industrial efforts. Adequate manpower to meet future requirements of underground mines, including labor, supervision, and technical personnel, will be extremely difficult to obtain and train; and productivity under anticipated conditions is not likely to accelerate at the same rate as the demand for the products of mining unless much energy is devoted to more effective mine mechanization, automation, and improvements in mining methods directed toward high-volume operation underground.

At greater mining depths, often under relatively incompetent rock structure conditions, future mining can be expected to encounter increasing problems of ground support. This expectation, together with lower grades and perhaps more limited areas of mineralization, will, in many instances, require changes in mining methods leading to a host of new evolutionary problems. As an example, increased rock stresses encountered at greater mining depths may require a reduction in the size and number of mine openings in a specified unit area,

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resulting in a lower extraction rate for the unit area, depletion of minable reserves, and generally reduced mining efficiency. As to problems normally associated with deep mining, obviously costs rise with increase in working depth because more power, facilities, and equipment are required for hoisting mined material, for dewatering, and for ventilation. Manpower efficiency is reduced in deep, extensive mines as transportation time to the working faces increases.

The more severe mining conditions resulting from mining at greater depths under more adverse conditions will require the development of new concepts of ore extraction and material handling. Equipment, designed and constructed to perform with a high degree of efficiency, will be needed to relieve, and in some cases, replace personnel.

Problems relating to underground rock stresses around mine openings are presently being considered in the light of a relatively new mineral science called "rock mechanics." This developing discipline is directed to the study, definition, and evaluation of residual and induced stresses that exist around mine openings and tend to close the openings. Research in rock mechanics and strata control in European coal fields has led to the design and operation of longwall extraction panels with a minimum disturbance of the overlying surface structures (see Figure 15). Present knowledge has evolved from a laboratory and reference book background with only limited field testing of associated theory. It can be expected that the science of rock mechanics will receive ever-increasing attention as ore extraction encounters less favorable conditions. The contributions of this fertile field of science to improvement of mining methods will become more positive as theories are developed, proved, and applied; and rock mechanics as a production tool will become as standard a part of the extraction program as the engineering of ventilation and materials handling.

Future mining methods will evolve from existing ones, but techniques, metals, and machines will be developed to enable, as in coal mining, continuous extraction of rock structures now considered too hard for fully mechanized mining (see Figure 16). Currently, coal mining methods and machinery are being applied in the mining of trona in Wyoming, potash in New Mexico and Utah, and salt in several states. Acceleration of the development of mining methods for continuous and rapid excavation is being encouraged by the federal government as well as by some private companies which recognize the potential for this type of mining.

Some equipment manufacturers are designing and fabricating machines that will serve as prototypes of a host of new mechanized mining units. Machines which will bore large-diameter openings in

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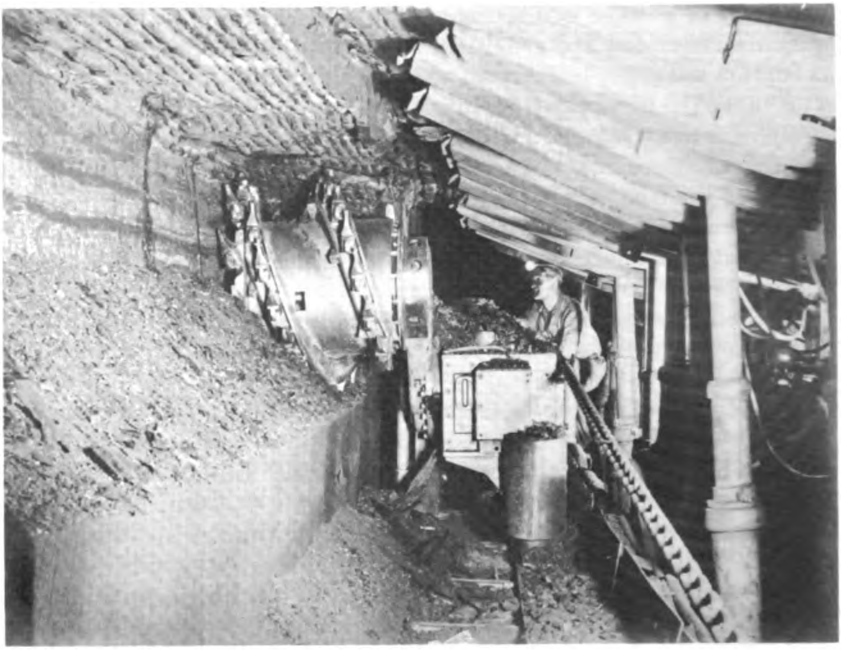

FIGURE 15 Longwall coal mining-self-propelled hydraulic roof jacks at top and right, conveyor at bottom, double-drum shearer in center, rear drum in low position.

rock have been successfully employed in excavating water diversion and vehicular tunnels. A unit is now under fabrication that is designed to speed development of mine openings by permitting near continuous excavation of a tunnel some 18 feet in diameter. Raise boring machines, accepted as standard mining tools in some active mines, also herald the approaching revolutionary mechanization of ore extraction.

With the increasing use of machinery and a comparative reduction in mining labor, ventilation of underground openings might be somewhat less demanding, particularly if energy other than petroleum fuels is used to power the mining machines. Mining functions such as blasting, ore handling by diesel-powered machines, and other activities that generate dust and fumes should be reduced or eliminated through automation, where possible, with a consequent reduction in ventilation requirements.

Dewatering requirements may or may not be lessened depending on the degree of replacement of the amount of water utilized in current mining methods by that needed in more mechanized techniques.

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Hydraulic mining and hoisting could greatly increase pumping needs. The problem of pumping ground or residual water will still exist.

Increasingly more methods and ideas used in industries other than mining are finding application in the extraction of ores. Some engineering and manufacturing concerns normally supplying the processing industries are diversifying their activities to help solve mining problems. The automobile industry has provided modified highway trucks and jeep-type vehicles for special underground applications. Ammonium nitrate, a chemical fertilizer, was developed as a low-cost ingredient in the manufacture of explosives. The electronics industry has supplied devices to both surface and underground mining installations to improve communications and permit remote monitoring of crucial production sequences.

While the area of innovative modifications, worked out on the job to meet specific conditions encountered, holds much promise of improving the underground mining picture, the greatest benefits to future mining will occur through directed technology. Research, both basic and applied, must be accelerated to meet the needs of the mining industry in a timely manner. Responsibilities in this area rest

FIGURE 16 Shuttle car and loader under bolted roof in a medium thick coal seam.

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with the industry itself, but it must motivate other sources of technology to the solution of the problems at hand and those which will develop.

Supporting industries such as equipment manufacturers and those companies providing mining materials and supplies must be encouraged to enlarge their participation in meeting the needs of mineral extraction. Much expertise is available in these organizations, and in other industries involving machine and material supply.

Foreign exchange programs for the dispensation of information and the investigation of world mining practices and equipment, while currently conducted on an informal basis, have accelerated improvements in the mining field. As an example, longwall mining techniques have been advanced in the United States by the importation of information and services from European countries in which longwall extraction has been practiced for many years.

OCEAN MINING

The potential of ocean mining has been extolled by the press, in the technical journals, from the podium, and in Congress so that we are aware of it even if skeptical of its early commercialization. But the prospect of continuing growth in the winning of mineral resources from the sea floor cannot be ignored on the basis that it is currently uneconomic, because of the technologic fallout that will come almost certainly from the huge research expenditures by government and industry in all branches of oceanography. Table 7 shows the 1965, 1966, and 1967 national oceanographic budget, and it is estimated that these expenditures will grow to $5 billion by 1975 (including all corporate and academic spending).

Since biblical times man has gotten salt from the sea by evaporation. Beginning with the discoveries of Sir John Murray and the Challenger Expedition of 1891, we have come to know of mineral occurrences on the bottom of the sea, and have begun to dream of their recovery (26). Despite intense interest in recent years by some mining companies, and also by many nonmining (particularly oil and aerospace) companies, the new work being done is really only in conceptual studies and a little exploration.

Many resource-based companies have shown minor interest in the resources of the oceans, and some of these companies have formed specific groups to study the situation, but, in general, the mining community is advancing slowly with regard to ocean mining.

Only the unconsolidated deposits on, and the bedrock deposits in, the ocean floor will be considered here. The dissolved minerals,

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TABLE 7 National Oceanographic Program Budget (Millions of Dollars)

	1965	1966	1967
By Department			
Defense	98.1	80.5	113.5
Commerce	20.1	13.1	16.4
Interior	20.2	19.5	19.4
NSF	44.0	43.2	43.0
AEC	6.0	11.6	13.5
HEW	5.2	6.3	9.7
Treasury	2.0	2.1	2.3
Smithsonian Institution	0.9	1.5	1.6
State	0.4	0.5	0.5
Totals	196.8	178.2	219.9
By Function			
Research	70.5	81.4	84.3
Surveys	26.3	29.5	38.4
Ocean Engineering	62.0	40.7	66.0
Ship Construction	20.7	12.5	16.2
Instrumentation	10.3	9.4	8.4
Facilities	6.0	3.5	5.2
Data Center	1.0	1.2	1.4
Totals	196.8	178.2	219.9

sulfur, oil and gas, and fresh water from desalination are excluded, as are those land-based mines that extend beneath the sea into solid rock. Thus defined, actual production has shown little growth, and publicity has overemphasized its importance. Even today it still comes from shallow water near shore, and excluding sand, gravel, and oyster shells, is derived from shore deposits (see Table 8).

These are all unconsolidated deposits—placers, beach deposits, and shell beds. No nodules have been produced from the shelf or deep sea floor, and except for one sulfur operation there is no production from a sea based, in-the-rock mine. The unconsolidated deposits, therefore, seem to offer the earliest possibility for exploitation of the sea floor. Over 65 dredging operations are actively producing $179.8 million annually, but when the production of shell, sand, and gravel is subtracted, the "real ocean mining" is only $49.8 million out of the estimated annual world mineral production of $70 billion. Ocean dredging does, however, account for 10 percent of the world's tin production.

The much-publicized dredging operations for diamonds off southwest Africa are interesting, but operating conditions are indeed se-

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TABLE 8 Unconsolidated Sea Floor Deposits

	Locations	Number of Operations	Annual Production	Year	Value in Millions
Diamonds	S.W. Africa	1	221,000 yds^3	1965-66	$ 8.9
Gold	Alaska	1		1966	—
Heavy minerals	America Europe S.E. Asia Australia	15	1,307,000 tons	1965	13.1
Iron sands	Japan	3	36,000 tons	1962	3.6
Tin sands	S.E. Asia England	4	10,000 tons conc.	1965	24.2
Lime shells	United States Iceland	9	20,000,000 yds^3	1965	30.0
Sand and gravel	England United States	38	100,000,000 yds^3	1966	100.0
Totals		71			$179.8

vere because of storms, fog, character of the bottom, and isolation. Of seven dredges tried thus far, only two remain afloat. Production has been up to 25,000 cubic yards per month, but erratic. During the first four and a half years of operations, there were three periods totaling 12 months, with no production.

Early attempts to use conventional on-shore ladder dredges off Nome, Alaska, encountered operational difficulties of storms, swell, and tough digging, and had to be abandoned.

The future of mining unconsolidated deposits from the ocean floor depends to a large extent upon our ability to adapt various components of the mining and beneficiation system to the environmental parameters encountered.

Romanowitz et al. (35) logically say that a system that works well on shore may be moved to shallow water off-shore in which the only serious environmental change is motion. When this problem is overcome, it can move further off-shore where the problem becomes depth. They predict that this transition will take place during the 1960's and 1970's, and that by 1980 completely submerged bottom operations will be effective.

For all the effort that has gone into the design of ocean mining schemes and equipment, it must be said that ocean mining concepts are still based on inadequate sampling. Literally hundreds of devices have been used, but very few "samples" taken so far by oceanographic cruises would merit the name "sample" as the mining engi-

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neer uses it. For the most part, they are merely tantalizing specimens from the depths and cannot be used for calculating tonnage and grade.

However, the problem for the would-be ocean miner is still fraught with legal and political problems. Jurisdiction over the sea bottom deposits adjacent to the continent, out to the 3-mile limit, or depth of 200 meters, or whatever depth is exploitable, is fairly well crystallized in international law. But jurisdiction over the deep sea deposits has not been settled. Four possible means of regulation are:

- The "national lake" or "coastal state" approach, providing for the division of the oceans equidistant from the shores of the coastal nations.
- The "flag nation" system, which would permit exploitation under jurisdiction of the nation of the discoverer.
- Exploitation under jurisdiction of an international authority such as the U.N.
- "Wait and see" attitude in which the deep ocean is under no authority so that when and if conflicting claims arise they would be solved on a case by case basis.

Needless to add, there is little consensus on the matter.

Austin has described exploitation of "in-the-rock" undersea deposits (2, 3). He visualizes early developments by slopes from the mainland, shafts and tunnels from natural or artificial islands, and later, sea floor entry by means of elaborate lock systems and life support devices. He maintains that we have the technology at hand, and that what remains is a problem of cost.

The growth in this field depends upon trained specialists. For the short term we will have to depend upon "retreads"—i.e., the pioneers, who recognize a new field and adapt their technical talents to it. However, the only long term answer is formal training in our universities, and few of the existing oceanography programs concern themselves with the mineral resources of the sea floor.

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CHAPTER 5

Present Organization of Research and Training

INTRODUCTION

An excerpt from an editorial by Rossiter W. Raymond, published in the "Engineering and Mining Journal" of November 25, 1869, is as pertinent now as the day it was written:

> "WANTED—A NATIONAL SCHOOL OF MINES"
>
> Our mineral fields are very extensive, and there is no doubt that the bullion product thereof, now variously estimated to be 50- to 70-million dollars per annum could be doubled, if not trebled, if a higher style of scientific knowledge and skill were made available in working mines and treating ores. We have, in different parts of the country, a few scientific men who have been trained in schools of Europe, but they are so few that their influence is hardly felt. We need a vastly larger number, and we ought to have a school at home in which they can be trained. We do not see why such a school would not be as useful to the country as the Military or Naval Academy.

The future of the mineral industry depends upon the research and development of greatly improved equipment and techniques, and the education and training of adequate numbers of people to do this and apply the results. Industry, the universities, and local, state, and national government all carry some responsibility to meet these needs. One of the most critical problems facing industry and the nation is the present status of mining engineering education and research. The present supply of technically trained personnel, both for operations and research and development, is totally inadequate. For the past 6 years there have been jobs vacant for several times the annual production of mining engineers, and each year the situation becomes more acute as the need increases while enrollments and

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TABLE 9 Degrees Granted in Mining Engineering, U.S. 1946–1966

Year	B.S. Mining	M.S. Mining	Ph.D. Mining
1946	43	27	1
1947	229	43	2
1948	318	40	2
1949	361	27	2
1950	483	32	1
1951	493	44	2
1952	412	30	3
1953	304	19	1
1954	254	22	3
1955	204	24	2
1956	213	24	3
1957	231	22	0
1958	240	20	2
1959	239	27	2
1960	242	35	3
1961	220	33	2
1962	193	49	6
1963	180	65	3
1964	144	43	4
1965	146	85	25
1966	138	80	27

graduates decline still more (see Table 9 and Figure 17). Not only has the number of mining engineers graduated been decreasing, but so has the number of departments of mining engineering (see Table 10).

The trends are especially disturbing when compared with those in other disciplines. Excluding the noncharacteristic years due to World War II, the largest number of engineering degrees granted in our history was in 1966. By contrast, in the same year, the smallest number of mining engineering degrees was granted: 138.

DEMAND FOR MINING ENGINEERS

A survey made in the fall of 1964 involved responses from 55 mining companies regarding their estimated needs for new mining engineers 5 and 10 years in the future (4). At that time the starting salary for young engineers was about $600 per month; in 1968 it was about $800. The results from just those 55 companies indicated a need for 147

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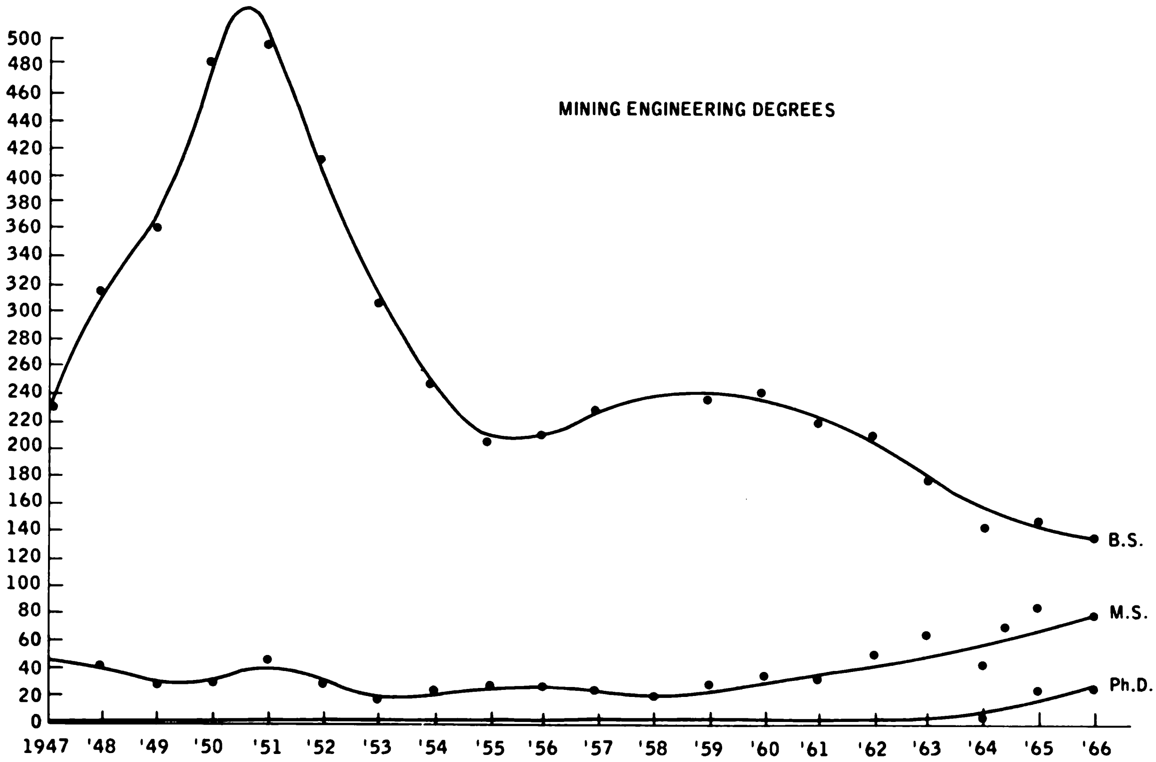

FIGURE 17 U.S. mining engineering degrees.

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TABLE 10 Accredited Departments of Mining Engineering in the United States

1937	26
1947	30
1948	31
1949	30
1950	28
1955	30
1960	26
1961	26
1962	26
1963	23
1964	23
1965	21
1966	19
1967	17

mining engineers per year over the next 5 years, or 162 per year over the next 10 years.

A similar survey of 26 employers in 1967 indicated a need for 153 mining engineers that year for their companies alone (see Table 11).

Meanwhile the total U.S. production of such engineers in 1964 was 144, and for 1966 it was 138. The postwar high reached its peak at 493 mining graduates in 1951.

At the Colorado School of Mines about 40 mining engineers graduate each year, so that a reasonably good assessment can be made of the industry's needs from the interviewing and hiring procedure each spring. On this basis it has been estimated that for the past 5 years the average graduate received about five job offers before commencement.

TABLE 11 U.S. Mining Engineer Requirement Trends 1963–1967 (Survey of 26 Companies Interviewing at CSM)

Year	Vacancies	Job Offers	Engineers Hired	Offers per Vacancy	Hirings per Vacancy	Vacancies per Company
1963	22	30	13	136%	59%	2.4
1964	25	29	19	116%	76%	2.8
1965	50	83	39	166%	78%	4.3
1966	95	140	50	147%	53%	5.1
1967	153	201	56	131%	37%	5.9

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In the 1967-68 season, 60 different organizations interviewed at the school with job offers for graduating mining engineers. This institution is dedicated exclusively to the mineral resources field, and is the only such institution left in the nation. In 1967-68, a total of 150 organizations interviewed in all 9 degree-granting departments. Many of these interviewers indicate that currently they only visit two or three other mining departments in the country because the rest have too few graduates to justify the cost of a visit.

In the face of our greatest need for mining engineers in the past 25 years, we find ourselves with the lowest production of first degree students, and the trend continues downward. The routine operation of the industry is by these first degree engineers, and reversing this trend is now a critical necessity. This is not meant to imply that advanced degrees are not needed, for they are. However, as shown in Table 11, the current trend towards advanced degrees is probably sufficient, while the production of first degree people to operate the industry is long since critically small. Furthermore, B.S. degrees provide the essential input from which the graduate programs must grow.

The shortage of mining engineers is worldwide except for the U.S.S.R. Three major mining countries of the world—Canada, South Africa, and Australia—each need several hundred new graduates annually but produce only 30 to 40. An extensive survey of Canada's needs was completed in September 1967 (9). The Canadian data for 1966 indicated a need for 1,306 additional professionals in the minerals field, of whom 244 were mining engineers. The situations in South Africa and Australia are similar. Meanwhile, in the U.S.S.R. there are several mineral engineering schools graduating thousands of people annually, of whom 500 to 1,000 are mining engineers (34).

The U.S. Department of Labor Occupational Outlook Report for 1966-67 reported that an estimated 300 mining engineers left the field in 1964, by retirement, transfer, death, etc., while only 144 new B.S. degrees were granted (40). The same agency reported that in 1966 there were an estimated 13,000 mining engineers employed, with 400 annual openings, and there were only 138 new B.S. degrees granted that year (37).

UNIVERSITIES

The primary responsibility for mining education rests with the universities. While they should do a reasonable amount of research in order to train students for graduate research degrees and to encourage innovation and development by their teaching staffs, they are

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neither funded nor best qualified to do the sort of applied research and development so badly needed by the mining industry. Too often, research becomes a goal in itself within the university, mostly to obtain capital and operating funds needed and not otherwise available, and as a result undergraduate teaching suffers, although it should be of primary importance.

Practically all of the universities producing mining engineers are state supported, and all are having great difficulty, even in states where mining is an important force in the economy (see Table 12).

Under the present extreme demands for higher education across the country, mining departments invariably have the status of a small specialized group with a minimal enrollment competing with large crowded departments for staff and funds. Under these conditions it becomes difficult for state legislatures to justify supporting such departments unless the critical need for their product is recognized.

The American minerals industry has many opportunities and needs for nonmineral disciplines such as civil, mechanical, and electrical engineers. Traditionally, such people have been recruited from the general technical manpower pool, and this has been difficult when the environment and even the technical language was quite unfamiliar to them. At best they have a distinct transition to make. In some educational systems abroad, notably in the U.S.S.R., the minerals schools include all the technical disciplines needed within the same mineral industry environment, and such an approach could prove stimulating here (34).

The student who comes from a state without a mining curriculum poses a particular problem. He must pay a high out-of-state tuition unjustly, and the school that accepts him is penalized within its state organization for accepting him. Interstate agreements should eliminate this unsatisfactory situation in cases of such specialized and critical curricula as mining engineering.

Highly educated and experienced teaching staff are very scarce in the field of mining engineering. People with doctorates in mining are rare, and those with doctorates plus experience almost nonexistent, yet these above all are what is needed if the schools are to do the job required. Furthermore, it is this same blend of practical experience plus advanced theoretical training that is so greatly needed to do research and development in industry and government research organizations.

Continuing education is needed very much in the mining industry, and the universities should meet this need, and are doing so to a limited degree. However, in the same way that routine teaching is hampered by insufficient staff and support, this "extra" phase of the

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TABLE 12 1966 Academic Statistics, Mining Engineering

University	Faculty	Undergraduate		Graduate Students		
		Fall 1966 Enrollment	1966 B.S.	Fall 1966 Enrollment	1966 Masters	1966 Doctorates
Alabama, Univ. of	6	40	8	7	2	
Alaska, Univ. of	4	8	1			
Arizona, Univ. of	4	58	8	15	2	
Colorado Sch. of Mines	5	187	42	16	3	3
Columbia Univ.	6	1	1	21	1	1
Idaho, Univ. of	2	12	4	2	1	
Kentucky, Univ. of	1	7	4			
Michigan Tech. Univ.	4	35	9	3	1	
Minnesota, Univ. of	5	11	3*	30	3	2
Missouri, Univ. of (Rolla)	7	24	9	26	8	2
Montana Col. of Min. Sci. & Tech.	2	6	2	2		
Nevada, Univ. of	3*	14	3	8		
New Mexico Inst. of Min. & Tech.	2	20	5	1	1	
Ohio State Univ.	1	12	7			
Penn. State Univ.	8	61	8	21	3	
Pittsburgh, Univ. of	3	12	2	5	1	
So. Dakota Sch. of Mines & Tech.	2	34	8	2	2	
Stanford Univ.	2	2	0	12	6	
Texas Western College	0	0	4	(Mining Engineering dropped 7/66)		
Utah, Univ. of	2	43	2	12	2	0
Washington, Univ. of	2	11	4	1	2	
Wisconsin, Univ. of	1	10	3	8	2	
Wisconsin State Univ.	2*	27*	6*			
Virginia Polytechnic Inst.	8*	30*	6*	8*	2*	
West Virginia Univ.	5*	25*	6*	5*	1*	
Total U.S.A.	87	679	155	195	43	8

*Estimated

From MINING ENGINEERING, January 1967

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educational process also suffers, and it often becomes the nonessential frill which is left undone.

Present supplementary nonstate financial assistance to the mining departments is predominantly directed toward graduate study and research, whereas the even greater need is to strengthen undergraduate training and enrollment. The need and impact of mining engineers is national and international in nature, and state support is local. Therefore, the states cannot be expected to support mining education to the extent that the nation needs it.

Industry could give very significant and immediate emphasis to the education and production of new mining engineers by grants-in-aid to the mining departments producing the men they employ. Such grants would be especially effective if they were presented on a 3-year continuing basis. In providing funds for scholarships and fellowships, matching funds to the department should be included to assist in providing the staff and facilities so drastically needed. Such industrial financial assistance to education could be encouraged by greater tax benefits.

Although the training of graduate students in mining to the master's and doctoral level is progressing well in numbers, not enough of these people possess the needed blend of practical knowledge with which to apply their theoretical training. Either before or after advanced study, but preferably before, industry must provide the practical experience so desperately needed, so that the research done for the degree will have real significance. The best way to accomplish this is for industry to sponsor graduate study for their most promising young engineers, selecting those who have already proven to have drive, initiative, practicality, the knack for investigation and innovation, and intelligence (32).

The developing countries need practically trained minerals engineers to develop their resources and thus stimulate their industrial economies. The United States should assist in the training of such people, but our present emphasis in foreign student education is at the graduate level, which is often little needed by the home nations. Usually the acceptance of foreign mining students is financially unfavorable to the school rather than helpful, and a state supported institution should not assume this burden. Rather, the true costs should be borne by the student's home government, a company operating in that country, or perhaps by the U.S. government if truly in our national interest.

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GOVERNMENT

The federal government does a significant amount of research in mining and mining-oriented areas, not only through the Bureau of Mines, but also the Departments of Defense and Transportation, the Bureau of Reclamation, the Geological Survey, and the Bureau of Public Roads, for example, are very active in such "mining" areas as tunneling, controlled blasting, rock mechanics, rock reinforcement, rock excavation and support, and slope stability. The emphasis in much of this research is on the fundamental side, and should remain so. However, much of the investigation for "nonmining" purposes is done by agencies having actual construction responsibilities, and there the emphasis is predominantly on applied research. The results will save the nation great future expense, not only in various civilian and military rock structures such as tunnels and underground chambers, but in mine development as well.

The state governments do almost no true mining research except perhaps indirectly as funds are allocated to the university mining departments for general student and faculty research. Many states do maintain a division of mineral resources (or mines, or geology), and their efforts are usually directed toward the collection of generally useful and commercially stimulating data such as figures on mineral production, reserves, availability, beneficiation, and mine safety. The few examples of state minerals research efforts usually emphasize metallurgical rather than mining problems, and they must of necessity be very specific as to the state's own industry. The Minnesota Mines Experiment Station is the prime example, and has been very effective within the state, but except for such isolated examples, the mining research and development efforts by state governments are insignificant.

The U.S. Bureau of Mines (USBM) is the agency primarily charged with mining research, with the emphasis on basic or fundamental investigations. Consideration should be given to USBM authorization to contract for research by industry for more effective applied R&D. A good successful example of this is the recent outstanding progress made by industrial contractors on shaft boring at the Nevada Test Site under AEC contracts. Similar progress is urgently needed on tunnel boring and tunnel systems analysis.

The Office of Coal Research (OCR), an agency of the Department of the Interior, established by Congress in 1960 to foster research on coal and its utilization, is currently contracting a group of liquefaction and gasification projects at the rate of about $10 million annually, all of them carefully screened for their individual economic merit. This program has totaled over $50 million for research from

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OCR during the past 5 years, and considerably more has been spent by industry. This may be small compared to some other industries, but for the coal industry it is a major step forward.

Under such applied research contracts by various agencies of the federal government, there should be a uniform policy on confidential information developed, patent and manufacturing rights, etc.

In general, it is preferable that government research be predominantly fundamental in nature, leaving applied R&D to industry. However, government research agencies should not be heavily staffed with researchers who have no practical experience at all, because they are unlikely to ever gain practicality in such a position, and the quality and usefulness of their research suffers accordingly.

A review of recent government spending in mineral science and technology leads to some significant conclusions (14). In general, support of materials modification is high compared to support for raw materials production. Engineering applications receive little support compared to scientific academic-oriented studies. In 1966, the AEC spent about three times as much as the Department of the Interior on "mining and excavation." A beneficial result of this is the truly revolutionary advancement made in shaft boring at the Nevada Test Site during the past 10 years. This is an excellent result, but similar major advances are needed in other areas of mining such as tunnel boring, rock reinforcement, materials handling, rock fragmentation, etc. Our critical national needs now are to find ways to mine what we need, and make the excavations we need, without despoiling the surface, cutting through urban developments, and polluting the waters and atmosphere. In view of this, federal support should be toward the applied engineering aspects of basic raw materials production, tunneling, and excavation.

Some states, such as Pennsylvania, are presently being forced to spend hundreds of millions of dollars to remedy the results of poor planning and unsophisticated mining methods of many years ago. The research must be done <u>now</u> to avoid this situation in the future. We cannot simply legislate mining out of existence to eliminate the problem, because we <u>must</u> have the useful products of mining. The contour strip mining presently being decried in the Appalachian area might be converted to underground mining with 100 percent extraction if the speed and efficiency of tunneling were improved several fold. The same technology is badly needed for high-speed nonmining tunneling and in mining other minerals as well, but not enough research is going into these areas of need.

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MINING RESEARCH IN INDUSTRY

Industry-supported mining research in the United States is just getting started, and only 5 or 10 companies have programs worthy of note. The manufacturers of mining machinery and explosives, however, have made significant progress. That the mining industry has a long way to go, and is far behind the other major industries of the country is shown in Table 13, which compares national research and development efforts, by industry.

