Basic and Strategic Metals Industries: Threats and Opportunities: Report (1985)

Pages
167

Size
8.5 x 10

ISBN
0309322359

Committee on Science and Technology Implications for Processing Strategic Materials; National Materials Advisory Board; Commission on Engineering and Technical Systems; National Research Council

NATIONAL RESEARCH COUNCIL
COMMISSION ON ENGINEERING AND TECHNICAL SYSTEMS

NATIONAL MATERIALS ADVISORY BOARD

The purpose of the National Materials Advisory Board
is the advancement of materials science and engineering in the national interest.

CHAIRMAN

Dr. Arden L. Bement, Jr.
Vice President, Technical
Resources
Science and Technology Department
TRW, Inc.
1900 Richmond Road
Cleveland, OH 44124

PAST CHAIRMAN

Dr. Donald J. McPherson
(Retired)
Kaiser Aluminum & Chemical
Corporation
1180 Monticello Road
Lafayette, CA 94549

MEMBERS

Dr. Richard C. Alkire
Professor of Chemical Engineering
Department of Chemical Engineering
University of Illinois
1209 W. California Street
Urbana, IL 61801

Dr. L. Eric Cross
Associate Director, Materials
Research Laboratory
Evan Pugh Professor of Electrical
Engineering
Pennsylvania State University
University Park, PA 16802

Dr. Raymond F. Decker
Vice President, Research
Michigan Technological University
Houghton, MI 49931

Mr. Edward J. Dulis
President
Crucible Research Center
Colt Industries Inc.
P.O. Box 88
Pittsburgh, PA 15230

Dr. James Economy
Manager, Organic Polymer Research
IBM Corporation
K42-282 Monterey & Cottle Road
San Jose, CA 95114

Dr. Merton C. Flemings
Professor and Chairman
Department of Material Science
and Engineering
Massachusetts Institute of
Technology
Cambridge, MA 02139

Dr. Brian R.T. Frost
Director, Technology Transfer Center
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Dr. Bernard H. Kear
Senior Consultant Scientist
Exxon Research & Engineering Co.
Clinton Township
Route 22E
Annandale, NJ 08801

Dr. Alan Lawley
Professor, Metallurgical
Engineering
Drexel University
Department of Materials Engineering
Philadelphia, PA 19104

Dr. Adolph J. Lena
Consultant
417 Temple Street
Dunkirk, NY 14048

Dr. David L. Morrison
President
IIT Research Institute
10 W. 35th Street
Chicago, IL 60616

Dr. R. Bryon Pipes
Director, Center for Composite
Materials
Department of Mechanical and
Aerospace Engineering
University of Delaware
Newark, DE 19711

Dr. Dennis W. Readey
Professor and Chairman, Department
of Ceramic Engineering
Ohio State University
2041 College Road
Columbus, OH 43210

Dr. James R. Rice
Gordon McKay Professor of
Engineering Sciences and Geophysics
Harvard University
Pierce Hall
Cambridge, MA 02138

Dr. John P. Riggs
Executive Director, Technology
Celanese Research Corporation
86 Morris Avenue
Summit, NJ 07901

Dr. William P. Slichter
Executive Director, Research
Materials Science and
Engineering Division
AT&T Bell Laboratories
600 Mountain Avenue
Murray Hill, NJ 07974

Dr. William A. Vogely
Professor and Head
Department of Mineral
Economics
Pennsylvania State University
University Park, PA 16802

Dr. James C. Williams
Dean of Engineering
Carnegie-Mellon University
4400 Fifth Avenue
Pittsburgh, PA 15213

NMAB STAFF

K.M. Zwilsky, Executive Director
2101 Constitution Avenue, N.W.
Washington, DC 20418

8/85

BASIC AND STRATEGIC METALS INDUSTRIES:

THREATS AND OPPORTUNITIES

Report of the Committee on
Science and Technology Implications
for Processing Strategic Materials

NATIONAL MATERIALS ADVISORY BOARD
COMMISSION ON ENGINEERING AND TECHNICAL SYSTEMS
NATIONAL RESEARCH COUNCIL

NMAB-425
National Academy Press
Washington, D.C.
1985

85-0126
c.1

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

The report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which established the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

This study was conducted under contract EMW-83C-1350 with the Federal Emergency Management Agency.

This report is for sale by the National Technical Information Service, Springfield, Virginia 22161.

Printed in the United States of America.

ABSTRACT

Five strategic metals processing industries (iron and steel, copper, aluminum, titanium, and superalloys) are assessed in terms of their capacity and survival problems in the worldwide competitive marketplace. The availability and economic issues of four critical alloying elements (chromium, cobalt, columbium, and tantalum) are discussed. An overview of the current status of each of these industries is presented in terms of its unique characteristics and needs. Some innovative technologies and processing steps are identified as having merit for improving the competitive posture of these industries.

COMMITTEE ON SCIENCE AND TECHNOLOGY IMPLICATIONS FOR PROCESSING STRATEGIC MATERIALS

Chairman

NICKOLAS J. THEMELIS, Krumb School of Mines, Columbia University, New York, New York

Members

JAMES C. BURROWS, Charles River Associates, Boston, Massachusetts

JAMES E. COYNE, Wyman-Gordon Company, Worcester, Massachusetts

NOEL JARRETT, ALCOA Laboratories, Alcoa Center, Pennsylvania

CHARLES L. KUSIK, A. D. Little, Inc., Cambridge, Massachusetts

ROGER N. KUST, EXXON Minerals Company, Houston, Texas

RICHARD K. PITLER, Allegheny Ludlum Steel Corporation, Brackenridge, Pennsylvania

BHAKTA B. RATH, Naval Research Laboratory, Washington, D.C.

JOHN B. WACHTMAN, JR., Rutgers University, Piscataway, New Jersey

Technical Advisor

JOHN K. TIEN, Krumb School of Mines, Columbia University, New York, New York

Liaison Representatives

WILLIAM F. CANNON, U.S. Geological Survey, Reston, Virginia

RICHARD E. CORDER, Federal Emergency Management Agency, Washington, D.C.

PAUL GUNTHER, Federal Emergency Management Agency, Washington, D.C.

GARRETT R. HYDE, U.S. Bureau of Mines, Washington, D.C.

G. PATRICK JOHNSON, National Science Foundation, Washington, D.C.

ROBERT C. REILEY, U.S. Department of Commerce, Washington, D.C.

LOUIS SOUSA, U.S. Bureau of Mines, Washington, D.C.

NMAB Staff

GEORGE ECONOMOS, Staff Officer

CATHERINE STEELE, Senior Secretary

PREFACE

The future availability of metals and the welfare of the domestic industries that produce them have been, for many decades, concerns of government agencies that are responsible for maintaining a healthy economy in peacetime or for ensuring an adequate supply of strategic materials during a national emergency. Problems of the mineral industry were discussed as far back as 1952 in the Paley Commission report, "Resources for Freedom." A 1969 National Academy of Sciences (NAS) report, "Mineral Science and Technology: Needs, Challenges, and Opportunities," reviewed the projected impact of technology on the mineral industry and a 1978 NAS report, "Technological Innovation and Forces for Change in the Mineral Industry," examined the barriers to technological innovation. As recently as 1980, a National Research Council (NRC) study focussed on the issues related to improving technological innovation in the mineral industries. Numerous other studies, some of which are referred to in the body of this report, have also been conducted.

One of the responsibilities of the Federal Emergency Management Agency (FEMA) is to prepare for comprehensive management of technical resources in the case of national emergency and in 1983, FEMA determined that a formal assessment was needed of the current state of technology and the potential impact of technological innovation on various industrial sectors, particularly the production and processing of basic and strategic materials. FEMA therefore requested that the National Research Council, through the National Materials Advisory Board (NMAB) of the Commission on Engineering and Technical Systems (CETS), form a committee to conduct such a study. Given the breadth of the topic and FEMA's request that the study be a "broad brush" review, which could be followed by future separate in-depth assessments, the committee concentrated on four basic metal industries--iron and steel, copper, aluminum, and titanium. Furthermore, because the basic industries assessed in this report are highly dependent on the availability of some imported alloying elements, the committee reviewed the status of some strategic alloying metals (cobalt, chromium, columbium, and tantalum). In addition, the superalloys industry was added to the examination because of its strategic importance to the nation and the industry's critical dependence on these imported materials.

The committee's goal was to identify the major problems in the domestic industries under consideration that could provide some insight concerning the likely future direction of these industries and to suggest technological options for maintaining or advancing the present industrial base. To the extent possible, answers were sought to the following questions:

1. Has the industrial base eroded in recent years and what is the expected trend if no significant technological changes occur?

2. What are the special advantages or disadvantages of the domestic industry in terms of its foreign competition?

3. Are there technological advances on the horizon that may decrease significantly overall operating costs (e.g., productivity, yield, and energy conservation) or the capital cost per unit of production?

4. Are there existing or foreseeable technologies that may not be economically viable under normal conditions but that could be actuated in an emergency to supply the particular metal or other material?

In the course of its examination, the committee found that although there are significant differences in the problems confronting the metals industries studied, some important commonalities do exist that clearly point the way to certain corrective actions. As noted above, no in-depth analysis is presented, since only a general review was to be provided by this study. The reader is referred to other industry assessments sponsored by government agencies and by private industry for additional background data. Follow-on studies based on this report can provide further valuable insights concerning the alternatives available.

Nickolas J. Themelis
Chairman

ACKNOWLEDGMENTS

The committee is grateful to the following individuals for their formal presentations to the committee: T. D. Kaufman of the Colorado School of Mines for his contribution concerning prospects of the aluminum industry between 1983 and 1993; W. H. Dresher of the International Copper Research Association for his contribution concerning copper consumption as influenced by world techno-economic advancements; H. W. Paxton of the U.S. Steel Corporation for his contribution concerning future developments in the integrated steel industry; and J. W. Pridgeon of Special Alloys, Inc. for his contribution concerning the current status and future developments of superalloys.

The government liaison representatives are thanked for participating in committee discussions and for providing support documents and data. Paul Gunther and Richard E. Corder, the FEMA liaison representatives, are thanked for assisting the committee in defining the scope of the study and for helping guide the study through its numerous stages of development. Louis Sousa of the Bureau of Mines is recognized for assisting the chairman and committee member Roger Kust in coordinating inputs for the copper industry assessment. Special thanks go to John K. Tien of Columbia University, technical advisor to the committee, who provided the discussion of the superalloys industry.

Finally, the chairman thanks the committee for its dedication and patience in the numerous iterations and revisions of the various issues being addressed. Particular thanks are given to the committee members who served as the chapter coordinators, assembled pertinent facts for the report, and presented the data in an open-minded and professional manner: Richard K. Pitler for iron and steel, Noel Jarrett for aluminum, James E. Coyne for titanium, and James C. Burrows for strategic alloying metals.

The chairman is grateful to John B. Wachtman, Jr. for assisting in the overall coordination of the report and acknowledges with thanks the important contributions of George Economos, Staff Officer to the committee.

CONTENTS

APPENDIXES

1

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A healthy, technologically advanced basic materials industry is essential to national preparedness. Several important basic materials industries are under heavy pressure from subsidized foreign competition, and if these domestic industries shrink too much, a dangerous situation may develop. The basic materials industries of tomorrow will employ new, more efficient technology that will be available on a worldwide basis. American industry needs an economic climate that will allow deployment of the technologies that are most advantageous to its circumstances, and U.S. research and development designed to help the domestic basic materials industries should concentrate on such technologies. A list of advanced technologies for each of the basic industries examined is given in this report, together with an indication of which ones are likely to be most helpful to domestic industry.

Some important points can be made regarding the total industrial picture:

1. There are two major concerns with respect to strategic materials. First is the classic concern surrounding the need to import strategic and critical materials because of a lack of domestic raw materials sources. Second is the concern surrounding increasing import percentages (or foreseen future increases) that reflect unfavorable economic conditions for the domestic industry. Prior strategic materials policy has dealt primarily with the first area of concern, which continues to be important for some of the materials examined in this study (i.e., cobalt, chromium, tantalum, and columbium). Today, however, there is the added concern that events affecting several domestic basic metals industries foreshadow a decline in domestic productive capacity, already under way in some cases, to the extent that an adequate productive base might no longer be available in a national emergency.

2. A number of the domestic basic materials industries are under severe and growing pressure from foreign competition, such as the steel, copper, and aluminum industries.

3. A strong domestic industrial base, such as steel, copper, and aluminum, is essential to preparedness for a national emergency; therefore, steps that will ensure the existence of these competitive domestic industries must be integral parts of national preparedness policy. Such a preparedness policy should not seek to preserve all existing elements of these domestic industries, but rather to preserve the technologically important parts and, preferably, only those parts that can be vigorous in fair competition in the world marketplace.

4. Use of the best available processing technology is important to preserving a competitive domestic industry but will not suffice by itself. Both economic and noneconomic trade factors also must allow U.S. industry to compete effectively. This report focuses on technology, but it must be understood that technology will be deployed by an industry only when economic factors permit. Thus, an approach based on technological opportunities is pertinent only if the economic climate allows these opportunities to be exploited by domestic industry. Since the committee was charged to focus on technical concerns and was composed of people whose expertise is primarily technical, no attempt is made herein to propose detailed policy solutions that would produce such a favorable economic condition. Rather, this report discusses threats to some domestic materials industries and considers the opportunities that technologies would offer under proper circumstances.

5. A historic change is occurring in the basic materials industries of developed nations. The intensity of basic metals use (measured, for example, in pounds of material per dollar of gross national product per capita) is decreasing in all the advanced nations (Tilton, 1985). This trend presumably reflects both population changes and a shift toward demand for different products and services in countries with a well-developed basic infrastructure. In the future, the materials industries in the developed nations will still have the opportunity to supply a significant, although probably smaller, domestic market for basic materials and to become suppliers to a growing market for specialty materials. On the other hand, developing countries with high population growth rates, good sources of raw materials, and a need to build a basic infrastructure as well as to supply their growing populations with basic services have strong incentives to build new basic materials production plants. Thus, an inherent competition in the basic materials industries between the developed and developing nations, based on fundamental worldwide factors, seems inevitable. A successful future for the basic materials industries of the developed countries requires concentration on markets, products, and technologies that provide competitive opportunities under these worldwide factors, which are largely beyond the control of any government (Tilton, 1985).

6. Basic and applied research on innovative technologies, especially those characterized as "high-risk," will not receive funding from an ailing mature industry, so industry-wide cooperative programs and the

research efforts supported by government agencies offer the best opportunity to evaluate technical feasibility and commercial justification of selected programs.

Points of importance to the specific industries are given below.

IRON AND STEEL INDUSTRY

The domestic iron and steel industry is under heavy subsidized competitive pressure (AISI, 1983). Domestic capacity is declining as less efficient plants are closed and written off. Imports are increasing. Specialty steels and mini-mills products are the healthiest portions of the domestic industry, but the latter depend heavily on scrap availability.

The advantages of the domestic iron and steel industry are its still-large domestic market, skilled labor, scrap availability, R&D capability, and this nation's abundant coal supply.

The major disadvantages are high capital and labor costs, high value of the dollar, low rate of capital generation, and low-grade ore sources, which must compete with high-grade, inexpensive subsidized imported ore. These factors make it difficult for the industry to maintain some degree of national self-sufficiency. Emergency needs would include basic steels for ship, transport, and military construction, as well as the full range of specialty steels and special parts (e.g., fasteners at one extreme and large castings and forgings at the other).

Of special importance to the U.S. iron and steel industry is the development and/or refinement of technologies listed under the following categories:

a. Related to ore resources:

- More energy-efficient and economical grinding for U.S. ores
- More efficient and economical metals separation processes including innovative processes

b. Related to coal resources as an energy source:

- Better coal transport methods, e.g., pipeline slurry transport
- Use of coal in direct reduction to replace natural gas
- Plasma reduction process that employs low-grade steam coal for generating the electrical energy required

c. Related to coal resources as an energy source:

- Improved, more energy-efficient electric furnaces
- Plasma arc melting furnaces

d. Related to reduced capital and operating costs:

- Specialty steel production
- Ladle metallurgy
- Continuous casting
- Direct casting of thin slabs or coilable strip
- Improved in-line sensors and control systems
- Scrap substitutes, such as direct reduction of iron

It is recognized that most new technologies applicable to the U.S. industry soon would be available to competitive interests worldwide, so technological advances that are unique to the U.S. industry offer the best opportunity for gaining an advantage in the market.

COPPER INDUSTRY

1. Some special factors threaten the survival of the U.S. copper industry: (a) The low grade of ore reserves, (b) the high cost of manpower, (c) the high cost of environmental control in comparison with other major world producers, and (d) heavily subsidized imports.

2. On the brighter side, domestic ore reserves constitute 18 percent of the world total and are surpassed only by Chile. Also, even at a very modest rate of growth, the domestic annual demand for copper is forecast to total about 2.8 million tons by the year 2000.

3. In the case of a long-term national emergency, the strategic needs of the nation would amount to over one million tons per annum.

4. The nature of the copper production process makes impractical any consideration of "mothballing" plants so that they can be reactivated on short notice in an emergency. Also, there are no prospects for developing radically different new processing technologies that could be implemented on short notice.

5. The U.S. copper industry, therefore, is expected to survive the current crisis but not to return to prior levels of production. In the long term, the size and health of the industry will depend on its ability to develop and adopt technologies that can compensate, to a certain extent, for the industry's special disadvantages.

6. The domestic copper industry today supports little in-house or academic research targeted for improving copper technology. Government may revive R&D in this area through existing agencies, such as the National Science Foundation and the Bureau of Mines, or by sponsoring joint industry-university institutes (e.g., Center for Metals Production at Carnegie-Mellon University) dedicated to advancing copper technology. Research areas that need to be addressed are

a. Computerization and automation of exploration, mining, and processing methods

b. In-situ or solution mining, "thin-layer," biotechnology, and other direct leaching techniques that bypass the costly step of mineral beneficiation

c. New, energy-efficient techniques for particle size reduction

d. Direct processing of polymetallic concentrates

e. Improved selectivity in mining and ore sorting techniques

f. Development of a direct smelting process that permits the elimination of converter step.

ALUMINUM INDUSTRY

1. The established aluminum industry has enjoyed a high growth rate for demand until recently; the market share of the six largest companies fell from 70 percent in 1970 to 50 percent in 1983.

2. The domestic industry relies on foreign sources for bauxite, and the industry in general is becoming increasingly more international with all recent smelters being located outside the United States.

3. Third-world competition is increasingly important.

4. The domestic aluminum industry is relatively healthy but its markets appear to be approaching maturity. With increased recycling, demand is expected to grow in the two to four percent per year range rather than the six percent traditional.

5. Domestic advantages include a large domestic market and the existence of a large, technically up-to-date and well maintained industry.

6. Disadvantages of the domestic industry include higher costs for electric power, higher labor costs, and distance from bauxite deposits.

7. Emergency needs for aluminum include components of aircraft and light-weight structures and devices in general.

8. Innovative technologies with promise of improving the efficiency of the Hall-Heroult Process include

a. Mathematically modeled computer process control

b. Development of stable cathodes

c. Development of inert cell sidewall linings (which permit higher power efficiency with heat recovery for cogeneration)

d. Development of inert anodes and retrofittable bipolar plates that could greatly increase space-time-yield (pounds Al/hr/cell/ft^3) and power efficiency in existing Hall-Heroult plants

9. Alternate processes for the production of aluminum that are only partially developed include

a. The Alcoa Smelting Process

b. Electrically heated direct carbothermic reduction of alumina

c. Other conceptual or presently noneconomically competitive processes such as direct carbothermic reduction of clay, sulphide electrolysis, nitride electrolysis, and the Toth Process

10. Technologies of special importance to the U.S. industry and worthy of further action can be grouped in three classes:

a. Incremental improvements in the efficiency of current processes are essential to maintaining the viability of the large existing domestic investment in aluminum smelters and are under way.

b. Retrofittable, high-risk breakthrough technologies being pursued on bench and small pilot scale, partially funded by the Department of Energy's Industrial Energy Conservation Program, Office of Industrial Programs, are steps in the right direction.

c. Alternate production technologies that could make the U.S. aluminum industry economically independent of imported raw materials are the Alcoa Smelting Process and electrically heated direct carbothermic reduction of alumina.

TITANIUM INDUSTRY

1. The U.S. titanium industry presently is not under the same competitive pressure as other strategic metals because major U.S. usage of the titanium alloys is primarily for military applications.

2. By the 1990s, considerable pressure is anticipated from foreign sources as offset agreements are initiated that involve foreign sales of aircraft and engines. The end result of such agreements will be the disincentive of domestic titanium metal producers, forgers, and casters to invest in new equipment or to upgrade existing equipment.

3. The major advantage of the domestic industry is that there exists sufficient capacity to produce metal and hardware to meet national needs for a three-year emergency, which is the basic FEMA goal requirement.