The official figures reporting industrial funding for R&D for primary metals show notable growth, but most of this is in metallurgy. Although mining R&D has increased, the gain is much less than the general figures indicate.

It should be noted that the mineral industry engages continuously in one form of activity not found in other industries, and that is the search for new ore deposits. However, although this activity is costly and essential to assure operational continuity, it does little to advance the technology of mining methods and equipment, and therefore cannot be considered mining research as such.

It is essential that all mining organizations of more than minimal size and resources develop some in-house applied research capability. Thus, practically-oriented and research-minded people become available, and whether they themselves develop and apply a new idea, or simply recognize and adopt an idea developed elsewhere, the essential link is forged between research and industrial application. Even a modest effort in this direction can be highly successful and rewarding. One major underground operator budgeted about $50,000 annually for mining research, and within 10 years miner productivity was almost tripled, explosives costs halved (saving $250,000 annually on that item alone), and much other valuable information and technology developed.

TABLE 13 National R&D Efforts by Industry (28)

	Numbers of R&D Scientists and Engineers per 1,000 total employees	
	1958	1964
National average	21	29
Minerals industry	5	5
Chemical industry	39	40
Electrical equipment	43	52

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Governmental agencies cannot do this sort of applied research efficiently because they have neither the personnel nor facilities. For large scale applied mining research, beyond the individual resources of most companies, there is a great need for a cooperative effort financed and directed by the U.S. mining industry. At least two very effective and successful examples of this exist abroad. One is the South African Chamber of Mines, and the other is the Swedish Iron Miners Association. The South African Chamber is entirely financed by subscription and closely directed by the industry it serves. It serves in many ways, but its research effort especially has expanded rapidly with very beneficial effects. Not only does the Chamber do in-house research, and research within given mine environments with Chamber personnel, it may also contract a specific job back to the very mine that proposed the research. Thus, in effect, this mine does the research with its particularly interested personnel, but pays only its small share of the cost, and everyone benefits from the result.

Although the more competitive nature of the American mining industry might somewhat complicate such a cooperative effort, it need not render it impossible. Certainly mining methods and equipment cannot long remain secrets, and the entire industry must benefit from such basic new developments. Federal antimonopoly policy must be applied with restraint and understanding in this area of cooperative mining research if progress for the common good is not to be stifled.

The American Mining Congress already has a National Mining Research Advisory Committee, but it meets infrequently and has little or no financial support or authority. Such a committee, with predominantly industrial representation, but also having members from government and the universities, should meet regularly to review, advise, and make recommendations relative to the mining research programs in the universities, the Bureau of Mines, and other government agencies, and within the industry itself. Properly supported, such an effort should assure that the research needs of the U.S. mining industry are recognized and met on an orderly and coordinated basis. At present there is essentially no coordination. The Canadian Advisory Committee on Rock Mechanics was organized for just such a purpose in 1962. By 1967 its efforts included a total of $250,000 in support over a 6-year period, and a much improved status of coordinated and progressive effort throughout Canada (6).

The need for faster development of mining technology in the United States is seen from the fact that some of the best work and new ideas in important mining areas have been developing abroad during the past 10 to 15 years, for example: longwall mining in Europe; rock mechanics in South Africa and Europe; ventilation and heat in South

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Africa; mechanization and industrial engineering in Sweden; and tunnel support in Europe.

It can be observed that an industry does not develop radically new technology through its old-line artisans, however skilled they may be, but rather through the persistent efforts of technically trained personnel paid to look ahead and develop solutions for the needs of the future.

A few major U.S. mining companies have initiated extensive mining research efforts during the last 10 to 15 years. Although these efforts are the exception rather than the rule, they should be cited to indicate what is possible and just how rapidly mining research can pay for itself for those with the foresight to do it.

One major company which began a program of mining research in 1960 had a mining R&D budget of almost $2,000,000 in 1967. A project to develop a new mining method cost $20,000 per month for 8 months. Another project aimed at pillar recovery with controlled caving increased total ore extraction from 77 percent to 91 percent, and cost only $20,000 in the salaries of research personnel. The benefits of the 14 percent additional recovery will become even more significant as mining goes deeper. At this same operation the 1967 budget for rock mechanics was $124,000; for equipment research, it was $300,000 for operation plus $1,000,000 for capital expenditure.

Another major company active in mining research estimates its expenditures for this purpose at about 1 percent of annual sales. Typical research projects include open-pit slope stability studies and a proposed project to fragment a large volume of rock with a nuclear explosion and <u>in situ</u> leach the material to recover copper. The slope stability studies involve full scale operations in large open-pit mines. The results will make millions of added tons of low grade ore available while moving less overburden, and the technology of quantitative slope design will also be valuable in other areas such as highway construction. Project Sloop, the nuclear fragmentation and leaching experiment, will be a joint cooperative venture between the company and the federal government. The $13,000,000 cost will be shared (39).

A third mining company has maintained a mining research group for about 15 years with an annual budget of about $50,000. Within the first 5 years one 18-month investigation cost $21,000 and developed a drill round capable of breaking rock to a depth of 10 feet instead of 5 feet. Next a 12-month project developed a fully mechanized drill carriage to accomplish the operation efficiently, at a cost of $19,000 (see Figure 18). As a direct result of these two projects, the company has been able to increase the drill man productivity in all its mines by 2.4 times, from 75 to 180 tons per drill shift, at an

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FIGURE 18 Two-man production jumbo mounting three pneumatic rock drills.

estimated savings of $180,000 per year. It would be hard to find a better investment!

For 20 years a major coal mining company has spent $1,500,000 annually for research. In addition, two oil companies contributed an equal amount in joint research, each for a period of 5 years. Out of this came advanced techniques on liquefaction and gasification of coal which have led in turn to two federally sponsored pilot plants in West Virginia and South Dakota. Another outstanding development is a 110-mile coal slurry pipeline in Ohio that operated successfully for over 6 years transporting about 1.2 million tons of coal annually. Although now shut down because of radical reductions in railroad unit-train rates, it is kept in standby condition to insure low cost haulage. A second coal pipeline, 225 miles long, is now under construction to transport 5 million tons per year. In addition, this company has had a separate R&D organization developing new mining machinery for over 20 years. This same company is active in research on equipment maintenance and modification, water and air pollution, fire suppression in refuse piles, and land reclamation after mining. The result of such investments in coal mining research can be seen in the rapid rise in productivity from coal mines since 1950 (10).

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VOCATIONAL AND TECHNICIAN TRAINING

In studying the U.S. mining industry and its manpower needs, it is evident that there is a distinct void between the practical miner with a high school education and the college graduate with an engineering degree. Mining technicians trained at the high school and junior college level are needed in many areas such as surveying, sampling, instrumentation, maintenance, work study, training, safety, etc. Vocational high schools and technical colleges to train mining technicians are common abroad, but are rare in the United States. As a result, many engineers are doing the work of technicians, and the rest are not nearly as productive as they could be with technician assistance. This is a very important factor contributing to the present shortage of mining engineers and mining students as well.

For years there have been a few technician training schools for coal mining in West Virginia, Kentucky, Pennsylvania, and Ohio, and the number is growing. Three new mining technician courses at the junior college level are being organized currently in Leadville, Colorado; Riverton, Wyoming; and Flat River, Missouri. Good examples in Canada are found at Haileybury, Ontario, and Vancouver, British Columbia. The education of mining technicians should be a priority effort, especially in established mining regions. The Engineers Council for Professional Development has prepared curricula standards for such training in other branches of engineering which are ready to serve as guides in developing the courses required for mining.

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CHAPTER 6

Future Requirements

TECHNOLOGICAL NEEDS AND OPPORTUNITIES

The mining industry has not been noted for its rapid technological advancement, and has long been considered more of an art than a science. This situation has been undergoing a revolution since World War II, but so has technology in general. Mining has a long way to go, and many opportunities beckon.

Areas of recommended research in surface mining technology may be divided into three classes: materials preparation, materials handling, and methods.

Research in materials preparation is a prerequisite to the development and adaption of new and existing equipment to provide more productive materials handling. Included should be such specifics as the development of improved explosives and their optimum utilization, and new drilling methods, such as the use of lasers, high voltage electricity, ultrasonic breakage, etc. These subjects can be researched by industry, equipment manufacturers, and government and university laboratories. The bulk of rock breaking in mining will be by drilling and blasting for a long time to come, and greatly improved methods for drilling blast holes more rapidly and efficiently are needed. Present methods are generally very inefficient and limited in the absolute amount of power they can transmit to the rock (23).

Research in materials handling for surface mining now represents an opportunity for significant cost reductions, since drilling and blasting costs have been improved in the last decade. Loading and haulage now represent a high cost area, and should be improved by such means as electrification of haul roads, improvement of existing equipment such as front-end loaders versus shovels, better tires,

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and the development of new equipment such as continuous mining equipment, air cushions, or tubular railways. These developments must be undertaken primarily by the industry and the equipment manufacturers.

Research in surface mining methods should include applications and adaptations of existing equipment and techniques, primarily by the mining and equipment companies. These efforts should include applications of the wheel excavator, extendable conveyors, portable pit crushers, and on-site comminution and pumping direct to the concentrator. In addition, government and university teams can contribute valuable assistance in rock mechanics research on slope stability, induced failure for fragmentation, computer technology, technical information systems, operations research, etc.

Safety improvements in warning devices and other features are the responsibility of all sectors.

The coal industry has been expanding production rapidly in the past decade, and must continue to do so in the future. At the same time many of its mining problems are becoming critical, and must be solved. There has been relatively little research in the coal industry because it is composed of hundreds of very small independent operators, and only a few major companies. These independents operate on an unsophisticated, often irresponsible, hand-to-mouth basis, and they do not have the capital, manpower, coal reserves, or understanding to do research. The two largest coal companies each have about 10 percent of the total U.S. production, and one of these has spent more money and effort on coal research over the past 21 years than all other coal producing companies combined.

The major problems facing the coal industry include air and water pollution, coal gasification and liquefaction, and the need to improve and extend underground mining, especially as a means to eliminate contour mining.

Coal gasification or liquefaction at the source has two important basic advantages. First, the sulfur and other impurities are rather easily removed and even become valuable by-products. Secondly, the transportation of energy in gaseous form is by far the cheapest of all, with liquid forming a fairly close second. Transporting solid coal or electrical power are both much more expensive per unit of energy.

The contamination and silting of streams by mining operations is a topic of much current public interest. Our need for the future is to so develop our mining technology that the minerals needed can still be produced at an economic cost while contributing no further to the permanent pollution of the streams or defacement of the landscape.

Major needs in mining technology are for greatly improved underground mining methods and equipment. This should include automatic

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face equipment, face and entry transportation, and automatic longwall roof supports. Sufficiently improved underground methods and efficiency will make available deep mineral reserves presently uneconomic.

The opportunities for further advances are many. Conventional tunneling methods, for all purposes, involve the familiar drill-blast-muck-support cycle, and are limited to an overall rate of advance of 40 to 50 feet per day. Recently, full face tunnel boring machines have reached sustained rates of over 200 feet per day. While setting such records, they are still sitting idle about half the time because obsolete tunnel logistics cannot remove the spoil and support and line the tunnel as fast as the machine can bore. The solution to this systems analysis problem alone would double our tunneling capacity with existing machines. In addition, the machines must be further developed to handle the harder rocks, and do this more efficiently so as to require less power and thrust. Basic research in the mechanics of rock fragmentation is needed. Shaft and raise boring machines, similar to tunnel borers, are also setting records, and all this rapid continuous excavation in hard rock represents a major breakthrough in mining technology. However, much supporting R&D is urgently needed to permit it to reach its full potential, and all tunneling technology is badly needed by many segments of our society (20,21,31,38).

The new science of rock mechanics has developed an understanding of the potential value of rock in situ as an efficient structural material. Controlled blasting techniques have been developed to permit careful excavation of the rock while leaving sound unfractured walls and roof. The advantages of active rock reinforcement by such means as rock bolts and pneumatically applied concrete, as compared with passive ground support by conventional shoring, are becoming recognized, but new developments in techniques, materials, and equipment are much needed. Many of the newest developments in this field are coming from abroad, from Europe, South Africa, Australia, and Sweden, because little of this R&D is being done in the United States. The potential savings in public works projects alone would repay the costs of such research many times.

Environmental control of ground water, ventilation, and heat are greatly complicated at depth. Our mines are rapidly becoming deeper in our search for new ore, and various nonmining excavations are also probing beneath our mountains and cities to an ever increasing extent, where environmental control becomes more critical. Again, little research is being done on these problems in the United States, and the most advanced technology and research in the world is found abroad, notably in South Africa where mining is carried on at a vertical depth of 2 miles, the deepest in the world.

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In several of these important mining specialties, the newest, best, and sometimes, only equipment available in the United States is foreign developed and manufactured.

HEALTH AND SAFETY

In spite of very significant improvements, underground mining still lags behind most other industry in matters of health and safety. Although the Bureau of Mines has had the responsibility to promote mine safety since its inception, funds allocated to the Bureau for research have always been relatively small, and parallel efforts by the mining industry have been insufficient.

Research on the causes and prevention of mine accidents and disasters must be increased drastically if our record is to be improved. The industry itself can do this most efficiently and effectively, while the Bureau of Mines continues its efforts as funds are provided.

As our technology for rapid underground excavation becomes fully developed, we will be creating new environment of a very confined sort at a rapid rate (see Figure 19). Therefore, our capability to

FIGURE 19 Rock bolts and wire mesh reinforce rock to support itself (U.S.A. Corps of Engineers).

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assure the health and safety of that environment must be radically improved. The research necessary to accomplish this must be done now if we are not to be found lacking in the near future. Fortunately, as mechanization increases, the number of men involved decreases, and although environmental control becomes more sophisticated, the physical proportions of the problem also decrease until we can even begin to consider self-contained environments for key personnel.

MINING ABSTRACTS AND TEXTS

In mining, as in all the technical disciplines, the "information explosion" has made it next to impossible for a busy professional to keep abreast of the latest developments in his field. This is made even more difficult by the lack of a unified abstracting service of mining literature.

A "mining abstracts" service is a primary need that should be met by such an organization as the AIME. It would be a relatively easy task if all mining periodicals were to print abstracts of the articles contained in each issue. This practice is typical of Canadian publications such as the CIMM Bulletin, and the AIME's "Mining Engineering."

Modern mining textbooks are another major need. Present publishing costs, and the relatively limited circulation for such texts, make their preparation and publication difficult and unattractive. Nevertheless, modern texts are absolutely essential for effective recruitment and teaching, and their publication must be assured and subsidized if necessary. The AIME is trying to meet this need on a voluntary writer's contribution basis, but this is a slow and inefficient process which can never hope to meet the need adequately. Loose-leaf publications that can be updated quickly and inexpensively may be a practical solution.

MINING'S PUBLIC IMAGE

Mining's public image has long created mixed emotions in the layman. Many are the tales of fortunes won and lost, of the dangers of mining, the abuses of the public trust, and the uncertainties of the future in a career in the mining industry. Most of this image is inaccurate, usually outdated, and too often based on hearsay. It should be emphasized that in most other countries in the world mining is recognized as the essential and honored profession that it is, and the layman has many reminders to convince him of that fact.

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Many countries, including the United States, honor and acknowledge their basic major industries in special issues of postage stamps. In Europe and Africa especially, where the mineral industry is acknowledged as a major national contributor, there are many modern stamps about mining and minerals.

In the United States, during the 118 years between 1847 and 1965, there were only eight stamps issued even remotely concerned with the mineral industry, most of these were historic, and only two referred directly to the steel and petroleum industries.

In contrast, during the same 118 years, about 25 stamps were concerned directly with some form of agriculture, and about 70 with transportation (41).

Postage stamps offer an effective and appropriate method to acquaint the layman with the mineral industry, and this opportunity should be used.

The U.S. mining industry itself must take notice of public misunderstanding, misinformation, and lack of appreciation for mining, and take strong and deliberate steps to improve its public image (22).

The industry should supply intelligent and comprehensive news releases pointing out its safety accomplishments and comparing them with those of the other major industries. About 140 men, women, and children are slaughtered every day on the highways, yet there is little effort to legislate automobiles out of existence or even to reduce the toll seriously. The industry must put its case favorably before the public or watch unpleasant and inaccurate news published by default.

In major mining areas there should be suitable monuments and statues to indicate that mining is the basis for the community's purpose and prosperity (see Figure 20).

Another effective means to demonstrate the essential nature of mining in lay terms is by use of displays of basic ores with descriptions of the amount of each required to produce a common article. Such permanent displays should be placed in museums, fairs, etc.

It is interesting to note that George Washington recognized the two basic industries of man—agriculture and mining—in the ceiling of his banquet hall at Mount Vernon where the universal mining symbol of the crossed pick and shovel is displayed.

Present museum displays on mining tend to picture it as dirty and dangerous work at low pay, using obsolete methods and equipment. The industry should update such displays and emphasize the sophisticated and complex systems and equipment actually used. Tours of actual mining operations should be readily available for school children as well as the general public.

Largely through the efforts of the American Geological Institute and the National Science Foundation, the study of earth sciences has

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FIGURE 20 Symbol of the gold miners—Johannesburg, South Africa.

been introduced into the nation's grade schools and high school science courses. Students in the lower grades are studying the same basic geology previously studied only by some students in college. The mining industry should build on this early interest, and offer supplementary assistance to the schools in the form of literature, movies, field trips to mines, and summer jobs for teachers and counselors.

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Mineral
Science
and
Technology

EXTRACTIVE METALLURGY

Report of the
Panel on Extractive Metallurgy
of the
Committee on Mineral Science and Technology
Division of Engineering, National Research Council

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FRONTISPIECE: Top, Primitive metal smelting (Agricola: "De Re Metallica"); center, modern blast furnace; bottom, computer control room for blast furnace.

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PANEL ON EXTRACTIVE METALLURGY

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Abstract

A careful review of all aspects of extractive metallurgy, including ore preparation, establishes a close correlation between educational activity, research accomplishments, and industrial proficiency. The competitive position of the United States relative to major foreign groups is deteriorating. National defense, economic well-being, environmental improvement, and conservation of natural resources are all dependent upon an adequate number of trained scientists and engineers with special competence in extractive metallurgy. It does not appear that current academic, industrial, and government research or student enrollments are adequate to meet the future requirements of our national goals. An undue proportion of the existing graduate program is now involved with foreign students.

Immediate action is needed to reestablish an adequate level of education and research in extractive metallurgy, and several specific recommendations center upon the fiscal support of the authorized responsibilities of the U.S. Bureau of Mines to meet these needs. They include the coordination of all government interests in extractive metallurgy under the administration of the Assistant Secretary for Mineral Resources of the Department of the Interior.

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CHAPTER 1

Introduction

OBJECTIVES AND SCOPE OF THIS STUDY

The objectives of this panel report are (a) to survey the history, present status, and trends in the field of extractive metallurgy in the United States and (b) to recommend a course of action to the federal government and the U.S. Bureau of Mines which will insure that this essential industry is able to meet the requirements necessary to sustain the growth of the nation's economy.

All aspects of extractive metallurgy—industrial and educational, technological and scientific—are considered, but stress is placed on education and research since a shortage of specially trained engineers and scientists and a lower than adequate research effort characterize this field at present. The separate panel report on mineral economics presents in detail the great importance of extractive metallurgy to our national welfare and it is self-evident that the technology cannot prosper without the properly educated manpower.

The panel held six meetings of one day's duration each for discussion of the issues and conclusions contained in this report. Several sources of information, in addition to the accumulated knowledge of individual members, were available to the panel. The most important of these were: (1) information prepared by the National Science Foundation, the U.S. Bureau of Mines, and the Office of Education; (2) a survey of education and university research in the mineral sciences and technology, conducted by the Committee on Mineral Science and Technology of the National Academy of Sciences; (3) a survey of the published literature on extractive metallurgy, conducted by Mr. Anthony Venett of The Pennsylvania State University under the guidance of this panel.

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DEFINITIONS

In order to insure a correct understanding of some of the technical terminology in this report the following definitions are provided:

Extractive Metallurgy The field of extractive metallurgy comprises the processes and technology by which raw materials from the earth's crust (ore) and other sources such as scrap are treated to recover their valuable metal content and to produce useful refined metals. Man has practiced extractive metallurgy on a small scale throughout recorded history—as a useful and aesthetic art in ancient and medieval times and on an ever-growing scale as an industry for the past several centuries. Today it provides the enormous supply of metals so essential to our modern industrial economy and military establishment. As long as man continues to use metals for armament, structures, machines, tools, electrical conductors, and for myriad other purposes, extractive metallurgy will remain an essential occupation and industry which is vital to the national welfare.

The processes employed in extractive metallurgy are conveniently summarized in the following four traditional categories:

Mineral Beneficiation (also called ore-dressing or mineral preparation) upgrades the ore to facilitate subsequent treatment. It usually involves a large reduction in bulk by rejection of unwanted minerals and includes improvement of physical characteristics by proper sizing. The first step is comminution by which ores are crushed and pulverized so as to free the valuable, metal-containing minerals from the waste rock (gangue). This is followed by separation processes which extract the valuable mineral particles from the gangue to produce a mineral concentrate. Separation processes select the valuable mineral particles from the gangue particles by utilizing differences in their physical or surface-chemical properties. Recovery of copper sulfide minerals by froth flotation and the beneficiation of iron-taconites by magnetic separation are examples of the widespread use of mineral beneficiation processes.

Mineral beneficiation is used wherever the ore lends itself to this kind of treatment because these processes—essentially mechanical in type and operated at ambient temperatures—are less costly than alternative chemical processes for removal of the bulk of the valueless rock. It should be understood, however, that mineral beneficiation alone never produces a finished product (refined metal in primary form). A mineral concentrate typically consists of a mixture of several metal compounds (usually oxides or sulfides). Often these concentrates are so finely divided that they must be agglomerated before chemical reduction to yield refined primary metal.

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Pyrometallurgy (also called smelting or thermal processing) ranks both as the most ancient means by which man extracted metals from ores and as the predominant method in use today, when measured either by the variety of metals or tons of metal produced. It consists of subjecting the ore or concentrate to chemical reactions at high temperature, typically in the range 800° to 2000° C—with, ultimately, the production of refined metal. High temperature has a number of advantages: It permits use of inexpensive agents (e.g., carbon) for reduction of metal compounds to the metallic state; it greatly increases the rates of the chemical reactions responsible for metal production; it permits the design of processes with large production rates per unit volume; it simplifies the separation of metal from residue (slag), and it produces consolidated metal as required for most applications. The iron blast furnace provides an excellent example of a process which displays the advantages inherent in pyrometallurgy.

Hydrometallurgy (sometimes referred to by its unit operations of leaching and precipitation) consists of chemical reactions, usually carried out in aqueous solutions, whereby ores or mineral concentrates are selectively dissolved (leached) and the metal values selectively precipitated or extracted from the solution. Perhaps the oldest known example is the leaching of copper oxide ores with dilute sulfuric acid, followed by precipitation of the copper by cementation on iron. In the late nineteenth century the development of cyanidation, whereby low-grade gold or silver ores are leached with a dilute solution of cyanide and the metal values precipitated by the addition of zinc, brought new attention to hydrometallurgy. The versatility of these processes has been increased by the introduction of pressure leaching and precipitation (in autoclaves, at temperatures above the normal boiling point of aqueous solutions), solvent extraction, and ion-exchange. In other cases hydrometallurgy has the potential to perform the functions of mining by underground leaching of suitable ore bodies. In the few cases where an inexpensive reagent (e.g., dilute sulfuric acid) is capable of highly selective dissolution of the valuable metal from the ore, the process cost is low and the method is preferred to pyrometallurgical treatment.

Electrometallurgy (also called electrowinning and electrorefining) comprises those processes which employ electrolysis to extract or refine metals. Aqueous electrolysis is used for processing the metals more "noble" than manganese in the electrochemical series (e.g., zinc, nickel, cobalt, lead, copper, silver, gold). Fused-salt electrolysis must usually be employed for the more reactive metals (magnesium, aluminum, titanium, sodium, and calcium). Refining of

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metals by electrolysis, in which the crude metal dissolves at the anode and is reprecipitated in pure form on the cathode, requires only a modest expenditure of electrical energy. Extraction of metals from their compounds by use of an inert anode requires more energy and the cost of this energy increment is often a large fraction of the total processing cost. Large capital investment per unit of production capacity probably represents the most severe limitation on the application of electrometallurgy. Refining of copper by aqueous electrolysis, in order to separate the silver, gold, and other valuable impurities, and extraction of aluminum from pure aluminum oxide by fused-salt electrolysis are important examples.

EXTRACTIVE METALLURGY: ITS ROLE IN THE METAL INDUSTRIES

Extractive metallurgy occupies the center part of the broad spectrum of the metal industry, which includes mining, extractive metallurgy, and physical metallurgy.

Mining concerns the excavation of metal-bearing ores from the earth's crust after they have been located. The processes of extractive metallurgy produce refined metals and carefully specified alloys from ores and secondary sources. The processes of physical metallurgy fabricate useful metal products from metals and alloys by metal forming, heat treatment, etc.

The boundary lines between these three parts of the metal industry are vague, and none of the parts can operate effectively without close attention to the problems inherent in the others. For example, the decision to mine a particular ore body cannot be made without prior determination that the metal values can be extracted at a profit; the extractive metallurgist, in turn, needs to understand how the nature of the ore-body and the method of mining are likely to affect the quality of the raw material (ore) he must process; at the other end of the spectrum, the needs of physical metallurgy impose the specifications for primary metal, and the extractive metallurgist must be unusually responsive to new developments in physical metallurgy.

In certain critical ways the problems associated with the extraction of metal values from ore represent the key to the most significant features of a particular metal industry: the price of the metal, its industrial utility, and the conservation of natural resources. The principal reason that aluminum (25¢/lb) is more expensive than carbon steel (5¢/lb) lies in the relatively expensive series of steps required to extract aluminum from bauxite ore compared with inexpensive production of steel from iron ores. Aluminum extraction

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requires a large amount of electrical energy which is expensive relative to the fossil fuel energy used in steel manufacture; the capital investment per annual ton of metal is five times greater than the investment for iron and steel manufacture.

The price of a given metal in turn determines, to a large degree, its utility in our modern industrial economy relative to other metals with similar physical properties. There is little doubt that aluminum consumption would be many times as large as it is at present if the price of aluminum were no greater than that of steel. Thus the efficient production of metals is directly related in many ways to the national welfare, defense, and standard of living.

The problems of extractive metallurgy have an equally direct bearing on conservation. Extraction of copper by a series of processes which recover only 85 percent of the copper contained in the ore represents common practice in the United States today. A new treatment scheme which recovers 95 percent of the copper from the same ore would represent a significant contribution to conservation of copper resources. As a second example, in the United States there are huge deposits of very low-grade copper ores (0.2–0.4 percent copper) containing too little copper to permit economical extraction of the metal by known processes. Cheaper treatment of these ores by new processes or the improvement of existing methods would add significantly to our natural resources of this metal.

It is important to recognize that the extractive metallurgy industry employs secondary materials (scrap metal and industrial wastes), as well as primary ore, as raw materials for production of refined metal. Thus nearly one-half of the steel and refined copper produced in the United States have secondary materials as their origin. Perhaps no other single route to conservation holds more promise than increased use of secondary materials in extractive metallurgy. Once again, however, the availability of suitable extractive processes to permit economical recovery of metal from such materials represents the key to success or failure in this effort. Thus, the lack of such a process for the separation of small amounts of copper from steel imposes a serious limitation on the utility of steel scrap.

TRENDS IN EXTRACTIVE METALLURGY

Beginning with the period following World War II the following trends have developed with increasing severity in U.S. extractive metallurgy:

1. The relative number of U.S. students specializing in this subject in engineering schools has declined. The number of schools offering

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specialized study in extractive metallurgy has declined. There has been increasing difficulty in recruiting first-rate young men to teach the subject. The amount of money available for support of academic research in extractive metallurgy has not begun to keep pace with the funds available in other scientific and engineering fields.

2. Industrial research and development have lagged to the point where the U.S. industry has produced few new extractive processes compared with those initiated in Russia, England, Western Europe, Canada, Japan, and Australia. The United States has become increasingly dependent on foreign countries for ideas, processes, and most recently, for trained personnel. This is reflected in a weaker competitive position of our industry.

When these trends of the recent past are compared with the estimates of the U.S. Bureau of Mines for metal consumption by U.S. industry over the next 15 years—an overall increase of 50 percent—the conclusion must follow that serious deficiencies exist. These require early remedy in order to restore vitality to this critical section of the nation's economy, and to insure that future needs for primary metals are satisfied. It is this picture of the present status of extractive metallurgy which justifies the analysis and recommendations which follow.

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CHAPTER 2

Development of Extractive Metallurgy

TECHNOLOGICAL

Extractive metallurgy developed as an art, passed on from master to apprentice, long before man understood the scientific basis of the processes he used. Production of copper, lead, and iron by smelting oxide ores with charcoal is mentioned in some of the earliest historical records. The renaissance writer, Georgius Agricola, in De Re Metallica showed that, by 1500 AD, a remarkable accumulation of pragmatic knowledge was available on both mineral beneficiation and pyrometallurgy.

It was not until the nineteenth century, with the vast growth in knowledge of chemistry, that the first attempts were made to apply scientific principles to the understanding and control of metallurgical processes. Le Chatelier, St. Claire Deville, and other prominent nineteenth century scientists, were fascinated by the art of pyrometallurgy and contributed to basic understanding of the chemistry underlying these processes. In the latter half of the century significant progress was made in coupling this chemical understanding with the engineering advances associated with the industrial revolution. Probably the most striking example was Bessemer steelmaking which increased the scale of production from pounds per hour to tons per minute.

Throughout the twentieth century, extractive metallurgy has been evolving from an art to a science-based technology. The change has been gradual and is by no means complete today. Compared with typical "new" science-based industries, like electronics or the chemical industry, extractive metallurgy lags far behind in its use of modern science and engineering for the solution of its problems. Reliance on

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the vast body of empirical knowledge, inherited from previous centuries, and the economic factors associated with high investments in specialized production facilities partly explain the slow adoption of modern science by extractive metallurgy.

Three periods in the growth of extractive metallurgy in the United States may be characterized by dependence, dominance, and equivalence. Prior to the latter part of the nineteenth century, as might be expected in a young nation, U.S. metallurgy was largely dependent on Europe for ideas, training of engineers, process design, and many essential raw materials.

The first school of mines in the United States was founded at Columbia University in 1864 when metallurgy was included. It was quickly followed by similar departments at MIT, Lafayette, and others. Whether these new schools were the cause or effect of change is open to debate, but the fact remains that U.S. metallurgy advanced to a world-dominant position by the early part of the twentieth century and retained this position until the time of World War II. Not only did many improved process designs originate in the United States during this period, but U.S. metallurgists designed and operated smelters throughout the world. Some of the major U.S. process developments in this period were:

1. The Hall process (simultaneously developed in France by Heroult) for electrolytic extraction of aluminum from aluminum oxide dissolved in molten cryolite.
2. The flotation process for separation of mineral species based on selective attachment of mineral grains to air bubbles in an agitated system. (Many of the early patents for this process originated in England, Australia, and Europe, but U.S. developments soon became important. An example is the use of depressants and activators to accomplish differential separation.) The original applications were exclusively to nonferrous ores.
3. Continuous smelting of zinc in vertical retorts and electrothermic furnaces and continuous fractional distillation for refining of zinc.
4. The sea-water process for recovery of magnesium metal.
5. Production of zinc by electrolysis of aqueous zinc sulfate (developed almost simultaneously in Canada and the United States).
6. Electrolytic refining of crude lead (A. G. Betts).
7. Slag fuming for recovery of zinc oxide from lead blast-furnace slag.
8. The use of vacuum distillation for the removal of zinc from lead.
9. The large scale exploitation of the porphyry coppers.

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Since World War II, U.S. developments in extractive metallurgy, with the few exceptions noted below, have lagged behind those of other countries. This has been particularly true for extraction of the traditional tonnage metals—iron and steel, copper, zinc, and lead. Major foreign developments for these metals have included:

1. Basic oxygen steelmaking, in which oxygen of 99 percent purity replaces air in the production of steel from crude iron (originally Austria, Sweden, and Germany and now almost universally adopted on a worldwide basis).
2. Flash smelting of copper sulfide concentrates, in which the finely divided sulfide minerals are burned in suspension (flashed) to produce copper matte and slag (Canada, Finland).
3. The zinc-lead blast furnace, a method for simultaneous recovery of zinc and lead from concentrates containing both metals (United Kingdom).
4. Continuous refining of crude lead, a continuous method which replaces numerous batch steps traditionally employed (Australia).
5. The hydrocyclone, a device for continuous separation of fine mineral particles from fluids (Holland).
6. Autogenous grinding, a method whereby large ore pebbles replace the steel balls commonly used as grinding media in ore milling (Canada).
7. Electroslag melting, a process for producing high quality alloy steels, has been developed and reduced to practice by the Russians from principles established in the United States many years ago.

Some of these new processes will be described in the section which follows. Each of these processes represents a significant advance in technology, permitting lower processing cost and/or increased recovery of valuable metal. Items 1, 5, and 6 have been adopted on a large scale in the United States.

The United States did lead after World War II in process design for production of uranium, titanium, zirconium, and hafnium. It is significant, however, that these "new" metals were urgently needed for national defense programs (Atomic Energy Commission and Department of Defense) and process development was heavily supported by government funds but poorly coordinated with industrial facilities. It is also worthy of note that the original process research underlying the production scheme for titanium, zirconium, and hafnium was done in Europe by W. J. Kroll (Luxembourg). The U.S. Bureau of Mines must be credited with the engineering developments, based on Kroll's patents, which resulted in successful reduction to practice.

There have been numerous U.S. process developments since World

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War II. Application of the fluid-bed concept to roasting of sulfide minerals and the large-scale beneficiation of iron taconites to produce high-grade iron oxide for blast-furnace feed are two examples of major importance. Many foreign installations have U.S. equipment or were built by U.S. firms, but foreign developments have exceeded those of the United States in number and importance in recent years.

EDUCATIONAL

A similar pattern of evolution and decline can be observed in the history of education for the profession of extractive metallurgy. In many instances the first smelters in the United States were built and operated by European-trained metallurgists. For example, the first successful zinc smelter in the United States, established in LaSalle, Illinois in 1860, was the work of F. W. Matthiessen and E. C. Regeler, both Germans trained at Freiberg. The development of lead blast-furnace smelting in the western U.S. was based to a great extent on the work of Ahrents, Eilers, Raht, and other German-trained metallurgists. Some of these men were natives of Germany, others were U.S. citizens who went to Germany for their training. The records of the famous Bergakademie at Freiberg show two to six U.S. students per year from 1850 to 1863 and then twelve in 1864 and twenty-one in 1865.

These years marked a turning point, because as mentioned before, the first school of mines in the U.S. was founded at Columbia University in 1864, although various individual courses in metallurgy offered previously at several schools had met with little interest. Soon thereafter departments of mining and metallurgy were established in eastern universities, and in turn were followed by separate schools of mines in almost every western state and as divisions of almost every large university.

At first the schools or departments had the title of "mining," although extractive metallurgy was an important aspect of the curriculum. Separate departments of mining and metallurgical engineering were usually organized as specialization developed. Extractive metallurgy dominated in the western schools, and the high interest in physical metallurgy referred to later was very slow to penetrate west of the Mississippi.

The contributions and prominence of the various schools and departments varied over the years, but the net result was to turn out such a number of competent metallurgists that the metal-producing industry of the United States became the foremost in the world and there were trained men to be sent to all of the new mining areas of

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the globe—Australia, South and Central America, and Africa—to carry the knowledge of our technical developments.

The decline of extractive metallurgy as a subject for instruction did not become serious until late in the period between the wars. The growing interest in physical metallurgy as a subject of study and the growing demand for graduates in the metal forming and fabricating industry was paralleled by a lessening demand for extractive metallurgists in the stabilized metal producing industry. At the same time the mills, smelters, and refineries looked less and less attractive to students in comparison to other segments of science and engineering.

A final blow came with the hard drive, financed by substantial federal funds at the beginning of the space age, to develop instruction and research in materials science and materials engineering. In many educational institutions the structure of materials viewpoint has displaced entirely any interest in the actual production of metals or materials. Department names have been changed and former schools of mines have changed both their names and their images.

It seems fair to say that few departments of competence to teach extractive metallurgy are left in the United States and that we are again in danger of relying upon other countries for our trained men and for our new concepts and developments. For the past 10 years the Imperial College (London) must be ranked preeminent in number and quality of its graduates, many of whom now occupy important positions in U.S. schools and industry.

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CHAPTER 3

Contemporary Developments in Extractive Metallurgy (Recent Major Accomplishments)

Modern extractive metallurgy is a sophisticated combination of science and engineering. In order to meet the United States' needs and contribute to its economic well-being, ores must be upgraded by proper beneficiation and the process selected for the smelting and refining of these prepared raw materials must make efficient use of the most appropriate energy sources. Examples have been selected to feature each of the above aspects of extractive metallurgy and to indicate the close relation between the science and engineering involved. The discussion of each example will show the major directions in which future improvements may be expected and the extent of American participation in these developments.

MINERAL BENEFICIATION

The initial step in extractive metallurgy is usually the selection of an economic process for the rejection of a significant fraction of the bulk of the ore as a waste product of essentially no value. The crystalline nature of many ore bodies allows for this rejection by physical methods which are inherently low in cost. The crust of the earth also contains numerous deposits in which the metal values are so diffused or are in such a mineralogical form that it is advantageous to use chemical methods as a primary concentration step. Examples are the leaching of copper oxide ores and uranium ores and the Bayer processing of bauxite ore. Under special conditions, such as the recovery of nickel at Riddle, Oregon, a pyrometallurgical process may be employed. These primary concentration processes are generally located near the mine site to minimize the cost of transporting

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the large bulk of unwanted waste. Although technical aspects have traditionally controlled the economics of process selection, the social implications of air and water pollution, as well as landscape disruption, are continually increasing in importance.

Recent advances in the physical concentration of minerals have been characterized more by engineering innovations than by the discovery of new processes. The development of flotation approximately 50 years ago was a major advance in the mineral industry, the benefits of which have not yet been fully realized and still require research. The present trend in the design of concentration plants results from the development of vastly improved processing equipment combined with the refined engineering that draws on known general principles. The general result has been the installation of higher tonnage processing plants treating ores of continually declining value. Processes for beneficiation, whether physical, chemical, or pyrometallurgical, are employed for the same objective, namely, the rejection of a large amount of waste at an early stage of processing. The clearest picture of the evolutionary stage of this step in the metal production scheme is obtained by considering groups of metals with closely related technologies.

Iron Ore Beneficiation By measures of tons of ore treated, capital investment, and effect on the mineral industry, the greatest single development in the post-war period has been the rapid growth of iron ore beneficiation, particularly of the taconites. The research, development, and engineering activities which resulted in the installation of many large new iron ore mills is undoubtedly the largest single concerted effort in the minerals beneficiation field in recent years. A major technical effort has developed large-diameter ball mills and autogenous grinding mills capable of handling huge tonnages at very low cost. The long known magnetic separation process was greatly improved by more efficient and higher capacity magnetic separators which produced a superior grade of magnetite concentrate. The resulting fines were not suitable for the iron blast furnace until processes of agglomeration and pelletizing resulted in a superior and uniform product. For ores not amenable to magnetic concentration, flotation processes were developed. Still other types of ore were found to respond to concentration by the newly developed Humphreys spiral, and by the end of 1962, spiral installations accounted for a rated capacity of 23 million tons of iron concentrates per year. These concentrators apply an old gravity principle and are important because of greater capacity and simplicity and lower operating costs. Another development in iron ore concentration is high capacity, dry, electrostatic separation. Thus, four methods of concentration of ores

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have been carried to a high degree of technical and commercial success. Although the application of each method is controlled by the mineralogy of the ore to be treated, they all have in common the one advantage of low-cost removal of impurities, primarily silica, prior to the smelting step. Agglomeration or pelletizing of the fine concentrates is a vital adjunct to all these processes in preparing the material for smelting. This properly sized feed results in a greatly increased capacity of the blast furnace.

The success of large-scale iron ore concentration has thus evolved not only from the incorporation of new metallurgical techniques, but also from the engineering of efficient plants, the use of newly developed equipment for all the accessory operations, and the installation of very large plants with low unit operating costs. The relative speed of these changes depended significantly on the ability to adjust principles learned from the nonferrous industry to the needs of the iron industry.

Major Nonferrous Ore Beneficiation The unit operations of crushing, grinding, flotation, filtration, and agglomeration employed for the production of the majority of copper, lead, zinc, and molybdenum concentrates have remained essentially unchanged since the advent of flotation several decades ago. Results produced in milling circuits, however, have been greatly improved. Costs are lower, production is higher and many mineral deposits which formerly could not have been processed economically now constitute important contributors to our mineral production. These changes have been brought about by the incorporation of more efficient equipment, better engineering design, and more selective flotation reagents. The introduction of the hydrocyclone as a classifier has been one of the significant new equipment developments. The demand for constantly lowering costs while treating a continually lower grade ore has resulted in efforts for the automation and control of milling circuits. Many successful computer control circuits are in use in portions of milling circuits. On-line analytical techniques, including X-ray fluorescence, have been employed with great success. Computers are in use as ancillary pieces of equipment. However, the control and automation of completely integrated circuits is still a future development which will require a major technical effort. The emphasis at the moment is on the development of equipment and techniques, both to sense changes in the milling circuits and also to make control possible.

The expansion of open pit copper mining and the discovery of the role of bacteria in leaching copper from waste dumps has led to major research and development in the whole field of leaching for the

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recovery of copper. The long practiced methods of vat leaching of oxide copper ores have also been improved and many plants have installed leach-precipitation-float circuits for the better recovery of oxidized copper minerals. The net result of this hydrometallurgical expansion is that an estimated 15 percent of the new copper production in the United States is now derived from leaching processes. Fracturing of low grade ore bodies, followed by leaching in place, is under investigation.

Beneficiation of the High-Temperature and Less-Common Metal Ores A phenomenal growth in the mining and beneficiation of uranium ores took place after 1950. Although the U.S. government program was aimed at the development of small ore deposits which were believed to be the principal sources of uranium in the United States, in the end it resulted in the discovery and exploitation of large, low grade ore bodies such as the Grants area in New Mexico and the Gas Hills region in Wyoming. Even though many methods of ore treatment were developed, the more successful ones were hydrometallurgical processes, including a leaching step followed by ion exchange or solvent extraction for separation of the uranium. The commercial development of these processes is significant because of its implications for future recovery of other metals. At the present time, copper, cadmium, columbium, zirconium, tantalum, the rare earths, molybdenum, tungsten, and rhenium are being recovered in whole or in part by these processes. The growth of leaching technology, including the in-place leaching of uranium ores, combined with these chemical separation techniques, forecasts a wholly new philosophy of beneficiation.

The physical beneficiation of sand deposits containing the minerals of titanium, tin, tantalum, zirconium, etc. has been greatly advanced by equipment innovations including Humphreys spirals, sluice-type concentrators, both wet and dry high-intensity magnetic separators, high-tension electrostatic separators, and hydrocyclones.

SUMMARY OF RECENT ACHIEVEMENTS IN PRIMARY CONCENTRATION

The near-term developments which appear to be significant in establishing the future trends may be summarized as follows:

1. The extensive growth of instrumentation and automatic control.
2. Ion-exchange and solvent extraction recovery of metals from leach solutions.

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3. In-place and bacterial leaching of uranium ores.
4. Bacterial leaching of copper ores.
5. The development of more efficient equipment including hydrocyclones, spiral and sluice concentrators, electrical and magnetic concentrators.
6. The increasing acceptance of autogenous grinding.
7. The development of ancillary agglomeration processes such as sintering, pelletizing, and fluid bed roasting.
8. The employment of new techniques of material handling and new materials of construction.
9. The use of galena and magnetite to extend the range of heavy media separations.

If the United States is to participate in the realization of the benefits to be derived from these developments, it is apparent that suitably trained manpower must be available in order to generate the science and engineering required for their reduction to practice.

Development of theory and the supporting experimental research is being carried out in relatively few organizations in the United States at the present time. Former strongholds of research and instruction have abandoned their efforts and those remaining suffer from lack of workers.

EFFECTIVE UTILIZATION OF SCRAP METAL

The metal-bearing raw materials consist of ores supplied by the mining industry and scrap obtained from various sources. The scrap piles in America can be considered to be a vast mine having several types of metallic deposits whose value can be regulated to advantage. Their present and future importance is commonly underestimated. This mine's deposits are constantly being replenished by (1) metallic waste from manufacturing operations and (2) metal objects that have been discarded. In conventional processing between 20 and 25 percent of the raw steel melted becomes scrap to be remelted. As the steel industry converts from the conventional casting of ingots to continuous casting, scrap probably will drop to 12 to 18 percent of the metal cast in the next 10 years. Another 10 to 15 percent of the crude steel tonnage becomes high quality scrap in the processing plants. This type of scrap commands a premium price because of its quality (a known analysis, not mixed with other alloys), and it may be returned directly to the primary producing plants or it may be sold to secondary manufacturing metal processors such as foundries.

A different type of scrap is generated in metal fabricating plants.

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It may be contaminated with other metals, cutting fluid, plated metals, solder and nonmetallic materials such as electrical insulation, and coatings of plastics or paints. Because of the contaminants, this type is used chiefly in the secondary processing plants.

The second class of scrap consists of the vast array of discarded metal-bearing objects that are scattered across the country. Tin cans, old automobiles, brass buttons, elements in electric light bulbs, gold and silver fillings in teeth, silver in photographic emulsions, etc. Potentially all of this metal could be returned for reprocessing into pure metals. The practical problems hindering this are the cost of collection, sorting, and return of the scrap to the processing plant and the contamination by other metals and chemicals. Refining requires different processes than for naturally occurring ores.

There are now effective and economical means for reuse of most of the high quality scrap by the metal producing plants. Discarded copper wire, bus bars, old steel rails, copper piping, zinc sheet, etc., usually are of sufficient value to pay for collection and shipment. For example, approximately 30 percent of the copper produced each year in the United States is derived from high quality scrap. Poorer grade steel scrap is blended with high quality scrap and virgin metal obtained by smelting ores, or it may be the raw material for cast iron foundries. The poorer grades of copper scrap are used as the raw material for brass production, and copper objects containing a high percentage of iron are sources for alloying in steel and cast iron production. Upwards of 100,000 tons of low-grade aluminum alloy made from aluminum scrap are used for deoxidation in the steel industry. Approximately 50 percent of the copper used in this country comes from scrap. One-third of this copper is so badly contaminated (one-sixth of the total copper supply) that it can be used only in brass mills. The fraction of the total supply of a metal that comes from scrap is shown for several major metals in Table 1. Titanium is included to indicate an opportunity for future research. It is typical of a new metal where obsolescence of products has not become important and where the refining problems are great.

Because of the gradual contamination of our important metals as they circulate from the producing plant to the processing plant to the user to the scrap pile and then back to the producing plant (see Figure 1), there is a steady loss of metal from the circulating stream. The contamination of the circulating stream will depend on the balance between the rate at which virgin metal and the contaminants are added to the stream. The tendency in the present day use of metals is to make thinner sheets, develop alloys, and to apply metallic and nonmetallic coatings to impart corrosion resistance. The result is an increased rate of contamination, but it also tends to increase the dis-

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TABLE 1 Portion of the Supply of Common Metals in the United States that Comes from Scrap

Metal	Percentage of Metal Supply Obtained from Scrap	
	1956[a]	1965[b]
Aluminum	17	19
Copper	46*	48*
	(30)+	(30)+
Iron	52	50
Lead	59	65
Silver	40 est.	46[b]
Zinc	37	37
Titanium	nil	nil

*All copper.

+Refined copper.

[a] U.S. Bureau of Mines Yearbooks.

[b] U.S. Bureau of Mines Minerals Yearbooks. Domestic production plus secondary; does not include metal from Treasury stockpile.

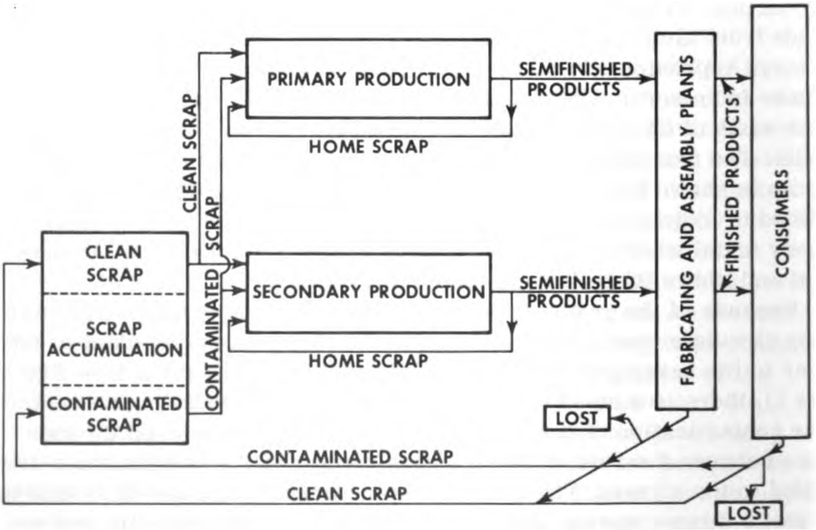

FIGURE 1 Scrap Cycle. Showing the flow of metals from sources to consumers and the generation and disposal of different types of scrap.

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persion of metal beyond the state where recovery is feasible by established processes. A major problem associated with this contamination is that significant quantities of the more valuable and scarcer metals are being lost beyond recovery year after year. The copper, chromium, nickel, molybdenum, tin, zinc, and tungsten that are alloyed with steel, or may be applied in coatings, eventually will be lost by dilution. For example, in a year when 120 million tons of crude steel are produced, approximately 20 million tons of miscellaneous scrap are collected from the countryside and remelted. This scrap will contain approximately 0.20 percent copper so that each year 40,000 tons of copper are lost to further use as copper and the steel scrap is also downgraded.

An example illustrates the type of process which should be developed for use in other situations in order to conserve valuable raw materials. A present practice of handling contaminated copper scrap may also be useful in treating certain types of complex copper-bearing ores. The waste from electronic assembly lines, discarded electronic equipment, and other copper scrap is smelted in a blast furnace to produce crude copper, a slag, and a fume. This crude copper, which contains some lead, zinc, and the precious metals, is charged to the copper converter. In converting, the lead and zinc are fumed off and the precious metals pass on with the copper to be recovered in the regular manner. The lead and zinc are removed from the slag as a fume which is treated to recover the separate metals.

Technological studies are needed to find other means for recovering metals from waste. It is quite possible that the slag product from a municipal incinerator could be treated to extract the valuable metals in useful form. Also needed are studies of the possibility of developing small-scale processing systems for extracting metals from the residue of various manufacturing operations at the point where the waste is generated.

Conservation of our supplies of metals requires that (a) we find ways of improving the collection of metal-bearing waste of our society; (b) we find means of processing scrap and waste to separate the contaminants and recover the valuable metals for subsequent use; and (c) existing processes be improved so as to generate less waste. The problems are closely related by economic factors and treatment of one aspect of a problem may solve another. For example, thus far no practical and economically sound technique has been devised for removing copper and tin from steel during normal processing. However, much of the contamination of steel scrap with copper could be avoided either by using aluminum instead of copper wire in automobiles or by designing the automobile so that the brass and copper parts could be removed easily when the unit is scrapped. Such pro-

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grams are for the public or national good, but usually offer little incentive to existing industry. They are therefore suitable for consideration by a federal agency such as the Bureau of Mines.

CHANGING PROCESSES IN NONFERROUS METALLURGY

The variety of ores and the specific chemical properties of individual metals make it necessary to cite a number of cases in order to provide a good cross section of nonferrous metallurgy.

The Zinc-Lead Blast Furnace The development, by the Imperial Smelting Company of England, of the first successful blast furnace for simultaneous recovery of zinc and lead from mixed ores represents a major breakthrough in nonferrous metallurgy. Since first announced in 1955, the process has been installed in eight countries throughout the world with notable success.

Zinc and lead sulfides commonly occur together in ore deposits. Traditional treatment of such deposits separates the ore into a zinc concentrate and a lead concentrate by mineral beneficiation followed by separate pyrometallurgical recovery of the metals from the two concentrates. Two shortcomings of this scheme are: (a) the intergrowth of zinc and lead sulfides in some ore deposits is so fine that satisfactory separation into zinc and lead concentrates cannot be made; (b) portions of the minor metal are either lost during processing of the major metal or are recovered only after special and costly by-product treatment schemes.

The zinc-lead blast furnace circumvents these problems by direct recovery of both metals in a single process of large capacity. The development which made this possible is an example of novel engineering combined with a thorough understanding of the physical chemistry involved, a special design of condenser in which zinc vapor in the blast-furnace gas is rapidly cooled (shock-cooled) from 1100° to 550°C in a spray of molten lead. In the absence of this special condenser, previous attempts to recover zinc from blast-furnace gases have always failed due to oxidation of the zinc vapor by carbon dioxide during cooling. Shock cooling reduces the rate of the oxidation reaction to an insignificant value.

Shock cooling of metal vapors represents a method where modern engineering research can be expected to yield additional advances which will improve metal recovery processes. During World War II, production of magnesium metal by carbon reduction of the oxide was a failure because the engineering problems associated with shock cooling magnesium vapor had not been solved satisfactorily. Perhaps

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the success of the Imperial Smelting Company condenser will suggest new ways to solve the problems in magnesium condensation, or in other processes which involve vapor condensation.

Observations on Lead Smelting in the United States In contrast to the Imperial-Smelting development, it is noted that there have been no comparable projects in this country. Lead smelting in the United States at the turn of the century was conducted at numerous small capacity smelters. Plants in the western United States usually smelted charges quite low in lead content because of lack of high-grade ore or high-grade concentrates and also because the lead blast furnace was a favorite method of treating gold and silver ores which diluted the charge. With the passing of years a few of the lead smelters in the United States survived and grew in capacity while the rest were closed down for lack of raw material.

Improved methods of concentration provided higher-grade concentrates for smelting; the invention of the continuous down-draft sintering machine provided more effective desulfurization and delivered a semi-digested charge to the blast furnace. These two factors plus a better understanding of the chemistry of smelting increased markedly the lead production of each furnace. Minor improvements were made in the equipment, but no basic changes were made in the concept of lead smelting.

The orthodox sintering of the lead concentrates and the subsequent smelting of the sinter in blast furnaces has never appeared to be the ideal method for treating the high-grade concentrates that can now be produced, especially from Missouri ores. The charge must be diluted with returned blast-furnace slag to lower the lead content to the neighborhood of 50 percent, which is about the maximum that can be successfully sintered by a down-draft machine. The ore hearth process successfully competed with blast-furnace smelting for treatment of the very high-grade concentrates until late in the 1950's when labor costs and other changing conditions eliminated the last ore hearth plant in the United States. Progress has been made in Germany by using a short revolving kiln and in Sweden by a combination of electric furnace smelting plus converting. Neither of these processes has been adopted in the United States.

At present lead smelting is experiencing a revival because of the recent discovery of extensive deposits in Missouri. The smelter of the St. Joseph Lead Company at Herculaneum is being remodeled with features adopted from Australian practice, particularly up-draft sintering and the use of larger furnaces. Other new smelters now under construction are not reported to have any new or unusual features.

It would appear that there has been a lack of research in lead

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smelting and refining in the United States although increased production is expected in this field.

Electrolysis of Nickel Sulfide In 1961 the International Nickel Company of Canada announced a new electrolytic extraction process which not only represents a significant advance in nickel metallurgy but also points the way to similar developments for other metals. Herein called the "sulfide anode process," the method consists in casting an anode shape from crude molten nickel sulfide, followed by electrolysis of the cooled anode in an aqueous electrolyte to produce pure nickel and solid sulfur. This replaces three separate steps: (1) roasting nickel sulfide to nickel oxide; (2) reduction of nickel oxide to nickel metal; and (3) electrolysis of the crude nickel—all of which were formerly required to produce refined nickel. It has the added advantage that elemental sulfur is recovered rather than a dilute sulfur dioxide gas.

The sulfide anode process represents a development which utilizes an innovation in process chemistry, i.e., an electrochemical reaction in which the anode material (nickel sulfide) provides the source of combined metal for the electrochemical reaction. Other commercial processes for metal extraction by electrolysis provide the metal compound which is to be electrolyzed as a soluble chemical added to the electrolyte. It is now recognized that many metal compounds, particularly sulfides and oxides, can be subjected to anodic dissolution, similar to that utilized for nickel sulfide. A fine opportunity exists for development of other new processes utilizing this same principle.

Announcement of an alternate treatment for sulfide concentrates by a high pressure carbonyl process with advantages in cost, metal recovery, product quality, and pollution control has been made by the same company.

Production of Titanium, Zirconium, and Hafnium Spurred by the needs of the Atomic Energy Commission, Navy, and Air Force, the development of commercial methods for extraction of these metals in the period 1948–1956 represents one of the brightest accomplishments of U.S. extractive metallurgy. Novel chemistry and engineering were combined in the design of a number of new processes used to make these urgently needed metals. Moreover, the influence of these new processes has spread to the production of other metals.

Solvent extraction, in which an organic liquid selectively removes one constituent from an aqueous solution, was perfected by the U.S. Bureau of Mines for the difficult task of separating zirconium from hafnium. The process has since been adapted to separation of niobium and tantalum.

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The use of metal chlorides as the basis of extraction chemistry is common to the new processes for production of titanium, hafnium, and zirconium (production of most other metals involves the chemistry of oxides and sulfides). The development of successful chloride processes involved major innovations in equipment design and materials of construction. Metallurgical extraction based on chloride chemistry has many attractive features resulting from the relatively low melting and boiling points of the chlorides. It is the low boiling point of titanium tetrachloride (135° C) which makes possible the use of fractional distillation as the means for purification of this compound. Fractional distillation has recently been extended to the separation and purification of niobium and tantalum chlorides.

Process development for titanium, zirconium, and hafnium must also be credited with the perfection of the consumable-electrode vacuum arc-furnace for the melting and ingot casting of metals. This process was essential to production of titanium, zirconium, and hafnium of useable purity. It has since been widely adopted in the steel industry for melting and casting of specialty alloy steels.

The intensive research and development on titanium metallurgy produced several processes which utilized electrolysis of fused-salt baths containing titanium chlorides. These processes were not developed beyond the pilot-plant stage because they were perfected at too late a date (1957–1958) to be included in the government-sponsored plant expansion program. In a recent (1967) announcement, however, the Titanium Metals Corporation of America has declared its intention of using this type of process for expansion of its titanium production capacity at Henderson, Nevada.

Fused-salt electrolysis will probably find other new applications in extractive metallurgy. The U.S. Bureau of Mines has been a leader in the study of this process as applied to titanium, zirconium, tungsten, molybdenum, tantalum, and other metals.

Nonferrous Smelting with Oxygen The common ore minerals of copper, lead, nickel, and zinc are sulfide compounds. Traditional methods for treatment of these concentrates involve, at some stage, the reaction of their sulfur content with oxygen from air to produce a relatively dilute (4 to 10 percent) sulfur dioxide gas. Even today this gas is discharged to the atmosphere by many metallurgical plants. Others clean the gas and produce by-product sulfuric acid from it, but the cost of doing this is often greater than the value of the acid produced.

If oxygen of commercial purity can be used in place of air for removal of sulfur from metal sulfides, a number of advantages result: (1) the gas produced is rich in sulfur dioxide (80–90 percent), much reduced in volume, and can be more economically processed

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to sulfuric acid, liquid sulfur dioxide, or elemental sulfur; (2) the heat produced by burning the sulfides is not consumed by the large nitrogen content of air so that much less or no extraneous fuel is required by the metal smelting process; (3) the higher temperature made possible by the use of oxygen results in more rapid reactions and increased capacity of the smelting unit.

One example of a new smelting process which takes full advantage of the use of oxygen is the flash smelting process for production of copper matte, developed by the International Nickel Company of Canada (1955). The finely powdered copper sulfide concentrate is sprayed into the hot smelting chamber in a stream of oxygen. The oxidation reactions are almost instantaneous, resulting in mineral particles becoming incandescent (flashing) as they fall into the quiescent molten pool at the bottom of the furnace. The heat required to maintain the furnace at 1300° C is supplied by the burning sulfide minerals, whereas, in traditional copper smelting with air, a large amount of oil or natural gas is consumed for this purpose. The furnace gas contains 80 percent sulfur dioxide and, after cleaning, this is compressed to by-product liquid sulfur dioxide. The use of oxygen for "converting" of molten copper sulfide (copper matte) and molten nickel sulfide (nickel matte) to their respective metals has been developed in Japan and Canada. In many ways this application of oxygen smelting bears a close resemblance to basic oxygen steelmaking, except that sulfur, rather than carbon and silicon, is the impurity being burned out with oxygen.

The lag in use of oxygen in the U.S. nonferrous metal industry is particularly unfortunate in view of the increasingly critical problem of air pollution.

The Aluminum Industry Its high chemical reactivity with oxygen puts aluminum in a special category relative to the other tonnage metals. There have been no basic changes in its metallurgy since the original invention of the Hall-Heroult process for the electrolytic reduction of Al_2O_3, dissolved in a molten cryolite bath. This requires pure Al_2O_3 which is obtained from crude bauxite by the Bayer process. However, there have been continual improvements in the individual operations which result in significant overall progress and these will be listed without detailed discussion. Magnesium may be considered as a parallel case.