4. The main disadvantage identified is the use of foreign (Australian) primary ore to produce titanium sponge. A cut-off of this source in an emergency would require that the needed sponge come initially from the National Defense Stockpile or be produced from lower grade domestic ore, possibly by diverting some pigment feed material to metal production. On-the-shelf technology for this last option should be ready for immediate implementation in an emergency.

5. Metal producers, forgers, and casters are currently operating at 50 percent, so output could be increased readily without major capital investment. This assumes that the excess capacity will not be dismantled and discarded.

6. Since major engine hardware in many cases requires triple melted material, a capacity increase could be attained by utilizing double-melted material. Available information indicates that reduced service life of components can be expected from such material. Technical data on the feasibility and limitations of this action need to be developed.

7. Improved utilization of material can be realized via near-net-shaping technologies; however, only a limited number of forgers and casters possess a capability for this type of processing. Currently, no incentive exists for others to invest in such equipment. Powder metallurgy (P/M), hot isostatic pressing (HIP) near-net-shape processing is being used for some special shapes, but is still in the development stage.

8. Better buy-to-fly ratios than the current 7:1 to 4:1 or less are possible for most titanium components. Considerable material loss results, mainly in the form of machining chips, because most of this scrap is sold to the steel making industry and is lost to the titanium cycle. Efforts are being made today, via electron beam and plasma arc remelting, to utilize properly identified scrap.

SUPERALLOYS INDUSTRY

1. The domestic superalloy industry is strongly linked to the aerospace industry (especially aircraft), which consumes 80 percent of the total output, while power generation uses 13 percent and chemical processing equipment uses 6 percent.

2. The superalloy industry is not integrated, but consists of three categories which are concerned primarily with

a. Superalloy refining and melting, including production of billet, bar, and sheet stock

b. Alloy remelt processing, including investment casting and forging

c. Engine manufacturing

3. Foreign competition has not been an important factor, but there are signs of Japanese activity and proposals for offshore production by other countries that suggest a developing future problem. Japanese industry has a collaborative activity, unencumbered by U.S.-type anti-trust laws, to develop its high-temperature materials and gas turbine industries.

4. Domestic advantages include the existing technical expertise of an industry largely developed in the United States. There is a close coupling of the industry to the large domestic market and a preference to purchase from domestic sources both for security of supply and to meet stringent industrial and government quality standards.

5. Disadvantages include the historically wide cyclic swings of the industrial market. Also, the fragmented nature of the industry and the smallness of some of the companies involved work against industrial support for needed long-range research.

6. Emergency needs could place extreme demands on the industry because the primary market is aerospace systems and the essential role that superalloys play in such systems.

7. Promising future technologies for the superalloy industry generally involve improvement of the cleanliness of the product and refinement of the microstructure of the current alloys and/or the development of new alloys. An important aspect of the latter is the possibility of developing new superalloy systems that have much lower requirements for the imported strategic materials (e.g., cobalt, tantalum, and columbium). Some technologies that would benefit U.S. industry if properly developed are:

a. Promising technologies for existing alloy systems, such as sophisticated filtering techniques, combined with vacuum induction melting, followed by (1) electron beam remelting or electroslag remelting, and vacuum arc double-electrode remelting, or (2) gas atomization and hot compaction to shapes. Further development of net shape technologies is needed.

b. Promising new alloy systems under development, such as oxide dispersion strengthened superalloys, rapid solidification rate alloys, fiber reinforced alloys, eutectic superalloys, intermetallics, and structural ceramics.

8. Substitution of new materials or changes in superalloys compositions is a high-risk activity, usually involving many years (5-10) of costly qualification testing, and therefore government's continuation of its pivotal role for funding of such efforts is justified.

CONCLUSIONS AND RECOMMENDATIONS

General Conclusions

The following general conclusions relate the domestic metals industry situation:

- The existence of a healthy domestic metals industry that produces a substantial portion of U.S. needs is essential to national security.
- The iron and steel, copper, aluminum, titanium, and superalloy industries differ greatly but share the common problem of a severe and growing subsidized foreign competition. In some cases (steel and copper), this competition is already acute. In the case of aluminum, competitive pressure is now developing. In others (titanium and superalloys), strong coupling to and large market dependence on defense and aerospace give a special character to the current and future industry situation.
- Further decline in the fraction of domestically produced metals seems likely unless the economic factors working to the disadvantage of the domestic industry are modified. The committee was not charged to study economic factors nor was it constituted to deal with such issues in an expert manner. Nevertheless, the committee wishes to emphasize the need for an economically healthy climate if technical advances are to be deployed by the domestic industry.
- Technical advances are important to all of the industries examined, and there are promising areas of research and development. It is important that the domestic industry be

adequately apprised of these opportunities and maintain a competitive edge by being a leader in the use of improved technology. It is also important that the United States remain in the forefront of the development of new technology for the metals industry and not become primarily a purchaser of technology developed abroad. To remain healthy, the U.S.-based metals industries may become increasingly multinational in character to differing degrees depending on the situation in each industry. It is an important asset in the management of such operations from a U.S. base to have the latest technical developments made in domestic laboratories closely coupled to the domestic firms.

- Furthermore, the committee feels strongly that U.S. leadership in developing and advancing new technologies will be meaningless if incentives do not exist or are not generated for introducing and deploying new technologies. A favorable economic climate must be present to make it attractive for investment in U.S. manufacturing industries so that the fruits of these new developments can be put into practice (see National Academy of Engineering, 1985). A fair and equitable free market also is essential for the U.S. industry to compete on an equal footing for a share of the world demand for the product.

General Recommendations

The committee recommends that consideration be given to the following actions:

- Recognize at a national administration level the fundamental importance to the nation of a healthy domestic metals industry, and formulate economic and trade policies that take this into account. These policies should provide incentives for the investments needed to deploy new technologies.

- Maintain support, at least in part through continued federal government involvement by such agencies as the National Science Foundation, National Aeronautics and Space Administration, Department of Energy, Department of Defense, and the Bureau of Mines, a strong program of long-range research and development focused on selected technologies that offer promise of assisting the domestic industry to meet worldwide competition.

- Identify unique advantages available to U.S. industry because of domestic materials availability or technological knowledge and experience that, if properly developed, could improve U.S. industrial production efficiency and cost reduction.

- Monitor closely the domestic strategic materials production capacity to ensure that adequate capability is available to meet emergency needs. Agencies having national security responsibilities (e.g., FEMA, Department of Commerce, and Department of Defense) should examine carefully U.S.-foreign manufacturing agreements that may jeopardize essential domestic production and processing capability.

- Foster increased cooperation among industry, universities, and government laboratories in examining how best to initiate innovative research studies that could provide advantages to the domestic industry, such as the recently established Center for Metals Production at the Mellon Institute of Carnegie-Mellon University (Lautenschlager, 1985). Many other examples of such mechanisms are in operation today, especially in high-technology fields that are believed to be the source of future industries. Similar collaborative mechanisms would be appropriate for advancing certain promising technologies for the metals industries that are high-technology and long-term, and offer important future areas of actvity for the metals industries. Usually these are too high-risk to be undertaken by a single company.

- Reexamine the effects of U.S. information-control actions on the overall competitiveness of the U.S. metals industry in the world markets.

- Identify basic technological areas common to an industry or a group of industries that can be moved forward by cooperative endeavors primarily between academia and industry; these would be in accordance with the new thinking on antitrust issues (National Academy of Engineering, 1985).

- Adopt a consistent and more flexible antitrust policy that does not place U.S. industries at a disadvantage in comparison with international competition.

Additional recommendations focused on specific segments of the metals industry are given in the chapter for each industry.

REFERENCES

AISI. 1983. Fair Trade and Steel. American Iron and Steel Institute, Washington, D.C.

Lautenschlager, S. 1985. American Metals Market/Metalworking News, Center for Metals Production Stresses Collaborative Research, May 27, p. 10.

National Academy of Engineering. 1985. The Competitive Status of the U.S. Steel Industry. The Steel Panel of the Committee on Technology and International Economic and Trade Issues, National Research Council, National Academy Press, Washington, D.C.

Tilton, J. E. 1985. Recent IISA research on the nonfuel mineral industries. Minerals and Materials, A Bimonthly Survey, U.S. Bureau of Mines, February/March, U.S. Government Printing Office, Washington, D.C., pp. 33-38.

2

INTRODUCTION

The eroding domestic industrial base continues to be a major concern to both the military and civilian sectors (Defense Industrial Base Panel, 1980; U.S. Congress, 1983). A number of processing industries have moved offshore in order to be closer to the source of raw materials or to take advantage of less costly foreign labor, less strigent regulatory policy (environmental), and investment environments. As a result, the nation's capacity for mining and processing certain strategic materials is decreasing significantly. In addition, segments of some industries (e.g., steel) have been and are being closed down because production is no longer profitable. If this trend continues, the consequences for national security can be disastrous. Enormous stockpiles for such things as steel and other ferrous metals would be required to meet strategic needs and stockpiling on this scale generally is economically unfeasible.

Even if all the nontechnical problems of the declining industries were solved, they could not be competitive without superior technology. What is needed to stem and possibly reverse the present trends is not an extension of existing technologies but rather completely new technologies. New technologies can be expected to emerge in the high-value, low-volume industries and may have the potential for adaptation to the primary metal industries. One or more of these technologies, perhaps supported by appropriate government policy, could drastically alter the outlook for the future.

The committee has directed its examination primarily to FEMA's nontechnical operations research activity, which needed authoritative background information. A detailed technical analysis is neither possible nor intended in this introductory assessment. The complexity of the problem is clearly shown in the analysis by John E. Tilton reprinted here as Appendix B. This report, therefore, is intended to present the results of a preliminary "broad-brush" review that strives to define the nature and scope of this problem. It is anticipated that in-depth follow-on studies, possibly supported jointly by several government agencies, will be conducted in the future to provide additional details. The committee has been made aware of an ongoing study on "strategic materials" being conducted by the Office of Technology Assessment (OTA), which critically examines many of the issues touched upon in this committee's report. Although the details of the data being assembled by OTA are not available to the committee, the membership of the OTA Advisory Committee and the subjects of some of the commissioned supporting documents indicate that the OTA document will be an excellent complement to this broad-brush survey, supplying the much-needed detailed analysis.

This report was prepared by a committee of industrial and technical experts representing a broad-based balanced view of the fields under examination and the industrial problems of concern. The main objective of the committee was to conduct a technical assessment of emerging and potential technological innovations likely to impact significantly on the domestic processing of the iron and steel,.copper, aluminum, titanium, and domestic superalloy and strategic alloy industries. The goal was to identify applicable technologies already under development or in need of further development, and not necessarily to recommend specific action for each of the industries under study. Developments in the field of advanced processing serve as the basis for identifying and defining innovative processing technologies that could replace existing processes in an efficient and cost-effective manner. Of particular concern is the movement and the loss of domestic industrial processing capacity. Recommendations are made concerning where development efforts on innovative processing should be directed and what government policy actions should be taken in an effort to assist in implementing the most promising innovations.

REFERENCES

Defense Industrial Base Panel. 1980. The Ailing Defense Industrial Base: Unready for Crisis. Report prepared for the House Committee on Armed Services, 96th Cong., 2d sess., Committee Print 29. Washington, D.C.: U.S. Government Printing Office (Report 70-554 0.)

U.S. Congress, House. 1984. Arctic Research and Policy Act of 1984, Title II, National Critical Materials Act of 1984. P.L. 98-373, 98th Cong., 1st sess.

3

THE IRON AND STEEL INDUSTRY

This chapter identifies the technologies that could, if fully developed, enhance the competitive position of the U.S. iron and steel industry. The development of these technologies should both improve the profitability of the industry and ensure that, in the event of a national emergency, a viable U.S. industry of reasonable size will remain to supply necessary steel products.

CURRENT SITUATION

The integrated steel industry in the United States has been undergoing continuous and extensive structural changes since the early 1970s. The appearance of mini-mills and their evolution into large market mills, plus the significant penetration of imported steel into the U.S. market, has put the large U.S. integrated steel producers under severe financial pressure. This pressure has led to the closing of relatively inefficient plant capacity, the merging of companies, and the partial purchase of U.S. companies by foreign producers (National Academy of Engineering, 1985).

It would be futile to attempt to achieve agreement on why this industry, which once dominated world steelmaking capacity (with over 45 percent of worldwide capacity) and had the most up-to-date technology, has lost its overwhelming competitive lead, even in its own market (Barnett and Schorsch, 1983). Some reasons advanced are tax policy on capital formation, *de facto* price control, failure to invest in new technology, high labor costs, lax enforcement of existing trade laws, slow growth of the U.S. market, the unusually strong dollar versus foreign currencies, and competition from foreign-government-subsidized producers abroad. Regardless of which combination of reasons is selected to explain what happened over the past 15 years, the important fact is that the domestic industry has been in decline as a worldwide competitor (American Iron and Steel Institute, 1980). Despite recent heroic measures to reduce costs, close less efficient facilities, and return to competitiveness (see Appendix C), the U.S. industry still faces formidable threats to its survival from the steel industries of both developed and developing nations.

It should be noted that it is not only the U.S. steel industry that is being subjected to the pressures resulting from new capacity now being installed worldwide at a rate in excess of world market demand. The European industry is undergoing severe contraction and rationalization and such changes have already occurred in Britain, France, Italy, Germany, and Sweden. The Japanese industry is under pressure in its own market areas from newer efficient greenfield plants in Korea and Taiwan and, as a consequence, has retired less efficient, older facilities. Because the cost of capital is lower in Japan than in the United States, however, it may be easier for the Japanese industry to adjust to changes in world steel capacity and demand (see Appendix C for details).

Current U.S. raw steel capacity is about 130 million tons, down from a peak of about 160 million tons. Continuing retirement of less competitive facilities probably will reduce raw steelmaking capacity to around 120 to 125 million tons over the next several years (Iron and Steel Engineer, 1984). The remaining integrated steel capacity will not sustain its competitiveness unless it can generate the investment capital needed for technological development and, more important, for the prompt implementation of cost-saving innovations.

PROBABLE FUTURE TRENDS

The trend toward a more distributed U.S. steel industry, with smaller mini-mills and market mills replacing, at least in part, the retired portion of the integrated steelmaking capacity is expected to continue. Although improvements probably will continue to be made in the operation of conventional coke oven and blast furnace installations, the high capital cost per ton of capacity of such plants plus the environmental problems associated with coke plants and the large increment of capacity required for an installation of efficient size (about 4 million tons per year) make it unlikely that any new coke oven and blast furnace facility will be installed in this country (Paxton, 1983). Plants with a capacity of 400 thousand to 1 million annual tons fed by scrap or some type of direct-reduced iron (DRI) and using a continuous caster offer lower capital cost per ton of capacity and a smaller increment of efficient capacity. Such plants are being installed not only in the mini-mills and market mills in this country but also around the world in both the developed and the developing nations (Brown et al., 1984). Most probably they will be the prototype for new steel plants in the next two decades.

TECHNOLOGIES FOR THE FUTURE

In assessing the technologies that might affect these smaller steel plants, it is important to consider the source of iron units for these installations. Without a blast furnace, iron units will have to come from either scrap or DRI. Although scrap would appear to be the most economical choice for iron units in the near future, certain grades of iron and steel that require low residual-element levels cannot be made using scrap alone. Combinations of scrap and DRI, however, can meet all the commercial requirements of sheet and strip steel quality. It would seem that iron reduction based on domestic coal (a very large U.S. resource) would benefit most the strategic needs of U.S. industry. Although coal-based direct-reduction technologies so far have not been as economic as off-shore natural gas-based direct-reduction processes, it would seem that continued development toward an economic coal-based direct-reduction technology would provide the United States with a source of DRI in time of emergency. Most DRI now comes from overseas and is produced by low-cost natural-gas-based reduction processes. As noted above, the development of a coal-based reduction process probably does not look economically attractive today and, therefore, such development might require support for other than economic reasons (e.g., the availability of a domestic capability in an emergency).

Much of the ore now being used by the U.S. industry comes from abroad because of economic reasons. U.S. ores are available but many require concentration and sintering or pelletizing before they can be used in either a blast furnace or a direct-reduction process. The concentration process requires extensive grinding to release the finely divided iron ore from the gangue. The energy efficiency of grinding is notoriously low and the energy cost is correspondingly high. A more fundamental understanding of the grinding process might result in the development of new, more cost-effective grinding processes would make domestic iron ore resources more competitive.

Another technology that might affect the availability of iron units reduced using coal as an energy source is plasma reduction. The use of plasmas to supply energy for iron ore reduction and, possibly, for melting permits low-grade steam coal to be used in power plants. This obviously would eliminate the need for high-grade coking coals, which are becoming less available, as is U.S. capacity for making coke. Substantial basic work already has been done in plasma steelmaking (Upadhya et al., 1984).

Another area for technological improvement is the steelmaking furnace. Electric arc furnaces now produce about 30 percent of domestic steel tonnage (Brown, 1984). These furnaces offer operational and metallurgical flexibility and optimize the scrap usage; they also can provide economical capacity in relatively small increments as compared to the coke oven/blast furnace and BOF combinations. Several integrated producers (LTV Steel Company, Crucible Steel Company, and Bethlehem Steel Corporation) have replaced their blast furnace combinations with electric arc furnaces to increase production scheduling flexibility and to eliminate the environmental problems associated with old coke batteries and the lower efficiencies inherent in smaller, older blast furnaces. Electric furnace development is continuing and is aimed at increasing productivity and reducing costs through more efficient use of electrodes and refractories. These and similar efforts funded by the industry and its suppliers are expected to continue (see Appendix D). In addition, arc furnaces and the electrical problems associated with them are being studied by the industry in cooperation with the Department of Energy (DOE) and the Electric Power Research Institute (EPRI).

The development of plasma arc furnaces and direct-current electric arc furnaces offers potential for improved operating efficiencies. These furnaces, however, are in a relatively early stage of development and their commercial installation probably will not occur for another decade. These advances, however, probably will contribute to electrical efficiency and will accelerate the change from integrated mills to mini-mills or market mills.

All the technologies discussed above (i.e., coal-based direct reduction, more energy-efficient grinding, plasma-assisted reduction and melting, and conventional and direct-current electric arc furnaces) are of interest primarily because they can take particular advantage of the unique coal reserves of the United States. However, to exploit this potential advantage in energy availability and cost will require that technologies be developed to permit the economic extraction, transportation, and use of energy from coal directly in metallurgical processes or to convert the coal into more readily usable electrical energy or fluid fuels. (ONRL's Fossil Energy Materials Program has examined this area quite extensively over the years.)

A means of increasing the productivity of steelmaking furnaces, and at the same time reducing the capital cost per ton of installed capacity, is to reduce the time in the melting furnace by using a second vessel for the refining steps and for making alloy additions. Much attention currently is focused on ladle metallurgy (McManus, 1984). In this procedure, steel from the melting furnace is transferred to a ladle or other secondary vessel where a variety of refining and alloying operations are carried out. In the meantime, the melting furnace is recharged and immediately used again for melting operations, thus eliminating the time normally required in the melting furnace for the refining steps. The capital cost of a ladle refining station is significantly lower than that for a melting furnace. Steps such as decarburization, desulfurization, dephosphorization, and alloying additions are carried out by ladle metallurgy techniques. These procedures also can improve the cleanliness and compositional control of the steel. In the case of stainless steel production, this secondary vessel also can be an argon and oxygen decarburization (AOD) vessel or a vacuum and oxygen decarburization (VOD) vessel.

Continuous casting naturally contributes to steelmaking cost- and energy-efficiency. The heart of the mini-mill or market mill is a billet continuous caster that eliminates the need for large blooming mills to reduce large ingots into bloom and billets for final rolling on smaller mills. Continuous casting is well developed and suitable for the production of bar, rod, and wire products. However, the use of continuous casting for flat-rolled product mills thus far has been restricted to the casting of relatively thick slabs. These slabs must be rolled on high-tonnage hot-strip mills that require huge investments because they must be of very large capacity to be economically sized. The capital requirements for such mills have effectively kept the mini-mill concept from being applied in the flat-rolled portion of the steel business.

If a continuous casting machine could be developed to cast relatively thin slabs, or perhaps even coilable sheet that required only subsequent annealing and cold rolling, the mini-mill concept, involving an electric furnace, continuous caster, and finishing mill could be extended to the manufacture of sheet and strip products. Efforts are now being made worldwide to develop some form of thin slab or strip casting, but it is yet unclear how successful these efforts will be in the near future. It seems, however, that the casting of coilable strip or thin slabs would eliminate a large portion of the capital requirement for producing flat rolled product. Recognizing these gains, the Department of Energy (DOE) has funded several studies of the feasibility of casting strip by a variety of techniques (Bureau of Mines, 1985). Recently DOE awarded a cooperative scale-up contract to U.S. Steel and Bethlehem Steel for the production of coilable sheet directly from molten metal.