Recent Advances in Extractive Metallurgy of Aluminum:

1. Increased Bayer process efficiencies through improved techniques and large automated plants.

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2. An economic "combination process" to extract aluminas suitable for smelting from high-silica (up to 13 percent SiO_2) bauxite. Red mud residues from the Bayer process are sintered with lime and soda to recover Al_2O_3 and recycle soda to the Bayer process.
3. Efficient processes to capture and utilize fluoride fumes from aluminum smelting cells.
4. Aluminum smelting cells (Hall cells) of more than 150,000-ampere capacity with continuous alumina feed, computer optimization of power and anode-cathode distance, and block linings for cathodes.
5. Production of special alumina grades for a variety of applications: low-soda and dense aluminas for ceramics; fine-particle aluminas for paper and rubber; pure aluminas for catalysts; gelatinous aluminas for desiccants.
6. Processes to degas and remove oxide from molten aluminum; decreased metallic impurities through superior operation.
7. Aluminum of 99.99 percent purity by a versatile and economic process based on fractional crystallization.
8. Improved formulation and baking of the carbon electrodes for Hall cells, based on selected heavy hydrocarbons from petroleum, coal, and Gibsonite.

Here again it is evident that such progress required the continued close interaction of metallurgists with chemists, electrochemists, chemical engineers, and electrical engineers, and that it cannot be expected to continue without comparable effort and manpower.

Continuous Steelmaking An appraisal of current world-wide activity in continuous steelmaking will show that, even in the well established iron and steel industry, change is continuing and will require increased attention in the United States if this country is to maintain its position of leadership.

Two events in the United States in the early 1920's, continuous processing on a large scale in the oil industry and the commercial exploitation of the hot strip mill in the steel industry, stimulated interest in the possibility of making steel on a continuous basis. However, this was short lived because of the formidable problems of refractory wear and process control. Interest was revived in the 1950's as evidenced by several technical articles in the Japanese, Russian, and British literature. Indifference by the American technical press caused an article by an American to appear in a Russian journal. During the middle 1960's, American interest in continuous steelmaking was stimulated by several conditions: the increase in capacities of steel plants and in the size of conventional steelmaking

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units, the large scale use of oxygen in the steel operations, the development of superior refractories for oxygen steelmaking, the need to reduce labor costs, and the example of significant foreign progress.

Spray steelmaking is a process that was developed by the Sheffield Laboratories of the British Iron and Steel Research Association, and it is being tried on a semicommercial basis at the Millom Ore and Iron Company, Ltd., Great Britain (see Figure 2). In the process, a stream of liquid, impure iron falls vertically within a circular curtain of powdered flux which consists of iron oxide and burnt lime. Multiple jets of oxygen under high pressure impinge on the falling stream and break it into a fine spray of molten metal. Simultaneously, the oxygen oxidizes the impurities in the liquid iron and some of the iron itself. The oxidized materials react with the powdered flux to form a slag. The refined metal and slag are caught in a refractory lined vessel to which scrap may be added to absorb the excess heat generated by the refining reactions. It appears that scrap may constitute up to 35 percent of the metallic materials charged to the process.

The method being developed by the Institut de Recherches de la Siderurgie at Metz, France, consists of two reactors through which the stream of iron flows. The refining action results from a jet of oxygen that impinges vertically downward onto the surface of the metal. In this respect it is similar to the conventional basic oxygen process.

An Australian development had several vertical jets of oxygen impinging on the surface of a stream of impure iron flowing down a slightly inclined trough. Development work on this process was stopped in 1965.

Two recent American developments might provide a continuous supply of liquid iron for continuous steelmaking. Inland Steel Company operated a pilot plant from 1960 to 1963 in which iron ore was partially reduced with the treated off-gas from the refining furnace. The heat for the process was provided in the furnace by impinging jets of powdered coal and oxygen. Solid carbon was charged with the reduced ore to complete the reduction process. A liquid was produced, which was intermediate in composition between blast-furnace iron and low-carbon steel. Work on this process has been discontinued.

Recently the U.S. Steel Corporation has announced that pilot scale work is being started on a new process (see Figure 3). A combined melting-reduction furnace is efficiently engineered to take advantage of commercial oxygen and heat exchange between reducing gases and incoming raw materials. An interesting aspect of the design is that the problems associated with refractory wear have been partially

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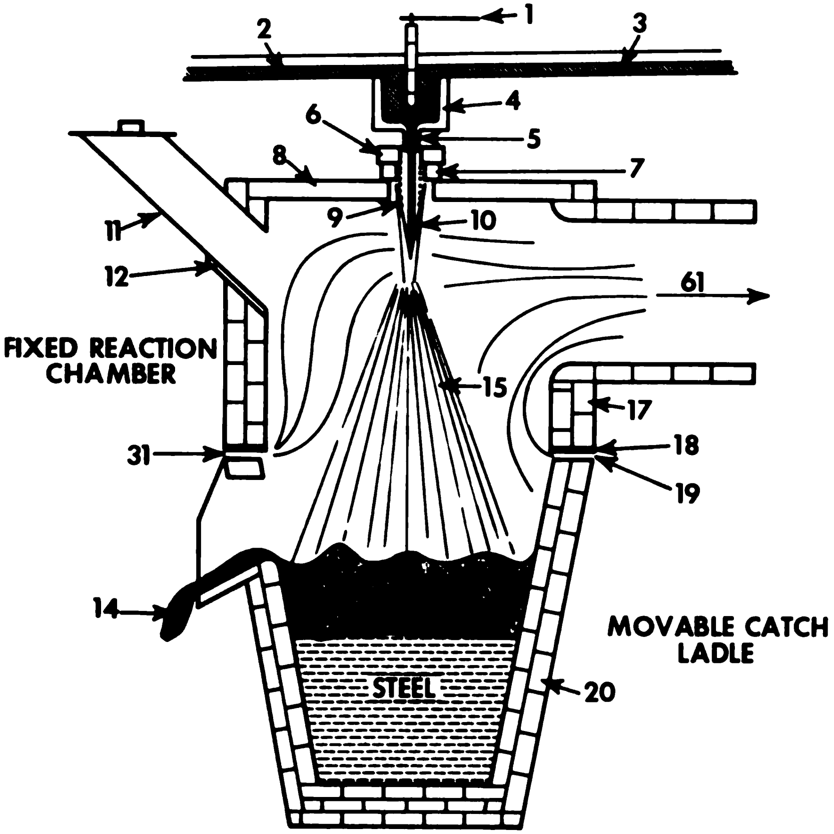

FIGURE 2 Cross Section of Millom Prototype of Spray Steel Plant.

1. stopper rod
2. excess overflow iron
3. molten iron from blast furnace
4. tundish
5. metal flow regulating nozzle
6. flux ring
7. water-cooled oxygen injection ring
8. water-cooled top plate
9. flux injection
10. oxygen injection
11. chute for additions
12. water cooling
13. air entrainment
14. slag overflow
15. spray
16. fume extraction
17. brick lining
18. water-cooled brick retaining ring
19. air entrainment
20. brick lining

avoided by making the melting-reducing furnace a water-cooled steel structure. The lining of a chamber becomes chilled oxide, slag, or metal.

True continuous steelmaking will require linking of continuous

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stages of ore reduction, melting, refining, and casting. A promising combination would be the linking of a large blast furnace, a spray steel-making furnace, and a continuous casting machine. Combinations of other stages discussed above may also be feasible.

Considerable thought, time, and money have been expended on an alternative scheme in which a bar or strip of steel is produced directly by compacting granules of reduced iron ore; no melting stage is required. The ultra-high purity ore required as a feed stock and a method for introduction of alloying elements are the key developments required for the commercial exploitation of the solid-state route to continuous steelmaking.

Two primary problems must be faced in the development of a commercially successful continuous steelmaking system. These problems are inherent in the design of virtually any continuous process for refining metals. The first is reliability of the system. Every stage of a continuous system must have a very high reliability, or the system must be designed with units operating in parallel; alternatively, it should be possible to replace units quickly. Because high temperature processing units are prone to breakdowns, the designer will probably resort to units in parallel and rapid replacement. The second is control. The full advantages of continuous steelmaking will

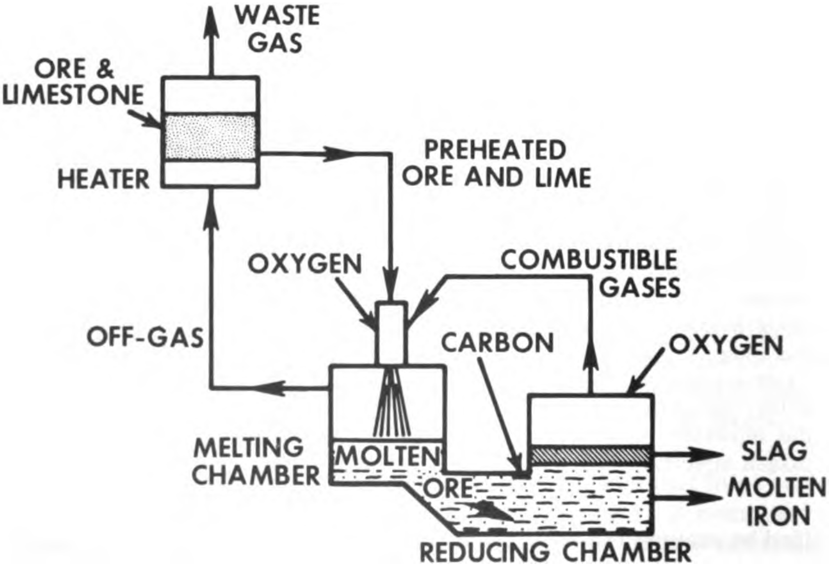

FIGURE 3 Schematic Presentation of U.S. Steel's Continuous Process for Iron Ore Reduction.

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not be achieved until it is possible to apply automatic control to the system. The problem that is yet to be resolved is the development of sensing techniques that will permit the control system to determine rapidly and continuously the temperature and the composition of the steel bath, and the rate of flow of materials from one stage to the next to produce a uniform product of desired specifications, which can be altered at will. It is recognized that, with few exceptions, the problem of sensing the control variables is a major barrier to applying automation to all metallurgical systems. Solutions to these problems require the combinations of science and engineering skills which form the basis of educational programs in extractive metallurgy.

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CHAPTER 4

Present Status of Extractive Metallurgy

Previous sections have provided a background showing the relations of extractive metallurgy to the national welfare with strong evidence for the need of continuing progress and activity. This section will appraise the present status of this activity in education, government, and industry with the special objective of determining whether it has sufficient momentum to meet future needs.

EDUCATIONAL PROGRAM

As already shown, extractive metallurgy is a part of the continuous spectrum which extends from the mining of raw materials to the end use of metal products. There are no sharp boundaries between the bands of this spectrum. The organization of research and its industrial application is such that it is difficult to obtain specific information on extractive metallurgy from the usual statistical presentations of budgets, expenditures, university enrollments, and manpower. In view of the importance of the educational program for providing both the basic research and trained personnel for future requirements, the Committee on Mineral Science and Technology (MST) has circulated a special questionnaire to those schools with known activity in this area. The returns represent essentially complete response, and it is believed they present the best and most recent specialized information available. (See Appendix for complete tabulation of MST questionnaire.) A similar survey of industry was not feasible but typical examples have been examined and the information on the iron and steel industry represents nearly complete coverage. Within the government, emphasis has been placed on the Bureau of Mines which is

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recognized as the focus for this work. Research productivity and its relative position on an international basis has been measured by an analysis of the published literature.

In considering the educational establishment, perspective is gained by evaluating the effort in extractive metallurgy and mineral engineering in relation to the larger sector of metallurgy and materials science and/or engineering, which is usually identified in more general reports.

The information contained in the 1964–1967 editions of the "Metallurgy/Materials Education Yearbook for the United States and Abroad" by John P. Nielsen has been reviewed. Table 2 shows the count of the faculty and graduate students for the entire metallurgy-materials program. The data show that during these 4 years there has been an increase of nearly 10 percent in the number of schools with active departments in the general area of metallurgy and materials and a comparable increase in the supporting faculty. At the same time there was an increase of more than 30 percent in the number of associated graduate students. Most of the new departments did not add undergraduate programs and it is believed that these increases can be attributed to the influence and support of research in materials science and engineering.

Comparable data for the same period are not available in the specific area of extractive metallurgy but the results of the MST questionnaire give this information for 1967 (see Table 3). The organization and distribution of the two surveys were not identical but an analysis is useful because it shows that the schools with departments within the scope of the MST Committee only constitute about 50 percent of the departments and faculty covered by the Nielsen survey of the whole of metallurgy and materials. Thus the MST survey cannot be considered to include or represent the level of education and research activity in physical metallurgy and material science, even

TABLE 2 Number of Departments, Faculty, and Graduate Students in Metallurgy and Materials Science in the United States*

Year	Departments	Faculty	Graduate Students
1964	64	581	1,413
1965	66	540	1,514
1966	67	560	1,677
1967	70	630	1,870

*Based on "Metallurgy/Materials Education Yearbook for the United States and Abroad," John P. Nielsen.

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TABLE 3 Evaluation of Extractive Metallurgy in the United States, 1967 MST Questionnaire*

Field	No. of Schools Having Field	No. of Faculty**	No. of Graduate Students
All respondents in metallurgy and materials science	38	340	1,260
Physical metallurgy and/or materials	38	245	992
Extractive metallurgy	21	95	268

*Questionnaire distribution included all schools with programs in any field of interest to the MST Committee. This excluded a large number of schools teaching physical metallurgy with no program in extractive metallurgy (see Table 2).
**Counting part-time as 1/2.

though it is essentially complete for extractive metallurgy. The faculty and graduate students in extractive metallurgy represent about 15 percent of the total included in the Nielsen survey and the graduate student/faculty ratio is about 3 in all areas. It is also believed that the monies spent for education and research in extractive metallurgy in academic institutions are no more (and probably less) than 15 percent of the whole spent for metallurgy and material science. This is because of the costs of the sophisticated equipment used in the broader areas.

Now consider more specifically this 15 percent which is the concern of this panel. The results of the MST questionnaire give more detailed information for the extractive metallurgy group. Undergraduate curricula in metallurgy and materials science are usually designed to provide some training in all areas so that a division of bachelor degrees into physical and extractive metallurgy is unrealistic, though most schools provide the possibility of some specialization. It is reasonable to expect that this limited specialization is predominantly in the 25 schools which report graduate enrollments in extractive metallurgy (see Table 3 of MST report). Another observation regarding undergraduate enrollment figures is that, of all the disciplines covered by the MST Committee, metallurgical engineering is in fact the largest single group, with 39 percent of the total enrollment. The next largest single group has only 19 percent (see Table 2 of the MST report). In view of the close interdependence of all MST groups it seems important to maintain a healthy metallurgy core.

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The questionnaire allows a separate analysis of enrollment for extractive metallurgy in graduate work, which is carried on in 25 schools. We note that 41 percent of the master's of science students are foreign, which leaves only about 75 students for the United States. Similarly, 41 percent of the Ph.D. candidates are foreign so there are again about 75 for the United States. Note that these are enrollment figures and not degrees per year. Most students require more than one year for an M.S. degree, which is not necessarily a terminal degree, as many continue for the Ph.D., which is normally a three or four year graduate program. The situation is too complex for an exact separation but one can estimate that in extractive metallurgy there are no more than 50 terminal M.S. degrees per year for U.S. students, and perhaps 25 Ph.D.'s per year for U.S. students. These do not appear to approach the manpower requirements which are indicated in other sections. There is also concern that these studies show that about one-third of the extractive metallurgy departments have but one or two faculty and zero to three graduate students!

Special consideration should be given to the specific area of minerals beneficiation, which is included in extractive metallurgy in the MST questionnaire. The number of faculty working in this field is decreasing steadily and now numbers less than 10 in the United States. (There appears to be essentially no related work in progress in chemical engineering.) The educational program is thus on the verge of extinction.

If enrollments and terminal degrees are to be increased in extractive metallurgy it is apparent that the discipline must be made more attractive to faculty and students alike. It is widely believed that the effectiveness of an academic program depends upon the proper balance of teaching and research and the best people will be attracted where the possibilities for achieving this are the most promising. Table 9 of the MST report serves to emphasize the peculiar position of extractive metallurgy with regard to support of research programs. Here 46 percent of the support is from industrial sources and 8.5 percent from endowments, compared to 15 percent from industry and 1.5 percent from endowments for physical metallurgy. It thus appears that the private sector is making a relatively substantial contribution to extractive metallurgy and the much needed additional stimulation should come from federal sources. Such federal support is necessary because the problems to be solved and the advantages to be gained from such research are vital to the national welfare but seldom promise financial gain to established private industry, as shown by this report as well as the general report of the MST Committee.

It should be expected that if the promise of extractive metallurgy

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is improved by such a recognition of its role, the young men attracted to the field will develop it with the necessary basic science in thermodynamics and physical chemistry coupled with the coverage at an adequate level of topics important to the related technological problems such as macroscopic transport processes, process dynamics and control theory, the application of computers, etc.

INDUSTRIAL PROGRAM

The industrial program which the educational system should support with trained manpower and stimulate by intellectual leadership will be pictured by three representative case studies: copper, aluminum, and steel:

(a) The American copper industry is typical of that of many nonferrous metals. It has maintained its technical position by the coupling of progress in ore beneficiation with increased scale of operations through sound engineering practice. Domestically it now depends almost exclusively on low-grade ores. Thus current activity focuses on further improvement and automation of existing methods for beneficiation and preparation of ores and research is directed toward such new approaches as bacterial leaching, hydrometallurgical recovery from flotation concentrates, and various means of recovery of copper from leach solutions, such as ion exchange and solvent extraction. With this emphasis, there has been a relaxation in the efforts to improve pyrometallurgical processes. As a consequence, most of the new developments in the pyrometallurgy of copper are being made in Japan, Canada, Europe, and Africa. However, many of the improvements, such as the use of oxygen, are pertinent to American operations as they are related to the recovery of valuable by-products and the reduction of emanations into the atmosphere.

The major research is conducted by the large producers in their own facilities, supplemented by a few independent research laboratories, limited efforts by equipment manufacturers, and a small amount of university work.

The mine output of primary copper in the United States for 1966 was near 1,500,000 tons which had a value of about $1,150,000,000. It is estimated that less than 1 percent of this was spent on related research activity in minerals beneficiation and extractive metallurgy of copper. If this is accepted as the minimum acceptable level, there is grave concern about providing the trained manpower required for its continued effectiveness.

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(b) Aluminum production represents an entirely different industry where acceptable grade raw materials are available for the foreseeable future and there is only one established process for metal production. This Hall-Heroult process for electrolyzing alumina in a bath of molten cryolite has been improved continually since its inception so that no competing process has become commercial on a permanent basis. Great efforts have been expended to find processes more efficient than the Hall-Heroult process. The massive accumulation of discoveries, inventions, and basic research has not yet produced, except in temporary circumstances, a commercial development. Proposed processes include carbothermic reduction of bauxite and subsequent purification by selective melting and extraction of impurities in the furnaces; monohalide purification; extraction of aluminum by zinc, magnesium, or mercury; and purification through carbide or nitride formation. Electrolysis of the sulfide, chloride, or of organic-aluminum compounds has been proposed. The search continues. It is estimated that about 500 technically trained men are involved in the research and development work required to maintain this progress in the United States.

Aluminum, with a U.S. primary metal production of 3 million tons in 1966 and a sales value of $1,500 million, is by far the largest representative of the group of metals produced by electrolysis of fused salts. Its technology is similar to that of magnesium and the more reactive metals.

(c) The iron and steel industry is in a class by itself, operating on a much greater scale with relatively low unit value for its raw materials and products. The 1966 production of the U.S. was 134 million ingot tons with a sales value in the range of 5 to 10 cents per pound, depending upon the specifications. The enormous capital investments required for such operations tend to make this an unusually conservative industry.

Within the last 20 years technical changes have been unusually rapid. Essentially all raw materials (ores, fluxes, and fuel) are now subject to some degree of preparation and the industry has led the way in the use of commercial oxygen so that the established open-hearth process is being rapidly replaced by new basic-oxygen facilities. This is being accompanied by major trends toward automation in all segments and a change from ingot to continuous casting. Such changes have forced the significant expansion of research facilities of the entire industry and it is estimated that about 2,000 professionals are now engaged in research in the area of raw materials preparation and metal production. The industry's trade association, the AISI, sponsors most of the related academic research.

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Responsibility for government research in mineral beneficiation and extractive metallurgy is centered in the U.S. Bureau of Mines with only occasional exceptions such as the significant mission-oriented work of the AEC. There has also been limited sponsorship of related academic research on the chemistry of metals and metal compounds by the engineering division of the NSF. The Bureau of Mines budget in this area for 1968 is $12.29 million and it has been relatively stable for several years. The professionally trained staff of the Bureau of Mines was about 150 for 1964, as listed in the NSF Survey of Science Resources Series, NSF 67–21. This represents about 33 percent of the Bureau's research. Frequent reference has been made to the Bureau's programs in other parts of the report. There is a clear need for a continual supply of qualified manpower if the programs are to be successful.

ESTIMATE OF PROFESSIONAL MANPOWER DEFICIENCIES

Considering these representative segments of extractive metallurgy, it is appropriate to appraise the status of the entire activity with regard to trained manpower. Even the most conservative and approximate estimates emphasize the imbalance between future supply and demand. Table 4 is based on information in this report. From Table 3 we find about 100 faculty members with an active interest in extractive metallurgy. The aluminum and copper industries are nearly equivalent on the basis of research activity and dollar value of product and may be considered as representing about two-thirds of the nonferrous industry, while the total effort in iron and steel exceeds all of these, as it should on the basis of tonnage or dollar value. These add up to an estimate of 3,600 people in the United States engaged in beneficiation and extractive metallurgy research and development. If this effort is to be maintained at its present level it will require about 360 new people per year with equivalent training in order to replace those leaving by retirement, promotion to administrative positions, and other normal diversions. Based on the information from Tables 2 and 3 and the MST questionnaire we can expect no more than 175 such people per year. The terminal B.S. degrees are the most difficult to evaluate since specialization is not clear at this level. However, the questionnaire indicates about 1,200 upper-class enrollment in metallurgical engineering, and if 500 of these graduate per year it is optimistic to hope that 20 percent of these will be employed in extractive metallurgy. The others will go on to advanced degrees or be diverted to physical metallurgy or other activities.

The critical nature of the above situation should be appreciated.

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TABLE 4 Professionals Now Employed in Mineral Engineering and Extractive Metallurgy, Research and Development, United States

Activity	No.
Education	100
Aluminum industry	500
Copper industry	500
All other nonferrous	500
Iron and steel	2,000
	3,600

Estimate 10 percent per year to maintain current activity 360/year needed.

Terminal Degrees	Year
B.S.	100
M.S.	50
Ph.D.	25
	175 available

The estimates are only the requirements to maintain the existing level of activity and this is apparently inadequate for the future requirements of the country. The needs of many small but essential organizations, such as the U.S. Bureau of Mines, have not been included. The technical sophistication of the processes involved requires highly trained personnel in operating as well as research positions and these substantial requirements will also increase. These operating needs have not even been considered in Table 4. The only conclusion is that it is imperative that education at all levels be improved and that the output of trained manpower be increased in all possible ways.

The suggestion has been made that this deficiency can be removed by using chemical engineers. In addition to the short supply of chemical engineers there are technical reasons why this is not satisfactory.

Other sections of this report stress the need for strengthening the education of young men specializing in extractive metallurgy. Implicit in this recommendation is the concept that education in classical chemical engineering falls short of the ideal training for one who intends to practice extractive metallurgy. The subtle but critical differences between these two subjects justify continuation of separate educational curricula and will be elucidated.

To contribute most effectively to research and development in extractive metallurgy the practitioner should be familiar with the

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science and technology which underlies the adjacent subjects of mining, geology, mineralogy, and basic physical metallurgy. The chemical engineer is seldom knowledgeable in these subjects.

The most significant difference between the extractive metallurgist and the chemical engineer arises from the need for different emphasis in their basic education. Both need strong grounding in diffusional processes (heat and mass transfer), unit operations, and elements of process design. Beyond these subjects, the chemical engineer will usually study organic chemistry and process applications in the petroleum, heavy chemical, and organic chemical industries. In contrast, the extractive metallurgist must develop a working knowledge of high-temperature inorganic chemistry, the surface chemistry of minerals as it relates to froth-flotation, the behavior of small particles in fluids, and the fracture of brittle solids.

If there is one factor of greatest importance which differentiates the chemical engineer and the extractive metallurgist it is familiarity on the part of the latter with high-temperature chemistry. The chemistry of liquid and solid alloys, of oxide solutions (slags), of sulfide solutions (mattes), of fused salts, and of metal-bearing vapors at high temperature are fascinating subjects, knowledge of which has expanded rapidly in the past 20 years, and which represent the very heart of the chemical background so essential to the extractive metallurgist. He needs familiarity with how high temperatures are produced, controlled, and measured in the laboratory and in industry, how typical inorganic chemical systems behave at high temperature, and how to predict the behavior of systems which have not yet been investigated.

INTERNATIONAL POSITION OF THE UNITED STATES IN EXTRACTIVE METALLURGY

The published technical literature provides a great deal of information regarding the research effort in any given area and will be examined in a number of ways in relation to extractive metallurgy. The procedures used must be described.

Various abstract services list publications under different classifications and in extractive metallurgy these services and classifications have changed over a period of years so that meaningful results require the exercise of considerable judgment and cannot always be obtained by simple counting procedures.

For a long-range indication of the rate of increase of published research in the twentieth century and the activity in the United States in relation to other important industrial countries the Abstracts of

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the Journal of the Iron and Steel Institute (London) have been used. This service has maintained the same objectives and basis for selection of items relevant to the iron and steel industry for the entire period reported. The years 1909, 1929, 1951, 1960, 1965 were used, following the pattern of the Westheimer Report (chemistry), as they tend to eliminate perturbations due to major wars. The tabulation was made by a professional technical librarian with experience in the steel industry. Thus all decisions were made on an informed and consistent basis so that changes and trends and relative positions of various countries are without bias from the panel.

These are plotted as Figure 4 for ore preparation, Figure 5 for extractive metallurgy, and Figure 6 for physical metallurgy; all for the iron and steel industry. The continued long-range increase of world research effort in all areas took a sharp upturn after 1950 with the greatest increase coming from Russia but with significant increments from France and Japan as well. Both ore preparation and physical metallurgy have fallen off since 1960 while extractive metallurgy has continued to increase. The United States has been passed by Russia in all three areas and if the trends continue both Germany and Great Britain will also pass the United States in physical metallurgy in less than 10 years. In extractive metallurgy the United States clearly dominated research with 41 percent of the publications up to 1950, but this was no longer true in 1960 when the U.S. share had fallen to 20 percent and remains at this level now.

In recent years the ratio of publications in physical metallurgy to those in extractive metallurgy has not fluctuated much and the United States has followed the world pattern. However, the data probably have little general significance for this purpose since much of physical metallurgy is not directed toward a specific metal and would not be included in this survey.

A similar analysis was attempted for the nonferrous metals but changes in abstracting procedures precluded a useful interpretation of the information. It is believed that the major features would not be much different from the iron and steel industry.

CURRENT RESEARCH ACTIVITY IN THE UNITED STATES

The professional activities of extractive metallurgy in the United States are centered in the Extractive Metallurgy and Iron and Steel Divisions of the Metallurgical Society of the AIME and most of the pertinent research is presented in the programs and publications of this society. Thus, the Transactions of the Metallurgical Society provide a good basis for appraising the structure of this research,

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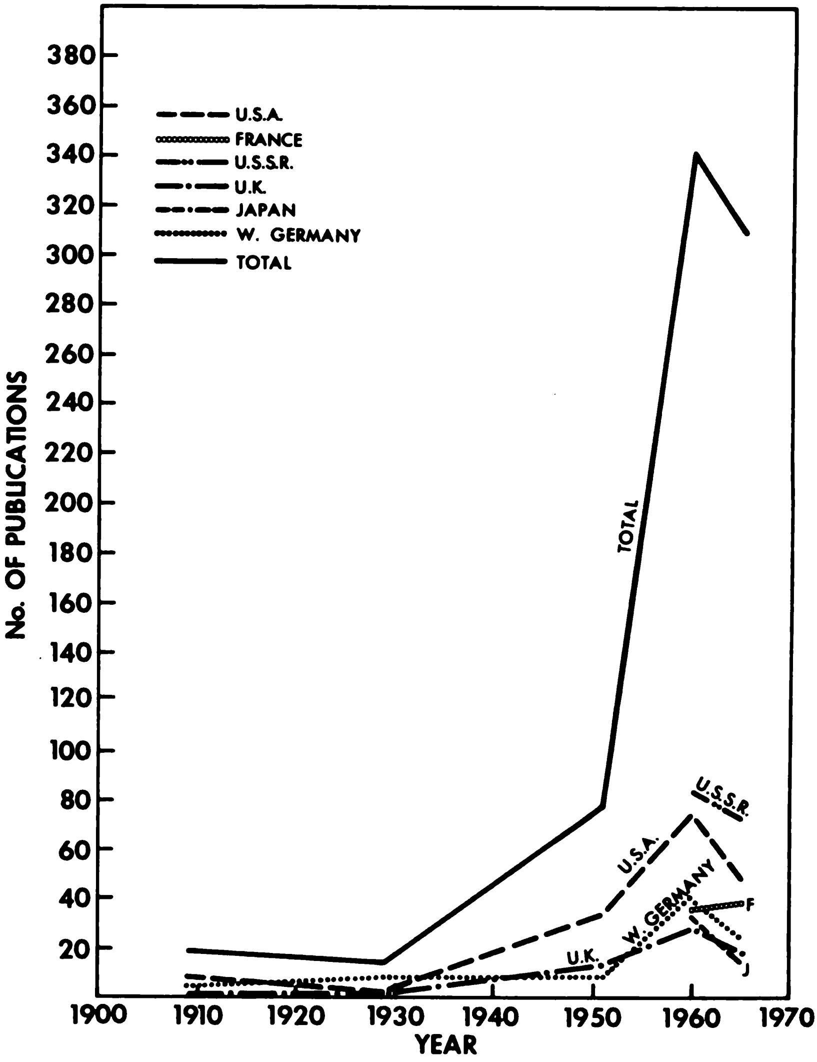

FIGURE 4 Number of Research Publications on Ore Preparation—Ferrous. Comparison of major national contributions in period 1909–1965. Based on Abstracts of the Journal of the Iron and Steel Institute (British).

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although some papers appear in the journals of peripheral societies such as the Electrochemical Society and the American Ceramic Society. Comparisons will be drawn with physical metallurgy publications in the same Transactions, but it must be pointed out that these represent a much smaller fraction of the total physical metallurgy effort.

For the sake of brevity, only a single year of publications will be used, since it is believed that rapid changes are not occurring in the areas considered. Table 5 presents the data for Volume 236 (1966).

TABLE 5 Number of Publications in the Transactions of the Metallurgical Society, AIME, 1966

Part A—Analysis of Source of Financial Support

**	Government		Industry		University		Foreign		Total
	No.	%	No.	%	No.	%	No.	%	No.
Physical (IMD)	105	51	79	38	10	4.8	14	6.7	208
Extractive EMD + ISD	21	42	10	20	6	12	13	26	50

Part B—Analysis of Establishment where Work was Performed. (U.S. Publications Only.)

	Industrial Laboratory		Research Institute		Government Laboratory		University		Total
	No.	%	No.	%	No.	%	No.	%	No.
Physical (IMD)	55	26.5	13	6.3	15	7.2	111	53.5	208
Extractive EMD + ISD	8	16	0	0	2	4	27	54	50

The remaining items are foreign origin:*

	No.	%
IMD	14	6.7
EMD + ISD	13	26

*Also note ~40% of EMD + ISD work is dependent on foreign graduate students.

** IMD = Institute of Metals Division.
EMD = Extractive Metallurgy Division.
ISD = Iron and Steel Division.

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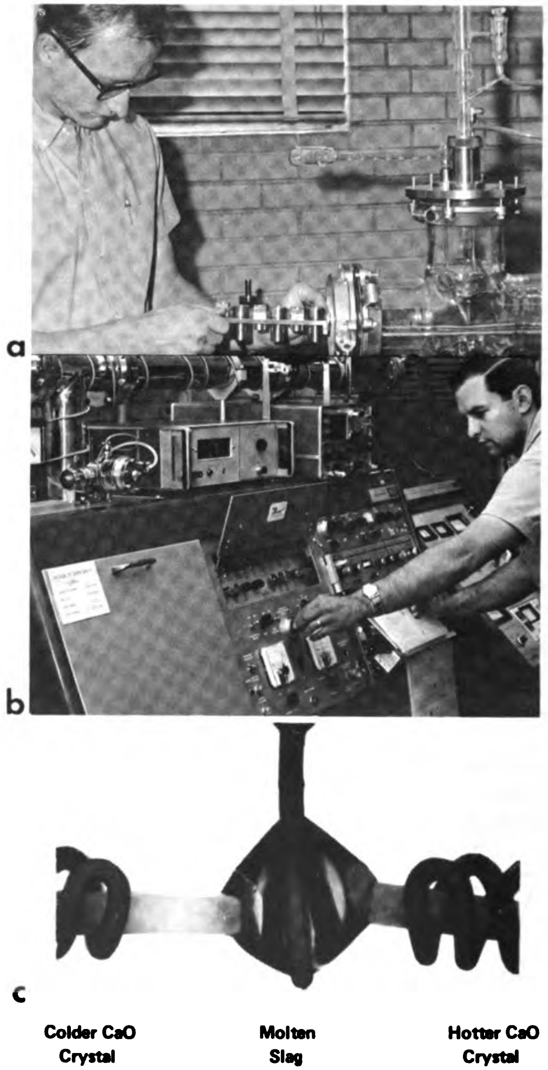

FIGURE 7 (a) Levitation melting of high purity metals to avoid contamination by contact with a crucible or other container. (b) Identification of gaseous species evolved during vacuum treatment of molten ferrous alloys by use of mass spectrograph. (c) Direct microscopic observation of mechanism of solution of CaO in slag. Original photograph in color at 1500°C. Magnification, 20x.

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Part A presents an analysis of the sources of financial support for the research papers both by number of items and percentage of items in both physical and extractive metallurgy. It is evident that both the total items and the percentage of items supported by both government and industry are much greater in physical than in extractive metallurgy. Part A includes a column of papers from foreign sources, without concern for the nature of financing. In extractive metallurgy 26 percent of the papers are from outside the country, compared to only 6.7 percent in physical metallurgy. Part B tabulates those papers of U.S. origin according to the laboratory or organization where the research was performed. Both in number and in percentage of effort, there is relatively little work being done in extractive metallurgy except in the universities. Most of this university research is closely related to graduate students and their training and it has already been seen that about 40 percent of the graduate students in extractive metallurgy are foreign. Thus, in extractive metallurgy 26 percent of the research originates abroad while 40 percent of the remainder involves foreign students and we must conclude that over one-half (~55 percent) of the American research in extractive metallurgy is in some way involved with non-U.S. citizens. This small amount of academic research in extractive metallurgy is comparable to physical metallurgy in sophistication and use of modern techniques (see Figure 7). There is no obvious reason why it should not be attractive to faculty and students alike if the career opportunities were clear.

The small percentage of extractive papers from industry and government compared to physical metallurgy should be noted. This is an important part of the image of the profession and new, young people will not be attracted to the field if there is no evidence of the opportunity for research and publication.

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CHAPTER 5

Future Opportunities and Needs

PROMISING AREAS FOR ENGINEERING AND CHEMICAL ADVANCES

Previous sections of this report have detailed the reasons for our belief in the following forces which will shape the future of extractive metallurgy: (a) There should be a continuous expansion of metal production to meet the needs of a growing economy; (b) The increased demand for metals will force greater reliance on lower-grade and more complex ores as the supplies of higher-grade ores are depleted. As the natural ore bodies become more difficult and costly to treat, there will be increased use of industrial scrap and domestic waste as sources for metal production; (c) Strong pressure will be brought to bear on the metal industry to minimize pollution of air and water and to provide more attractive and healthful working conditions; (d) Specifications for primary metal will become more stringent and exacting as the metal-working industry strives for improved quality of products; (e) "New" metals will be needed in tonnage quantities, much as the need for titanium and zirconium developed in the 1950's.

Each of these forces will put severe financial and technical pressures on the metal-producing industry in the United States. Assuming reasonably favorable conditions in the market place, and an adequate supply of trained manpower, it is believed these challenges can be met in time and without a general increase in metal prices (relative to the costs of other goods and services). The critical problem is the availability of well-trained manpower that is competent to carry out the intensive programs of research and development on improved and less costly methods of production.

If the industry is to satisfy the above-mentioned goals, the pace of

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research and development on mineral beneficiation and extractive metallurgy must be accelerated far beyond that now existing, particularly in the nonferrous industries. The metal-producing industries have, to a large extent, relied on technology developed as an art over the centuries. They are many years behind other technology-based industries—such as electronics and the chemical industry—in their use of modern science and engineering for the solution of their process problems. They are also unaccustomed to spending for research the amount needed to insure an adequate rate of process development. Unless these instances of technological backwardness are swept away rapidly the industry will be unable to meet its future challenges.

In addition to the traditional metal-producing industry we can expect new developments in metal production from the chemical and petroleum industries. Both of these "new" industries are process oriented and far ahead of the metal industry in their ability to use and profit from research and development. This ability includes science-oriented personnel in management and plant operations. In addition, the petroleum industry is experienced in prospecting the earth's crust—one of the prime talents needed for sustained metal production. Chemical companies have already contributed in important ways to metal production in this country—particularly in the production of the newer metals, such as titanium, tantalum, and uranium. Competition from these industries may supply part of the incentive needed to force a more rapid modernization of the traditional industry.

KEY ROLE OF PROFESSIONAL TRAINING

Whether the intensified research and development on new processes needed for the future of extractive metallurgy comes from the metal industry, the chemical industry, or the petroleum industry, the supply of highly trained scientists and engineers to man the effort will be of the utmost importance. Although much of the work, perhaps more than 50 percent, can be done by chemists, chemical engineers, mechanical engineers, and others, the problems to be faced are unique to the field and specialists in extractive metallurgy are required. Such specialists are needed to assure that the work is relevant and to guide the effort in research on new processes. No engineering curriculum—except a specialty in process metallurgy—is likely to combine the kinds of training needed by the process metallurgists. A second factor which justifies the training of this specialist is that only in this way can the universities be encouraged

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to engage in research directed towards the problems of the metal-producing industry.

TRENDS IN PROCESS DEVELOPMENT

Many promising directions exist for the search for more economical means of metal production, and it is useful to generalize these in three categories: (1) reduction of manpower, maintenance, and fixed costs through use of larger units for earth moving, material transport, and processing; (2) the development of new processes by application of novel engineering concepts and design to traditional metallurgical chemistry; (3) the design of processes which are novel in both chemistry and engineering.

The first of these will not be discussed in any detail because this is the area in which the industry has already made great progress and is likely to continue to do so without special encouragement. It is also an area in which the mechanical and industrial engineer are more likely to make significant contributions than the metallurgist.

Novel Engineering

If we recognize that current processes for producing iron, copper, lead, zinc, tin, etc., have been developed over many centuries, it should not be surprising that the basic chemistry employed is difficult to improve. This in no way rules out significant process developments which retain essentially the same chemistry as older processes, but which achieve their special value by engineering ingenuity—by use of tonnage oxygen, high vacuum, substitution of electrical energy for fossil fuels, or by novel reactor design. Four processes, introduced within the past 20 years, exemplify this kind of development: basic-oxygen steelmaking, the lead-zinc blast furnace, the fluid-bed reactor, and Asarco's shaft furnace for melting copper cathodes.

Basic oxygen steelmaking is the most revolutionary new process in metallurgy today. In the past five years the installed capacity of this process in the United States has grown to over 25 percent of total. To the metallurgist the new process seems almost familiar. He has been using air to burn carbon, silicon, and other impurities out of molten pig iron for more than 100 years. Substitution of pure oxygen for air did not change the basic chemistry even though it had a drastic change on the rates of the reactions. He still makes the same kind of slag and uses the same fluxes as before. Even the design of the reactor is partly familiar. It looks like an oversize Bes-

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semer converter, but it is blown from above by a lance instead of through tuyeres in the bottom.

The principal novelty of the process lies in the use of oxygen, which makes possible the production of quality steel with greatly increased productivity per unit of manpower and capital investment. This is an engineering development of a kind which we can expect to see often in the future. It is a significant development for it both reduces the cost and increases the availability of steel. Simple as it may seem, now that years of development have led to its perfection, it was not an easy process to develop. It required years of costly development on relatively large-scale equipment to attain its present stature.

In many ways, the use of tonnage oxygen in nonferrous metallurgy offers more potential advantages than for steelmaking. These have been amplified in Chapter 3. Much research and development must precede more widespread use of oxygen smelting, but the ultimate potential benefits seem clearly to justify the effort.

The Imperial Smelting zinc-lead blast furnace is another example of a new process which employs the chemistry of traditional metallurgy but incorporates a unique engineering development. In this case the novel feature is a shock-cooling condenser whose potential application to other metals has also been shown in Chapter 3.

The fluid-bed represents a novel engineering design for a gas-solid reactor. For roasting of sulfides in a fluid-bed we use the same chemical reactions that have been employed for hundreds of years. The advantages gained are improved heat and mass transfer rates which permit close control of temperature and gas composition, greater throughput, freedom from moving parts, and greater ease of materials handling.

We have only begun to make use of the full potential of the fluid bed. Its use is spreading from roasting to calcination, heat exchange, chlorination, and metal reduction. Most likely, the full potential of the fluid bed will only be realized when it is combined with novel chemistry that depends on precise control of temperature and gas composition—for selective sulfation, selective chlorination, and selective reduction.

A final example of novel engineering is Asarco's shaft furnace for melting copper cathodes. Judging from the rapid acceptance of the process it must have a decided economic advantage over conventional melting, blowing, and poling in a reverberatory furnace. The use of a shaft with countercurrent flow of metal and gases yields high mass and heat transfer rates and large throughput. The key to success, however, is precise control of combustion of gaseous fuel which permits control of oxygen transfer between metal and gas.

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The Asarco furnace is essentially a "packed tower" for countercurrent liquid-gas contact. Packed towers should find many more uses in the future of extractive metallurgy for such operations as poling of anode copper, retreatment of slags, and fire-refining of metals. The packed tower may do for liquid-gas reactions what the fluid bed is doing for solid-gas reactions: provide a means to increase rates and achieve superior control of process variables.

We now summarize briefly areas where it is believed engineering development will lead to improved processes: (a) use of tonnage oxygen—particularly in the nonferrous industries for sulfide smelting; (b) use of electrical energy in place of fossil fuels. The cost of electrical energy has steadily decreased relative to the cost of fossil fuels. Electrical heating permits closer control of temperature and of the furnace atmosphere, and much higher temperatures can be obtained and the problems of atmospheric pollution are minimized. In the extreme, the temperatures of plasmas might prove useful for some extractive processes; (c) use of high vacuum and inert gases; (d) increased application of the fluid bed for gas-solid reactions; (e) use of the packed tower for gas-liquid and liquid-liquid contacting; (f) development of shock-cooling devices for high temperature vapors; (g) development of efficient means for separation of solids from liquid metals by filtration or centrifugation. Many potential processes for metal extraction or refining would become practical if efficient solid-liquid separation at high temperature were possible.

Novel Chemistry

Similar opportunities exist in the application of what is now unconventional chemistry to metal production. In order to avoid making this report encyclopedic, a few of these promising approaches are listed without detailed discussion: (a) vapor-phase chemistry; (b) fused-salt chemistry; (c) plasma chemistry; (d) high temperature aqueous chemistry; (e) solvent extraction and chemistry of nonaqueous liquids; (f) use of HNO_3, HCl, and NH_3 in hydrometallurgy.

A PROGRAM TO ASSIST UNDERDEVELOPED NATIONS IN EXTRACTIVE METALLURGY EDUCATION AND DEVELOPMENT

Earlier sections of this report have shown that other highly industrialized nations have made heavy inroads on the position of leadership once held by the United States in extractive metallurgy. They have also shown that our present university education and research program is heavily weighted by foreign students. A major segment of

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these students are from more backward nations which do not pose a threat to our economy. Indeed, if the United States can establish a position of leadership in metallurgy for these nations it will in turn establish a favorable source of essential raw materials and an export market for related machinery and equipment. This section of the report proposes a plan for accomplishing this and at the same time strengthening our own educational facilities.

Probably the most important ingredient needed to permit an underdeveloped country to exploit the opportunities afforded by its mineral resources is a cadre of young men who have a good background in the applied sciences and technology pertinent to mineral engineering and process metallurgy. To provide these men with the requisite technical background it is necessary:

(a) To develop national or regional technical institutes with curricula in extractive metallurgy that are relevant to the modern technology and are pertinent to the needs of underdeveloped countries. The Indian Institute of Technology at Kanpur, India, is an example of a program which is moving to meet this need in India. The organization was started under the auspices of U.S. AID program by having college professors in technology and sciences from a consortium of American universities spend a year or two at Kanpur to help develop curricula and to get a competent academic program underway. The operation of the organization is being transferred to the Indian staff with continued American guidance.

(b) To have a few young nationals do graduate work in some of the technically advanced institutions of the United States. Where possible, they should also obtain 1 or 2 years of industrial experience. The program for doing this should be directed specifically to the needs of a man's home country. At all stages, it should be understood that he is expected to return to his native land when he has completed his program.

The problem of the loss of people who have a competence in extractive metallurgy from the underdeveloped countries to those that are technically advanced must be faced in the near future. There is a widening disparity in the technical competence of the two types of countries, and the loss tends to aggravate the difference.

If a young man obtains a portion of his technical education in the United States and he wishes to remain here to pursue his professional career rather than return home he would be permitted to do so. However, it would be stipulated in advance that he or the organization employing him, or both, should compensate the agencies in

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his country for the expense of his higher education. An alternative would be that the compensation would take the form of having someone with a related technical background from his new organization spend 3 or 4 years in technical work in the underdeveloped country.

Actually, the educational program for extractive metallurgy in American universities is now operating somewhat along the lines suggested, but in a very ineffective manner; without plan, direction, or adequate financial support. If a program with the characteristics suggested above were properly coordinated and implemented it would serve the double purpose of strengthening our own educational system and providing constructive assistance to underdeveloped countries.

If the United States is to undertake the development of an adequate exchange program in mineral engineering and process metallurgy with national or regional technical educational institutions in the underdeveloped areas, we must begin with a concerted program for the development of faculty in the field in our own colleges and universities. First, the number of our faculty who are productive in the field should be increased by at least 20 by raising the general support of academic research in the field. With this increase, there should also be an increase of approximately 60 graduate students. In addition, there should be developed an exchange program which will permit young faculty and technical people in industrial positions to trade responsibilities for periods of approximately a year at a time. The cost per unit (one faculty member and three graduate students) would be approximately $50,000 per year. Some funds for capital equipment would also be needed. An increase in support of the field to meet the needs of the program suggested would be approximately $1.50 million annually. (Funding of the institutions in foreign locations is not included in this figure.) Universities sharing in this program would be expected to arrange for members of their staff to spend a suitable amount of time, i.e., 1 man-year per 5 man-years of support, in the underdeveloped countries.

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CHAPTER

6

Conclusions and Recommendations

Improve the Educational Program in Extractive Metallurgy

In order to provide the immediate trained research and development manpower needs in the government, industrial, and academic areas in the field of extractive metallurgy it is recommended that:

- Congress designate budgetary support of at least $5 million per year for 10 years to implement the newly authorized function of the Bureau of Mines to contract research in extractive metallurgy.

- These funds should be concentrated in departments with an established and continuing record of performances and a demonstrated capacity for professional leadership.

- An additional sum of at least $1,500,000 per year should be directed to a coordinated program to provide educational support for backward nations which will improve their economy and provide the mineral raw materials for our national welfare.

- Other research-sponsoring agencies both within and outside of the federal sphere should be made aware of the critical importance of research in extractive metallurgy.

Improve Government Planning Procedures to Include Essential Support Technology

To this end it is recommended that:

- Related extractive metallurgy research should be included with each end-product program.

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- Public programs of conservation and environmental control should include and be coordinated with the raw material and process development requirements of the metal-producing industry.

Strengthen the Image and Stature of Extractive Metallurgy

In order to attract the quality and quantity of manpower required for national needs it is recommended that:

- All extractive metallurgy-oriented research which is now thinly and sporadically scattered through the various defense, space, welfare, commerce, etc., agencies of the government should be concentrated under and administered by the Assistant Secretary for Mineral Resources of the Department of the Interior, thus providing a strong center which will be generally recognized for its essential role.

- The cooperation of industry and education in solving public problems related to extractive metallurgy can be made effective by organization of joint projects by the Assistant Secretary for Mineral Resources.

- Industry and universities should independently arrange for mutually advantageous programs involving long-range research planning and exchange of personnel.

The Extractive Metallurgy Program of the Nation Must Be Continuously Effective in the Public Interest

To this end it is recommended that:

- The NSF should organize a civilian commission of high level professional personnel. The commission would hold regular meetings to establish policies governing research and educational programs in extractive metallurgy.

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Appendix

TABULATIONS FROM THE REPLIES TO THE QUESTIONNAIRE OF THE COMMITTEE ON MINERAL SCIENCE AND TECHNOLOGY

TABLE A-1 Upper-class* Undergraduate Enrollment, Fall 1967

Field	No. Depts. Reporting	Number of Students						Percent Total
		Total	Min.-Max.	Av. No.	Med. No.	Foreign	Percent Foreign	
Mining	21	392	2-120	19	12	13	3	13
Met. eng.	36	1,199	3-156	33	28	31	3	39
Cer. & cer. eng.	17	579	4-154	34	24	13	2	19
Petrol. eng.	13	412	8-73	31	29	74	19	12
Fuel sci.	3	20	1-11	7	8	7	35	1
Other MST	13	510	2-326	39	15	25	5	16
Totals	103	3,112				163	5	100

Number of institutions reporting = 54.

Average number of upper-class,* mineral science, and engineering undergraduates enrolled per institution = 57.

*That is, excluding freshmen and sophomores.

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TABLE A-2 Enrollment in M.S. Degree Programs, Fall 1967

		Number of Students						
Field	No. of M.S. Programs Reported	Total	Min.-Max.	Av. No.	Med. No.	Foreign	Percent Foreign	Percen Total
Mining	19	117	1-20	6	5	56	48	8
Ext. met.	25	140	1-18	6	4	58	41	9
Phys. met.	38	498	1-55	13	11	81	16	33
Nonmetallics	32	333	1-33	10	8	63	19	22
Petrol. eng.	15	210	1-45	15	6	85	41	14
Fuel sci.	5	29	1-16	6	4	16	55	2
Other MST	18	179	1-91	10	5	17	10	12
Totals	152	1,506				376	25	100

Number of institutions reporting M.S. degree programs in one or more of these fields = 59.

TABLE A-3 Enrollment in Ph.D. Degree Programs, Fall 1967

		Number of Students						
Field	No. of Ph.D. Programs Reported	Total	Min.-Max.	Av. No.	Med. No.	Foreign	Percent Foreign	Percer Total
Mining	9	67	1-17	7	5	33	49	5
Ext. met.	18	128	1-17	7	7	52	41	9
Phys. met..	30	424	1-78	14	11	78	18	31
Nonmetallics	31	513	1-81	17	10	80	16	37
Petrol. eng.	10	66	2-23	7	5	25	38	5
Fuel sci.	6	40	1-18	7	6	15	38	3
Other MST	15	143	1-40	10	6	25	17	10
Totals	119	1,381				308	22	100

Number of institutions reporting Ph.D. degree programs in one or more of these fields = 50.

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ABLE A-4 Total Graduate Enrollment, Fall 1967

	No. of Graduate Programs	Number of Students						
ield	Reported	Total	Min.-Max.	Av. No.	Med. No.	Foreign	Percent Foreign	Percent Total
ining	19	184	1-31	10	8	89	48	6
xt. met.	25	268	1-26	11	10	110	41	9
hys. met.	39	922	1-105	24	18	159	17	32
onmetallics	35	846	2-106	24	15	143	17	30
etrol. eng.	15	276	1-57	20	7	110	40	10
uel sci.	7	69	1-34	10	4	31	45	2
ther MST	19	322	1-131	17	8	42	13	11
otals	159	2,887		18		684	24	100

ABLE A-5 Number of Faculty and Other Professional Members of Staff, Fall 1967

		Regular Faculty (Professional Ranks)				
Field	No. of Depts. Reporting	Full Time	Part Time	Other Professional Personnel, Not Degree Candidates*	Total	Percent Total
Mining	21	81	21	2	104	10
Ext. met.	28	90	10	14	114	11
Phys. met.	44	228	31	55	314	31
Nonmetallics	35	206	13	56	275	27
Petrol. eng.	16	55	24	1	80	8
Fuel sci.	7	26	2	9	37	3
Other MST	21	76	16	9	101	10
Totals	172	762	117	146	1,025	100

Number of institutions reporting = 59.

*Such as visiting professors, postdoctoral fellows, etc.

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TABLE A-6 Support of Graduate Students by Fellowships, Assistantships, Traineeships, Fall 1967

		Number of Students						Financial Support of Students $ Thousands			
		Scholarships, Fellowships, Traineeships		Research Assistantships		Teaching Assistantships		Annual Support Over and Above Tuition		Annual Tuition Support	
Field	No. of Depts. Reporting	Total	Median	Total	Median	Total	Median	Total	Median	Total	Median
Mining	17	41	3	98	7	12	1	327	17	71	6
Ext. met.	18	99	4	152	4	29	1	799	25	208	4
Phys. met.	32	215	5	380	9	74	2	2,107	42	792	7
Nonmetallics	25	148	3	220	3	40	2	1,515	32	355	6
Petrol. eng.	11	28	2	47	4	17	3	229	15	26	3
Fuel sci.	9	40	3	34	1	3	1	241	10	58	3
Other MST	17	115	4	198	7	59	2	1,007	38	235	7
Totals	129	686		1,129		234		6,224		1,745	

Number of institutions reporting = 59.

TABLE A-7 Distribution by Fields—Annual Rate of Funding of University Graduate and Research Programs by Outside Agencies, Fall 1967

Field	No. of Depts. with Graduate-Research Programs Reporting	$ (Thousands)	Percent Total	Percent of Total less Phys. Met.
Mining	19	681	4	6
Ext. met.	25	1,744	10	16
Phys. met.	38	6,702	38	
Nonmetallics	32	4,735	27	44
Petrol. eng.	15	745	4	6.5
Fuel sci.	6	595	4	5.5
Other MST	18	2,324	13	22
Totals	153	17,526	100	100
Totals less Phys. met.	115	10,824		

Number of institutions reporting = 53.

Number of institutions reporting only physical metallurgy on this questionnaire = 2.

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TABLE A-8 Distribution by Fields and by Agencies—Annual Rate of Funding of University Graduate and Research Programs by Outside Agencies, Fall 1967 (Thousands of Dollars*)

Field	NSF	DOD	NASA	USBM	NDEA	AEC	Other Federal Agencies	Total Federal	State Agencies	Industry	Endow-ments & Other	Totals	Percent of Total
Mining	82	1	0	40	19	0	130	(272)	195	101	113	681	4
Ext. met.	234	75	2	138	41	26	90	(606)	222	775	141	1,744	10
Phys. met.	1,117	2,260	498	20	73	1,272	372	(5,612)	74	928	90	6,704	38
Nonmetallics	761	1,609	466	19	66	751	186	(3,858)	298	547	31	4,734	27
Petrol. eng.	5	0	22	10	6	140	162	(345)	109	245	46	745	4
Fuel sci.	156	39	27	35	0	0	87	(344)	89	157	5	595	4
Other MST	523	166	184	6	61	15	693	(1,648)	483	121	71	2,323	13
Totals	2,878	4,150	1,199	268	266	2,204	1,720	(12,685)	1,470	2,874	497	17,526	
Percent of Total	16	24	7	2	2	12	10	73	8	16	3		100
Total less Phys. met.	1,761	1,890	701	248	193	932	1,348	(7,073)	1,396	1,946	407	10,822	
Percent of Total	16	17	7	2	2	9	12	65	13	18	4		100

*Figures rounded off to nearest thousand.

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Mineral
Science
and
Technology

FUEL SCIENCE AND TECHNOLOGY

Report of the
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PANEL ON FUEL SCIENCE AND TECHNOLOGY

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Abstract

Minerals are absolutely essential to modern industrialized civilization. Rising populations coupled with demands for higher standards of living are resulting in greatly increasing requirements for minerals and mineral products.

Mineral economics is the study of supplies of and requirements for minerals and mineral products. Past and present data are used to make projections into the future, taking into account technological trends. Where possible, cost data are developed, looking to the ultimate calculation of profitability. Studies may cover individual mineral deposits, company operations, regional areas, national problems, or international matters. Along with purely technological considerations, studies consider such politicoeconomic matters as tariffs, taxes, regulations, and customs, both in the nation furnishing capital for development and in the host country where the mineral venture is planned.

Mineral economics studies are made by companies, consultants, banks, universities, foundations, one or more agencies in each of the 50 states, upwards of 30 major agencies in the U.S. Government, and many international and supranational agencies. Thus far only one university, The Pennsylvania State University, offers degree-granting programs in both undergraduate and graduate mineral economics.

Viewing the total effort in all quarters, the United States is a leader in mineral economics, but more must be done to meet future needs. Recommendations of the Panel for effective action to this end are presented in Chapter 4 of this report.

The Committee on Mineral Science and Technology reviewed this panel report and used some of the information therein in the preparation of its over-all committee report titled Mineral Science and Technology: Needs, Challenges, and Opportunities. The consultants to the Panel presented valuable information to assist in the Panel's deliberations. However, only the Panel members themselves are responsible for the statements in the complete panel report.

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CHAPTER 1

The Importance of Minerals to the World Economy

Man's progress toward higher standards of living, from the Stone Age to the present, is reflected by his usage of minerals. The aborigines of Australia—living relics of the Stone Age—use only a few pounds of stone per year for tools and weapons, and heat on cold nights is supplied by twig bonfires or the body warmth of their dogs. In contrast, for each of the 200 million U.S. citizens, our industry uses over 36,000 pounds of minerals and metals annually, a total of over 3.6 billion tons (detailed in Table 1).

U.S. use of energy, 56.968 × 10^{15} Btu's in 1966, is equivalent to the energy of over 12 horses working day and night for each U.S. citizen. Or, assuming a more reasonable 8-hour workday for a single horse, our annual energy use is equal to the combined output of over 7.2 billion horses! In 1966 mineral fuels provided 96.4 percent of this energy (petroleum, 39.6 percent; natural gas and natural gas liquids, 33.9 percent; coal, 22.8 percent; nuclear energy, 0.1 percent), while water power provided the remaining 3.6 percent.

Many minerals and metals serve mankind continuously for long periods of time. Some stone bridges and aqueducts have been in service for over 2,000 years. Railroads, pipelines, electrical networks, and other physical structures of modern civilization continue to contribute to the standards of living for many decades after they are once in place.

In the past decade or so the value of U.S. mineral production has dropped from 4 percent to about 3 percent of the U.S. gross national product. Figure 1, based on Table 2, demonstrates the close correlation between the value of U.S. mineral production and the gross national product. Of course, in addition to domestically produced minerals, the United States uses substantial quantities of imported

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TABLE 1 U.S. Consumption of Minerals and Metals in 1966, in Those Cases Where Over 1 Million Tons of Each Material Was Used

Sand and gravel	934	million short tons
Stone	811	
Petroleum	520	
Coal	497	
Natural gas	430	
Iron ore	135	
Cement	74	
Clays	55	
Salt	38	
Phosphate rock	27	
Lime	18	
Bauxite	14	
Gypsum	10	
Sulfur	9	
Potash	4	
Pumice	3	
Manganese	2	
Copper	2	
Sodium carbonate	2	
Chromite	1	
Barite	1	
Zinc	1	
Lead	1	
Total	3,589	million short tons, plus lesser quantities of many more materials of mineral origin

Source: U.S. Bureau of Mines.

minerals and metals, and thus the United States is involved in world mineral markets to a major degree. Indeed, the United States, with only 6 percent of the world's land area and only 6 percent of the world's population, uses much greater percentages of the world's mineral production. For example, U.S. 1966 consumption was the equivalent of the following percentages of total world mineral production: coal, 16 percent; petroleum, 25 percent; steel, 26 percent; copper, 35 percent; and aluminum, 53 percent (see Table 3). In a few cases, notably molybdenum and phosphates, the United States produces within its own borders sufficient minerals to meet domestic needs plus major exports. In the case of many large-bulk, low-cost items where handling and transportation costs are significant, the United States is self-sufficient and the marketplace matches produc-

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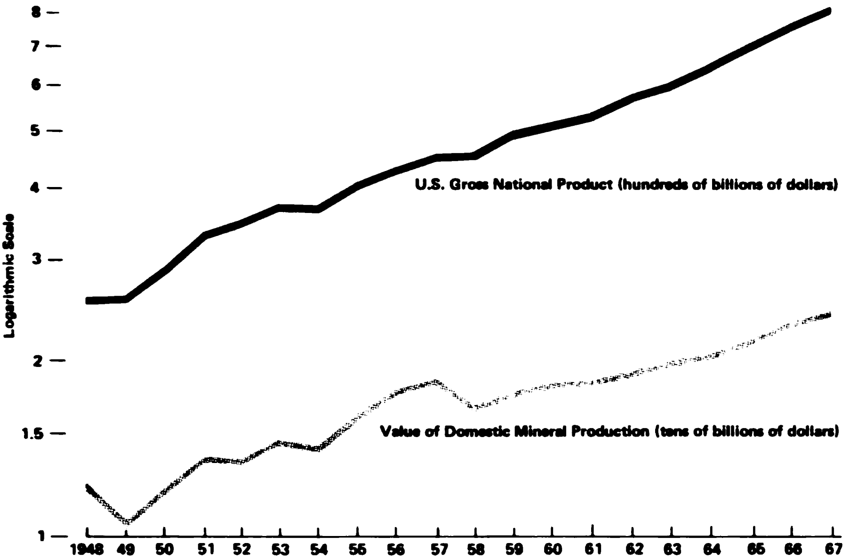

FIGURE 1 The U.S. gross national product and the value of domestic mineral production.

tion and demand, as in the case of sand, gravel, stone, coal, cement, and clay. In the case of many other minerals and metals the United States in peacetime imports some or all of its supplies. In recent years the United States has tended to depend more upon imports. Table 4 indicates that the net value of mineral imports over exports has tripled over the last decade, with 1966 imports valued at $6.7 billion compared to exports valued at $3.4 billion. Table 5 lists certain major commodities for which domestic production in 1966 supplied a smaller percentage of domestic consumption than in 1950.