The efficient use of any technology will depend on the sophistication of the measurement and control techniques that are used with that technology. The industry has need for better sensors that will operate continuously in high-temperature and other severe industrial environments, so that real-time measurements can be made and fed into on-line control systems. Techniques for the rapid analysis of hot metal, for temperature measurements within hot bodies, and for on-line defect inspection currently are under development (see Appendix D). A host of other potentially valuable real-time control measurements are possible. Although this might be considered by some to be a peripheral area, it is nonetheless a very important one for improving quality and efficiency in the steel industry of tomorrow.

In summary, some of the related technologies that, if developed, would help enhance the competitive position of this country's steel industry vis-à-vis the steel industries of other countries are listed below.

1. Coal-based technologies to reduce energy costs, including mining technology, transportation technology, direct coal reduction technology, liquifaction and gasification technology, and power generation technology

2. Energy-efficient grinding processes

3. Coal-based direct reduction of iron ore

4. Plasma reduction of iron ore
5. Electric arc furnace efficiency
6. Direct-current arc furnaces
7. Plasma arc melting furnaces
8. Ladle metallurgy
9. Thin slab or coilable strip casting
10. Sensors and control systems

TECHNOLOGIES MOST REQUIRED FOR AN EMERGENCY

To assess technologies that would be directly useful in a national emergency, it must first be assumed that the total productive capacity of the domestic industry will not fall below the level of 100 to 110 million tons of raw steel capacity. This quantity would be adequate to fill the expanded needs of an emergency if the domestic civilian consumption requirement were severely limited.

Under these assumptions, the impact of an emergency would involve the curtailment of supplies of iron units (ore, semi-finished product, finished product), chromium, and manganese. Chromium and manganese requirements will have to be filled from stockpiles, both industrial and government-held, and by conservation and substitution since no significant North American sources exist. Over the past several years, the United States has imported 25 to 30 percent of its iron ore requirements and exported about 5 to 7 percent of its output. Thus, net iron ore imports accounted for about 20 percent of requirement (Bureau of Mines, 1985). The net import reliance of other iron units (pig iron, castings, mill products, and major iron and steel products) also has been about 20 percent of apparent consumption (Bureau of Mines, 1983). Thus, a shortfall of these iron units during an emergency could affect adversely the industry's ability to produce at capacity, even at the projected reduced capacity.

Technologies that permit the use of domestic iron units will be required during an emergency. Energy-efficient grinding technologies to permit utilization of domestic ores need to be developed. If electric furnace melting replaces a significant portion of the oven/blast furnace/BOF capacity, increased scrap and direct-reduced iron will be required. Technologies employing natural gas, coal-based, and plasma-assisted direct reduction could supply the iron units from domestic ores to feed the electric furnace melting capacity. Electric furnace melting also can be deployed more quickly than coke oven/blast furnace/BOF complexes.

Utilization of bottom-blowing techniques and secondary top blown oxygen in BOF vessels provides additional flexibility in the melting of larger quantities of direct-reduced iron or scrap in these vessels. This can reduce the demand for blast furnace hot metal in a period of limited supply that results from a shortage of either blast furnace or coke-making capacity. Ladle metallurgy techniques also are able to increase steelmaking capacity rapidly and at low capital cost.

The implementation of continuous casting can materially affect available capacity. The available yield improvement adds about 10 percent more finished product per ton of raw steel capacity and significantly reduces the energy required to produce a ton of finished product. Continuous casting certainly should be maximized in any emergency.

The list of technologies summarized above recognizes that recent and future changes are caused by forces over which the industry itself has little or no control. Also, the development of these technologies may be a necessary, but are an insufficient, condition for the survival of the industry. These developments will stagnate if the industry does not have the capital to install them. It may prove even more harmful if foreign steel industries with more investment capital are able to adopt these developed technologies faster than the U.S industry. Technology in the steel industry is available to anyone worldwide because there are no technological secrets. Whoever has the capital assets to deploy a new technology will use the best available technology first and, therefore, be the most competitive industry. The arguments on how to attract capital have been discussed by others (Barnett and Schorsch, 1983; Behr, 1984). All agree that no technological developments can improve the competitiveness of the U.S. steel industry, or keep it competitive, unless the industry can attract capital to install new technologies. Thus, the capital issue must be addressed.

OTHER PERTINENT ISSUES

Some other issues related to the steel industry's ability to respond to emergency conditions can be discussed. The decline in U.S. competitiveness means that very little new capacity has been added to the industry. In fact, as stated above, capacity in the U.S. steel industry has shrunk over the past several years and is expected to shrink even more. As a result, the related infrastructure of furnace and mill builders, foundries, and engineering and construction firms that serviced a once healthy U.S. steel industry also have suffered. In a national emergency, if the United States wanted to quickly install new steelmaking capacity, it would be hard-pressed to find domestic suppliers of the hardware needed for such an expansion. The industry probably would have to go overseas to purchase furnaces, continuous casters, rolling mills, and some of the control systems required.

In addition, it must be recognized that for a number of years the steel industry has not been attractive to the young, bright, energetic, technically trained people who are vital to a strong competitive industry. Any expansion of the industry in time of emergency will require such people in addition to the necessary technology and equipment. It should be recognized that training the people for an expanded industry may take a decade.

SPECIALTY STEELS

This discussion has thus far concentrated principally on the integrated steel industry and mini-mills or market mills, but another segment of the domestic industry--the specialty steel industry--is important and is technologically much healthier in comparison with its overseas competitors, than the U.S. integrated steel industry. Recent reports recognized that the U.S. specialty steel industry is technologically equal, if not superior, to its overseas competitors (Hirschhorn, 1980; Old et al., 1981). The specialty steel industry also has tended to be more profitable and, so far, has kept abreast of relevant new technological developments. Thus, it currently does not have the same problems as the integrated portion of the industry. It is modern and, in recent years, its capacity has not been seriously strained by demand (Table 3-1).

TABLE 3-1 Stainless and Alloy Tool Steel Industry (Capacities and Shipments in Thousands of Tons)

	Stainless			Alloy Tool Steel		
Year	Shipping Capacity[a]	Shipments	Capacity Percent Utilization[b]	Shipping Capacity[a]	Shipments	Capacity Percent Utilization[b]
1982	1,601	809	44.7	205	45	22.8
1981	1,564	1,041	60.2	231	67	34.5
1980	1,472	1,005	60.9	227	79	40.6
1979	1,481	1,215	73.8	227	96	44.9
1978	1,447	1,060	68.9	228	92	43.5

[a] Practical Capacity - Based on greatest level of output a plant can achieve.
[b] Capacity Percent Utilization is affected by inventory level fluctuations.

SOURCE: U.S. International Trade Commission (1983)

It must be recognized, however, that in 10 or 20 years the specialty steel industry might be in the same position as today's integrated industry relative to worldwide competition (Pitler, 1982). If it continues to be subject to the predatory assaults on its markets that occur from foreign government-subsidized specialty industries, its ability to reinvest could be affected and it too could decline competitively. Events in world steel trade are well documented, but what is not so well documented is the gradual erosion of a healthy industry's ability to reinvest in its future as profit margins are eroded. When market growth is supplied from overseas, new capacity cannot be economically justified, and this significantly reduces an industry's ability to invest in a new technology as it fights for survival. U.S. specialty steelmaking capacity is probably as healthy today as it ever has been, but its status 10 to 20 years from now will depend on government policy as much as on intelligent use of technology.

CONCLUSIONS

This chapter briefly reviewed the current status and future trends for the steel industry in this country. How well the industry will be able to serve the country in an emergency cannot be defined in detail without knowing the specific needs arising from such an emergency. It is projected that the future U.S. integrated steel industry will certainly be smaller and more distributed geographically with each producing location being more specialized in terms of product.

A large proportion of steelmaking capacity will be served by the mini-mill and market mill producers. Various technologies which, if developed, could help improve and maintain competitiveness, reduce capital costs for capacity additions, provide for smaller increments of added or replacement capacity, and accelerate the trend toward plants that are more geographically distributed and produce specialized products were listed earlier.

Investment capital and international trade issues also must be addressed. The now technologically competitive specialty steel industry will not be sustained unless these issues are given attention.

There is no magic technological "black box" that will, by itself, transform a mature capital-intensive industry into a competitive superstar, especially when the technology flows easily throughout the world. The response of each nation to the current worldwide overcapacity in the steel industry will determine how that nation's industry develops, changes, or disappears.

REFERENCES

American Iron and Steel Institute. 1980. Steel at the Crossroads: The American Steel Industry in the 1980s. Washington, D.C.: American Iron and Steel Institute.

Barnett, D. F., and L. Schorsch. 1983. Steel: Upheaval in a Basic Industry. Cambridge, Massachusetts: Ballinger Publishing Co.

Brown, J. W. 1984. Growth of arc furnace steel expected to continue. Iron and Steel Engineer 61, 4 (April):88.

Brown, J. W., R. L. Reddy, and P. J. Solomon. 1984. The future of direct reduced iron in the industrialized world. Metallurgical Plant and Technology: 10-21.

Bureau of Mines. 1983. Mineral Commodity Summaries, p. 78. Washington, D.C.: U.S. Department of Interior.

Bureau of Mines. 1985. Federally Funded Research. Minerals and Materials, A Bimonthly Survey. February/March. Washington, D.C.: U.S. Government Printing Office.

Hirschhorn, J. S. 1980. Technology and Steel Industry Competitiveness. Washington, D.C.: Office of Technology Assessment.

Iron and Steel Engineer. 1984. The steel industry--forging a recovery. Iron and Steel Engineer, 61, 4 (April).

McManus, G. 1984. Ladle metallurgy moves to a more active state. Iron Age (March 19).

Old, B. S., A. H. Frederic, and M. Tenenbaum. 1981. Brief Technology Assessment of the Domestic Steel Industry. Prepared for Lehigh University and the U.S. Department of Commerce under Project 99-26-09886-10. Washington, D.C.: January.

Paxton, H. W. 1983. Future materials research in the steel industry. Paper presented at the Materials and Science and Engineering Symposium, University of Texas, Austin, Texas, October 17.

Pitler, R. K. 1982. Specialty steels: prospects for the 80's. Paper presented at the 4th Technology Briefing, Focus on Materials Technology for the 1980s, Battelle Columbus Laboratories, Columbus, Ohio, November 9-10.

National Academy of Engineering. 1985. The Competitive Status of the U.S. Steel Industry. A Study of the Influences of Technology in Determining International Industrial Competitive Advantage. The Steel Panel of the Committee on Technology and International Economic and Trade Issues. National Research Council, National Academy Press, Washington, D.C.

U.S. International Trade Commission. 1983. Stainless and Alloy Tool Steel. Publication 1377. Washington, D.C.: U.S. Government Printing Office.

Upadhya, K., J. J. Moore, and K. J. Reid. 1984. Application of plasma technology in iron and steelmaking. Journal of Metals 36(2):46-55.

4

THE COPPER INDUSTRY

For many years the abundance of copper resources in the United States provided the underpinning for the world's largest copper industry. U.S. leadership in world copper production began late in the nineteenth century and continued virtually unchallenged for almost 80 years. In 1950, the United States accounted for 35 percent of world copper output. Over the past 30 years, however, U.S. dominance in the world copper industry gradually diminished as several other countries steadily expanded production. By 1979, the United States, although still the world's largest producer, had seen its share of world mine production decline to 19 percent of the world total.

CURRENT STATUS OF THE INDUSTRY

Since 1979, the rate of erosion of the U.S. position as the world's largest copper producer seems to have accelerated (Table 4-1). Several developing-country copper producers continue to operate their mines at near capacity despite faltering world demand (Figure 4-1). As a result, U.S. copper companies, which are among the world's highest-cost producers, have had to reduce their output, temporarily close numerous facilities, lay off several thousand employees, and suffer large financial losses. Simultaneously, imports of refined copper have continued to increase. In 1983, imports of refined copper amounted to almost 500,000 metric tons and accounted for 25 percent of U.S. consumption. As a result, the competitive cost position of domestic producers has become a matter of utmost concern. Relief has been sought through U.S. legislative initiatives for restraints on foreign copper production (HR1520 and S627). In comparison with most other major copper-producing countries, U.S. industry has three major competitive disadvantages:

1. The low ore grade of U.S. reserves (averaging 0.3 to 0.8 percent copper content)--about 30 percent less than the world average. This means that domestic producers must mine and process considerably larger volumes of ore per unit of copper output.

TABLE 4-1 U.S. Production, Exports, Imports, Change in Stocks, and Apparent Consumption of Refined Copper, 1974-1983 (thousands of metric tons)

	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983[a]
U.S. Production										
Primary refined	1,501.1	1,309.4	1,396.4	1,357.3	1,499.1	1,515.4	1,210.9	1,544.0	1,227.1	1,212.1
Secondary refined[b]	438.6	334.9	380.2	349.6	420.1	498.5	515.1	493.6	467.5	410.0
Total[c]	1,939.6	1,644.3	1,776.7	1,706.9	1,919.2	2,013.8	1,725.9	2,037.6	1,694.6	1,622.2
Exports	114.8	156.4	101.5	46.7	91.9	73.7	14.5	24.4	30.6	72.0
Imports for Consumption[d]	275.5	128.9	345.9	360.9	402.6	203.9	426.9	330.6	258.4	498.5
Change in Stocks[e]	(146.0)	(122.0)	76.0	26.0	(108.0)	(182.0)	62.0	171.0	232.0	45.0
Apparent Consumption[f]	2,246.4	1,738.8	1,945.1	1,995.1	2,337.9	2,326.0	2,076.4	2,172.8	1,690.5	2,003.6
Ratio of Imports to										
Production (%)	14.2	7.8	19.5	21.1	21.0	10.1	24.7	16.2	15.3	30.7
Apparent Consumption (%)	12.3	7.4	17.8	18.1	17.2	8.8	20.6	15.2	15.3	24.9

[a] Estimated.

[b] Amounts for 1974-1976 include all secondary copper recovered from old scrap; amounts for 1977-1983 include only copper recovered as refined copper by primary and secondary plants from copper-based scrap.

[c] Data may not add to totals due to rounding.

[d] Imports from U.S. Department of Commerce; 1977 figure is different from Bureau of Mines figure.

[e] Decline in parentheses. Stocks of refined copper held by producers, wire rod mills, brass mills, miscellaneous other plants, and New York Commodity Exchange.

[f] Apparent consumption equals production minus exports plus imports minus net change in stocks.

SOURCE: Data from various Bureau of Mines publications and from the U.S. Department of Commerce's import statistics.

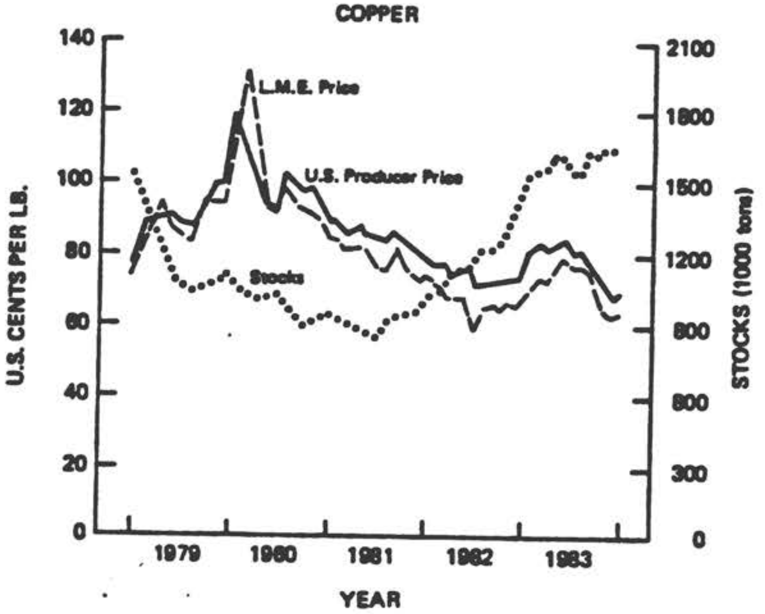


FIGURE 4-1 Copper stocks and price, 1978-1984. From Noranda, Inc. (1983).

2. The high labor cost (estimated at 40 to 50 percent of the total operating cost) per unit of copper producer. This is due to the high standard of living in the United States rather than to domestic labor productivity, which generally is higher than in other major copper producing countries.

3. The enactment and enforcement of stringent environmental legislation, particularly the Clean Air Act and amendments. This has increased the capital investment and operating costs of U.S. copper producers and has made them even less competitive with producers in less developed countries. In addition to the above special disadvantages, the U.S. copper industry, like all other producers, requires the large consumption of progressively costlier energy; about 100 million Btu are required to produce a ton of copper.

The conditions described above do not seem to bode well for the future of the U.S. copper industry. From the viewpoint of global resources, the U.S. reserves of copper amount to about 90 million tons of contained metal or 18 percent of the known world total and are surpassed only by those of Chile. Futhermore, even with a modest projected rate of growth in copper demand of only 1.1 percent; U.S. consumption is forecast to total about 2.8 million metric tons in the year 2000. Despite its huge reserves and the anticipated growth in demand, there are those who believe that the U.S. copper industry may not survive to the end of the century. Some of its competitors in the less developed nations feel that the United States should leave the "low technology" industries, such as base metal production, to them and should concentrate on "high technology" industries, such as metal fabrication and product manufacturing.

Copper is an important strategic material for national defense. The Department of Commerce estimates that U.S. military usage of copper in ordnance alone during the Vietnam War amounted to 10 percent of total domestic consumption. Even this quantity understates the amount of metal that would be required in the enormous industrial mobilization effort necessary to support national defense programs in a long-term emergency situation. The estimated needs of the nation in such a situation are exemplified by the current copper stockpile goal set by FEMA (1984) at 1 million tons of metal. (Today the quantity of copper in the National Defense Stockpile is only about 30,000 tons.)

Thus, it seems highly questionable from economic, political, and strategic considerations whether the U.S. can afford, on a long-term basis, to depend on foreign sources for this commodity, which is basic to our needs. Greater attention should be devoted to developing and implementing new technologies that may help maintain the competitive position of domestic producers. As a result, the emphasis of this study is on identifying and describing major innovative technologies which may

- during peacetime, improve the viability of the U.S. copper industry by decreasing the operating costs (e.g., by improving labor and equipment productivity, increasing metal yield and energy efficiency) and by decreasing the capital requirements for new facilities so that modernization of obsolete mills and smelters can occur; and,
- during a national emergency, provide alternate methods of copper production which, though they may not be competitive during normal times, could be activated on short notice.

The following discussion of the major segments of the copper production flowsheet will address both of the above questions.

FORECAST OF TECHNOLOGICAL CHANGE

The U.S. Bureau of Mines (BOM) recently developed a forecast of expected technological change in the copper industry over the next 20 years (Sousa et al., 1983). The Bureau's forecast was developed from a canvass of the views of over 60 technological experts in various phases of the copper industry and provides an interesting perspective on the expected future role of exploration and other technology in the industry. Table 4-2 summarizes some of the technology "diffusion forecasts" that were developed in the Bureau's study. These forecasts

TABLE 4-2 Forecast Diffusion (at 50 percent cumulative probability) of Innovative Technologies in the U.S. Copper Industry, 1980-2005 (thousands of metric tons)

	Scenario[a]	1980-1985	1985-1990	1990-1995	1995-2000	2000-2005
Exploration						
Geologic models	Opt	150	250	650	1,350	2,500
	Pess	75	200	200	400	500
Integration of multidisciplinary data	Opt	50	350	800	1,000	2,000
	Pess	50	250	250	350	750
Multispectral satellite scanning (LANDSAT)	Opt	175	225	475	675	750
	Pess	20	30	125	150	200
Mining						
Overland belt conveyors	Opt	260	500	725	975	1,150
	Pess	180	250	275	275	325
On-line (automated) production monitoring and control	Opt	450	650	900	1,500	2,500
	Pess	400	400	450	700	1,000
In-situ solution mining	Opt	60	120	200	300	400
	Pess	40	45	105	115	175
Beneficiation						
Autogenous and control of concentrators	Opt	250	450	800	2,000	2,500
	Pess	350	425	450	550	575
Improved selectivity of the beneficiation process	Opt	100	200	450	600	1,000
	Pess	100	200	250	350	600
Smelting						
Continuous smelting and converting	Opt	275	325	600	750	1,400
	Pess	275	375	410	525	525
Flash smelting	Opt	375	825	1,000	1,400	1,550
	Pess	375	575	675	700	725
Hydrometallurgical processes (sulfide ores)	Opt	100	200	300	525	540
	Pess	100	140	330	420	510
Solvent extraction-electrowinning	Opt	200	225	225	350	500
	Pess	200	225	225	275	300
Refining						
Automation of refinery operations	Opt	225	250	400	700	1,000
	Pess	225	250	250	400	700
Periodic current reversal	Opt	250	300	400	400	600
	Pess	250	260	300	400	400

[a] Opt = optimistic scenario; Pess = pessimistic scenario (see Table 4-3).

SOURCE: Sousa et al. (1983)

represent the experts' consensus concerning the physical quantity of copper expected to be discovered, mined, or processed by each technology on an annual basis through the end of the forecast period. The forecasts were developed under both optimistic and pessimistic scenarios(Table 4-3) and are given in Table 4-2 at the 50-percent confidence level.