In a complex and advanced economy such as that of the United States there is great flexibility and interchangeability in the choice of materials or fuels. Thus, the situation in the case of a single material cannot be judged in isolation. For example, common food containers may be "tin" cans, aluminum cans, glass jars and bottles, plastic containers, wood boxes and barrels, paper containers, or combinations of these materials. The ordinary home may be heated by an oil furnace, a gas furnace, a coal furnace, or electricity. The electricity in turn now is most likely to be derived from burning coal, gas, or oil at some other location, and in the future nuclear fuels should assume increasing significance. In peacetime the decision as to which material or fuel to use is dictated directly or indirectly by economic considerations.

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TABLE 2 The U.S. Gross National Product and the Value of U.S. Domestic Mineral Production in Billions of Dollars

	U.S. Total		Major Constituents of the Mineral Total:			
Year	Gross National Product	Minerals	Metals	Nonmetals	Coal and Lignite	Petroleum and Natural Gas
1948	257.6	12.3	1.2	1.6	3.0	6.0
1949	256.5	10.6	1.1	1.6	2.1	5.4
1950	284.8	11.9	1.4	1.8	2.5	5.8
1951	328.4	13.5	1.7	2.1	2.6	6.7
1952	345.5	13.4	1.6	2.2	2.3	6.9
1953	364.6	14.4	1.8	2.4	2.2	7.7
1954	364.8	14.2	1.5	2.7	1.8	7.9
1955	398.0	15.9	2.1	3.1	2.1	8.5
1956	419.2	17.5	2.4	3.4	2.4	9.1
1957	441.1	18.2	2.1	3.4	2.5	10.0
1958	447.3	16.6	1.6	3.5	2.0	9.4
1959	483.7	17.4	1.6	3.9	2.0	9.8
1960	503.7	18.0	2.0	3.9	1.9	10.0
1961	520.1	18.2	1.9	3.9	1.8	10.3
1962	560.3	18.8	1.9	4.1	1.9	10.7
1963	590.5	19.6	2.0	4.3	2.0	11.1
1964	631.7	20.5	2.3	4.6	2.2	11.2
1965	681.2	21.4	2.5	4.9	2.3	11.6
1966	739.5	22.9	2.6	5.2	2.4	12.5
1967	785 p*	23.8 p	2.3 p	5.2 p	2.6 p	13.5 p

*p = preliminary

Source: Council of Economic Advisers and U.S. Bureau of Mines.

Under a broad view of the world mineral supply and demand picture, nations can be divided into five major categories as follows:

1. Major industrialized nations that are almost wholly self-sufficient, a good present example being the U.S.S.R., where mineral self-sufficiency has been a major policy objective.
2. Major industrialized nations that produce the greater portion of their needed minerals and mineral products at home, but which at the same time also import important quantities to supplement inadequate domestic production, a good present example being the United States.
3. Major industrialized nations that rely heavily on imports, a good present example being Japan.
4. Underdeveloped nations that earn important revenues from mineral exports, a good present example being Saudi Arabia.

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5. A good number of underdeveloped nations that thus far contribute little or nothing to world mineral supplies.

The diversity among producers, exporters, and importers, the complexity of world mineral production, and the general rise in world production over the last decade or so, are shown in considerable detail in Appendix A.

TABLE 3 Portion of World Production of Basic Industrial Metals and Minerals Consumed by U.S.

Material	U.S. 1966 Use	World 1966 Production	Percentage of U.S. Use of World Production
Coal, including lignite	497,000,000 tons	3,137,459,000 tons	16
Steel production, ingots and castings	134,101,000 tons	524,700,000 tons	26
Petroleum	3,009,900,000 barrels	12,015,830,000 barrels	25
Copper, primary and old scrap	2,128,000 tons	6,073,000 tons	35
Aluminum, primary	4,002,000 tons	7,561,000 tons	53

Source: U.S. Bureau of Mines.

TABLE 4 Value of U.S. Imports and Exports of Minerals and Metals in Billions of Dollars

Year	Imports	Exports
1955	3.0	1.8
1956	3.4	2.4
1957	3.7	2.7
1958	3.2	1.7
1959	3.4	1.5
1960	3.4	2.0
1961	3.4	1.9
1962	3.6	2.2
1963	4.7	2.7
1964	5.4	3.2
1965	6.1	3.2
1966	6.7	3.4
1967	N.A.	N.A.

Source: U.S. Bureau of Mines.

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TABLE 5 Domestic Production of Certain Major Minerals and Metals Expressed as Percentage of Domestic Consumption

	1950 (%)	1966 (%)	Decline (%)
Aluminum	80	74	6
Barite	88	71	17
Bauxite	40	13	27
Fluorspar	71	24	47
Silver	39	18	21
Iron ore	92	67	25
Lead	35	26	9
Petroleum	91	81	10
Platinum	15	4	11
Zinc (slab)	64	41	23

Source: U.S. Bureau of Mines.

Looking ahead to the future, there is general agreement that world population, now over 3 billion, is likely to double within the next 40 years. A population increase of this magnitude will greatly increase worldwide demand for minerals. At the same time, superimposed on population growth are worldwide demands for higher standards of living, which can be realized only through greatly increased per capita consumption of minerals and fuels. For example, while the United States is using over 1,000 pounds of steel per person per year, India is using only 30 pounds. Clearly then, to raise substantially the standard of living in the many underdeveloped nations of the world will require quantities of minerals far in excess of present or planned productive capacity.

Wars impose special strains on the normal world mineral economy by increasing demand for many materials in armaments production and associated defense activity while also disrupting or completely cutting off traditional sources of mineral supplies. In World War I, World War II, and in the Korean war, U.S. national security production programs required: costly materials supply expansion programs, priorities for, and allocations of, materials, conservation orders, and end-use limitations involving materials, and price controls on materials and products. Nevertheless, despite these government actions, military production was often delayed or limited by materials shortages, and defense-supporting production was also restricted. Thus far (October 1968), production for the Vietnam war has not necessitated the imposition of drastic controls. However, the government has tried to hold down materials prices without direct

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controls, while at the same time assuring continuity of defense production, by a combination of defense "set-asides" of materials and stockpile sales.

The United States must be prepared for a variety of national security emergencies, including: massive nuclear attack upon the United States or her allies; conventional attack upon the United States or her allies; chemical, biological, or radiological warfare; long, drawn-out, peripheral wars of the Korean or Vietnamese type, with the possibility of two or more such wars going on at the same time; and persistent political and social unrest that undermines stability in important materials-producing nations and limits the flow of metals and minerals to the United States and to other free-world industrialized nations.

The need for having adequate supplies of materials for national security purposes has been recognized by many laws, including the National Security Act, the Defense Production Act, and the Stock Piling Act. Present stockpiles are intended primarily to meet the estimated deficit in foreseeable supplies for a 3-year conventional war period. These stockpiles, plus other supplies, are considered by the government generally adequate for nuclear war. A total of 77 materials, of which 63 are metals and minerals, are stockpiled. At the end of 1967, the stockpile totaled 47.5 million tons, valued at $6.6 billion, or about $33 per U.S. citizen. With respect to stockpile policy for 1968, President Johnson, in his February 1, 1968 "Economic Report" stated that some $3.3 billion worth of materials exceeded stockpile requirements, and that excesses should be disposed of in order to relieve taxpayers of the burden of carrying unneeded stocks while also providing industry with the materials necessary to assure continued high levels of production.

Most supplies of materials in an emergency are expected to come from ongoing productive capacity of the nation and nearby dependable sources. Hence, the necessity exists for maintenance of a domestic mineral and metal industry adequate to support continued growth of the economy and to serve as a mobilization base in time of emergency. Petroleum provides a major example where reliance is placed wholly on continuity of existing industry. The mandatory oil import controls that have been in effect since early 1959 have as their primary purpose the maintenance of an adequate mobilization base within the continental United States. Some other vital metals and minerals, such as iron ore, pig iron, and steel, are not stockpiled by the government at all.

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CHAPTER 2

Technological and Politicoeconomic Factors Affecting Mineral Supplies

Appendix A demonstrates clearly that world mineral supplies are irregularly distributed, following as they do the geology and topography of the earth. Until modern times, search for mineral deposits was confined to looking for surface outcroppings. Only in the last century have the scientific principles of economic geology been developed and then applied to exploration for hidden underground deposits or extensions of known deposits. Increasing scientific competence in the twentieth century has added a variety of tools and techniques that aid in the search for mineral deposits. Improved geophysical and geochemical methods of prospecting are now helping to uncover the secrets of the earth's crust and the shallower areas of the ocean basins. So far our deepest mines reach down only about 2 miles, and our deepest wells, about 5 miles. The development of deeper mining methods, deeper well-drilling, and feasible ocean mining should add importantly to world mineral supplies.

Also, in the past, production of minerals has come largely from deposits of higher grade. It is only in the twentieth century that mineral beneficiation, extractive metallurgy, and chemistry have made possible extensive treatment of low-grade disseminated deposits. Today, some low-grade ores or tailings of yesteryear prove to be valuable deposits, and this trend will continue into the future.

As increasing quantities of minerals are needed, new techniques are being developed to recover used materials once thrown away. The more valuable the material, the more attention is paid to its recovery and reuse. Gold and silver have been reclaimed and reused since the dawn of history. At present, reclaimed materials are sig-

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nificant supply supplements in the case of copper, tin, iron, lead, platinum, mercury, and many other minerals and metals. The development of more efficient reclaiming processes, for example, those currently under way in the case of old automobiles, should prove increasingly beneficial in the future.

If effective mineral exploration, extraction, and processing are to take place, the prospective commercial activity must yield a satisfactory profit under existing laws and institutions. In this respect mineral studies in no way differ from other pursuits and must take into account whatever constraints and obligations are imposed by the prevailing economic, social, and regulatory climate. There are, however, a number of specific factors that have for a long time shaped scope, conduct, and success of mineral ventures. Among these factors are: (1) permanent depletion of the resource provided; (2) high degree of uncertainty of exploration success; (3) unattractiveness and dangers of working conditions and surroundings, especially in developmental phases; (4) frequent conduct of activity in remote and isolated locations; (5) direct involvement of governments where land or subsurface is publicly owned; (6) more recently, spread of mineral activities, on a large scale, to less-developed countries and consequent concern for and attempts to promote health, education, and political as well as economic stability; (7) strategic importance of minerals in warfare, both historic and current; (8) importance of technology in widening the supply base.

Most, if not all of the following elements of current policy that affect mineral development either positively or negatively can be traced back to one or more of the eight characteristics noted above:

Taxation Minerals commonly receive special tax treatment, most of it designed to encourage exploration or production or both. The following two are most prominent: (1) provision for treating part of exploration costs as current expenses (rather than as depreciable investment), as is done for research (of which exploration is a variety), thus minimizing current tax liability and attracting venture capital that would not otherwise come forth; (2) provision for deducting from gross producing income a stipulated percentage, different for different minerals, to compensate for the deposit's depletion as production proceeds. Percentage depletion is the only means so far designed to treat the exhaustion of a wasting asset in relation to the tax treatment of depreciating a replaceable asset. Percentage deplection is firmly built into the cost structure of the mineral industries and modification in any direction would significantly affect the economic health of the mineral industries as well as affect the output and prices of mineral products.

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Foreign Trade Few minerals are not affected by tariffs or quotas. Because its products enter into so many activities, the mineral industry has long enjoyed some protection on its home ground, at least up to a substantial minimum level of production. Because many countries now can deliver minerals to U.S. ports at competitive costs, barriers to entry form a crucial part of the economic environment in which the U.S. mineral industry operates. The controversy over the exact point at which society's interest in low-cost minerals from whatever source should take precedence over the claim to protection of domestic industry will probably never subside. Protection finds strongest justification in concern for national security, but of late has also incorporated elements of a balance of payments approach, aid to distressed regions, and even concern over adequacy of future supply irrespective of national security. The degree of protection to be afforded the mineral industry against competition from abroad is thus a very important politicoeconomic factor influencing exploration and production.

Conservation Since minerals cannot be replenished, many states have instituted conservation measures. These generally prescribe maximum rates of production, such as in oil, or prohibit wasteful producing methods that would make it too costly or perhaps impossible at some later time to recover minerals not extracted in current operations. These measures are commonly drawn up in terms of combating physical rather than economic wastefulness; but this renders the economic consequences no less significant. It is often difficult, however, to judge whether such provisions have an encouraging or limiting effect on exploration and production. As in the case of taxation, substantial modification of existing regulations would be likely to alter the prevailing pattern of exploration and development.

Foreign Investment As it takes a number of years to bring a mineral deposit from geological concept to fruition in production, a continuity of government treatment is vital, both in the producing country and in the country that is the source of funds. Both the treatment of investments from the country providing the funds and the politicoeconomic environment in the resource country must be sufficiently stable to encourage the investment of funds in the risky business of mineral exploration and production if there is to be any meaningful development.

Environmental Effects Increased population density and mobility combined with rising incomes have pushed to the fore health and

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esthetic issues associated with minerals production, distribution, and consumption. What formerly was purely a concern about the hazards of employment in mines has been broadened to cover mineral activities in general, from acid mine effluents or uranium waste products to smokestack emissions and scrapped automobiles. Because of their comprehensive nature, the effects of pollution-regulating measures differ between different minerals, rewarding one and penalizing the other. Each mineral is faced with specific problems making generalization unfeasible, but there is nothing at present that would discourage production and use of minerals as a class of materials. Indeed, much progress has been made in pollution control and land rehabilitation in the mining of coal, phosphates, and sand and gravel for example, and plans for further improvement are under constant development.

Research and Development With the rapid expansion of man's knowledge and manipulation of his material environment, investment in geological and geophysical exploration and in research and development has become an important factor in mineral industry growth. The emergence of a viable nuclear power industry in only two decades, largely as a result of government research and development funding, has an important impact upon competing energy producers. Government and industry research designed to produce new classes of materials largely for space and military effort, is having important effects upon the use pattern of metals and minerals. Increased utilization of such items as petrochemicals, ceramics, titanium, new alloys, and new fibers reflects employment of the fruits of research. Industrial research is motivated by the urge or hope for greater profits. The important question posed is the goal of government research, including the allocation of funds between alternative approaches, and the effect on existing industries, including measures of relief during periods of rapid change caused by technological progress.

Price Policy The pervasive nature of minerals in the economy, both energy and nonenergy, has led to frequent government efforts to influence price movements of mineral products. Where such efforts make more difficult a rational price policy based on calculations of profitability commonly followed in industrial enterprises, government price policy can strongly influence an immediate increase or decrease in both exploration and production.

Control Schemes Attempts to modify the operation of the laws of supply and demand, other than as required for purposes of national security, are likely in the long run to prove self-defeating to the

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long term interests of those they are supposedly intended to benefit. Nevertheless, the world mineral industry has seen a variety of international control schemes that generally have as their objective realization of higher prices than would otherwise prevail.

Many agencies of the U.S. Government possess some authority to modify conditions under which the U.S. mineral industry and the international mineral industry operate. Appendix B lists these agencies and briefly identifies the fields of their authority with respect to mineral economics. Additionally, there are one or more agencies in each state with authority to modify the state climate under which minerals are produced. These state agencies are listed in Appendix C. However, the United States does not have a coordinated and unified national minerals policy. Instead, there is only the sum total of all the various laws, regulations, administrative decisions, and industry activities and policies that happen to be in effect at one time.

There is a tendency to welcome any factor or measure that encourages and to decry any that limits the growth of the mineral industry. In a private enterprise economy the government is not obligated to keep the output of any commodity from declining nor to keep any industry from experiencing losses or a decline in output. Policies, which include abstention from interference, should have as their general objective the provision of supplies at least cost to society, where cost is broadly conceived and reasonable allowance is made for a variety of national objectives, such as security, maximum promotion of competition, equitable allocation of economic resources, and promotion of new technology. In such a framework, encouragement of mineral resource development may be useful in one case and wasteful in another. Minds open to this insight are perhaps as important a factor in promoting the long-term welfare of the mineral industry as those cited above.

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CHAPTER 3

The Subject and Scope of Mineral Economics

GENERAL

Mineral economics consists of the application of appropriate economic theory and analysis to the mineral industry and the study of its role in industrial operations, local, national, and international. It encompasses the study of all economic aspects of minerals including those related to availability, production, processing, distribution, and utilization. It covers the activities of private firms and industries as well as the mineral-related activities of state and federal governments.

Mineral economics studies are made by government agencies for policymaking with regard to local and national resources, the national economy and national defense, for the guidance of research and other programs, and for activities directed toward national or regional development. Such studies are also made by private industry and associations for current management decisions, future planning, and policy formulation. In addition to these, universities, research organizations, and others engage in studies for the purposes both of expanding our fund of knowledge on mineral resources and their utilization and providing solutions to specific problems.

The most common types of mineral economics analyses deal with such items as economic aspects and trends of specific mineral commodities or groups of commodities, product mix, substitutes, transportation, efficiency, and prices. Such analyses commonly require large quantities of statistical data. Studies of the occurrence and economic potential of undeveloped regional or national resources are perhaps the second most common. At the individual company level, projects of more limited scope, such as the economic evaluation

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of mineral deposits and the analysis of specific markets for mineral products, frequently are undertaken.

Important among the outside factors considered are the economic effects of political and social developments including taxation, zoning, regulation of imports, and regulation of the production and use of minerals.

A number of other disciplines such as economic geology, geography, resource economics, and extractive engineering also are closely related to the field of mineral economics.

U.S. GOVERNMENT AGENCIES AND INTERNATIONAL AGENCIES

Many agencies of the federal government are involved in various aspects of mineral economics and resource studies covering metals, minerals, fuels, and water. Under many different laws these agencies have various authorities to modify the politicoeconomic circumstances surrounding mineral discovery, production, and use, not only in the United States, but also abroad (see Appendix B). Thus, while the Department of the Interior is commonly considered to be the focal point for mineral problems, there is a multiplicity of other agencies outside the Department of the Interior that must be considered. In fact, the total authority of these outside agencies is certainly greater than the authority vested solely in the Department of the Interior. Within the Department of the Interior itself, there are many important subdivisions (see Appendix B) that handle various portions of the Department's responsibilities. All of these agencies deal with the mineral industry in one way or another, some have standing industry advisory committees, some hold major hearings from time to time, some act on their own initiative by requesting information and making investigations. In view of the many agencies involved, there is much information pertinent to mineral economics scattered throughout the federal government, but much of this information is held by only one or more agencies on a confidential basis and is thus ordinarily unavailable to other agencies. When important issues arise, it is customary for the government to form interagency committees to pull together the information held in different places and to try to formulate coordinated government policies for handling major problems.

In addition to the agencies of the executive branch, several committees of the legislative branch (see Appendix B) are concerned with mineral economics. From time to time these committees hold extensive hearings on important topics of mineral economics with a view to enacting new legislation or modifying old legislation.

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Also listed in Appendix B are a number of international agencies with which the United States is involved that have direct interests in resource development. Inasmuch as resource development almost invariably involves minerals (even agricultural projects require water and fertilizers), these international agencies make studies involving mineral economics and sponsor projects designed to add to known world mineral resources.

STATE AGENCIES IN THE UNITED STATES

Of the 50 states of the Union, almost all have a geological survey, bureau of mines, department of mines and minerals, or a similar organization to which is assigned the responsibility for conducting research or other work related to the mineral resources and mineral-related activities of the state. Appendix C lists most of the agencies that are currently working in this field in the United States. In some states, responsibilities are shared by two agencies, and in others the organization has little or no staff other than the director himself. The largest state geological survey (Illinois) has a staff of more than 140 full-time employees.

Mineral economics activities of the state agencies range from the accumulation and publication of statistics on mineral production to detailed studies of the mineral industries and the numerous factors that affect their economic position and well-being. Only a few of the agencies have staff members whose full time is devoted to mineral economics work extending beyond the compilation of statistical data. In most organizations, whatever other economics work is done is performed by geologists or engineers who devote only a portion of their time to such activities.

Activities and projects of state agencies that might be considered in the broad category of mineral economics are listed below:

Annual Reports of Statistics Most states prepare or participate in the preparation of an annual report of production of minerals within their boundaries. Examination of Volume III of the U.S. Bureau of Mines "Minerals Yearbook" shows that all but seven of the state reports are prepared under a cooperative agreement between the Bureau and the state involved. In addition, some state geological surveys issue their own annual reports of mineral production. State departments of mines and minerals in most of the coal mining states issue annual reports giving details of individual mines including location, production, employment, identification and thickness of coal bed mined, and other items.

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State or Regional Studies of Mineral Resources and the Production, Utilization, and Economic Aspects of These Resources A number of the state agencies undertake regional studies in which the mineral resources are identified, the production and uses are given, and economic factors influencing the potential use of these minerals are discussed.

State Directories of Mineral Producers and Operations Some state geological surveys issue directories of producers operating within the state. Within these directories the producers customarily are listed by commodity. The annual reports of the departments of mines discussed above also are, in effect, directories.

Studies of the Effects of Urbanization on the Demand for and Availability of Resources States are becoming increasingly aware of the fact that deposits of minerals near population centers are being made unavailable as sources of material. This is occurring to an increasing degree, not through depletion, but through zoning restrictions or through being covered by urbanization. A few of the state agencies have studied and prepared reports on this problem.

Analysis and Forecasting of Trends These studies include trends in production or consumption and the projection of these trends into the future. Analysis is made to determine factors influencing past and future trends and their probable effect on the state or regional mineral industry.

Reports on Aspects of Production, Processing, Distribution, or Utilization Having Special Economic Significance This type of study usually is concerned with economic aspects of a specific commodity or industry. It may involve such things as the potential effects of a new process on the marketability of a mineral, various factors influencing productivity, or changes resulting from new transportation methods.

Studies of the Trends in Competition Between Sources and Types of Minerals, Especially as Regards Substitution Studies on the interchangeability of fuels and trends in their competitive positions are examples of this type of study. Another example is analysis of the effects of new forms of transportation on the delivered cost of materials and hence on their competitive position.

Ore Reserve Evaluation Activities In some states an agency is involved in the evaluation of ore reserves for tax or royalty purposes.

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Preparation of Handbooks for Producers and Prospectors These handbooks, prepared by state agencies in some of the less populated regions of the nation provide economic information as well as technical data.

Promotion Preparation of information designed to promote the economic interests of the state by proper listing of mineral resources available.

While each of the above types of activities is performed by one or more state agencies within the United States, no one agency of any state undertakes them all. The principal mineral economics activity of most state agencies is the preparation of production statistics, and in the majority of the states this is the only activity. Second most common is preparation of reports of mineral resources in a given area that may have special economic significance. Mineral industry directories are produced by several states. In perhaps 10 percent of the states, studies in addition to these three types are undertaken.

UNIVERSITIES IN THE UNITED STATES

At the present time there is only one university that offers an undergraduate degree in mineral economics, The Pennsylvania State University. There are a few universities at which undergraduate courses in mineral economics are given, but these courses are not sufficient in number or so integrated in scope that a bachelor's degree in mineral economics can be offered. These courses are given by such schools as Illinois, MIT, Colorado School of Mines, Stanford, Minnesota, and California at Berkeley. Although Penn State is the only university with a department of mineral economics offering graduate work in that field, several others do grant (or have granted) the M.S. and Ph.D. degrees in mineral economics. These include Cornell, Illinois, and Minnesota.

The economics departments of several universities have, in recent years, granted degrees in economics for work that is usually categorized as natural resource economics but that actually is not greatly different from mineral economics as carried out at Penn State. Probably all major universities with departments of economics turn out an occasional M.S. or Ph.D. degree, the thesis for which is a study in mineral economics. Such theses are characteristically strong in economics, but they may not adequately reflect an understanding of the technical problems faced by the mineral industries. This, in turn, leads on occasion to errors in the application of economic principles

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to mineral problems, errors that could have been avoided had the graduate program in question placed essentially equal stress on the technological aspects of the problems being studied. Nevertheless, the number and depth of the mineral industries problems being studied in economics departments has been increasing impressively over the last few years with some fine work being done at MIT, Minnesota, Colorado, Denver, and Stanford. Resources for the Future is a foundation which sponsors research work at qualified institutions, thus aiding in both the conduct of research and the training of graduate students in the field of mineral economics.

Few entering students at Penn State have heard of mineral economics; the Department of Mineral Economics seldom has more than one freshman in any given fall term. However, the department graduates an average of 10 B.S. students a year because many transfer into the curriculum from other fields of study. The majority of these transfers come from the various engineering curricula, but some come from the earth sciences. The average transfer student has completed about 2 years of work in an engineering discipline and has decided that his talents and interests do not lie in the plant operation or research aspects of industry but, instead, in the management side of the business. His engineering and science training provides ability to understand the technical problems of the mineral industry in which he decides to work, and his mathematical background enables him readily to understand and use the mathematical tools of economic analysis and decision making that are so important in today's world of business. Appendix D lists the course requirements for a B.S. degree in mineral economics at Penn State. There is no standard textbook in mineral economics, the closest approach to a textbook being the 787-page volume "Economics of the Mineral Industries," published by the AIME, 2nd edition, 1964. An updated version is currently being prepared.

The typical graduate student in mineral economics at Penn State holds a B.S. degree in mining or petroleum engineering, metallurgy, or geology; he has had 2 to 5 years of experience in industry; and he has decided that he wants to concentrate his efforts in management. Most of the men who receive the M.S. or Ph.D. degree in mineral economics go back into industry where they occupy positions in corporate planning departments or in the intermediate levels of management.

Since Penn State receives more requests for its mineral economics graduates than it can fill, it would seem that not enough students are being trained to look for solutions to the increasingly complex politicoeconomic problems of the mineral industries. Until programs of undergraduate and graduate training in mineral economics

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are made available at a considerable number of schools, firms in the mineral industries will have to hire economists and train them in the technical aspects of their industry or will have to train their technical people in economics.

FOUNDATIONS

The program in mineral and energy economics at Resources for the Future is the only sustained foundation input in this area. The National Bureau of Economics Research has not financed research in mineral economics since its 1941 publication of a study of output, employment, and productivity in mining. The Brookings Institution in the early 1960's sponsored research in mineral taxation problems, as part of its general program in the economics of taxation. Individual fellowships may be awarded by a foundation to someone focusing on a problem in mineral economics. But such efforts are not part of a programmed approach, valuable as they may be in illuminating segments of the scene. Other organizations, such as the Denver Research Institute or the Colorado School of Mines Research Foundation form an integral part of universities and are outside the scope of this section.

At Resources for the Future, research is conducted by a small resident staff that has in the past ranged from three to five professionals and by making grants in support of research elsewhere, most commonly at universities. To the degree to which they merit publication, research results are made available in book or pamphlet form. Some studies have been comprehensive, covering all resources, or all forms of energy, while others have been limited to a specific industry, or to a particular problem. Publications since 1960 that are devoted only to minerals are listed in Appendix E. Many studies are currently under way covering fossil fuels, nuclear power, and various metals and minerals.

Annual expenditures directly attributable to Resources for the Future's energy and mineral program are in the vicinity of $200,000 (excluding administrative and publication costs, but including both resident and grant-supported research). Under the doctoral fellowship program, initiated in 1961, 10 to 12 fellowships are awarded annually to Ph.D. candidates specializing in such fields as natural resources economics or administration to assist them during the period of their dissertation work. During the period 1961 to 1967, 16 of 74 fellows had an aspect of mineral economics as their thesis subject, ranging from the economics of the sulfur industry to investment planning in nuclear energy. This program both stimulates

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interest in mineral economics and brings successful scholars to the attention of organizations that are potential users of their talents.

CONTRACT RESEARCH AND MANAGEMENT CONSULTING ORGANIZATIONS

Work heavily involved with mineral economics has been done on a substantial scale for many years by contract research organizations, and in the past decade such work has been increasing at an accelerated pace. This work is done largely for individual companies, groups of companies, or trade associations, but a considerable amount is also done for government. Firms of consulting management engineers also conduct similar studies. The "Directory of Membership and Services" published by the Association of Consulting Management Engineers, Inc., lists many firms engaged in this type of work.

Contract studies generally involve considerations of the past and present supply and demand picture for one or more minerals or metals and usually include projections into the future for a period of from 5 to 25 years. Studies are usually heavily weighted on the demand side with projected present and potential new uses and markets. They include considerations of industry structure and competition within the industry, extent and effects of various degrees of integration, prices and costs, and sales methods and practices. The present and future competitive situation with other materials is also considered, along with the impacts of relative price changes involving the various competitive materials under study.

Studies of this nature for individual companies are commonly concerned with interests in diversification—analyzing the attractiveness of expanding a company's activities into fields that are relatively new to it. A study may involve a single metal or mineral, or it may consider a substantial number in which case the work covers a screening and rating procedure as to their relative attractiveness for a company with given interests, capabilities, and capital. Studies of this nature have covered, in varying depths, virtually every metal on the periodic chart, along with large numbers of industrial minerals such as sulfur, potash, phosphate, salt, talc, titanium dioxide, minerals for refractories, and industrial diamonds.

Mineral economics studies may be only a portion of much larger regional economic studies, in which minerals are but one of a group of many resources studied in a region. In such studies consideration of the need for improved transportation facilities, increased availability of power, industrial water supplies, and other factors are integrated.

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Costs of individual projects vary with the breadth and depth of coverage desired but generally fall within the range of $5,000 to $25,000 covering a period of 2 to 6 months. Large group research projects generally cover a period of 1 to 2 years or more and cost from $100,000 to upwards of $500,000.

Personnel handling such studies on mineral economics generally have a background of education in some field of science or engineering closely related to minerals (geology, mining, metallurgy, or chemistry) plus education or experience in economics, marketing, or business administration, with emphasis on experience in uses and marketing of metals and minerals.

PROFESSIONAL SOCIETIES, TRADE ASSOCIATIONS, AND TRADE PUBLICATIONS

Masses of important data on various economic aspects of metals and minerals are developed or assembled and published by professional societies, trade associations, and trade publications. This information runs the entire gamut from data on production (ores, metals, mill products, fuels and products, industrial minerals, and intermediate or final products of use), consumption (intermediate or end-use patterns), prices, international trade, discoveries, company and industry tax and financial data, and business or economic news in general. Many of these data may originate from government sources, but large quantities are developed independently by the organizations themselves. Although much of this work is purely of a clerical or statistical nature, personnel trained or experienced in the economics of the particular minerals involved must plan and supervise the work and actually conduct much of it. Information releases range daily to weekly, monthly, or annually. Professional societies and trade associations also contribute heavily to mineral economics by organizing national, regional, or local meetings for presentation of papers concerned with various aspects of mineral economics, many of which are published. The main professional society concerned with mineral economics is the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME), which has as one of its constituent bodies the Council of Economics. A representative listing of professional societies and trade associations is included in Appendix F, while Appendix G lists many frequently consulted publications in the English language, showing the extensive nature of the literature in this field. The number of publications and the growing number of technical societies make it clear that traditional methods of communicating scientific information need to be updated and streamlined.

Finally, it should be pointed out that many trade associations con-

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tract with outside organizations, research foundations, management consulting firms, and consultants for special studies heavily involved with economics of metals, minerals, and fuels. This has been done quite frequently by the American Petroleum Institute, American Gas Association, American Iron and Steel Institute, Copper Development Association, Institute of Scrap Iron and Steel, and others.

COMPANIES IN THE MINERAL INDUSTRY

Studies involving metal and mineral economics, including fuels, are performed by all companies engaged in the production, processing, and/or sale of these materials. However, there are great differences in the breadth and depth to which such studies are carried, and in the type of personnel conducting the work.

Only a small proportion of companies in the mineral industry (petroleum excepted) have a division strictly identified as "economics." However, economists or mineral economists are involved in a wide range of activities running the gamut from exploration, development, production, purchasing, marketing, market research, finance, and company planning. Company officials, from the very top to the lower echelons, must deal constantly with problems of mineral economics to various degrees in the efficient conduct of their work. Moreover, many of the working staff members must be familiar with the economic aspects of various phases of their work: the exploration geologists reporting on the advisability of purchasing a new ore deposit or bringing one into production as a result of their own exploration; mining or petroleum engineers estimating production costs; market research analysts figuring future sales opportunities in competition with other suppliers of the same mineral or with suppliers of other competitive materials; and many others in different company activities, all performing functions that relate in varying degrees directly to mineral economics.

Oil and gas companies generally have been more heavily engaged in studies relating to the economics of their products and industry than are metals and industrial minerals companies. In this report they share in the more progressive strides made by the chemicals industry, with its growing interests in economics, especially relating to market studies. This is reflected in the heavy and increasing membership and activities in marketing and economic aspects of various professional societies of the chemical industry. However, there are and have been exceptions in metals and in industrial minerals companies for many years; and it can also be said that interest and action in improving this past-neglected field is being

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shown by more and more companies in the minerals and metal fields. Moreover, in the past such companies have benefited from economic studies either performed by or contracted with outside organizations by the trade associations representing the companies. Also, it has been common practice for such companies to contract directly with outside contract research or management consulting firms or individuals for economic studies pertaining either to their own products or processes or to new fields or diversification under consideration. This trend, too, appears to be advancing at an accelerating pace.

COMMERCIAL BANKS

Another important broad field of business in which studies involving mineral economics are pursued with varying intensity is commercial banking and investment services. Large companies in these businesses commonly have staffs of engineers and economists who specialize in the technological-economic aspects of minerals, metals, and fuels from production and processing to markets, in analyzing and appraising loan and investment potentials for specific undertakings in the United States and throughout the world.

In view of the extensive and diversified literature in the field of mineral economics, and in view of the efforts under way in this field in so many different quarters, as described above, it is apparent that the United States has a commanding position in the world. However, the accelerating demands for minerals and the increasing tempo of modern industrial and economic activity leave little room for complacency; and more must be done along the lines of the recommendations in Chapter 4.

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CHAPTER 4

Recommendations

Mineral economics provides quantitative information frequently reduced to the most useful common denominators of cost and profitability. Reliable information must be the foundation for union, company, local, regional, state, national, international, and supranational planning and decision making. Minerals and their products pervade every industrialized economy, and the increasing complexity of all economics requires integrated and comprehensive bodies of knowledge as well as specialists in their interpretation and application. Mineral economics now provides much valuable information and a small, but growing, number of such specialists. But, in view of a generally rising demand for minerals, throughout the world, there is much that must be done now if mineral economics and the mineral industries are to make maximum contributions toward meeting the needs of the years ahead. Hence, the Panel on Mineral Economics recommends:

- That government decisions and programs be formulated only after adequate study and interagency and industry consultation so that a sound and integrated national mineral policy is developed.

- That national security related programs (i.e., stockpile programs, oil and other import regulations, active and standby supply expansion programs, current and standby conservation programs, and others) be frequently reviewed to insure that the United States maintains a sufficiently large and flexible mobilization base to meet the uncertainties of any emergency.

- That in the formulation of national economic or security measures, government agencies give careful consideration to the important role of foreign mineral operations.

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- That continuous and quantitative cost-benefit analyses be made in assessing alternative routes to environmental enhancement.

- That the Assistant Secretary for Minerals in the Department of the Interior be designated as the primary point of contact for interagency and industry consultation on matters of national mineral policy.

- That the Bureau of Mines expand collection of domestic and foreign mineral economics information, and that it expand dissemination thereof through timely abstracting and through expansion of the statistical and supporting textual material in the "Minerals Yearbook" series.

- That the Department of State increase its use of minerals attachés.

- That the government agencies, professional societies, trade associations and publications, and individual companies all exert more effort to collect, publish, disseminate, and analyze detailed statistical data relative to the mineral industries, including costs, profits, reserves, production, distribution, secondary recovery, and ultimate mineral consumption in end-items.

- That the Public Land Law Review Commission give full consideration to the contributions that modern science and technology can make toward the fuller understanding of our nation's mineral resources.

- That research in mineral economics be expanded and supported in a degree commensurate with needed expansion of other components of mineral science and technology.

- That the formal education of people being trained for responsible positions in or connected with the mineral industry include one or more broad courses in mineral economics.

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APPENDIX A The Changing Pattern of World Mineral Production, Exports, and Imports

Producer	1953–57	1961–65	Exporter	1953–57	1961–65	Importer	1953–57	1961–65
BAUXITE, millions of long tons, 5-year totals[a]								
Jamaica	13.6	40.1	Jamaica	13.0	28.8	U.S.	27.0	57.6
U.S.S.R.	9.1	21.5	Surinam	17.0	18.2	Canada	11.0	11.2
Surinam	16.4	18.2	Greece	3.0	5.2	Japan	2.0	7.0
Guyana	11.7	12.9	Guyana	9.0	7.9	W. Germany	6.0	7.7
France	7.0	11.4	Dominican Rep.		4.7	U.S.S.R.	5.0	2.1
Rep. of Guinea	2.0	8.3	Yugoslavia	3.0	3.8	U.K.	2.0	2.0
U.S.	8.5	7.4	Hungary		3.4	Italy	1.0	1.8
Hungary	5.6	7.1	Indonesia		3.0			
Yugoslavia	3.7	6.6	Malaya		2.7			
Greece	2.7	6.0	Haiti		2.1			
Dominican Rep.		3.9	Ghana		1.2			
India	0.4	2.9	Australia		1.2			
Indonesia	1.1	2.7	France	2.0	1.1			
Malaya	1.1	2.5	U.S.		1.1			
Haiti	0.3	1.7						
ALUMINUM, millions of short tons, 5-year totals								
U.S.	7.6	11.6	Canada	2.2	1.5	U.S.	1.0	1.7
U.S.S.R.	2.2	5.5	Norway	0.3	1.0	U.K.	1.1	1.4
Canada	2.9	3.8	U.S.	0.1	0.8	W. Germany	0.3	0.7
France	0.7	1.7	U.S.S.R.	0.2	0.7	Belgium	0.1	0.5
Norway	0.4	1.2	France	0.1	0.2	Sweden	0.1	0.1
Japan	0.3	1.2	Austria	0.1	0.2			
W. Germany	0.7	1.1						
China (mainland)	0.6	0.6						

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APPENDIX A (continued)

Producer	1953–57	1961–65	Exporter	1953–57	1961–65	Importer	1953–57	1961–65
CHROMITE, millions of short tons, 5-year totals[b]								
U.S.S.R.	3.8	6.6	Rep. of S. Africa	2.6	3.5	U.S.	9.0	6.2
Rep. of S. Africa	3.5	4.8	U.S.S.R.	0.6	2.8	Japan	0.5	1.5
Philippines	3.3	2.9	Philippines	2.6	2.6	W. Germany	0.9	1.2
S. Rhodesia	2.5	2.6	S. Rhodesia	2.2	2.2	U.K.	0.8	1.0
Turkey	4.3	2.4	Turkey	2.8	1.7	France	0.5	0.9
Albania	0.7	1.5	Albania		1.3	Sweden		0.6
Iran	0.2	0.6	Iran		0.5	Poland		0.5
Yugoslavia	0.7	0.5				Norway		0.4
						Italy		0.4
						Austria	0.4	0.3
COAL, millions of short tons, 5-year totals[c]								
U.S.	2,293.0	2,494.2*	U.S.	253.3	241.3	Canada	94.0	74.0
U.S.S.R.	2,150.6	3,051.5*	W. Germany	111.8	84.6	W. Germany	78.4	39.6
U.K.	1,249.3	1,062.8*	Poland	105.0	106.8	France	67.0	69.3
W. Germany	886.7	1,329.4†	U.K.	56.4	28.1	Italy	51.3	59.1
China (mainland)	522.7	1,585.0*	Belgium-Luxembourg	25.7	9.8	The Netherlands	36.9	46.2
Poland	464.5	743.8*	France	15.3	5.3	U.K.	23.6	0.4
France	274.3	295.1*	U.S.S.R.	14.4	120.3	Japan	21.6	80.3
Japan	230.0	288.9*	India	9.3	n.a.	Belgium-Luxembourg	20.9	36.7
India	197.0	372.0*	Czechoslovakia	8.8	n.a.	Austria	20.4	n.a.
S. Africa	157.7	248.1*				Denmark	20.0	n.a.
Belgium-Luxembourg	147.9	111.6*				Czechoslovakia	13.6	n.a.
Czechoslovakia	111.7	554.9‡				U.S.S.R.		30.7
Australia	98.2	267.2*						
E. Germany	1,088.2	1,401.0*						

COPPER CONCENTRATES, millions of short tons of contained copper, 5-year totals[u]

U.S.	5.0	6.2	Canada	0.2	0.4	Japan	0.2	2.7
U.S.S.R.	2.0	3.7	Philippines	0.1	0.4*	W. Germany	0.3	0.7
Zambia	2.2	3.4	Cyprus	0.2	0.2*	Sweden		0.3
Chile	2.4	3.3	Chile		0.1	U.S.	0.5	0.2
Canada	1.6	2.4	Australia		0.1			
Congo	1.3	1.6	Peru		0.1			
Peru	0.2	1.0	Norway		0.1			
Japan	0.4	0.6						

*Estimate based on 30 percent copper content.

COPPER METAL, millions of short tons, 5-year totals

U.S.	5.5	6.6	Zambia	1.9	3.1	U.K.	2.0	2.1
U.S.S.R.	2.0	3.7	Chile	1.9	2.6	W. Germany	1.0	2.1
Zambia	2.1	3.3	U.S.	1.0	1.6	U.S.	2.2	2.1
Chile	2.2	3.1	Belgium	0.6*	1.2	Belgium	0.9*	1.5
Canada	1.4	2.0	Canada	0.7	1.0	France	0.8	1.2
W. Germany	1.3†	1.8†	Congo	1.2	0.9	Italy	0.5	1.0
Congo	1.3	1.6	W. Germany	0.2	0.4	Sweden	0.2	0.3
Japan	0.5	1.4	U.K.	0.2	0.3			
Peru	0.2	0.9	Australia		0.1			
China	0.1	0.6						

*Belgium-Luxembourg.

†Includes scrap.

IRON ORE, millions of long tons, 5-year totals[e]

U.S.S.R.	353	671	Canada	60	122	U.S.	116	180
U.S.	503	389	France	63	114	W. Germany	70	157
France	243	306	Sweden	77	107	Japan	32	137
China (mainland)	43	173	U.S.S.R.	40 ±5	101	Belgium	63*	107

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APPENDIX A (continued)

Producer	1953–57	1961–65	Exporter	1953–57	1961–65	Importer	1953–57	1961–65
Canada	67	139	Venezuela	43	71	U.K.	67	80
Sweden	87	124	India		51	Czechslovakia	8	44
India	33	100	Brazil	12	44	Poland	6	42
U.K.	81	78	Liberia		40	Italy	5	26
Venezuela	42	71	Chile	11	40	Canada	19	24
W. Germany	80	70	Malaya		32	France		15
Brazil	19	66	U.S.	23	32	The Netherlands	6	14
Liberia	8	39	Peru	11	28	Romania	6	10
			Algeria	15	13			
			Spain	12	11			
			Sierra Leone		10			
			Philippines		7			
			Norway		6			

*Belgium-Luxembourg.

LEAD CONCENTRATES, millions of short tons of contained lead, 5-year totals[f]

Producer	1953–57	1961–65	Exporter	1953–57	1961–65	Importer	1953–57	1961–65
Australia	1.6	2.0	Morocco	0.3	0.6	Belgium	0.6*	0.7
U.S.S.R.	1.3	2.0	Australia	0.2	0.4	W. Germany	0.4	0.6
U.S.	1.7	1.3	Peru	0.3	0.4	U.S.	0.8	0.6
Canada	1.0	1.1	Canada	0.2	0.3	France	0.5	0.6
Mexico	1.2	1.0	S.W. Africa		0.3	Japan	0.1	0.3
Peru	0.7	0.8	Sweden		0.2	U.K.		0.1
Yugoslavia	0.5	0.6	Bolivia	0.1	0.1			
China (mainland)	0.2	0.5	Algeria		0.1			
Bulgaria	0.3	0.5	Greece		0.1			
Morocco	0.5	0.4	Honduras		0.1			

U.S.	2.5	2.1	Canada	0.4	1.3	U.S.	1.4	1.1
U.S.S.R.	1.3	2.0	Australia	0.9	1.1	U.K.	0.9	1.0
Australia	1.3	1.5	Mexico	0.9	0.6	W. Germany	0.3	0.5
Mexico	1.1	1.0	U.S.S.R.		0.5	Japan	0.1	0.2
Canada	0.8	0.8	Peru	0.3	0.4	U.S.S.R.		0.2
W. Germany	0.6	0.6	Belgium	0.3*	0.3	The Netherlands	0.2	0.2
Yugoslavia	0.4	0.6	Yugoslavia	0.2	0.3			
Belgium	0.5*	0.5	Sweden		0.2			
Japan		0.5	U.K.		0.2			
China (mainland)		0.5	W. Germany	0.2	0.1			
France	0.4	0.4	Morocco	0.1	0.1			
Peru	0.3	0.4	Spain	0.1	0.1			
Spain	0.3	0.4	Tunisia	0.1	0.1			
Bulgaria		0.3	Burma		0.1			
			Zambia		0.1			

*Belgium-Luxembourg.

MANGANESE ORE, millions of short tons, 5-year totals[g]

U.S.S.R.	26.5	37.4	U.S.S.R.	2.9	4.8	U.S.	11.1	12.0
Rep. of S. Africa	3.9	7.8	Rep. of S. Africa	2.4	4.4	France	3.0	3.7
India	10.1	7.7	India	7.2	3.8	W. Germany	1.8	2.9
Brazil	2.0	6.6	Brazil	1.5	3.3	U.K.	2.4	2.1
China (mainland)	2.1	5.1	Gabon		2.7	Japan	0.9	1.6
Gabon		3.4	Ghana	3.1	2.3	Norway	1.0	1.6
Ghana	3.4	2.5	Morocco	1.9	1.8	Poland		1.6
Morocco	2.4	2.3	Congo	1.4	1.6	Belgium	0.5*	1.3
Japan	1.2	1.6	Guyana		0.9	Italy	0.5	0.6
			Egypt		0.9			
			Mexico		0.6			
			Ivory Coast		0.6			

*Belgium-Luxembourg.

Producer	1953–57	1961–65	Exporter	1953–57	1961–65	Importer	1953–57	1961–65
MERCURY, thousands of metric tons, 5-year totals[h]								
Spain	7.8	11.1	Italy	8.6	10.6	U.S.	9.2	5.4
Italy	9.8	9.6	Spain	7.1	10.6	Japan	1.3	5.1
U.S.S.R.	2.9	5.9	Mexico	3.6	3.5	W. Germany	2.8	4.3
China (mainland)	2.1	4.5	Yugoslavia	1.8	2.1	U.K.	3.4	3.6
U.S.	4.2	3.8	U.S.S.R.	0.8	2.0	France	1.8	2.6
Mexico	3.3	2.9				Canada	0.9	1.7
Yugoslavia	2.4	2.8				S. Korea		1.6
						Poland		1.1
						India		1.0
						The Netherlands		0.7
						Sweden	0.4	0.5
						Brazil		0.5
						Belgium		0.4
						Australia		0.4
NICKEL CONCENTRATES AND MATTE, hundreds of thousands of short tons of contained nickel, 5-year totals[i]								
Canada	8.5	11.8	Canada	3.3	4.0	Japan	0.5	2.5*
U.S.S.R.	2.4	4.4	New Caledonia	1.0	2.5*	U.K.	1.4	0.3
New Caledonia	1.0	2.3				Norway	1.0	0.3
Cuba	0.8	0.9				France	0.3	0.1
U.S.	0.2	0.6						

*Estimate

Producer	1953–57	1961–65	Exporter	1953–57	1961–65	Importer	1953–57	1961–65
NICKEL METAL, hundreds of thousands of short tons, 5-year totals								
Canada	4.7	11.8	Canada	4.4	5.6	U.S.*	4.5	5.2
U.S.S.R.	2.3	4.4	Norway	0.9	1.4	W. Germany	0.7	1.0

						France	0.2	0.3

*Includes scrap.

CRUDE PETROLEUM, millions of short tons, 5-year totals[j]

U.S.	1,841.4	2,033.9	Venezuela	431.4	571.6	U.S.	214.2	328.8
Venezuela	581.3	834.4	Kuwait	246.6	430.3	Netherlands W.I.	207.4	197.3
U.S.S.R.	359.1	1,008.8	Saudi Arabia	180.0	339.6	U.K.	138.4	280.3
Kuwait	253.9	480.2	Iraq	136.9	263.9	France	117.6	219.7
Saudi Arabia	230.0	406.3	Iran	45.0	268.3	Italy	81.4	237.8
Iraq	143.4	275.3	Brunei	26.5	18.9	Canada	66.2	97.7
Canada	83.6	172.6	Qatar	25.9	43.5	The Netherlands	53.8	108.2
Iran	80.3	360.6	Colombia	20.2	21.1	Bahrein Islands	40.9	41.2
Indonesia	60.1	112.0	Indonesia	18.6	20.0*	Japan	40.7	264.2
Mexico	59.7	79.9	U.S.	16.9	1.3	W. Germany	33.3	209.6
Romania	50.7	59.7	Canada	15.0	60.9	Sarawak	25.7	18.3
Colombia	30.4	42.4	U.S.S.R.	12.5	157.5	Belgium-Luxembourg	21.8	56.3
Qatar	26.4	43.7	Netherlands W.I.	7.9	1.8	Australia	21.5	72.8
Brunei	25.7	18.5	Mexico	3.2	5.3			
Argentina	22.7	67.3						
Trinidad	2.2	34.6						
Algeria	0.2	110.3						

*Estimate.

TIN CONCENTRATES, hundreds of thousands of long tons of contained tin, 5-year totals[k]

Malaya	3.0	3.0	Bolivia	1.5	1.0	U.K.	1.7	2.3
China (mainland)	0.8	1.4	Indonesia	1.6	0.8	Malaya	0.5	1.1
Bolivia	1.5	1.1	Thailand	0.6	0.7	The Netherlands	1.3	0.7
U.S.S.R.	0.5	1.0	Congo	0.6	0.4	Belgium	0.4*	0.4
Indonesia	1.6	0.8	Nigeria	0.4	0.1	W. Germany	0.1	0.4
Thailand	0.6	0.8				U.S.	1.0	0.3

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APPENDIX A (continued)

TIN CONCENTRATES (continued)

Producer	1953–57	1961–65	Exporter	1953–57	1961–65	Importer	1953–57	1961–65
Nigeria	0.4	0.4				Spain		0.1
Congo	0.7	0.3				Brazil		0.1

*Belgium-Luxembourg.

TIN METAL, hundreds of thousands of long tons, 5-year totals

Producer	1953–57	1961–65	Exporter	1953–57	1961–65	Importer	1953–57	1961–65
Malaya	3.5	3.9	Malaya	3.5	3.9	U.S.	3.3	2.0
China (mainland)	0.8	1.4	China (mainland)		0.6	W. Germany	0.4	0.8
U.S.S.R.	0.5	1.0	The Netherlands	1.4	0.5	Japan	0.3	0.7
U.K.	1.4	0.9	Congo	0.5	0.4	France	0.5	0.5
The Netherlands	1.4	0.5	Nigeria		0.4	U.S.S.R.		0.4
Nigeria		0.4	U.K.	0.5	0.4	U.K.	0.2	0.3
Belgium	0.5*	0.3	Belgium	0.5*	0.3	Italy		0.2
U.S.	1.1	0.2	W. Germany		0.2	India	0.2	0.2
Bolivia		0.1	Bolivia		0.1	Canada		0.2
			U.S.		0.1	Poland		0.1
			U.S.S.R.		0.1	Spain		0.1
						Belgium		0.1
						The Netherlands	0.2	0.1
						Brazil		0.1

*Belgium-Luxembourg.

ZINC CONCENTRATES, millions of short tons of contained zinc, 5-year totals[1]

Producer	1953–57	1961–65	Exporter	1953–57	1961–65	Importer	1953–57	1961–65
Canada	2.0	3.1	Mexico	0.8	1.7	Belgium	1.2*	2.3
U.S.	2.6	2.7	Canada	0.9	1.4	U.S.	2.3	1.6
U.S.S.R.	1.4	2.2	Peru	0.6	0.9	France	0.7	1.6
Australia	1.5	1.9	Sweden	0.3	0.7	U.K.	0.5	1.1
Mexico	1.3	1.3	Australia	0.6	0.7	Japan	[illegible]	[illegible]

Poland	0.9	0.8	Morocco	0.2	0.4	The Netherlands	0.2	0.4
Italy	0.7	0.7	Algeria		0.3	Norway	0.2	0.4
W. Germany	0.5	0.6	Italy	0.2	0.3	Austria		0.1
Congo	0.6	0.6	Iran		0.2			
China (mainland)	0.2	0.6	Belgium	0.1*	0.2			
N. Korea	0.3	0.5	S. W. Africa		0.2			
Sweden	0.3	0.5	W. Germany		0.2			
Spain	0.5	0.4	Argentina		0.1			
Bulgaria	0.2	0.4	Yugoslavia		0.1			
			Greece		0.1			
			Spain	0.2	0.1			
			Burma		0.1			

*Belgium-Luxembourg.

ZINC METAL, millions of short tons of metal, 5-year totals

U.S.	4.7	4.6	Canada	0.9	1.0	U.K.	0.7	0.8
U.S.S.R.	1.4	2.5	Belgium	0.6*	0.6	W. Germany	0.3	0.7
Japan	0.6	1.5	U.S.S.R.	0.2	0.6	U.S.	1.0	0.6
Canada	1.3	1.5	Poland	0.5	0.5	India	0.2	0.4
Belgium	1.1*	1.2	Australia	0.2	0.4	U.S.S.R.		0.3
Poland	0.8	1.0	Congo	0.2	0.2	Brazil		0.2
France	0.6	1.0	Peru		0.2	Rep. of S. Africa	0.1	0.2
Australia	0.6	1.0	Zambia		0.2	Italy		0.1
U.K.	0.4	0.6	Norway	0.2	0.2	Sweden	0.1	0.1
China (mainland)	0.1	0.5	Mexico	0.2	0.1	Japan		0.1
Mexico	0.3	0.3	U.S.		0.1	France	0.1	0.1
			W. Germany		0.1	Belgium		0.1
			The Netherlands		0.1	Switzerland	0.1	0.1
			Spain		0.1	The Netherlands	0.1	0.1

*Belgium-Luxembourg.

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APPENDIX A (continued)

Major World Producers of Other Important Minerals[m]

Antimony:	China (mainland), Republic of South Africa, Bolivia, U.S.S.R., Mexico
Asbestos:	Canada, U.S.S.R., Republic of South Africa, Southern Rhodesia, China (mainland)
Barite:	U.S., West Germany, Mexico, U.S.S.R., Canada
Beryllium:	Zambia, Brazil, Argentina, Mozambique, Uganda
Bismuth:	Peru, Mexico, Bolivia, Canada, U.S. (position uncertain, probably first)
Cadmium:	U.S., U.S.S.R., Canada, Belgium, Mexico
Cobalt:	Congo, Canada, Morocco, Zambia, U.S. (position uncertain)
Columbium and tantalum:	Nigeria, Canada, Norway, Brazil, Southern Rhodesia
Diamonds:	Congo, Republic of South Africa, Ghana, Sierra Leone, Angola
Fluorspar:	Mexico, U.S.S.R., France, China (mainland), U.S.
Gold:	Republic of South Africa, U.S.S.R., Canada, U.S., Australia
Graphite:	South Korea, Australia, North Korea, U.S.S.R., China (mainland)
Gypsum:	U.S., Canada, France, U.K., U.S.S.R.
Lithium minerals:	Southern Rhodesia, Brazil, Republic of South Africa, Canada, U.S. (position uncertain)
Magnesium:	U.S., U.S.S.R., Norway, Canada, Italy
Mica (all grades):	U.S., India, Republic of South Africa, Brazil, Malagasy Republic
Molybdenum:	U.S., U.S.S.R., Chile, Canada, China (mainland)
Phosphate rock:	U.S., U.S.S.R., Morocco, Tunisia, Nauru Islands
Platinum metals:	U.S.S.R., Republic of South Africa, Canada
Potash:	U.S., West Germany, U.S.S.R., East Germany, France
Pyrites:	U.S.S.R., Japan, Spain, China (mainland), Canada
Salt:	U.S., China (mainland), West Germany, U.K., France
Silver:	Mexico, U.S., Peru, Canada, Australia
Sulfur:	U.S., Canada, Mexico, U.S.S.R., France
Talc, etc.:	Japan, U.S., U.S.S.R., France, India
Titanium concentrates:	U.S., Australia, Canada, Norway, Malaya
Tungsten concentrates:	China (mainland), U.S.S.R., U.S., South Korea, North Korea
Uranium:	U.S., Canada, Republic of South Africa, France, U.S.S.R. (position uncertain)
Vanadium:	U.S., Republic of South Africa, Finland

[a] Before bauxite can be converted to aluminum by present processes it must first be changed into alumina (Al_2O_3). The amount being converted to alumina in countries where ore is mined is steadily increasing, but trade in bauxite remains considerably more important. Eventually, however, alumina will surpass bauxite as the raw material of aluminum in international commerce. Major areas of bauxite production now are the West Indies, northern South America (and, less importantly, the south-central United States), the U.S.S.R., and in the belt running from southern France through Yugoslavia and Hungary to Greece. Australian production is rising.

[b] The production of ferro-chrome in countries where chromite is mined has not advanced to any appreciable degree since the 1953 to 1957 period.

[c] Although coal production has grown between the two periods considered here, the rate has been appreciably less than that for petroleum. Total coal trade, during this time span, probably has declined in absolute terms and certainly the ratio between coal and petroleum trade was far smaller in the 1962 to 1966 period than it was from 1953 to 1957. Only the U.S.S.R. has shown a large increase in coal exports, yet even this increase is less than that shown by the Soviets in petroleum. Although several countries have increased their imports of coal, Japan most especially, in each instance the increase has been far less than the increases of these countries in their imports of petroleum. Only the U.K., Canada, and West Germany, of the major importers, imported less coal in the 1962 to 1966 period than they did in 1953 to 1957.

[d] Although the annual world production of copper in mined ore is about 5 million tons of contained copper, only about 300,000 tons of the contained copper is traded as copper in ore or concentrates; the remainder is taken through one or more processing steps before it is offered to the market. The small trade in copper concentrates is due to the pressure of the countries containing the mines to increase profits that can be made domestically through the various stages of refining. Also, there is a savings in freight charges achieved by shipping metal rather than the generally low-grade (≈30 percent copper) copper concentrates.

[e] Up to the present, there has been little effort made to convert iron ore into some more advanced form, such as pig iron, before trading it abroad. Since World War II, there has been, however, a huge rise in the total amount of iron ore traded because of the opening of new deposits in many countries, e.g., Venezuela, Canada, and Liberia. The newly discovered deposits of iron ore in Australia will have an appreciable effect on the pattern of international trade in iron ore in the near future. The larger fraction of the ore from these new mines is sent to the United States, but other countries, Japan and Germany in particular, also receive large tonnages. In this country the development of processes to recover magnetite and hematite from taconite has greatly increased domestic reserves of iron ore, and the conversion of these concentrates to pellets or sinter has provided a premium blast furnace feed.

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APPENDIX A (continued)

[f] Because of the relative ease (though not simplicity) of lead smelting, the large part of lead ores are not only concentrated in the country of their origin, but also are smelted there. This trend should at least continue in the decade to come.

[g] Although manganese ores are traded in several grades, a growing trend has been to convert manganese ore into ferro-manganese for international trade. In 1955, the U.S.S.R. exported no ferro-manganese, in 1965 it exported 66,000 tons but also shipped over 1 million tons of ore. South Africa exported no ferro-manganese in 1965 but 120,000 tons of that material were exported in 1964 as opposed to about 870,000 tons of ore. India exported no ferro-manganese in 1955 but shipped nearly 87,000 tons in 1964, as opposed to over 1 million tons of ore. Obviously, the major ore exporting countries have made only a minor step toward full conversion of their ore to ferro-manganese.

[h] The smelting of mercury is such a straightforward process that no mercury concentrates are shipped; all mercury is converted to native metal at the sites of the mining of the ores.

[i] Mine production of nickel is largely concentrated in Canada, the U.S.S.R., and New Caledonia. None of Canada's production is exported as concentrates, although a considerable tonnage of it leaves that country as matte or speiss; this material is sent in considerable amounts to the U.K. and Norway for further processing. The United States imports essentially no nickel matte. Most of the New Caledonian production of ore goes to Japan in that form; some ore is converted to ferro-nickel (55,000 tons produced in 1965); most, but far from all, of the ferro-nickel goes to France, while essentially all of the matte goes to that country. The U.S.S.R. does not export nickel in any form.

[j] The increase in petroleum production and trade from the 1953 to 1957 period to that of 1961 to 1965 has been phenomenal. Of the 17 producers listed in this appendix, Brunei alone produced less in the later period than in the earlier one, and this reduction amounted only to about 7 million tons. Although the increase in production in any single country was greatest in the U.S.S.R., the total increase in the Middle East was even larger than that in Russia. The increases resulted from a great expansion in petroleum consumption in both the U.S.S.R. and eastern and western Europe. U.S. imports still remain a minor fraction (less than 20 percent) of U.S. production. The largest percentage increases in petroleum imports were in Japan and West Germany. Iran has the greatest tonnage increase in exports of any of the major exporters. Although the United States produced about as much petroleum in the 1961 to 1965 period as the Middle East countries combined, the center of gravity of petroleum production has shifted definitely in an easterly direction, a trend that will be accentuated by rising North African production as exemplified by Libya.

[k] The smelting is accomplished with relative ease and simplicity, except for that of the complex Bolivian ores, so that the major portion of the world's tin ore is smelted in Malaya, in or near which they were mined. Other producing countries

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traded than is true of the other two metals mentioned. In recent years, zinc mining has increased even more rapidly than zinc smelters could be built so that trade in concentrates has actually increased even though the long-range trend will be for larger portions of the concentrates to be smelted in countries where they were mined.