Exploration

Most mining companies consider exploration to be an activity essential to maintaining the lifeblood of the company and, in general, they spend a great deal more on exploration than on research and development (R&D) on processes and products. There is general agreement that most of the more easily identified surface or near-surface deposits of copper have been found, and each new discovery is becoming progressively more costly and difficult to exploit.

The Bureau's forecast showed that future developments in copper exploration are expected to concentrate on techniques that facilitate analysis and interpretation of geologic and other data relating to copper deposits rather than on technologies for the collection of additional data. In particular, improved geologic models would facilitate the understanding of the vast quantities of data collected in the exploration process and lead to better prediction of deposit location and ore body parameters. Furthermore, the integration of multidisciplinary deposit data should become increasingly amenable to computerized methods. Until recently, proper interpretation of the huge amounts of exploration data gathered could be accomplished only manually.

Mining

Most copper in the United States is produced by open pit mining in which mobile drills are used to fracture the ore body and shovels to load trucks that convey the ore to crushers and the "waste" to dumps. The copper technology forecast described above indicated that future developments in copper mining are expected to be largely evolutionary extensions of existing equipment and systems. The principal mechanical advance expected is the gradual adoption of continuous mining systems consisting of movable conveyor belts and crushers that significantly reduce truck haulage at open pit copper mines. As mines deepen and ore face-to-concentrator distances increase, the attractiveness of overland belt conveyors grows. The widespread adoption of automated production monitoring and control systems also is expected.

In recent years, there has been considerable interest in the use of in-situ mining methods in which a leach solution is injected into a copper deposit and the metal-rich solution is subsequently recovered and processed. Many technical problems remain to be solved before in-situ methods can be adopted on a significant scale; a major obstacle is the

TABLE 4-3 Assumed Scenarios for the Business Environment

	Optimistic	Pessimistic
Environmental regulations: air and water quality health and safety	Same standards, relaxation in implementation and enforcement, and faster permitting.	More rigid standards, more rigid enforcement, and more rigid permitting.
Access to federal lands	Reevaluation of withdrawn lands with objective of multi-use.	Status quo and further withdrawals.
Support of U.S. domestic industry	Yes	No
Demand growth world-wide for copper	Greater than 3%/year	Less than 2%/year
Return on investment (after taxes)	Greater than 15%	Less than 5%
Infusion of capital for R&D and implementation of new/advanced technologies	Yes	No
Ability of personnel and organizations to assimilate new technology	High	Low

SOURCE: Sousa et al. (1983).

very low recovery of copper unless means are found to increase the permeability of the rock. At the current rate of development, this technology will not become a significant source of copper in the near future.

Open pit mines require constant maintenance and development. In a mine that is abandoned for more than a few months, access roads and working benches become unusable and unsafe. Also, mines and mills usually are located in fairly remote areas and, consequently, develop their own manpower pool and infrastructure. A long shut-down period may make it difficult to reassemble and retrain the labor force needed to operate the mine. Under normal conditions, up to a year may be required to re-open a mine that has been closed for a considerable length of time because the unused infrastructure may have fallen into serious disrepair during the idle period. In a national emergency, however, skilled labor provided on a short-term basis from other open pit mining operations conceivably could reduce by half the time required to re-open the mine.

Beneficiation

Low grades of ore cannot be economically transported over long distances. Consequently, the mills that grind and float the ore to produce a copper concentrate are invariably located within a few miles of the mine. The recent Bureau of Mines (BOM) technology forecast indicated that no substitute is on the horizon for the basic beneficiation technology currently in use in the United States. The principal technological advances expected include increased use of automated process controls, gradual adoption of semi-autogenous grinding mills in place of conventional ball and rod mills, and improvement of the selectivity of the flotation process through a better understanding of the physicochemical phenomena involved.

Automated process controls today utilize the wide array of sensors available for measuring the major process variables in grinding and flotation circuits. Information thus detected enables concentrators to operate closer to peak efficiency while still ensuring maximum metal recovery. In semi-autogenous grinding, the ore is self-grinding in the mills, which reduces the use of grinding media such as steel balls or rods. Semi-autogenous grinding eliminates secondary and tertiary crushing and, thus, allows for more economical use of electric power.

Smelting and Refining

Because copper concentrates contain 20 to 30 percent copper, smelters need not be located near the copper mines. In fact, the Japanese copper industry has flourished by importing concentrates and smelting, refining, and fabricating the metal into finished products. In contrast to their U.S. counterparts, Japanese and European copper smelters have long controlled sulfur dioxide emissions, mainly because they possessed the advantage of nearby markets for the by-product sulfuric acid that is produced. Relatively little was done in the United States to control sulfur dioxide emissions until the early 1970s, after which nearly a quarter of the industry's capital expenditures went toward installing emission control systems to improve the capture of sulfur dioxide.

Some copper industry specialists have suggested the construction of a "super-smelter" in this country. Such a facility, located on a seaport and near sulfuric acid markets, could process the concentrates of more than one company. At a time when most copper companies are fighting for survival, however, such an imaginative but expensive alternative is impractical.

A number of hydrometallurgical processes have been proposed as alternatives to conventional pyrometallurgical smelting techniques. Hydrometallurgical processes are based on the dissolution of the copper concentrates by acids or other suitable solvents and the subsequent separation of pure copper from the solution by means of chemical or electrochemical reactions. Although the use of hydrometallurgical techniques in treating copper oxide ores is well accepted, numerous technical obstacles have prevented their widespread application to the much more prevalent copper sulfide ores. Such processes have been found to be very energy-intensive and costlier than the conventional smelting process. The latter involves smelting the concentrates in a reverberatory furnace and then converting the resulting "matte," a mixture of copper and iron sulfides, in a furnace by injecting air into the melt.

The search for more energy-efficient smelting technologies, which also provide for better environmental control, has resulted in the development of several novel smelting processes. The BOM technology forecast notes that, assuming normal economic conditions, a high probability exists that by the end of this century most U.S. smelters will have adopted one of three processes: the Outokumpu flash smelting process, which has already been installed at the Phelps-Dodge Hidalgo smelter; the INCO flash-smelting process, which was installed at ASARCO's Hayden, Arizona smelter; or the Noranda continuous smelting and converting process, adopted at Kennecott's Utah copper smelter. Hydrometallurgical processing is expected to be limited to oxide ores or to the recovery of copper from waste dumps by heap leaching.

Since refining accounts for less than 10 percent of the total cost of producing copper, it generally is not considered by producers to be a priority area for investment in innovative technology. Hence, the only major advance expected in this area over the next 20 years is the gradual automation of a variety of refinery operations.

Recycling

Recycled scrap typically accounts for over half of the U.S. consumed copper raw materials. Of the U.S. total copper consumed in 1983, one-fifth consisted of old scrap, and about one-third was prompt-industrial or new scrap. The BOM survey of recycling experts, however, revealed that little can be expected in the development and adoption of new recycling technologies until the price of copper scrap improves considerably.

Three innovative recycling technologies frequently considered for commercialization include cryogenic processing methods, eddy currents, and shredding. Cryogenic processing methods subject scrap to very cold temperatures at which certain materials become very brittle while others remain malleable; this phenomenon also can be used to differentiate the valuable from the unusable materials contained in the scrap. Eddy currents utilize electrical current to produce an "anti-magnetic" force in certain materials; this force can be the basis for separating and recovering copper and certain other nonferrous metals from scrap. Shredding of items such as condenser tubes or radiators permits the easy removal of dirt and debris, thereby yielding clean, contaminant-free feed materials for further processing.

COMMENTS ON EXISTING TECHNOLOGY

Copper ore beneficiation, smelting, and refining, are capital-intensive processes. They require massive expenditures for equipment and working capital before production can commence. It is estimated that a "greenfield" plant built today would cost about $10,000 per annual ton of copper capacity. Of this amount, about $3,000 would be required for the smelter, $1,000 for the refinery, and the remainder for the mine/mill complex. In addition, copper mines are usually massive projects that have their own infrastructure. When operations cease, the community that was created to operate them is effectively dismantled. Even partial curtailment of operations can result in social disruption in the community. It therefore is not practical to consider "moth-balling" copper plants with the objective of maintaining them so that they can be reactivated on short notice in an emergency.

"Moth-balling" a mine and mill operation would require continuous maintenance of the equipment and facilities. A start-up period of up to one year, depending on the particular circumstances, would be required to reactivate the mine. In the case of the smelter and refinery, the volume of equipment and manpower requirements is considerably smaller and, therefore, the start-up period should be shorter; again, considerable maintenance activities would be required during the shutdown and a specific plan for re-activation would be necessary.

A review of existing and expected technological changes indicates that no prospects exist today for radical new processes that can be used to augment domestic copper production on short notice. However, innovative processing alternatives do exist that are easier to shut down and re-activate (e.g., the novel flash-smelting and bath-smelting technologies) than the conventional reverberatory furnace. Such alternatives do not change significantly the overall industry picture.

CONCLUSIONS AND RECOMMENDATIONS

The base of the U.S. copper industry has been eroded substantially in recent years and, unfortunately, this trend is expected to continue. The special disadvantages of the industry with regard to foreign competition are: (1) the relatively low grade of domestic ore, (2) the high cost of manpower, and (3) the need for domestic environmental controls associated with the U.S. standard of living. These disadvantages could be overcome by optimal use of superior technology. By this is meant the sum total of processes, equipment, and operating know-how. Regrettably, however, the domestic industry in general is not in the forefront of copper technology (e.g., three innovative smelting technologies implemented in the United States in recent years were developed abroad).

In contrast to the aluminum industry, discussed elsewhere in this report, the domestic copper industry has yet to identify a number of critical operating performance factors that it could work on and improve year by year. In addition, despite the great progress made in other U.S. industries in the areas of automation and computerization, most domestic copper processing plants are not making more effective use of such tools than their competitors in less developed countries.

At the present time, the effort expended on research and development by the domestic copper industry is at its lowest level in many decades. Most companies have either ceased research activities or curtailed them to the minimum required for maintaining operations. It is doubtful, therefore, whether the existing R&D groups can provide, on their own, the impetus required to "leapfrog" the competition by ensuring that the overall quality of the technology used in U.S. copper operations counterbalances the special disadvantages mentioned above. Also, because of its poor economic condition, the domestic copper industry presently supports very little academic research designed to improve copper technology. An area that in recent years has been receiving increasing attention as an extraction process is biotechnology. This technology for extracting specific ion species, has the potential of selective metal separation from low-grade ore and from mine and metals processing wastes in an energy-efficient, low-cost, and environmentally acceptable manner.

The inescapable conclusion is that unless the government finds ways to stimulate research that is addressed specifically to advancing domestic mineral resources and processing, the very survival of the copper industry is threatened. There are practical reasons why the government should invest its money and effort. The copper goal for the U.S. National Defense Stockpile has been established at 1 million tons. If, as discussed earlier, it is not practical to "mothball" mines and plants for use only in an emergency, the government may find it much less expensive to take whatever steps are needed to maintain a viable domestic copper industry than to build huge stockpiles of metal; available production capacity reduces the stockpile goal.

The government may revive R&D in this area through existing agencies, such as the National Science Foundation or the Bureau of Mines, by sponsoring joint industry-university institutes dedicated to copper technology or by establishing appropriate centers of industrial technology. Such efforts must be focused closely on the needs of the specific industry and not dispersed on a myriad of projects proposed by individual researchers. Recently enacted legislation (i.e., The Mining and Mineral Resources Research Institute Act, P.L. 98-409, signed on August 29, 1984) provides for such a cooperative university-industry effort.

The areas that should be addressed by such R&D groups include the following:

1. Computerization and automation of the conventional methods for mining, mineral processing, and metal extraction of copper with the objective of increasing productivity and compensating for the relatively high cost of manpower in the United States.

2. Research and development of the in-situ, or solution, mining of domestic ores. Major breakthroughs are necessary to enhance the permeability of deposits and increase metal recovery. In addition, a better understanding is required of anisotropic flow through mineralized zones and of environmental effects.

3. Advancement of dump, heap, and thin-layer leaching of ores to bypass the costly step of mineral beneficiation and development of bacterial strains (biotechnology) capable of sustaining higher temperatures, acidities, and toxic metal concentrations. Biotechnology has the potential of selective metal extraction from low-grade ores and from mine and metal processing wastes.

4. Development of size reduction techniques that can produce narrower size distributions at much higher energy efficiencies. Current processes use only 2 percent of the energy input in creating new surfaces and generate excessive amounts of very fine particles.

5. Processing of polymetallic minerals to produce economically a number of metals from a bulk concentrate.

6. Improvement of existing mining and ore sorting techniques to increase their selectivity and reduce the amount of waste sent to the concentrator.

7. Development of a process for the direct smelting of copper to eliminate the use of converters and reduce the cost of environmental control, which is saddling the U.S. industry but not its major foreign competitors.

REFERENCES

FEMA. 1984. Stockpile Report to the Congress, October 1953-March 1984. FEMA 36/October, Government Printing Office, Washington, D.C.

HR1520 and S627. 1985. National Copper Policy Act of 1985. Introduced by both the Senate and the House of Representatives on March 7, 1985. 48 pp.

Noranda Mines. 1983. Annual Report. Noranda Mines, Ltd.

Sousa, L. J., A. Weiss, N. Themelis, and N. Guernsey. Assessment of projected technological innovation in the U.S. copper industry. Mining Engineering 35, 10 (October): 1402.

5

THE ALUMINUM INDUSTRY

In the past decade, world economic and political trends have resulted in significant structural changes in the aluminum industry. This chapter reviews these changes and examines trends that will affect the future of the domestic industry.

PRESENT STATUS

The domestic industry has become international in scope, and there is a trend in the developed countries toward divorcing primary metal production from product fabrication that could reduce U.S. independence in aluminum production. Some major political and economic factors contributing to these trends are discussed below.

High Demand Rate Increase

In 1950 there were three primary aluminum producers in the United States--Alcoa, Reynolds, and Kaiser--and another thirteen worldwide. Between 1965 and 1970, these three, along with Alcan in Canada and Pechiney and Alusuisse in Europe, controlled more than 70 percent of the Western world's primary aluminum production capacity. By 1984, the number of primary producers had climbed to 83, and the same six major aluminum companies owned only slightly over 50 percent of the primary production capacity (Figure 5-1). Since total production rose rapidly during this period, significant growth took place in the United States but far greater expansion occurred abroad. The principal reason was that the demand for aluminum simply exceeded the capital availability and possible growth rate of the major producers and their raw materials supplies; during this period, the rate of increase of Western world primary aluminum shipments exceeded 8 percent compounded annual growth--more than twice the growth rate of the United States gross national product.

The traditional sources of bauxite and alumina were no longer sufficient to meet this increase in demand and the development of new sources by both domestic and foreign producers became necessary.

Figure 5-2 shows that total bauxite production was 7.1 million tonnes in 1950 with the United States and Europe providing about one-third and the remainder coming from the Carribean area. By 1980 total production had increased tenfold to 81 million tonnes with the U.S. output being virtually negligible and Europe, Guyana, and Suriname reduced to about one-fourth of the production. It should be noted that the giant share in 1980 was provided by Australia, a very distant source of supply. Jamaica and Guinea were new sources that together nearly equal Australia. By 1980, the bauxite supply was definitely international and, with Brazilian and additional Australian capacity coming on line, the trend continues (Ligon, 1984).

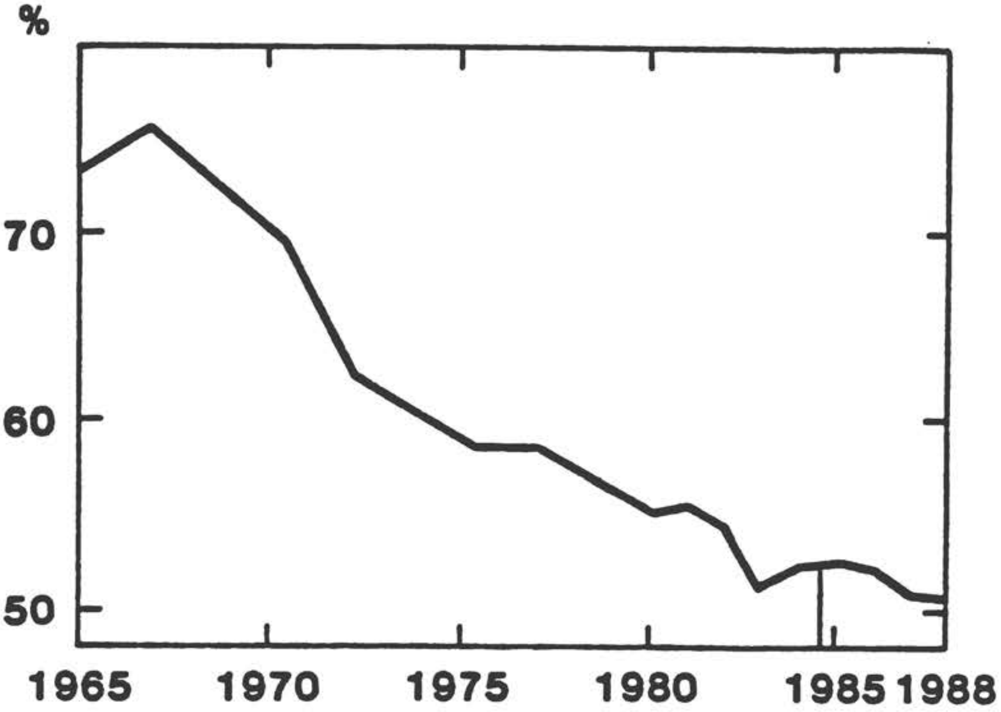
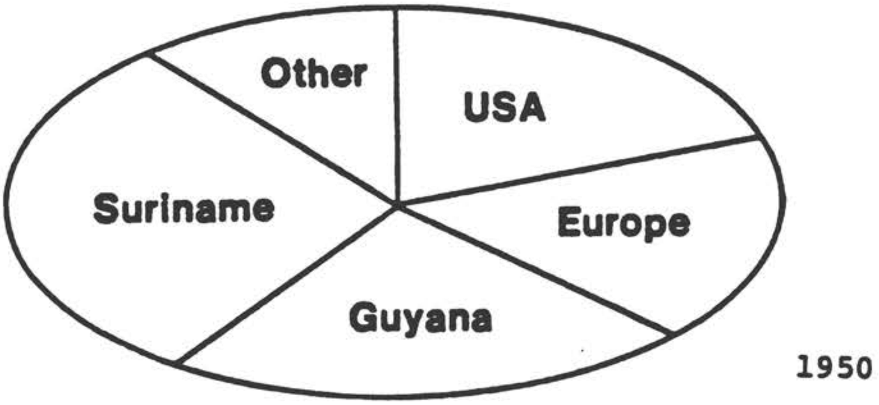


FIGURE 5-1 Primary aluminum capacities of the major Western producers (Alcoa, Alcan, Reynolds, Pechiney, Kaiser, Alusuisse). From Ligon (1984).

Coupled with the internationalization of bauxite sources has been the desire of those who have these reserves to integrate forward for greater profit by refining the bauxite to alumina (Al_2O_3), the actual feed to the smelting cells, close to the mine. Bauxite imports into the United States are gradually being replaced by alumina imports, which in 1983 constituted 35 percent of the cost of aluminum ingot (Figure 5-3) (Castera, 1984).



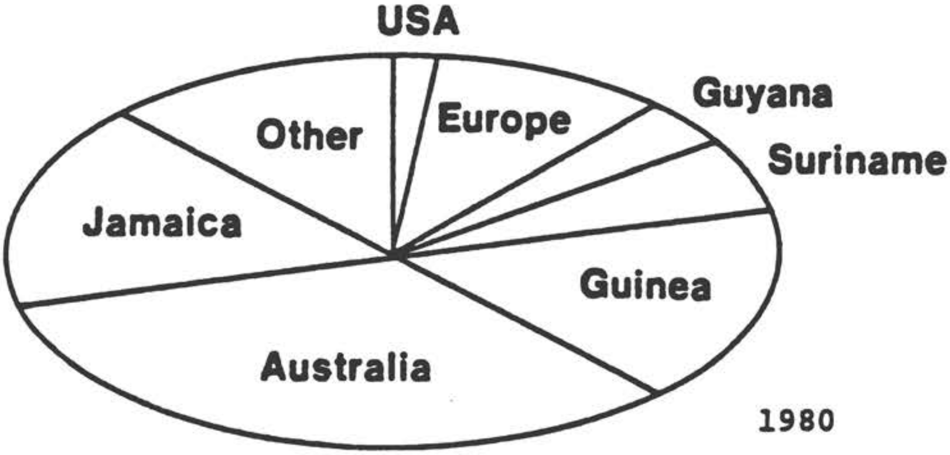


FIGURE 5-2 Bauxite production in 1950 (7.1 million tonnes) and 1980 (81.0 million tonnes). From Ligon (1984).