[m] For the 30 commodities here given, the United States is the leading producer in 13 (14, if bismuth is counted), of which seven are nonmetallics, one (two, if bismuth is counted) is a by-product of base metal smelting operations (cadmium); and four (magnesium, molybdenum, titanium, and uranium) are important minor metals. For the remaining 16 materials, four countries lead twice: mainland China (antimony and tungsten concentrates), Mexico (fluorspar and silver), the U.S.S.R. (platinum metals and iron ore), and the Congo (diamonds and cobalt). The other 9 are Canada (asbestos), Zambia (beryllium), Nigeria (columbium and tantalum), Republic of South Africa (gold), South Korea (graphite), Southern Rhodesia (lithium minerals), Japan (talc), Australia (zirconium and hafnium), lead once.

Source: U.S. Bureau of Mines and Department of Mineral Economics, The Pennsylvania State University.

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APPENDIX B Major U.S. Government and International Agencies Concerned with Mineral Economics

Many agencies of the federal government are involved in various aspects of economics and resource studies covering minerals, metals, fuels, and power. The list below is intended to merely outline the agencies involved and to suggest in only a few words some of their relevant functions.

I. EXECUTIVE OFFICE OF THE PRESIDENT

The President from time to time is required to make decisions in the field of mineral economics and resources; for example, in recent years removing import quotas on lead and zinc, price-wage policy in the case of major metals, and stockpile releases.

The Bureau of the Budget (BOB) includes a Natural Resources Programs Division, and an Economics, Science, and Technology Programs Division.

The Council of Economic Advisers (CEA) analyzes the national economy and advises the President. In recent years it has been concerned with raw materials including key metals and minerals such as copper, steel, aluminum, and ferro-alloys.

The Office of Emergency Preparedness (OEP) is responsible for emergency use of resources including stockpiling strategic and critical materials, and determining whether imports of commodities threaten to impair national security. Under the National Security Act, the Defense Production Act, the Stock Piling Act, and other legislation, the OEP has broad authority to develop programs involving materials, metals, and fuels. The OEP organization includes The National Resource Analysis Center (NRAC).

The Office of Science and Technology (OST) assures that science and technology are used effectively in the interest of national security and general welfare. The Federal Council for Science and Technology is chaired by the director of the OST, and it has made studies of research and development on natural resources, including minerals, metals, energy resources, and fuels.

The National Security Council (NSC) advises the President on policies relating to the national security. The Central Intelligence Agency (CIA), which is under the NSC, undoubtedly makes studies regarding minerals, metals, and fuels.

The Office of the Special Representative for Trade Negotiations assists in carrying out the trade agreements program, which involves various minerals, metals, and products thereof.

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II. MAJOR DEPARTMENTS AND AGENCIES

The Department of the Interior, created in 1849, is "the custodian of the nation's natural resources," and under the Defense Production Act and related legislation the Interior Secretary was delegated additional defense emergency responsibilities for petroleum and natural gas, solid fuels, electric power, and metals and minerals.

The Assistant Secretary for Mineral Resources has jurisdiction over the following agencies (among others):

The Office of Minerals and Solid Fuels makes studies and evaluations that serve as the basis for departmental policy decisions.

The Office of Oil and Gas gathers information and makes recommendations for government policies and programs. It can secure information from industry through the National Petroleum Council, the Foreign Petroleum Supply Committee, and the Emergency Advisory Committee for Natural Gas.

The Oil Import Administration allocates imports of oil and petroleum products.

The Oil Import Appeals Board hears petitions to modify oil imports.

The Office of Coal Research seeks new and more efficient methods of mining, preparing, and utilizing coal and makes research and development contracts with trade associations, research associations, educational institutions, etc., including economic analyses.

The Bureau of Mines (USBM) develops programs to conserve and develop mineral resources, promotes safety and healthful working conditions in the mineral industry, and makes economic and statistical studies. Within the USBM the Assistant Director for Mineral Resource Evaluation is the focal point for mineral economics and resources studies. Reporting to him are five Divisions: Mineral Studies, Environmental Activities, Mineral Economics, Statistics, and International Activities.

The Geological Survey (USGS) makes geological and topographic surveys and collates and synthesizes geological information on minerals and mineral fuel resources and water resources. In the Resources Research Branch there are about 50 geologists who spend from 10 percent to nearly all of their time on mineral economics problems, largely in connection with strategic materials. The Conservation Branch is concerned with oil, phosphates, and other minerals on the public lands. The USGS estimates "inferred" reserves and cooperates with the USBM on reserve appraisals. The Office of Minerals Exploration (OME) assists domestic exploration by paying part of the costs thereof for certain scarce minerals.

The Assistant Secretary for Public Land Management has jurisdiction over the following agencies (among others):

The Bureau of Land Management is concerned primarily with the mining and mineral leasing laws and makes studies relative to minerals and other resource development and use. It recently established a Mineral Economics Group.

The Bureau of Indian Affairs is concerned with mineral resources on Indian lands.

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The Assistant Secretary for Water and Power Development has jurisdiction over the following agencies (among others):

The Bureau of Reclamation investigates and develops plans for potential projects to regulate, conserve, and utilize water and related land resources.

In addition to the above, the regional Power Administrations (Alaska, Bonneville, Southeastern, Southwestern) sometimes become involved in mineral economics in cases where power and mineral production are related, as for example in aluminum production.

The Assistant Secretary for Water Pollution Control has jurisdiction over the Office of Saline Water and the Federal Water Pollution Control Administration, both of which are concerned with minerals in water.

The Department of Commerce fosters, promotes, and develops foreign and domestic commerce and manufacturing.

The Office of Foreign Direct Investments regulates overseas direct investments by U.S. corporations in the interest of maintaining the U.S. balance-of-payments position.

The Assistant Secretary for Domestic and International Business has jurisdiction over the following (among others):

The Business and Defense Services Administration (BDSA) collects business statistics and exercises defense emergency controls over industry. The BDSA includes an industrial materials staff.

The Bureau of International Commerce is charged with increasing exports, including metals and minerals and manufactures thereof.

The Assistant Secretary for Economic Affairs has jurisdiction over the following (among others):

The Bureau of the Census makes a census of manufactures, the mineral industry, business, and transportation generally every 5 years. The mineral industry census covers mining, coal, iron, and other metals and minerals, extraction of oil and gas, employment, payrolls, and value added.

The Office of Business Economics provides basic economic measures of the national economy.

The Maritime Administration subsidizes construction and operation of vessels that hold liquid and solid cargo.

The Department of State, through its various embassies, legations, and consulates abroad, is well aware of the worldwide nature of resource problems. As of mid-1967 the Department had seven minerals attachés, one petroleum attaché, and six professionally trained minerals and petroleum reporting officers, in addition to regular Foreign Service officers. In Washington, the various Regional Affairs Bureaus: African, Interamerican, East Asian and Pacific, European, Near Eastern and South Asian, consider resource problems peculiar to their respective areas. In the Bureau of Economic Affairs are located the Office of International Resources and Food Policy and the Office of International Trade Policy. A separate Bureau of Intelligence and Research undoubtedly considers minerals, metals, and fuels, as appropriate.

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The Department of the Treasury is involved in mineral economics in at least two ways: tax policy affecting all mineral production and monetary policy affecting precious metals.

The Internal Revenue Service makes detailed interpretations of the tax laws pertaining to minerals, including depletion allowances, expending of exploration costs, research and development expenditures, and amortization and depreciation.

The Bureau of Customs through administration of the customs laws has some effect on imports of metals and minerals and products thereof, and it also serves as the prime source for collection of detailed statistics on imported articles that pass through customs.

The Bureau of the Mint among its other functions analyzes general data of worldwide scope relative to gold, silver, and coins.

The Office of Domestic Gold and Silver Operations helps to develop and implement government policy with respect to these two metals.

The Office of International Gold and Foreign Exchange Operations studies gold and foreign exchange.

The Department of Defense has within it many subordinate units that from time to time make detailed studies involving minerals, metals, and fuels. Such studies may be made for research and development purposes to ascertain the potential availability of materials, for intelligence purposes, or for logistics purposes to insure that procurement planning is realistic. The Assistant Secretary for Defense (Installations and Logistics) is the focal point for supply and logistics matters including materials and petroleum. The Defense Fuel Supply Center in the Defense Supply Agency is the focal point for petroleum and fuel. Also, within the Department of the Navy is the Office of Naval Petroleum and Oil Shale Reserve. The Industrial College of the Armed Forces instructs military and civilian management personnel in techniques of resources management in an emergency.

The Department of Justice has within it the Antitrust Division that from time to time studies antitrust violations and advises on the anticompetitive effects of government and industry activities connected with the nation's defense program, the Interstate Oil Compact, the development of nuclear energy, and disposal of government-owned facilities. The Land and Natural Resources Division supervises legal matters relating to land, water, and other resources.

The General Services Administration (GSA) has within it the Property Management and Disposal Service, which, pursuant to directives from OEP, acquires, stores, and manages inventories of strategic and critical materials, including metals and minerals in all forms from ores to manufactured forms. It also aids in expansion of production, assists in barter, and administers the lead-zinc stabilization program.

The Department of Agriculture has within it the Commodity Credit Corporation that is authorized to exchange surplus agricultural materials for strategic and critical materials produced abroad, and the Office of Barter and Stockpiling in the Foreign Agricultural Service from time to time develops programs affecting worldwide minerals and metals trade.

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The Atomic Energy Commission (AEC) has jurisdiction over fissionable and source materials (such as uranium, plutonium, and thorium) and has encourage programs needed to produce special reactor materials (such as zirconium, halfnium, and beryllium). Within the AEC the Division of Raw Materials is responsible for the U.S. uranium program, including estimates of reserves and maintenance of uranium mining and milling facilities.

The Department of Transportation by its regulation and encouragement of various forms of transportation has important impacts on metals, minerals, and fuels, which generally are large-bulk, low-value items accounting for a significant portion of the nation's rail and water traffic.

The Federal Maritime Commission regulates common carriers engaged in water-borne foreign commerce or domestic offshore trade.

The Panama Canal Company operates the canal through which pass substantial quantities of minerals and metals.

The Interstate Commerce Commission (ICC) among other things regulates rail carriers and pipelines (except water and natural gas), motor, and water carriers, and by its regulation, including rates, has major influence on minerals and mineral products and fuels that account for a substantial portion of the nation's freight movement.

The Federal Power Commission (FPC) among other things regulates the interstate aspects of the electric power and natural gas industries, including rates, and it gathers, analyzes, maintains, and publishes information on natural gas companies.

The Tariff Commission investigates and reports upon the tariff and foreign trade matters. The Commission has a Metals Division, a Ceramics Division, and a Chemicals Division among its various subdivisions. Many of its reports are detailed mineral economics analyses, as have been made in recent years on mercury, lead and zinc, and tungsten.

The Securities and Exchange Commission (SEC) among other things regulates trade in mining and metal and petroleum securities, and some of its recent investigations have dealt with detailed questions of minerals economics related to newly discovered mineral reserves and resulting public announcements of property valuations.

The Commodity Exchange Commission regulates commodity exchanges.

The Federal Trade Commission (FTC) among other things involves itself in cases of alleged monopoly or unfair or deceptive trade practices.

The Department of Health, Education, and Welfare (HEW), through establishment of human tolerance levels for environmental contaminants, is playing an increasing role in the field of mineral economics and resources.

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The Export-Import Bank (Ex-Im Bank) facilitates exports and imports, including metals and minerals, and the capital goods to mine and process them.

The Tennessee Valley Authority (TVA) is concerned with the conservation, development, and use of the resources of that region, and has special interests in the development of new types of fertilizers and in power generation.

The National Science Foundation (NSF) encourages research in the physical, engineering, and social sciences, but has sponsored no major projects in mineral economics.

III. QUASIOFFICIAL AGENCIES

National Academy of Sciences (NAS), National Academy of Engineering (NAE), and the National Research Council (NRC) bring scientists and engineers together for concerted attacks upon specialized problems, including advice to the federal government. Within the NAS-NAE-NRC complex, the National Materials Advisory Board (NMAB) is specifically organized to cover materials, including strategic and critical materials, the greater portion of which are metals. The NMAB makes supply and demand studies and endeavors to foresee developing technology.

IV. THE CONGRESS

The Congress from time to time makes detailed studies in the field of mineral economics and resources, usually through the various committees having jurisdiction over certain specific matters. Among these are:

The Joint Committee on Defense Production
The Joint Committee on Atomic Energy
The Committees on Armed Services (House and Senate)
The Committees on Interior and Insular Affairs (House and Senate)
The Committees on Interstate and Foreign Commerce (House and Senate)

Within the Library of Congress, the Legislative Reference Service has a Natural Resources Division, which provides specialized information and services in the resources field.

In addition, the Public Land Law Review Commission is currently studying the public land laws, and it is scheduled to report recommendations by June 30, 1970.

V. SELECTED MULTILATERAL INTERNATIONAL ORGANIZATIONS IN WHICH THE UNITED STATES PARTICIPATES

The International Bank for Reconstruction and Development (World Bank) makes loans for resource and industry development. Affiliated with the World Bank are the International Finance Corporation (IFC), which invests in manu-

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facturing enterprises, and the International Development Association (IDA), which meets the needs of developing countries for capital on soft terms.

The International Monetary Fund (IMF) among other things makes recommendations on the role of precious metals in monetary policy.

The Organization for Economic Cooperation and Development (OECD) promotes policies for economic development by participating countries, including the United States.

The United Nations (UN) in which the Economic and Social Council (ECOSOC) makes resource studies of various areas. Under ECOSOC is the Commission for Social Development. The UN also sponsors the International Lead-Zinc Study Group, which seeks ways of balancing supply and demand, and to which the U.S. Government sends observers.

The Organization of American States, through the Inter-American Economic and Social Council, under the Alliance for Progress, seeks to accelerate economic development in Latin America.

The Inter-American Development Bank promotes development by providing technical assistance and making loans.

The Asian Development Bank fosters growth and development and makes loans.

The South Pacific Commission promotes economic advancement in the South Pacific, and in Pacific Islands held by the United States.

The General Agreement on Tariffs and Trade (GATT) through which participating nations endeavor to reduce barriers to trade.

The International Tin Council is concerned with tin stockpile disposals. The United States, while not a member, consults with the Council.

Source: U.S. Government Manual and J. D. Morgan.

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APPENDIX C Partial List of State Agencies Concerned with Mineral Economics

Alabama	Geological Survey of Alabama
	Department of Industrial Relations
Alaska	Division of Mines and Minerals
	State Department of Economic Development and Planning
Arizona	Arizona Bureau of Mines
	Department of Mineral Resources
Arkansas	Arkansas Geological Commission
	Arkansas Oil and Gas Commission
	Department of Revenue
California	Department of Conservation
Colorado	Oil and Gas Conservation Commission
	Coal Mines Inspections Department
	Colorado Bureau of Mines
Connecticut	Connecticut Geological and Natural History Survey
Delaware	Delaware Geological Survey
Florida	State Board of Conservation, Division of Geology
	Florida Development Commission
Georgia	Georgia State Division of Conservation, Department of Mines, Mining, and Geology
Hawaii	Department of Land and Natural Resources
Idaho	Bureau of Mines and Geology
Illinois	Illinois State Geological Survey
	Illinois Department of Mines and Minerals
Indiana	Indiana Geological Survey, Department of Natural Resources
Iowa	Iowa Geological Survey
Kansas	State Geological Survey of Kansas
	Department of Economic Development
	Kansas Corporation Commission
Kentucky	Kentucky Geological Survey
	Kentucky Department of Commerce
Louisiana	Louisiana Geological Survey
	Louisiana Department of Conservation
	Department of Labor, Division of Employment Security
	Department of Commerce and Industry
Maine	Maine Geological Survey, Department of Economic Development
Maryland	Maryland Geological Survey
Massachusetts	Massachusetts Department of Public Works
Michigan	Geological Survey Division
	Department of Conservation
Minnesota	Minnesota Geological Survey

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Mississippi	Mississippi Geological Survey
	Mississippi State Oil and Gas Board
	Oil and Gas Severance Tax Division, Mississippi State Tax Commission
	Mississippi Employment Security Commission
Missouri	Missouri Geological Survey and Water Resources
	Division of Commerce and Industrial Development
Montana	Montana Bureau of Mines and Geology
	The Oil and Gas Conservation Commission
	State Planning Board
Nebraska	Nebraska Geological Survey
	Oil and Gas Conservation Commission
Nevada	Nevada Bureau of Mines
	Nevada Oil and Gas Conservation Commission
New Hampshire	Department of Geology, University of New Hampshire
New Jersey	Bureau of Geology and Topography
New Mexico	New Mexico Bureau of Mines and Mineral Resources
	Oil Conservation Commission
New York	New York State Geological Survey
	New York State Department of Conservation
North Carolina	Department of Conservation and Development
	Department of Labor
North Dakota	North Dakota Geological Survey
	State Mine Inspector
Ohio	Division of Geological Survey
	Division of Oil and Gas
	Division of Mines
Oklahoma	Oklahoma Geological Survey
	Oil and Gas Conservation Department, Oklahoma Tax Commission
	Bureau of Business Statistics
Oregon	State Department of Geology and Mineral Industries
Pennsylvania	Bureau of Topographic and Geologic Survey
	Department of Mines and Mineral Industries
Rhode Island	Rhode Island Development Council
South Carolina	Division of Geology, State Development Board
South Dakota	South Dakota Geological Survey
Tennessee	Tennessee Division of Geology, Department of Conservation
Texas	Bureau of Economic Geology, University of Texas
	Oil and Gas Division, Railroad Commission
	Oil and Gas Division, State Comptroller of Public Accounts
Utah	Utah Geological and Mineralogical Survey
	Oil and Gas Conservation Commission
Vermont	Vermont Geological Survey
Virginia	Virginia Division of Mineral Resources
Washington	Washington Division of Mines and Geology
	Department of Natural Resources

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West Virginia	West Virginia Geological and Economic Survey
Wisconsin	Geological and Natural History Survey
Wyoming	Geological Survey State Board of Equalization
Puerto Rico	Mineralogy and Geology Section, Economic Development Administration

There are many other state agencies, in addition to those listed above, that from time to time become involved in studies involving mineral economics or in regulatory decisions in which questions of mineral economics are involved. Additionally, many state universities make studies that involve questions of mineral economics.

Source: H. E. Risser and U.S. Bureau of Mines.

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APPENDIX D Course Requirements for a B.S. Degree in Mineral Economics at The Pennsylvania State University

Total Credits	Course	Term 1, 2, 3	Term 4, 5, 6	Term 7, 8, 9	Term 10, 11, 12
9	COMMUNICATIONS				
	Composition and Rhetoric, plus the Writing of Ideas	6			
	Effective Speech		3		
18	MATHEMATICS AND STATISTICS				
	Calculus I, II, and III	9	3		
	MnEc 491—Analysis of Mineral Data and either Calculus IV and 3 credits of Statistics or 6 credits of Statistics			3	3
16	PHYSICAL SCIENCE				
	General Chemistry, plus Chemical Principles and Qualitative Analysis	8			
	Physics		8		
12	GEOLOGICAL AND BIOLOGICAL SCIENCES				
	Physical Geology, Historical Geology, Petrography, and Economic Geology or	6	3		
	Geology of Oil and Gas			3	
12	BUSINESS ADMINISTRATION AND INDUSTRIAL MANAGEMENT				
	3 credits of Accounting and 9 selected from: International Business, Physical Distribution, Legal Environment of Business, Corporation Finance, Business Management, Marketing Management, Industrial Organization and Administration, Management Science	6	6		

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Total Credits	Course	Term 1, 2, 3	Term 4, 5, 6	Term 7, 8, 9	Term 10, 11, 12
9	ECONOMIC PRINCIPLES				
	Introductory Microeconomic Analysis and Policy, Introductory Macroeconomic Analysis and Policy plus Intermediate Microeconomic Analysis or Intermediate Macroeconomic Analysis	3	6		
9	MINERAL ENGINEERING AND SCIENCE				
	At least 3 credits in each group: A. Mining, or Petroleum and Natural Gas and Mineral Preparation B. Ceramic Science, Fuel Science, Metallurgy			6	3
19	MINERAL ECONOMICS				
	MnEc87—Principles of Mineral Economics; MnEc400—Seminar; MnEc453—Nonmetallic Minerals; MnEc483—The Metals and Their Ores; MnEc-484—Economics of Energy Resources; MnEc486—Petroleum and Natural Gas Economics; MnEc490—Mineral Valuation		3	6	10
6	HUMANITIES AND SOCIAL SCIENCE*				
	Not including Economics, must include 3 credits of Humanities, approved by adviser				6
15	ELECTIVES*				
	Approved by adviser			3	12
4	PHYSICAL EDUCATION	2	2		
129	Totals	31	31	33	34

*Six credits of basic ROTC may be substituted for 3 credits Social Science and 3 credits electives.

APPENDIX E Publications on Mineral Economics, Based on Research Sponsored by Resources for the Future, Inc., 1960 to 1967

Economic Aspects of Oil Conservation Regulation, Lovejoy and Homan, 1967*
Trends in the World Aluminum Industry, Brubaker, 1967*
Supply and Competition in Minor Metals, Brooks, 1966*
Low-Grade and Nonconventional Sources of Manganese, Brooks, 1966*
Methods of Estimating Reserves of Crude Oil, Natural Gas, and Natural Gas Liquids, Lovejoy and Homan, 1965*
Minerals and Men: An Exploration of the World of Minerals and Its Effect on the World We Live In, McDivitt, 1965*
Supply and Costs in the U.S. Petroleum Industry: Two Econometric Studies, Fisher, 1964*
Resources in America's Future, Landsberg, Fischman, and Fisher, 1962*
Three Studies in Minerals Economics, Herfindahl, 1961†
The Future Supply of the Major Metals, Netschert and Landsberg, 1961†
Energy in the American Economy, 1850–1975, Schurr and Netschert, with Eliasberg, Lerner, and Landsberg, 1960*
Historical Statistics of Minerals in the United States, Schurr, 1960†
Exploration for Non-Ferrous Metals: An Economic Analysis, Preston, 1960†

*Johns Hopkins Press, Baltimore, Md.
†Resources for the Future, Inc., Washington, D.C.

APPENDIX F Professional Societies and Trade Associations Concerned with Mineral Economics

PROFESSIONAL SOCIETIES

American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME)
and its Council of Economics and Council of Education
and its three constituent societies:
  Society of Metallurgical Engineers
  Society of Mining Engineers
  Society of Petroleum Engineers
American Association of Petroleum Geologists
American Ceramic Society
American Society for Metals
Society of Economic Geologists

TRADE ASSOCIATIONS

American Bureau of Metal Statistics
American Iron and Steel Institute
American Iron Ore Association
American Petroleum Institute
American Mining Congress
American Gas Association
American Potash Association
American Zinc Institute
Aluminum Association
Copper Development Association
Copper Institute, Inc.
Institute of Scrap Iron and Steel
Lead Industries Association, Inc.
National Sand and Gravel Association
National Lime Association
National Coal Association
Independent Petroleum Association of America
Structural Clay Products Institute
Portland Cement Association

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APPENDIX G English-Language Sources of Information Related to Mineral Economics

UNITED STATES

All the federal agencies listed in Appendix B and the state agencies listed in Appendix C issue reports from time to time. For the U.S. Government, the *Federal Register* serves as a current listing of administrative decisions. Of special note are the *Information Circulars*, the *Mineral Industry Surveys*, the annual multivolume standard reference work, the *Minerals Yearbook* (and chapter preprints thereof), and *Mineral Facts and Problems* (1965) issued by the U.S. Bureau of Mines. The *Professional Papers*, *Bulletins*, and *Circulars* of the U.S. Geological Survey as well as its topographic and geological maps, are of great help.

The American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME) annually publishes the "Proceedings" of its Council of Economics. AIME's monthly publications: *Mining Engineering*, *Journal of Metals*, and *Journal of Petroleum Technology* carry articles of interest. In 1964 AIME issued a special volume "Economics of the Mineral Industries."

Daily newspapers, including *The New York Times*, *The Wall Street Journal*, *The Journal of Commerce*, and *The American Metal Market*, provide current information, as do publications of the groups listed in Appendix F.

A number of weekly, semimonthly, and monthly magazines are important, including:

Engineering and Mining Journal (and its *Directory of Mining and Mineral Processing*, 1967)
Business Week
Coal Age
Mining Congress Journal
Rock Products
Pit and Quarry
Engineering News Record
Iron Age
Chemical Processing
Metal Mining and Processing
Journal of Economic Abstracts (quarterly)
Metals Week
Steel
Nuclear Industry
Land
Oil Daily
Coal Mining and Processing
Oil and Gas Journal (Tulsa)
World Oil
Chemical Engineering
Chemical Week
Chemical and Engineering News
World Mining
Ceramic Industry
Brick and Clay Record
Economic Geology
Mechanization
Coal—Today and Tomorrow
Skillings' Mining Review
Barron's
Chemical Economics Handbook
The Magazine of Metals Processing

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GREAT BRITAIN

The weekly newspaper
The Economist
Magazines as follows:
Mining Journal
Mining Magazine
Mining Annual Review
Chemical Engineering
Colliery Engineering
Petroleum Times
Oil and Gas Journal (London)
Journal of Industrial Economics
Mining and Mineral Engineering
Colliery Guardian
The Mining Engineer
Iron and Steel
Metal Bulletin
Steel Times
Gas World and Gas and Coke
Skinners' Mining Yearbook
Skinners Oil and Petroleum Yearbook

Publications of the British Bureau of Nonferrous Metal Statistics

OTHER PUBLICATIONS ARE:

Canadian Mining Journal
Northern Miner
Canadian Mines Handbook
Far Eastern Economic Review
(Hong Kong)

Publications of:
- Mineral Resources Division, Dept. of Mines and Technical Surveys, Ottawa, Ontario, Canada
- Bureau of Mineral Resources, Commonwealth of Australia, Canberra
- South African Chamber of Mines

Bank News Letters, including:
- 1st National City Bank (New York)
- Chase Manhattan Bank (New York)
- Royal Bank of Canada
- Bank of Montreal (Canada)

The above is of necessity only a sampling. There are many more publications in English, and the literature in other than English would require a special project to document.

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GEOLOGICAL
SCIENCES

MINERAL SCIENCE AN

EXPLORATION


Remote Sensing
By Satellite


Magnetic Surveys


Deep-Sea Drilling


Seismic Prospecting


Geochemical Analysis


tratigraphy

PRODUCTION OF RAW MATERIALS


Surface Mining


Petroleum & Natural Gas
Wells


Dredging


Quarrying

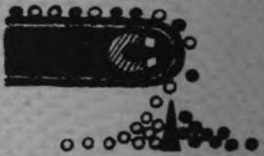

Sulfur Wells


Underground Mining

BENEFICIATION OF RAW MATERIALS


Crushing & Grinding


Screening


Magnetic Separation


Electrostatic Separation


Hindered Settling


Flotation

EXT
AND
PRO

Blast


Oxy


Fire


Ope


Elec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TECHNOLOGY

MATERIALS SCIENCE

N

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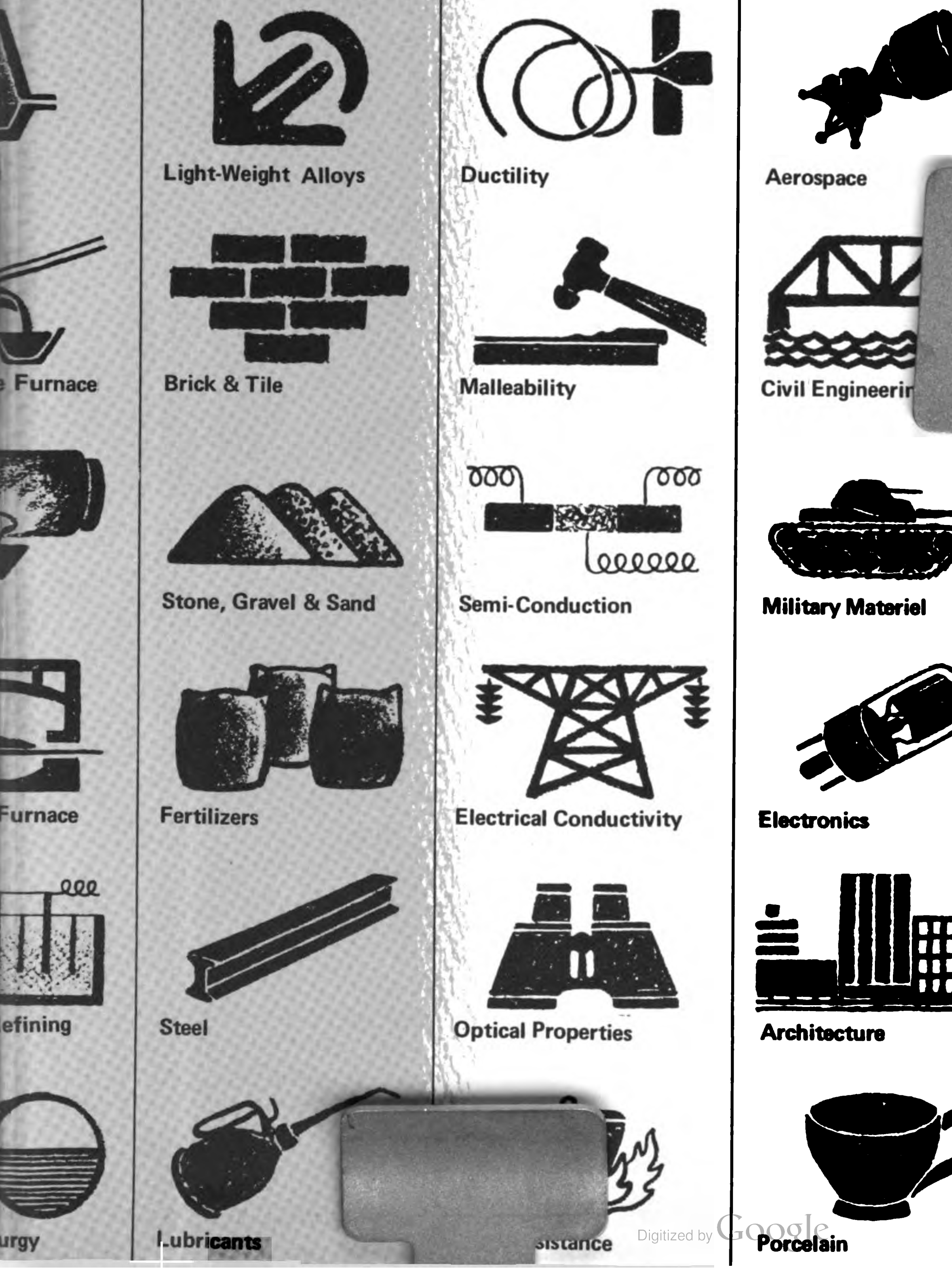
PRODUCTION OF FINISHED MATERIALS

PROPERTIES OF MATERIALS

USES OF MATERIALS



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