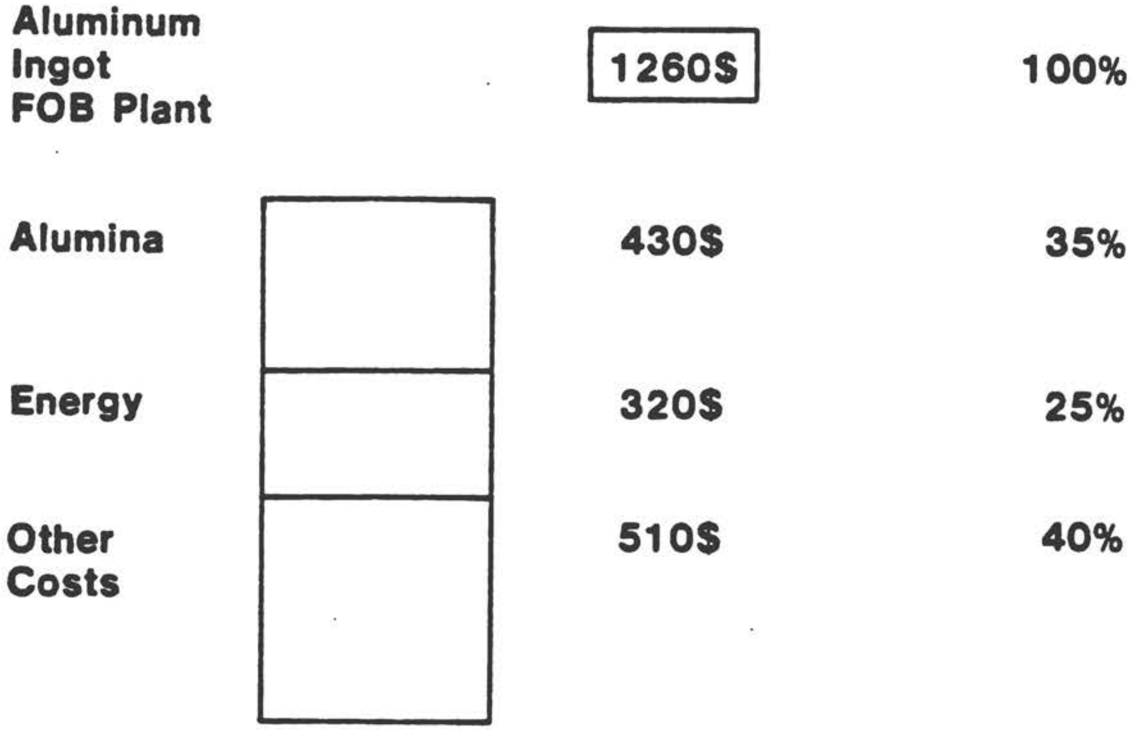


FIGURE 5-3 Aluminum ingot direct cost (1983 dollars). From Castera (1984).

Rapid Escalation of Power Costs After 1972

Aluminum production is energy-intensive with 64 percent in the form of electrical energy for electrolytic decomposition of alumina. In 1983 energy constituted about 25 percent of the cost of aluminum ingot (Figure 5-3) (Castera, 1984). The availability of cheap hydropower from the Tennessee Valley Authority (TVA) in the South and the Bonneville Power Authority (BPA) in the Northwest enabled the U.S. aluminum industry to cope with this energy intensity from the early 1950s through 1972. During this period, the BPA was actually courting the aluminum industry by offering excess generating capacity at low cost.

The OPEC boycott in 1973, however, caused a dramatic upheaval in this pricing structure and a tremendous escalation in energy costs. This may be demonstrated by comparing the unit costs of Western world primary producers in 1972 and in 1983. Figure 5-4 shows that in 1972, relative to the total cost of aluminum ingot, there was little difference between the primary producers with regard to power costs (Ligon, 1984). However, since 1983 the power cost range for different producers has widened dramatically (Ligon, 1984). Although some hydropower contracts remain in the order of 5 mils, thermal power has reached a level as high as 90 mils per kWh. This created a dramatic difference in the cost of metal production between low- and high-power cost smelters.

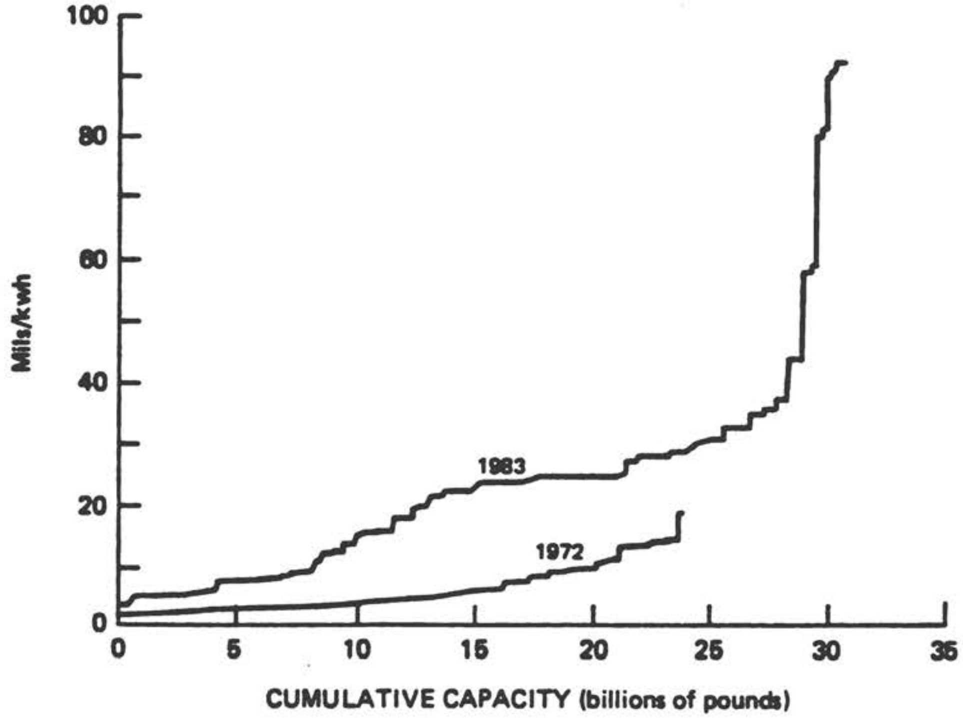


FIGURE 5-4 Energy cost for Western world smelters in 1972 and 1983. From Ligon (1984).

Although energy-efficient technology can be important, its total effect can account for only about 2 cents per pound of aluminum between the lower efficiency quartile and the higher efficiency quartile of producers, whereas the power unit cost effect between the same two segments can account for 14 cents per pound (Castera, 1984). This major change in energy costs has had a profound effect on the primary aluminum industry. Most Japanese domestic producers have ceased operations; even with highly efficient cells and capital already invested they could not remain world competitive because of their high oil-based power costs. Similarly, some U.S. smelters have been shut down permanently due to high power costs; for the same reason others have occasionally shut down smelting lines in favor of buying aluminum ingot on the open market. Access to cheap and available power has become the most important factor that determines the world competitive position of a primary aluminum producer (Bureau of Mines, 1985).

The Role of Governments as Aluminum Producers

In the more developed countries, in spite of high power costs, a government may wish to maintain an aluminum industry through subsidy. In the less developed countries, usually where both bauxite and water power are available, governments often choose to build refining and smelting capacity without fabricating facilities and even without an assured market for the metal. This often occurs because the risk and cost of new power plants in developing countries is far too great for private capital. The government usually owns the power plant and therefore controls aluminum production. In the 1960s, fully integrated profit-oriented producers (from mine to fabricated product) controlled 84 percent of the smelter capacity. By 1983, 40 percent of the Western world primary aluminum production capacity was owned or controlled by governments and by 1986 the percentage is expected to grow to more than 50 percent. This non-integrated capacity is having the effect of divorcing the ingot production from the fabricating segments of the industry. Integrated fabricators, particularly in the United States where with one exception--the Northeast--power costs are significantly higher than the world operating average, may find it advantageous in some instances to shut down their marginally competitive smelters and buy ingot on the world market (Figure 5-5) (Metal Bulletin, 1983).

As seen in Figure 5-5, Canada, with its extensive and newly developed hydropower, is a notable exception among the developed nations. In a recent article on the opening of Alcan's Grand Baie smelter, power rates were estimated to be 0.25-0.30 cents per kWh (Metal Bulletin, 1983). Using this figure, Grand Baie operating costs may be estimated at 44-45 cents per pound aluminum, probably making it the Western world's lowest cost smelter. Negotiations under way between Pechiney and the Province of Quebec will probably result in a consortium that will build a smelter with even lower power costs. With power cost as low as this nearby, it is not sufficient to be power-cost competitive only within the United States. The world is the competitive area in primary aluminum production, and 70 percent of the Western world's smelters have lower power costs than the U.S. average (Figure 5-5).

However, multinational U.S.-based companies may have sufficiently low world-average power costs to remain competitive while still operating domestic smelters and, if fully integrated, can adjust their operations to remain competitive in world markets with products of their choosing. It is likely, then, that in the developed countries with the exception of Canada, no new smelters will be built, and if expansion is necessary it will be brownfield add-ons to existing facilities and smelters gradually will phase out of the high (power) cost areas. Integrated companies will not operate smelters when production costs exceed ingot market price, preferring to shut down smelters and supply their fabricating facilities with purchased ingot. This decoupling of the industry is already under way; Figure 5-6 (Castera, 1984) shows that the percentage of industry integration in energy, alumina, bauxite, and fabricated extrusions has fallen steadily since 1970.

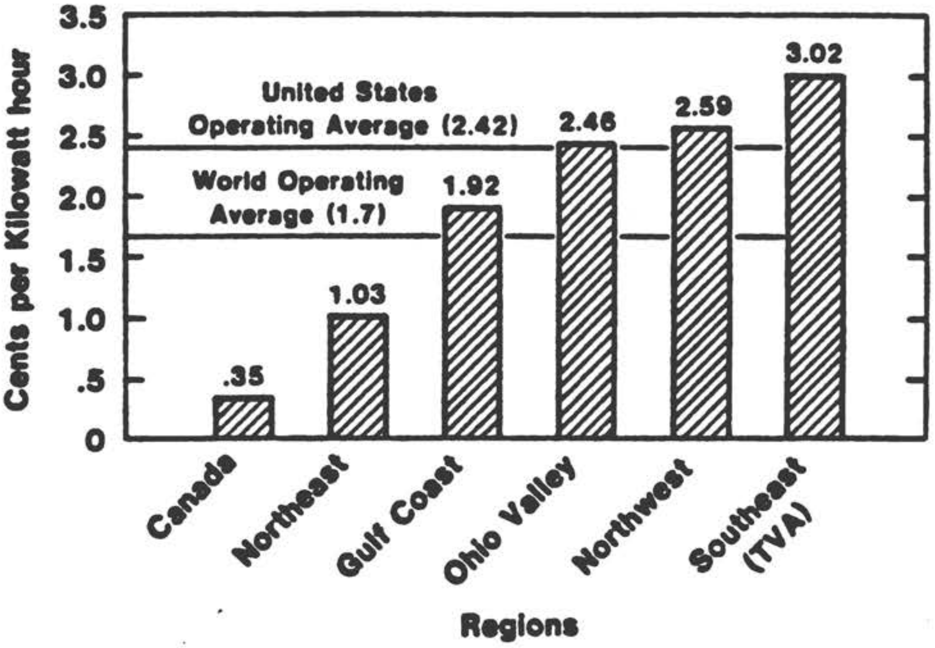


FIGURE 5-5 North American primary aluminum power costs versus world average for operating smelters, 1983 estimate. From Metal Bulletin (1983).

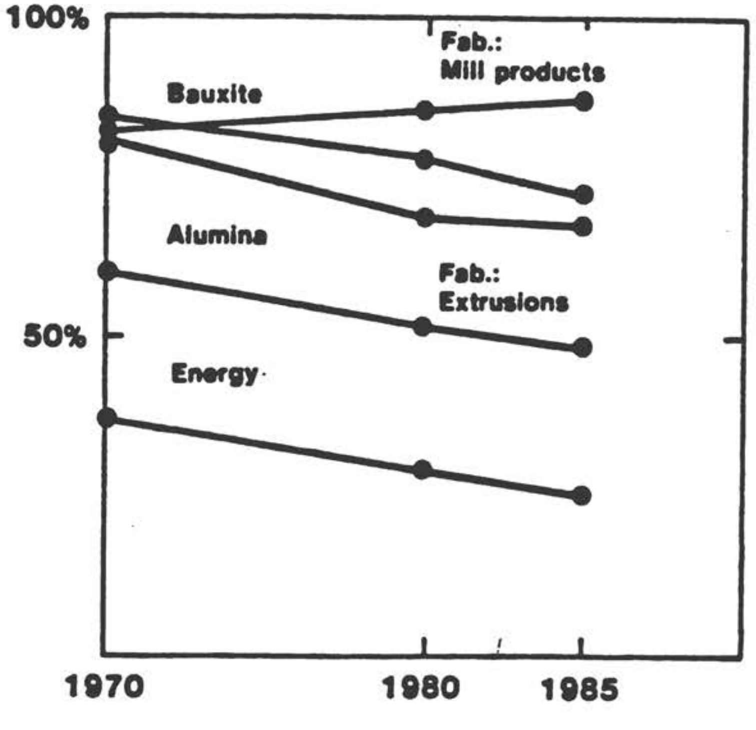


FIGURE 5-6 Decoupling of the aluminum industry. From Castera (1984).

Aluminum Ingot Trading in Commodity Markets

For 80 years the price of aluminum was relatively stable, being governed largely by the market forces of supply and demand. In 1978, however, trading of aluminum ingot in a similar manner to wheat or soy beans began at the London Metal Exchange (LME). After a difficult start, such trading is now accepted and takes place in both the London Metals Exchange (LME) and the Commodity Exchange (COMEX), the two largest commodity exchanges in the world. Such trading is not a cause of the internationalization of the aluminum industry, but more probably came about as a result of the increased availability of ingot on the world market. This has had a profound effect on the market and will probably accelerate decoupling in the developed countries through more sensitive response to short-term swings in supply and demand. This causes significant price fluctuation and encourages speculation, further enhancing price instability.

Market Maturity

The aluminum industry has come to expect a growth rate of about 6 percent per year in U.S. aluminum consumption. Best estimates for the future, however, are 3 to 5 percent annual growth with some of this growth being supplied by recycling, which further reduces primary production growth to 2 to 4 percent. This slower rate is due to the saturation of many markets. For instance, the aluminum industry's single largest market, containers and packaging, has 95 percent of total beer and beverage cans, successfully replacing steel, tinplate, and glass bottles. Unless a totally new market such as food cans is opened, growth must cease in this area due to market saturation.

Figure 5-7 shows the per capita consumption of aluminum versus gross national product (GNP) per capita for individual countries. The United States is the world's single largest consumer of aluminum at 60 lb per capita, compared to 40 lb for Australia, 20 lb for the United Kingdom, and only 6 lb for Brazil. The market for aluminum outside the United States is constrained by the correlation between GNP and per capita consumption. Of necessity, the large U.S. aluminum producers are looking outside to developing nations, not only for bauxite and inexpensive electrical energy and less costly labor but also for new markets to counter the slower growth at home.

Although some of the preceding international factors have affected other U.S. metal industries, there are significant differences to the advantage of the aluminum industry:

1. The North American aluminum industry is based on four continents affording opportunities to average costs and put together the most economical combination of raw materials, smelting, and fabricating facilities for the desired market.

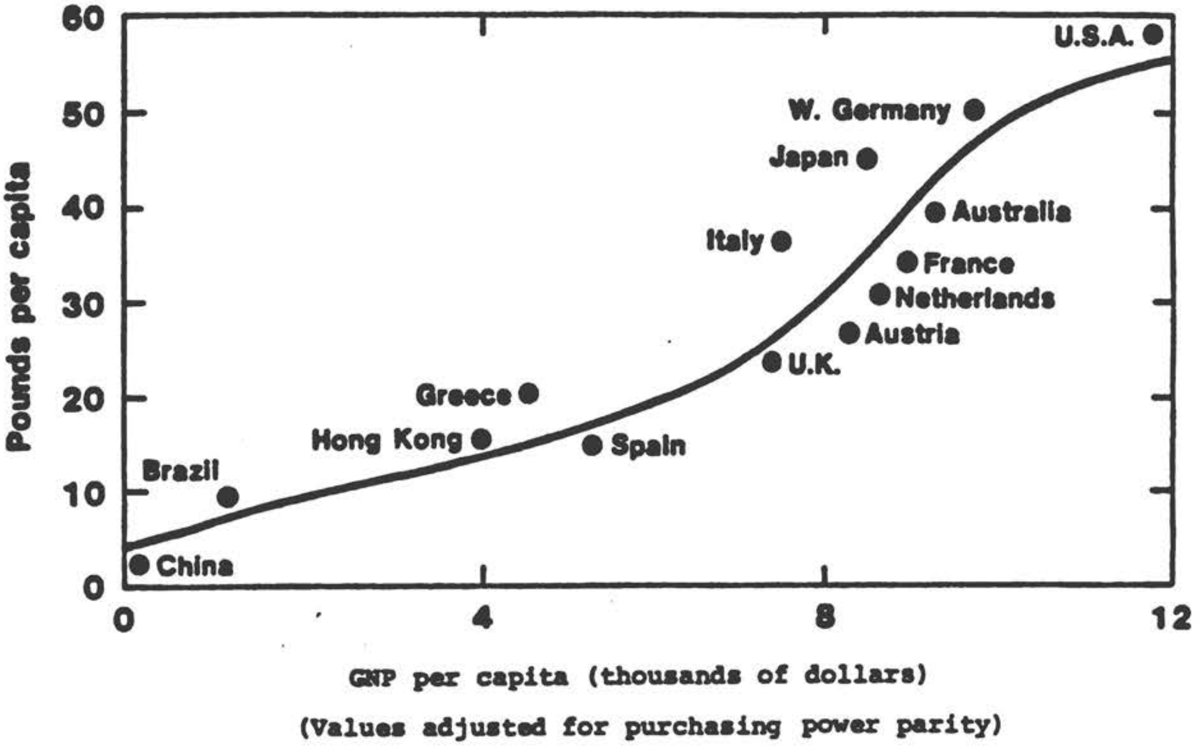


FIGURE 5-7 Aluminum consumption behavior in 1980.

2. The technology of the U.S. aluminum industry is second to none in the world. The commitment to research and development has been and is unique in the basic industries and, as will be shown later, has yielded steady incremental improvement with significant possibilities remaining to be exploited in the next five years.

3. For the most part, the major producers' plants are in good shape. Even through recessionary cycles, repair and maintenance expenditures have been sustained, and expansions and modernizations have been funded even during the uphill portion of business cycles.

4. Whereas steel markets matured about 10 years ago, limiting growth to that of the population, aluminum markets are just now approaching maturity. There is time to develop new products and markets that may restore the growth rates of the recent past.

FUTURE PROSPECTS

Unless major technical breakthroughs occur or new markets for aluminum are developed that may restore the earlier growth rate, the future prospects of the industry can be summarized as follows:

1. Basic world demand for new aluminum probably will fall from the traditional average growth of 6 percent per year to between 2 and 4 percent.

2. World overcapacity of bauxite mining and refining will result in idle facilities for a significant period; this, coupled with high capital requirements, will discourage large-scale backward integration even though traditionally this has been a profitable course of action.

3. Low costs of hydroelectric power coupled with low labor costs and the strategic importance of aluminum will continue to lead countries outside the United States to subsidize aluminum smelting capacity, which will maintain production even during periods of low demand.

4. Inefficient smelters will be closed and, unless there is some unforeseen major technical or political change, it is unlikely that new primary production facilities will be built in the United States in the foreseeable future.

5. When increased production is needed, brownfield expansion of existing facilities (preferably overseas) to take advantage of fixed capital will take precedence over greenfield expansion.

6. The primary aluminum industry, unless it is government subsidized or protected, will gradually move out of the United States and Europe. Any future greenfield growth will take place in Australia, Brazil, Canada, and India (Kaufmann and Bras, 1983).

7. New overseas smelters will be financed by partnerships or consortia of several aluminum producers and a host government; the latter will probably own the power source.

8. Further decoupling of primary producers and fabricators will lead to two types of aluminum companies in the developed countries: worldwide, totally integrated producers who can put together the most economical combination of refining, smelting, purchase of ingot, and fabrication and national industries that will drastically cut back primary aluminum production, buy long-term ingot contracts, and concentrate on fabricating selected products.

These changes may have a profound effect on research and development in primary aluminum production. Traditionally, the integrated producers have carried on this effort. It is unlikely that new primary producers, who have purchased off-the-shelf technology, will do much R&D in basic aluminum production.

In summary, even if no technical or political changes are made to improve the economics of domestic aluminum production, there will still be multinational profitable aluminum companies and a well-developed fabricating industry based on ingot purchased on the open market. However, U.S. production of aluminum metal will decline and there will be increased dependence on imported aluminum ingot.

MEETING NATIONAL SECURITY EMERGENCY NEEDS

Providing surge capacity for short emergencies in the aluminum industry is relatively easy since national security needs only consume about 3 percent of present U.S. aluminum production. Even though some of the 97 percent would be needed for essential civilian requirements (i.e., power transmission, air, rail and truck/trailer transportation and chemical process industries), modest curtailment of nonmilitary uses could release sufficient aluminum, even for long lasting emergencies, if raw materials were available. The Jamaica and Suriname bauxite in the U.S. stockpile inventory as of March 31, 1984 (FEMA, 1984), including the 2,080 tons of aluminum metal held in the stockpile, totals an equivalent of 4.04 million tons of aluminum. Since it is projected that 7.6 million tons of aluminum will be consumed in the United States in 1984, it would appear that the present inventory would supply about one-half the total national needs for one year at the 1984 estimated rate of consumption. With civilian curtailment, this inventory could easily be extended to approximately one year. Therefore, there is no need to go beyond the present stockpile goal of 27 million tons of bauxite (7.15 million tons of aluminum) which could provide at least a 3-year supply under emergency conditions, if smelting capacity remains available.

TECHNOLOGICAL OPPORTUNITIES

Examination of possible future technical developments in the Bayer-Hall-Heroult process requires discussion of the forces driving such developments and inclusion of the possibility that new technologies may arise that address these forces more effectively. Past performance of the industry and the present rate of improvement must be considered before attempting to predict the probable future path of the present technology.

Figure 5-8 shows world production of aluminum and average selling price from 1930 through 1982. From 1946 through 1961, production rose at a compounded average of 14 percent per year and then only dropped to 9 percent through 1973. The 1972 OPEC oil price increase caused a brief dip in production, but resumption in 1975 was at 5 percent until the recession of 1981 (Brondyke, 1983; Roskill, 1982), which bottomed out in June of that year. Recovery was slow through 1982 but accelerated rapidly to a projected rate of about 4 percent in the last six months of 1983.

If even this reduced rate of rise is to continue, however, the price of aluminum must rise at a slower rate than that for competing materials and inflation, which is in direct contrast with price increases seemingly

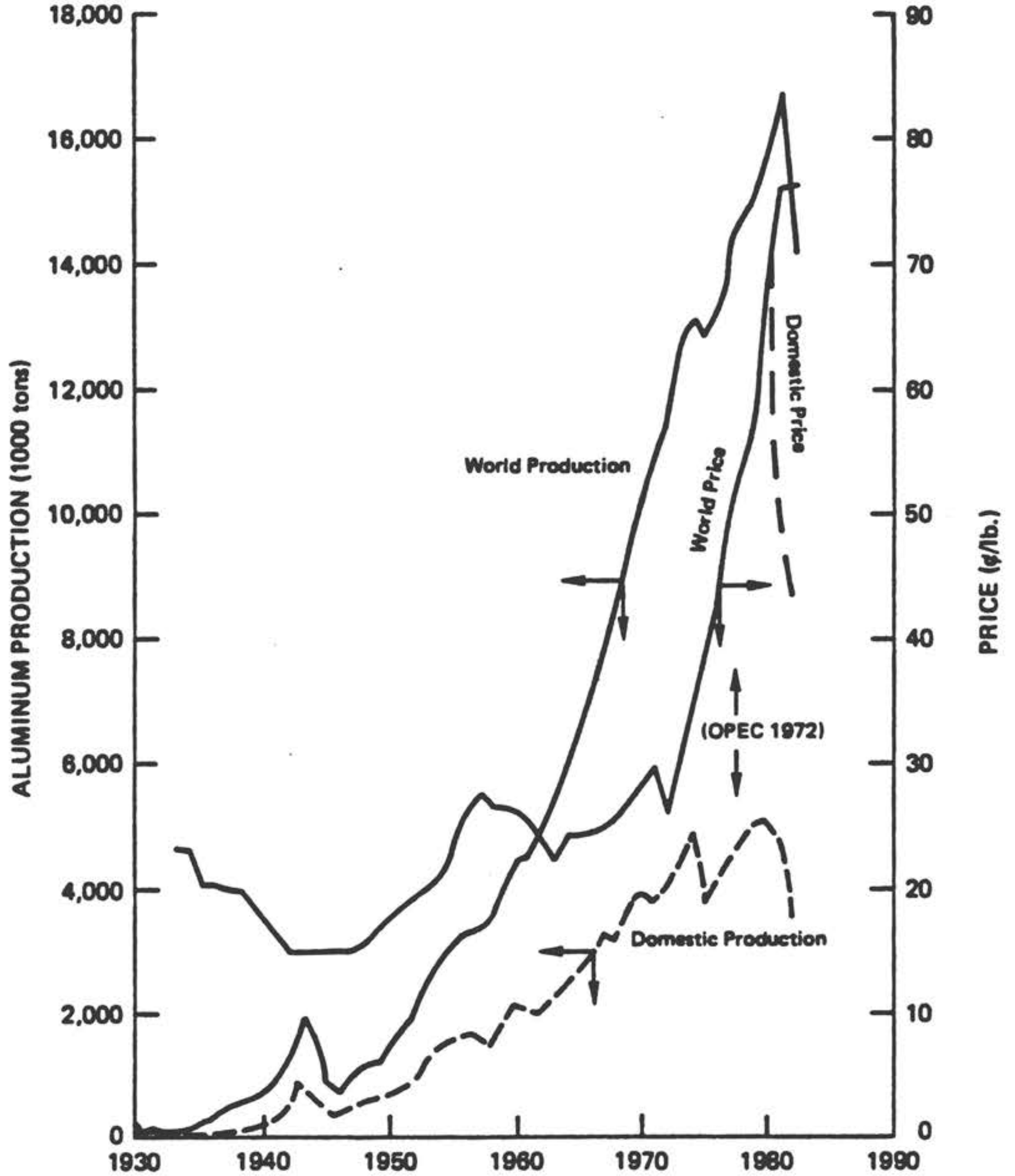


FIGURE 5-8 Aluminum price history and world production.

necessary to generate capital needed for expansion. Lower cost follows increased productivity and the more efficient use of raw materials. Major technological gains tend to appear cyclically and, to some extent, reflect when installations must be modernized or new facilities built for increased production. Aluminum pricing seems to follow this pattern (Figure 5-8) (Aluminum Association, Inc., 1982; American Metals Market, 1983). From 1930 through 1972 periodic technological improvements caused reversals of the upward price trend. In 1973, the OPEC oil price increase offset all gains and prices rose rapidly, reflecting the increased cost of raw materials and power.

In all probability, any developments that could effect a major reduction in production costs in the foreseeable future must be made on existing facilities due to the high capital costs of new plants and equipment.

Figure 5-9 shows how the total energy required to produce aluminum ingot is distributed among the various processing steps, assuming that electric energy is generated using fossil fuels at an energy consumption 11.1 Mj/kWh. It can be seen that 64 percent of the total energy, which is 25 percent of direct ingot cost (Figure 5-3), is consumed in electrolytic smelting cells that operate at only 50 percent power efficiency. The other major cost items--capital charges, labor and environmental control--are distributed along similar lines, showing that the most significant opportunities for primary ingot cost-reducing technical advances lie in the alumina reduction step.

Past Progress

The reduction of kilowatt hour per kilogram of aluminum accomplished by the industry since 1940 is shown in Figure 5-10. Through technological improvements, the industry average has been reduced until it is now less than 16.3 kWh/kg of aluminum (40 percent efficient). The most advanced cells operate at 13.0 kWh/kg of aluminum (about 48 percent efficiency) while the new aluminum chloride smelting process may have an energy consumption as low as 9.2 kWh/kg of aluminum. These advances have been made largely by increasing current efficiency through control of operating parameters to near optimum conditions, the use of larger anodes to reduce current density, and attention to incremental voltage drops in both anodes and cathodes.

Cell productivity, as measured in kilograms of aluminum produced per cell per unit of time, strongly affects both capital and labor charges. The largest cells in operation have progressed from 50,000 amperes in 1940 at 341 kg/cell day to 235,000 amperes in 1981 at 1727 kg/cell day (Figure 5-11).

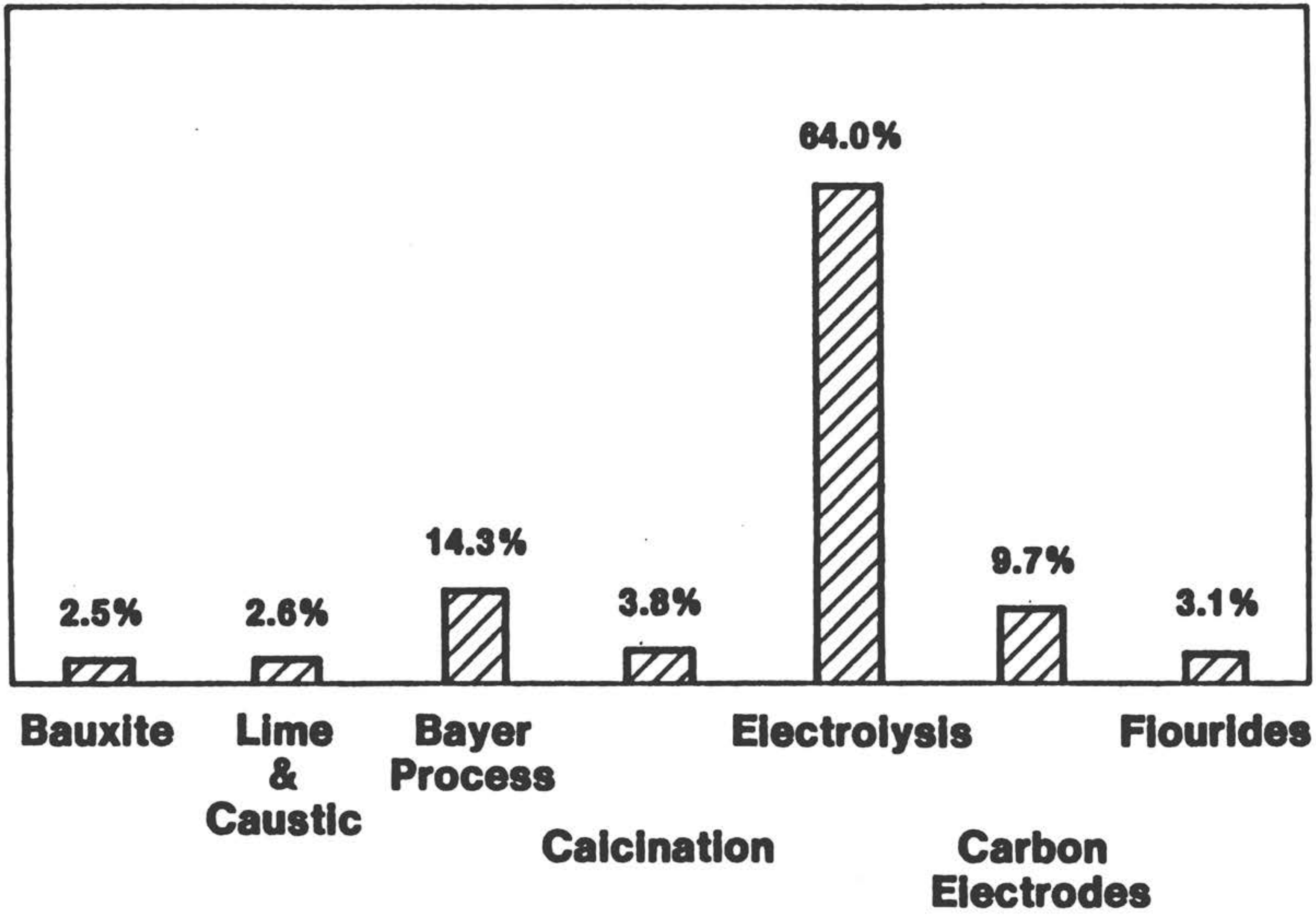


FIGURE 5-9 Percent energy consumption by various steps in the aluminum production total. Energy consumption = $\frac{284 \times 10^6 \text{J}}{\text{kgm}}$ or $\frac{244 \times 10^6 \text{BTU}}{\text{t(short)}}$

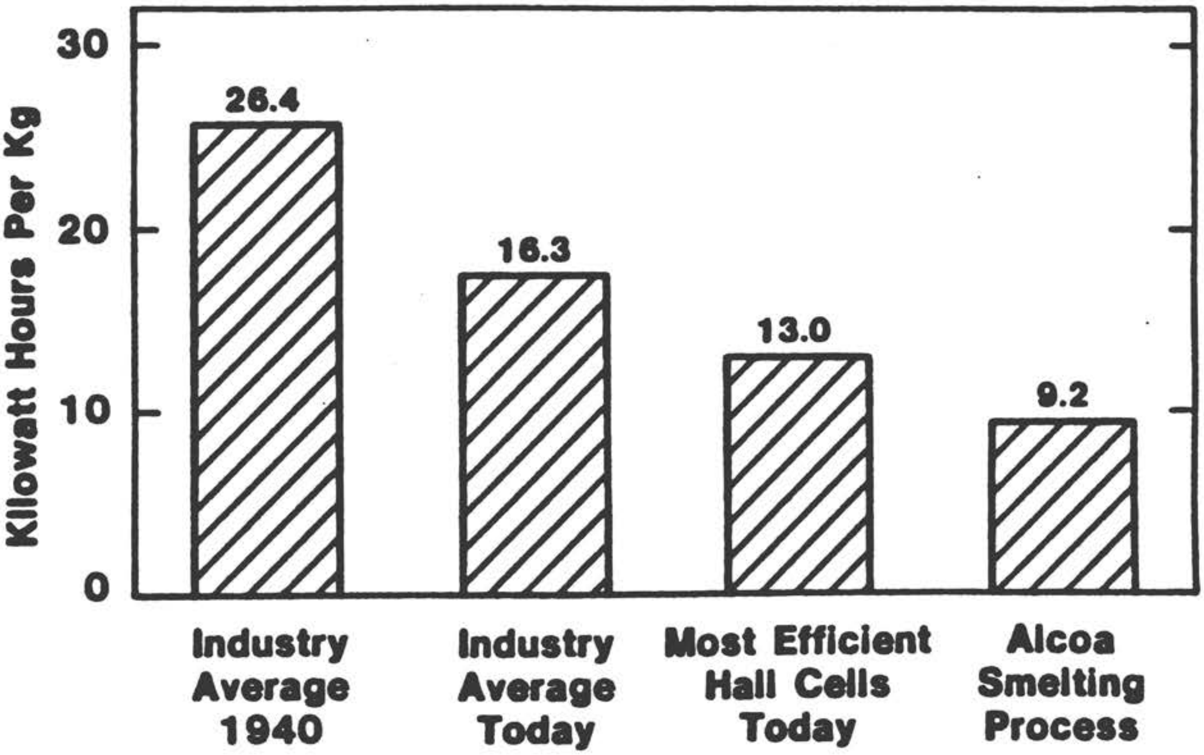


FIGURE 5-10 Powder reduction in aluminum smelting.

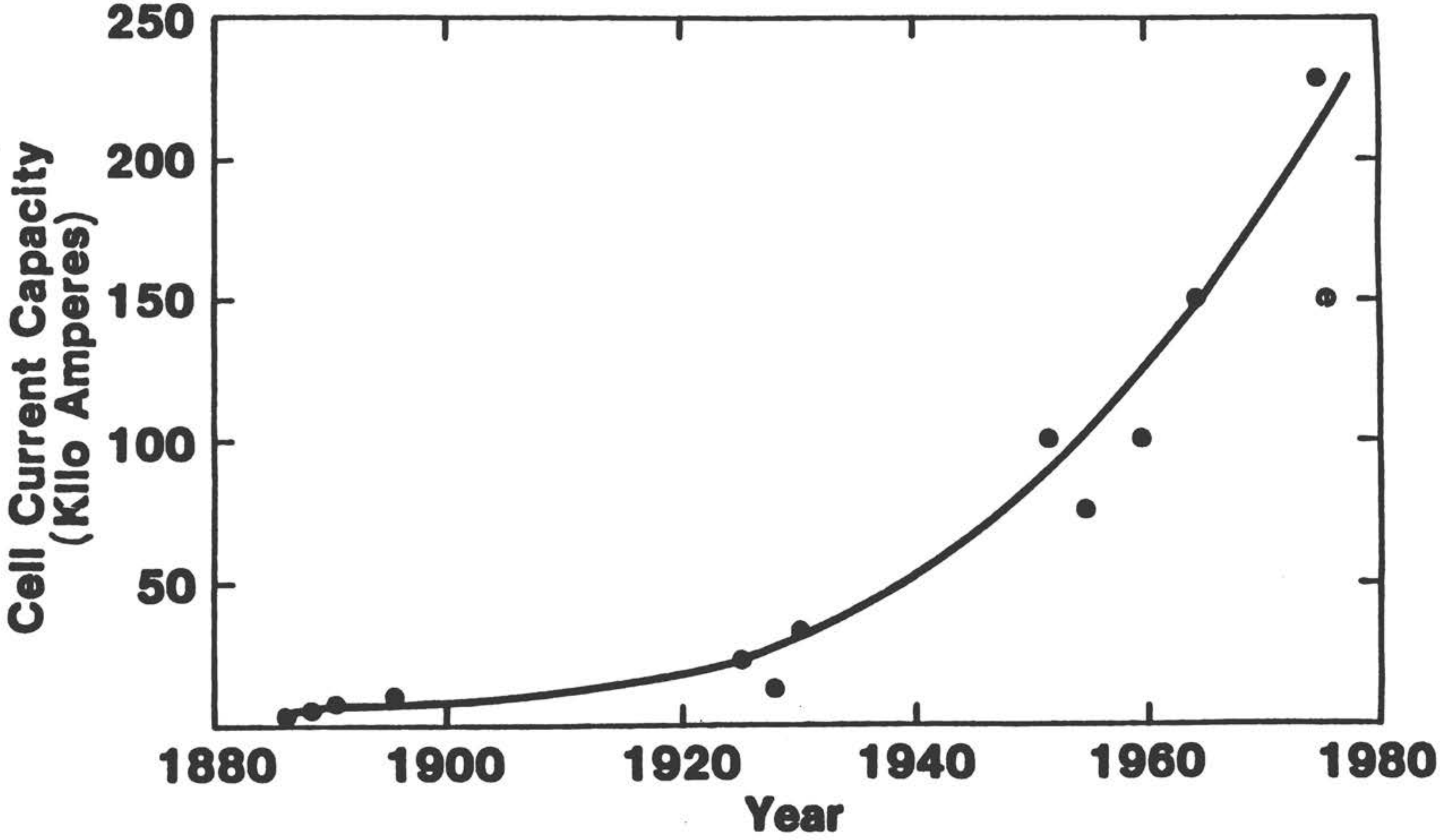


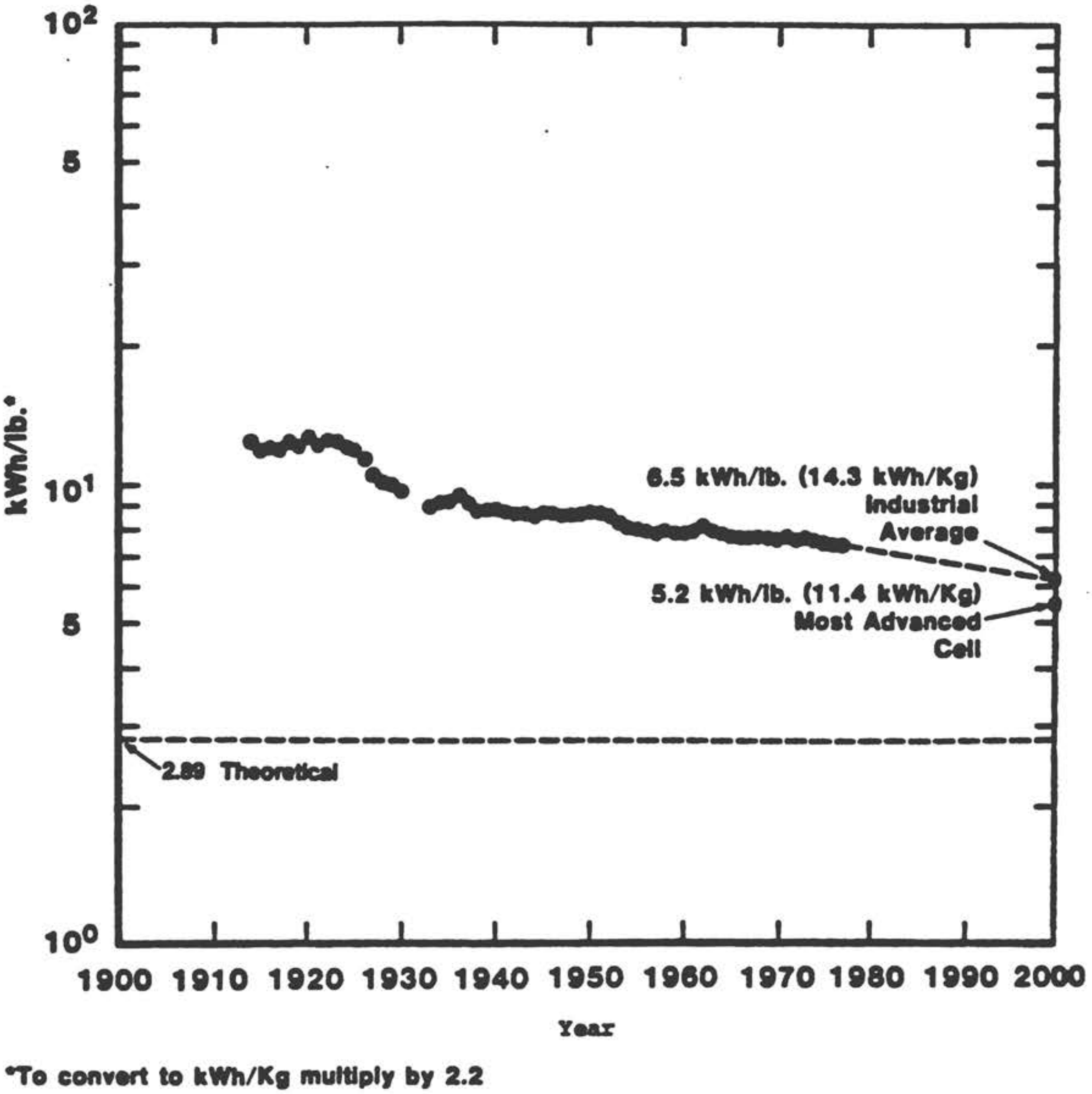
FIGURE 5-11 Trends in Hall-Heroult cell current capacity.

During the same period (1940-1982), current efficiency was increased from 82 to 90+ percent with some modern cells exceeding 94 percent. Carbon consumption, which at 100 percent efficiency and 100 percent CO_2 evolution has a theoretical consumption of 0.33 kg of carbon per kilogram of aluminum, has been reduced to less than 0.43 kg.

This is an impressive record of steady, continuous improvement that may be expected to continue into the future at the present level of research effort. Figures 5-12, 5-13, and 5-14 show the advances made over the years in current efficiency, power consumption, and cell productivity for the industry average as well as individual points for the best cells available at present; all figures show extrapolation of the present trend to the year 2000, assuming that R&D is continued at the present rate.

This would be continued steady progress, but it is not good enough to permit the continued growth of the industry as in the past. These future cell parameters project to a maximum reduction of about 8 percent in the price of aluminum at the end of a 10-year period (constant dollars), approximately 1 percent reduction per year compounded. In contrast, between 1977 and 1981 energy costs in the United States rose at a compounded yearly rate of 16 percent. During this same period, raw materials, salaries, and benefits also rose in the order of 8 percent compounded. The Total Energy Resource Analysis (TERA) and Wharton Econometric Forecasting Analysis (WEFA) reports in the spring of 1982 base case projected average U.S. industrial fuel prices (in constant 1982 dollars) into the future (American Gas Association, 1983). Between 1980 and the year 2000, electrical energy is estimated to rise at 4 percent per year compounded while the other energy sources are estimated to rise at 2 to 3 percent. It is evident, then, that energy costs, in particular electrical energy which represents over 20 percent of the operating cost of aluminum ingot, are important forces driving the development of technology to significantly increase the present 42 to 50 percent power efficiency.

For existing facilities, labor and carbon costs follow close behind energy, and for new installations all of these costs fall in behind capital charges (which can be as high as 34 percent of the selling price), driving the search for technology to reduce these costs. If domestic smelters are to remain sufficiently competitive to continue operation, costs must be reduced to offset the low cost of power and labor and government subsidy outside the United States. The important technological challenge to the aluminum industry today is to make <u>major</u> breakthroughs in productivity and power efficiency in existing cells through innovative modifications, better control, heat recovery, and more efficient use of raw materials. Analysis of the present Hall-Heroult cell using consumable anodes and operating at less than 50 percent power efficiency shows that there is significant room for such major improvement.



*To convert to kWh/Kg multiply by 2.2

FIGURE 5-12 History and forecast of Hall cell performance (electrical energy consumption).

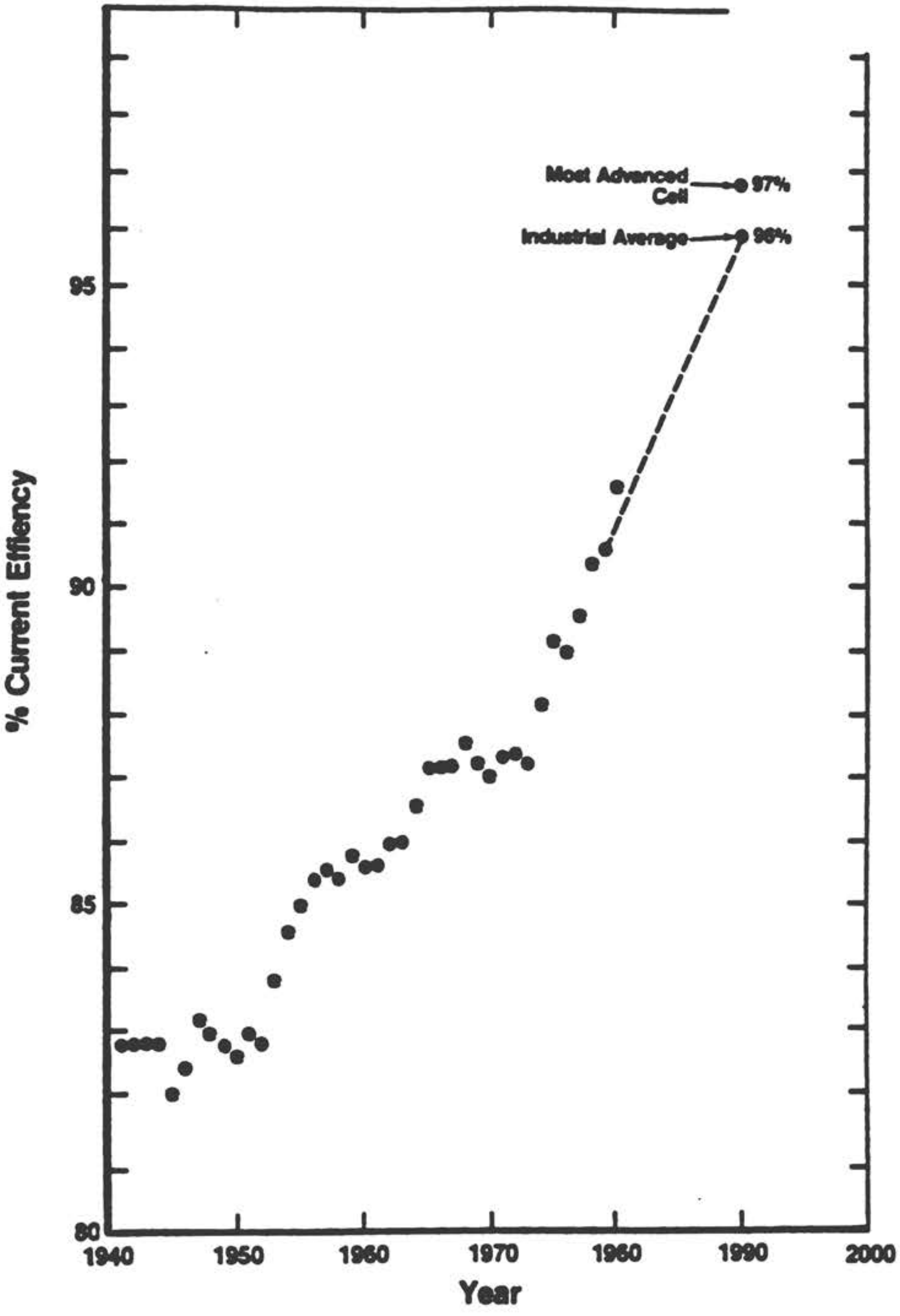


FIGURE 5-13 History and forecast of Hall cell performance (current efficiency).

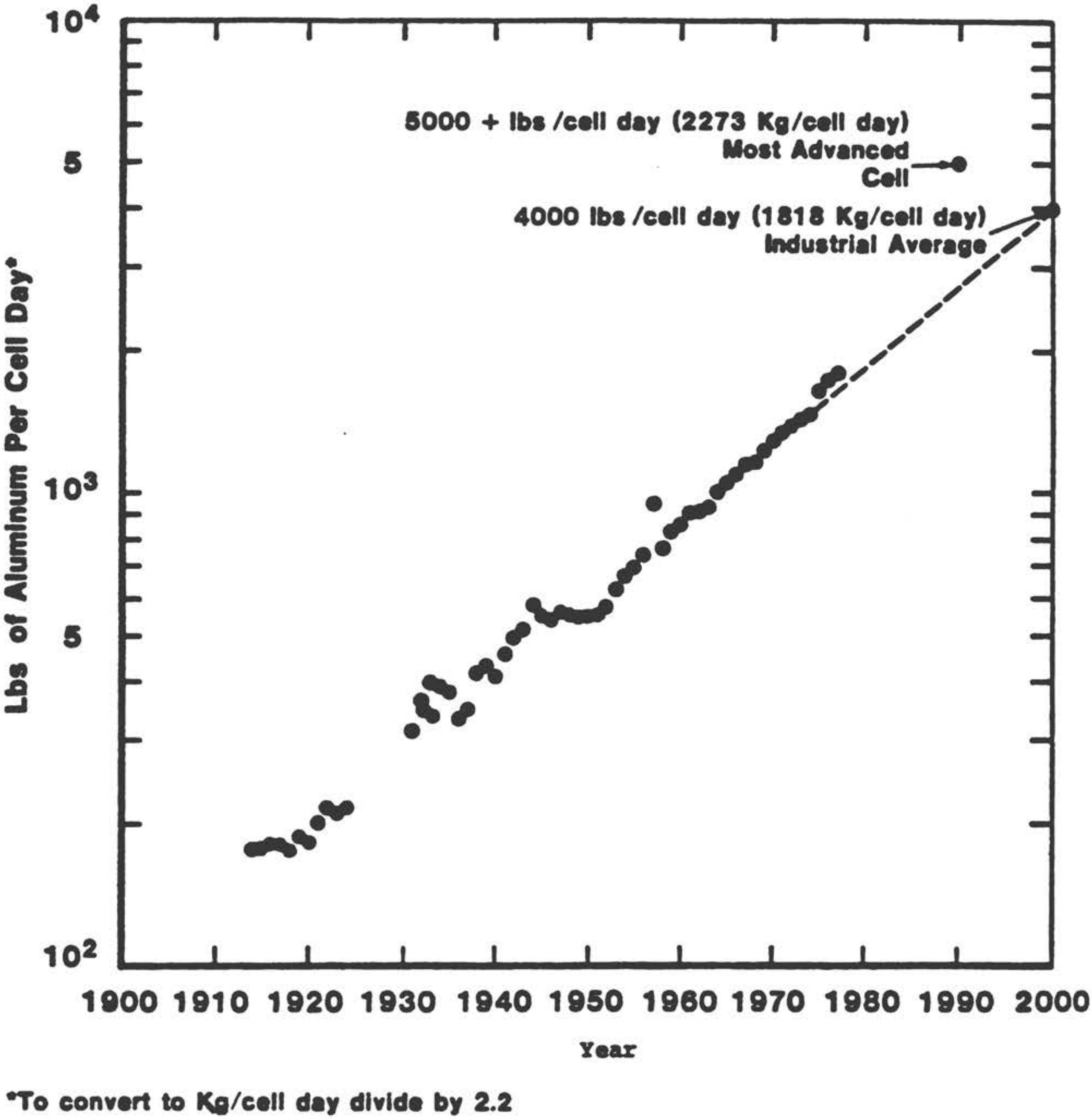


FIGURE 5-14 History and Forecast of Hall cell performance (pounds of aluminum per cell day).

Opportunities for Major New Developments in Hall-Heroult Technology

The voltage distribution in a Hall-Heroult aluminum smelting cell at typical current density is shown in Figure 5-15. From the free energy requirement or decomposition potential, it is evident that only 25.9 percent of the energy entering the cell could be electrolytically reversibly extracted from the aluminum produced. The balance must be dissipated as heat, increasing the kilowatt hours that must be expended per kilogram of aluminum produced and limiting the current (metal production) that can be applied without overheating the cell. This value (1.2 V) represents the free energy of the reaction and is thermodynamically fixed as the minimum energy requirement for aluminum production.

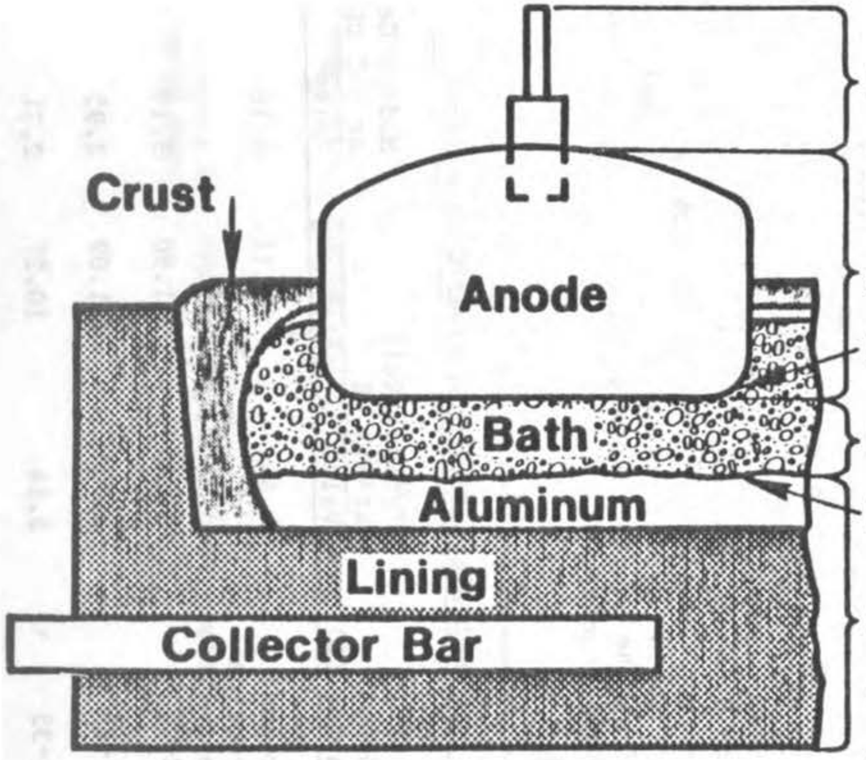
Although some reduction in polarization and anode, cathode and external resistances might be made, the most promising area for energy conservation is in the reduction of the interelectrode spacing where 38 percent of the energy entering the cell is converted to heat by resistance of the electrolyte and must be wastefully dissipated to the atmosphere.

Interelectrode Spacing and Heat Balance: The effect of the interelectrode spacing on power consumption is shown in Table 5-1. If the typical interelectrode spacing of 4.45 cm were reduced to 1.27 cm, power consumption would be reduced by about 30 percent. Such increased efficiency would be possible if all other variables, including current efficiency, remained constant. If, under similar conditions, the spacing could be reduced to 0.64 cm, the power saved would be 32 to 35 percent and the best Hall-Heroult cells would exceed the 9.2 kWh/kg of aluminum shown for the new chloride process (Figure 5-10). Three major problems must be solved before the anode-cathode distance can be shortened to take advantage of this opportunity.

TABLE 5-1 Effect of Electrode Spacing on Power Consumption

Interelectrode Spacing (cm)	Power Saving (%)	Typical Cell at 91% CE		Modern Cell[a] at 94% CE	
		Volts	kWh/kg	Volts	kWh/kg
4.45	Present practice	4.64	15.18	4.16	13.17
1.91	22-23	3.64	11.90	3.19	10.10
1.27	27-29	3.39	11.09	2.95	9.33
0.64	32-35	3.14	10.27	2.71	8.58

[a] Lower current density and higher current efficiency.



Voltage Component	Volts	% Of Total
External	.16	3.4
Anode	.32	6.9
Polarizations	.60	12.9
Bath	1.76	38.0
Decomposition	1.20	25.9
Cathode	.47	10.1
Other	.13	2.8
Total	4.64	100.0

FIGURE 5-15 Voltage distribution in a Hall-Heroult aluminum smelting cell.

The first of these is the periodic shorting that occurs between the molten metal pad and the anode with increasing frequency and for longer periods of time as the anode-cathode spacing is reduced. Magnetic fields and escaping anode gas cause the molten metal to undulate and periodically touch the anode as it circulates around the cell.

The second most important problem to be solved, assuming metal shorting has been overcome, is temperature control. To maintain operating temperature as the interelectrode space is reduced, either the current must be increased to hold the resistance heat energy constant or the cell must be insulated to reduce heat loss. The graphite inner sidewall lining is attacked and penetrated by the electrolyte, leading to eventual mechanical failure unless it is protected by a frozen layer of electrolyte. If the cell is externally insulated to reduce the heat loss to equal the lower heat energy released in the interelectrode space, the frozen sidewall melts and the graphite lining is exposed to attack. Unless a material inert to the molten electrolyte is developed so that an electrolyte freeze line can be established in the lining, some combination of increased productivity by higher current loading and increased power efficiency through insulation, just short of losing the protective sidewall, must be practiced.

The third problem is reported loss in current efficiency and increased voltage drop resulting from greater retention of the anode gas bubble layer as the interelectrode space and electrolyte turbulence are reduced. Investigations must be carried out to firmly establish these values so that the most economic cell design and operating conditions can be determined.

Stable Cathode: An easy solution to the first problem (molten metal shorting to the anode) would be to eliminate the metal pad by draining the metal into a sump and exposing a solid carbon cathode that could be closely approached by the anode without shorting. This solution is not viable with the present cell design, however, since aluminum reacts with the carbon bottom lining to form aluminum carbide, which dissolves when exposed to electrolyte.

Some reduction in anode-cathode spacing can be realized by designing to counteract the magnetic field and reduce horizontal currents in the metal pad, but a major breakthrough in this area requires a stable cathodic material that can be substituted for the molten-metal-on-carbon-lining cathode. Such a material would require the following properties:

1. Inert to the environment of electrolyte (Na_2AlF_6, CaF_2, Al_2O_3) and molten aluminum (960-1000°C).

2. Good electrical conductor with resistivity less than 150 $\mu\Omega$-in.

3. Withstand severe differential thermal gradients imposed during cell startup and operation.

Ransley's patent showed that high-purity titanium and zirconium borides meet these requirements. These materials are presently expensive (at the purity levels required), difficult to fabricate, and sensitive to thermal shock. Recent developments on this feature are encouraging, however, and show a high likelihood that all criteria can ultimately be met. The Kaiser drained cathode technique also has potential but needs further development work to prove its applicability. Heat balance and cell design calculations are described in the literature (Haupin and Frank, 1981; Jarrett, 1981; Jarrett et al., 1981).

Non-Consumable Anode: At 9.7 percent, the manufacture of carbon anodes is the third highest energy consuming step in the manufacture of aluminum ingot (Figure 5-9). This energy is in the form of gas, oil, and carbon rather than electricity and represents nearly 7 percent of the cost of aluminum ingot. There is also a significant labor cost attached to the production and frequent changing of the consumable carbon anode. The accessibility required for anode replacement also restricts the degree to which heat loss can be reduced through insulation and makes the collection and processing of the effluent gases for environmental control more difficult and costly. If a nonconsumable electrode that emitted oxygen instead of carbon oxides could be developed, significant cost and energy savings would accrue.

Table 5-2 lists the advantages of such a development. Carbon anodes in the Hall-Heroult process are changed at the rate of one anode per cell day. With the successful development of an inert anode, this rate would be reduced to one anode per cell month, allowing the cell to be totally closed except during anode change when special fume-collecting equipment could be placed over the opening. This would not only reduce labor but would allow gases to be processed in a more concentrated form. In present Hall-Heroult cell practice, over 56.63 m^3/min of air is drawn through the loose fitting cell hoods to capture 1 percent of that amount in effluent gases. This is necessary to have easily removable covers for anode changing. From a totally enclosed inert anode cell, the effluent gases could be drawn with virtually no air dilution, reducing the gases that must be scrubbed by 99 percent. Significant capital savings in the fume treating equipment in new facilities would result and the operating costs of existing fume-handling equipment would be reduced by using only 1 percent of the present installation.

However, no new development is without its price, and a thermodynamic penalty must be overcome if the inert anode is to be economical. The technical aspects of this problem are discussed in Appendix E. In addition to a stable anode and cathode, two more developments are necessary to bring the monopolar fluorides or Hall-Heroult cell into the twentieth century. A means of removing heat in a useful form while insulating the cell to avoid heat loss would allow cell temperature control, independent of the electrical system, and permit operation at optimum power efficiency. The heat removed for cogeneration or other use should be recovered at as high a temperature level as possible, probably through heat exchangers in the inner cell wall. Such a device would have an added advantage by permitting a variable current loading, which could be a major benefit to utilities in peak shaving in the future. The second requirement is a multivariable control system to replace the present cascade system and allow operation at steady state as near optimum conditions as possible. To do this an accurate mathematical model of the system is needed. This model would operate in parallel with the actual cell, receiving the same perturbations, predicting the outcome, and making adjustments to the cell to offset less than optimum conditions developing.

TABLE 5-2 Advantages of Inert Anodes

Feature	Benefit
Lower anode consumption	Saves carbon, reduces labor
Reduced interelectrode spacing and bubble polarization	Saves power
Smaller fume system	Lower capital intensity
Produces oxygen	By-product value
Permits bipolar design	Saves power, lowers capital intensity, reduces labor

Five technological opportunities have been discussed that, with proper emphasis on research and development, could be retrofitted to existing smelting equipment. This would result in significant cost reduction for the domestic primary aluminum production industry. The opportunities are

1. Mathematically modeled computer process control,
2. Stable cathode,
3. Inert cell sidewall lining,
4. Heat conservation and cogeneration, and
5. Inert anode.

With the exception of computer control, these are all high risk, low probability projects with a high payoff if successful. The success of all of these, however, probably would not maintain the competitive position of the U.S. primary aluminum production industry in the world market for an extended period. From past experience it seems probable that reduced power consumption or conservation would result only in higher overall unit power costs (i.e., the power authorities and private utilities probably would simply raise their rates). In addition, technology advancements usually must be regarded as transitory since technology transfer to overseas facilities of the multinational companies and to other producers of necessity will occur in time and, thus, power conservation ultimately will happen for everybody. The only exception to this might be a strong patent position supported by the U.S. government based on domestic raw materials not readily available in other parts of the world, and this is a possibility, as will be discussed below.

In spite of the above, it is still advantageous for the U.S. industry to vigorously pursue these technological innovations. They not only will extend the life of the United States primary smelting capacity but also could result in overall lower prices for aluminum ingot. This could result in the application of aluminum to entirely new markets, addressing the area of greatest strength in the American industry, metal fabrication technology. This is the real strength of the United States industry as well as the area in which the greatest room for improvement in productivity exists and where private capital for research and development will continue to be available to acquire and maintain worldwide technological leadership.

Development of Processes to Use Domestic Raw Materials: Through the years much ingenuity and expensive research has been devoted to the development of an alternate to the Hall-Heroult process for the production of aluminum. One incentive has been the high capital intensity of the Hall-Heroult process, partially caused by the necessary monopolar configuration required to permit anode changing. This hinders space-time-yield productivity improvement by eliminating the use of height and results in a multiplicity of small units. The other major incentive has been the inherent low power efficiency of electrolytic processes resulting from the high resistance of the electrolyte space between the anode and cathode necessary to ensure that shorting and back reaction do not take place. Although most of the suggested alternate processes have been directed at the use of domestic raw materials, this has not been a major consideration since bauxite is still the richest mineral in alumina and is readily available around the world. To use all domestic ore it is necessary only to develop a process for the extraction of alumina from lean domestic ores competitive with the extraction of alumina from bauxite, with its added cost of transportation. Although much work has been done on such a process with significant technical success, involving acid leaching, until now no economical process has been developed. Recently, however, Alcoa has patented a process for the extraction of alumina from domestic gibbsite that has been carried through bench-scale study and is projected to be competitive with imported bauxite for the Bayer process.

Alternate processes, not aimed at producing feed for the Hall-Heroult process, that have received significant attention are: the Alcoa smelting process (ASP), the direct carbothermic reduction of alumina, the direct carbothermic reduction of clay or mixtures of alumina and silicon oxide to produce an aluminum-silicon alloy, the subchloride or Gross process, disproportionation of aluminum sulphide (Al_2S), the nitride intermediate process, sulphide electrolysis, nitride electrolysis, and the Toth process. To date only the Alcoa smelting process has been demonstrated to be commercially viable. In its present form (Figure 5-16), clay is leached with hydrochloric acid to produce $AlCl_3 \cdot 6H_2O$, which is calcined to alumina. The hydrochloric acid driven off during calcination is recycled back to the leaching process and the alumina is chlorinated in the presence of carbon in a fluid bed reactor to produce aluminum chloride feed for the ASP bipolar cell. This process is competitive with the Bayer process because small amounts of retained chloride are not detrimental to the chlorination process.

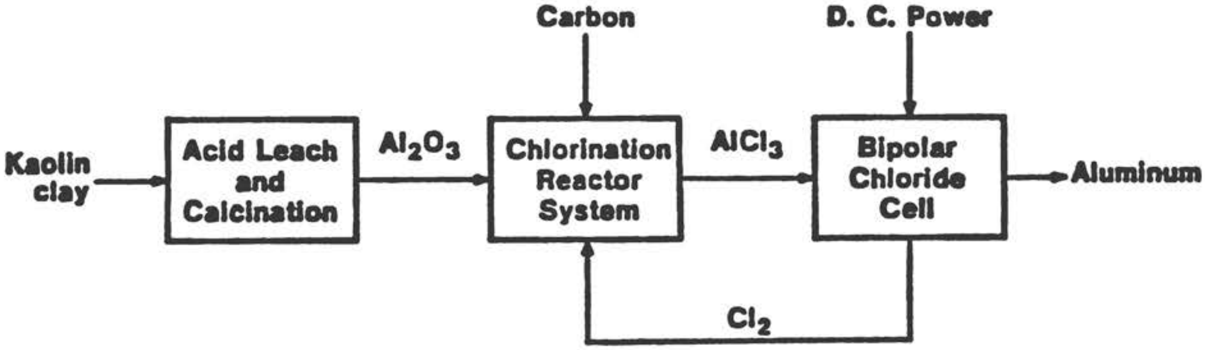


FIGURE 5-16 Clay-based smelting process.

Although significant improvements are possible in a monopolar design, limits on the economic advantages of larger cells have already been approached because of the very high current at low voltage (5 V) needed to introduce the required energy. If the electrical energy could be introduced as higher voltage rather than amperage, a more compact and less capital intense cell per unit of production could be designed. When the energy is introduced as voltage, space requirements for increased bus bar volume and problems resulting from an increased magnetic field are avoided.

Another major drawback to the monopolar design is the cell shape. Metal is produced in a single narrow horizontal slot 4.45 cm wide and about two to three acres in area. The fact that this area is broken into segments called cells and further subdivided into anodes is irrelevant. This shape, essentially a thin, flat plate, is the worst possible configuration for energy conservation. Both of these problems can be overcome if current is replaced with voltage in a bipolar system. In a bipolar system the same amount of metal produced in a monopolar system of equivalent current is produced each time the current passes through a bipolar plate and another decomposition voltage in the interelectrode space. Thus, a 100,000-ampere cell with 10 bipolar plates is the equivalent in production to a 1-million ampere monopolar cell, the extra energy being carried in as voltage. In one version of such a cell, bipolar plates are spaced one above the other with a terminal anode at the top and a terminal cathode at the bottom (Figure 5-17). The plates are propagated vertically rather than horizontally to permit collection of the aluminum product in one sump without allowing the current to bypass the bipolar plates through the aluminum metal as would be the case in a horizontally propagated plate system. Channels of the proper configuration on the anodic underside of the bipolar plates guide the electrolytically produced gas through a side or center channel, where gas is collected from all of the plates and rises through the fused salt. The geometry of the channel is adjusted so that displacement of the low density mixture of gas and electrolyte, by the more dense electrolyte, causes circulation in such a manner that each slot is fed fused salt saturated with the material to be decomposed at uniform velocity. This circulation permits aluminum chloride feeding at only one location. Much of the aluminum circulates as droplets with the gas over the top of the terminal electrode and down the opposing channel to be collected in the sump. In the chloride system, back reaction is negligible, high efficiency has been demonstrated, and a cell exceeding a million amperes equivalent production has been commercially operated for long periods. The Alcoa-developed cell and reactor combined with Arco demonstrated capability in acid leaching has resulted in a process that will be equivalent to a 75 percent efficient Hall-Heroult cell utilizing 4.5 kWh/lb instead of the present 6 kWh/lb for the best Hall-Heroult cells and using domestic kaolin clay. This could result in cost reductions exceeding 10 percent of Hall-Heroult costs and restore the domestic industry to a competitive position with future world production while eliminating importation of both bauxite and the crude oil for petroleum coke production.

Neither the new bicarbonate leach process, to produce feed economically from domestic materials for the Hall-Heroult process, nor the alternate Alcoa smelting process will be commercialized in the foreseeable future due to the high cost of capital, the existence of excess refining and smelting capacity, and the low cost of overseas power and labor. The development of on-line capability to use domestic raw materials to produce aluminum will occur only if the government is willing to share in the capital costs of such developments.

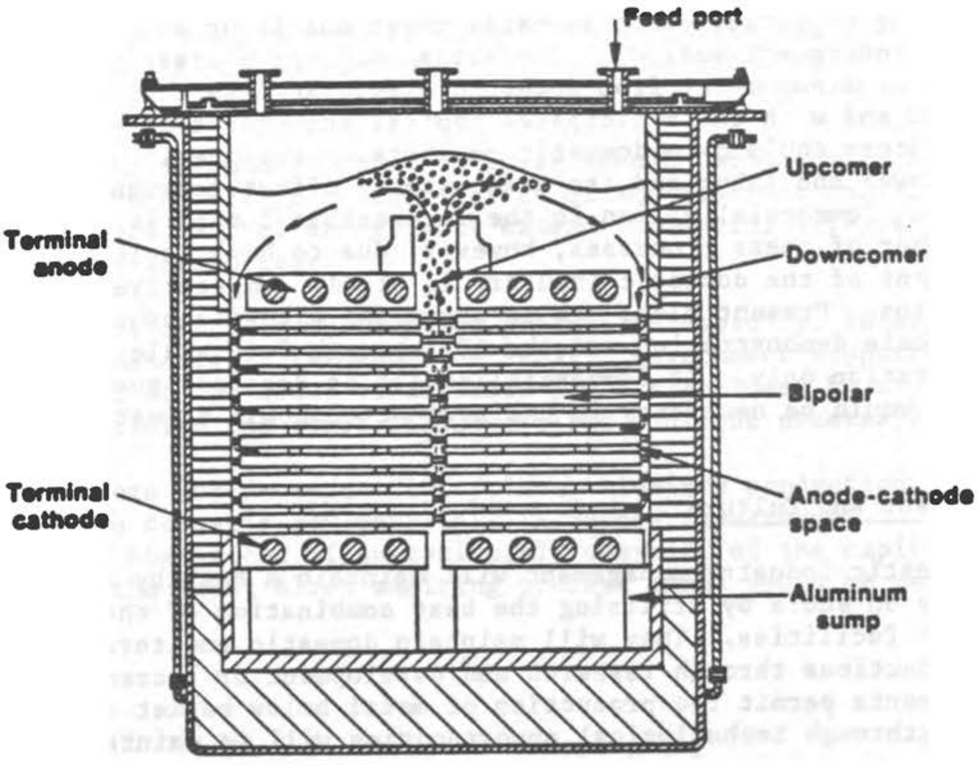


FIGURE 5-17 Industrial bipolar cell.

CONCLUSIONS AND RECOMMENDATIONS

Technology

Useful technology that may be exploited to accomplish different objectives exists on three levels:

1. Incremental improvements have been identified that could reduce domestic smelter costs by 8 to 10 percent over the next 10 years. Exploitation of these is under way, privately funded, and should extend to some extent the profitable life of domestic smelters.

2. Some retrofittable, high-risk, low-probability-of-success (less than 30 percent) breakthrough technologies may, if successful, restore for a time the competitive position of domestic smelters and greatly extend their useful life. Some of these projects, such as a stable cathode and inert anode, are under way with Department of Energy conservation programs.

3. Alternate production technologies exist that would make the U.S. aluminum industry economically independent of imported raw materials.

Hall-Heroult smelter-grade alumina can be produced from domestic gibbsite cost competitive with imported bauxite, but this process would do nothing to offset cheap overseas power and labor and foreign-government subsidy. The Alcoa smelting process can be used to produce aluminum metal from domestic clay. At less than 4.5 kWh/lb of aluminum and with the anticipated capital and operating cost reductions, this process could make domestic smelters cost competitive with overseas cheap power and labor and, to some extent, offset foreign-government subsidy. Commercialization in the foreseeable future is not anticipated for either of these processes, however, due to high capital costs and the investment of the domestic industry in highly competitive overseas metal production. Present plans are to carry the gibbsite process through bench-scale demonstration and the ASP through full scale pilot demonstration only. If commercialization is desired, government capital support would be necessary in the present economic climate.

Management and Culture

Domestic industry management will maintain a healthy aluminum industry on shore by utilizing the best combination of their overseas and domestic facilities. They will maintain domestic smelters as long as cost reductions through research and development or incremental improvements permit the production of metal below market value. Support of breakthrough technological opportunities will be maintained while government participation continues, but no effort will be made to create world competitive smelting facilities based entirely on domestic raw materials with private capital. Such technology will be held in abeyance unless bauxite prices are raised unreasonably. Research and development will be concentrated on fabricating technologies and new market opportunities to restore growth rate of aluminum usage at home and overseas. No expansion of aluminum production facilities beyond those already announced is foreseen in the next decade. If such expansion is necessary, it will be brownfield expansion overseas unless breakthrough technologies have enhanced the domestic position.

Government Action

If it is deemed necessary for national security purposes that a strong aluminum industrial base be maintained in the United States, certain government actions in the following areas could help:

1. The Buy American Act, including tariffs, has been eliminated for NATO countries. This has encouraged the Department of Defense to buy, on waivers of this act, foreign aluminum for defense needs to get a better price. Government purchase of domestic products can be used to assist in the retention of smelter and fabricating capacity on shore.

2. Implementation of investment tax credits for research and development directed toward improving the cost-effectiveness of fabricating and smelting capacity would enhance the retention of a strong industrial base.

3. Continue government support of breakthrough technologies, which could have a profound effect on the ability of the domestic industry to compete in the world market and greatly extend the useful life of domestic smelting facilities.

4. If an on-shore primary aluminum production capacity, independent of imported raw materials, is deemed necessary, government support of pilot development of the Alcoa bicarbonate process followed by capital assistance in building the first refining plant would be necessary.

5. If on-shore world-competitive primary aluminum production capacity based on domestic raw materials is needed, government participation to the extent of approximately one-half of the capital requirement for the first Alcoa smelting process plant would be necessary.

REFERENCES

Aluminum Association, Inc. 1982. Aluminum Statistical Review--Historical Supplement. Washington, D.C.: Aluminum Association, Inc., p. 22.

American Gas Association. 1983. Total energy resource analysis. Heat Treating (February):27.

American Metal Market. 1983. May 12.

Brondyke, K. J. 1983. The aluminum industry in 1982 and outlook for the eighties. Journal of Metals (April):63-78.

Bureau of Mines. 1985. Federally Funded Research. Minerals and Materials, A Bimonthly Survey. February/March. Washington, D.C.: U.S. Government Printing Office.

Castera, M. 1984. Movement in vertical integration with the aluminum industry. Paper presented at the AIME 113th Annual Meeting, Los Angeles, California, February 29.

Federal Emergency Management Agency. 1983. Stockpile Report to the Congress, October 1982-March 1983. FEMA 36/October. Washington, D.C.: U.S. Government Printing Office.

Haupin, W. E., and W. B. Frank. 1981. Electrometallurgy of aluminum. Pp. 301-305, vol. 2, Comprehensive Treatise of Electrochemistry. New York: Plenum Press.

Jarrett, N. 1981. Aluminum smelting: past, present, and future challenges. AIChE Symposium Series Vol. 74 (204):27-37.

Jarrett, N., W. B. Frank, and R. Keller. 1981. Advances in the smelting of aluminum. Pp. 137-158, Metallurgical Treatises. Warrendale, Pennsylvania: The Metallurgical Society of AIME.

Kaufmann, T. D., and P. Bras. 1983. Aluminum industry prospects, 1983-93. Mineral and Energy Resources, 26(5).

Ketteringham, J. M., and J. R. White. 1982. Making technology work for business. In Latest Advances in Strategic Management, Robert Lamb, ed., New York: Prentice Hall.

Ligon, C. K. 1984. Driving forces behind the uncoupling of the traditionally vertically integrated aluminum industry. Paper presented at the AIME 113th Annual Meeting, Los Angeles, California, February 29.

Metal Bulletin. 1983. September 23.

Ransley, C. E. British Patent 684,695.

Roskill Information Services. 1982. Roskill's Metal Databook, 3rd ed. London: Roskill Information Services, Ltd.

6

THE TITANIUM INDUSTRY

The U.S. titanium industry, a relative newcomer to the basic metals industry, emerged in the 1950s primarily to meet the needs of the military aircraft and aerospace industries. Today it is struggling to establish itself securely in the commercial sector, apart from the ever-fluctuating demands of military procurement programs. Pertinent issues related to this strategic metal are reviewed briefly in this chapter.

SOURCE MATERIALS

Titanium is the ninth most abundant element, making up about 0.6 percent of the earth's crust (Lynd, 1983). It occurs in nature only in chemical combination, usually with oxygen and iron. The titanium industry is based on the unique properties of titanium metal and titanium dioxide. Titanium metal, because of its high strength-to-weight ratio and resistance to corrosion, is an important strategic and critical material and is widely used for high performance military and civilian aircraft (both in airframes and engines), for powerplant surface condensers, and for a wide variety of chemical processing and handling equipment (National Materials Advisory Board, 1983; U.S. Department of Commerce, 1981; Wachtman, 1981). Titanium metal is produced by highly sophisticated chemical processes and is, therefore, much more expensive than aluminum or steel. Only about 5 percent of the world's annual production of titanium mineral goes to make titanium metal. The remainder is used primarily to produce white titanium dioxide pigment. Because of its whiteness, high refractive index and resulting light-scattering ability, titanium dioxide in its two main allotropic forms, rutile and anatase, is the predominant white pigment for paints, paper, plastics, rubber, and various other materials.

The third largest application, mainly in the form of rutile, is for coating welding rods used in a wide spectrum of industrial and military applications. Other minor applications of titanium and its minerals include the manufacture of titanium carbides, ceramics, and chemicals and the recently developed use of ilmenite as a substitute for barite in well-drilling muds.

The present mineral sources of titanium are ilmenite, an iron titanate, along with its alteration product leucoxene, and rutile. Rutile ore is usually 90 percent to 95 percent titanium dioxide. Other potential sources of titanium that may become important in the future include deposits of anatase in Brazil and perovskite, a calcium titanate, in Colorado.

INDUSTRY ACTIVITY

The quantities of world titanium raw materials used and the resulting end products in 1981 are shown in Figure 6-1.

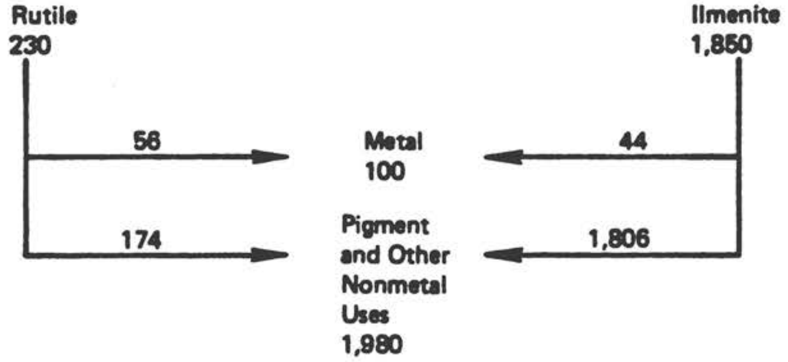


FIGURE 6-1 Estimated world titanium raw materials and end products in 1981 (thousands of short tons).

Net U.S. shipments of titanium metal mill products in 1982 were approximately 18,000 tons valued at about $520 million. U.S. production of titanium dioxide pigment was about 640,000 tons valued at about $900 million. In 1982, these two major uses accounted for over 96 percent of domestic titanium consumption.

High-titanium slags containing 70 to 85 percent titanium dioxide are made by electric furnace smelting of low-grade ilmenite with coal or coke. Smelting has the advantages of producing a low-iron, high-titanium slag for pigment plant feed raw material and a salable iron by-product.

Rutile substitutes, generally known as synthetic rutile, are made from high-grade ilmenites using various combinations of reduction and leaching treatments. Synthetic rutile concentrates are similar to rutile in composition and particle size, and contain from about 88 to 95 percent titanium dioxide.

The sulfate process for producing titanium dioxide pigment utilizes as feed material either ilmenite, containing 45 to 60 percent titanium dioxide, or titanium slag, containing 70 to 75 percent titanium dioxide. Most chloride-process pigment plants and titanium metal plants require rutile, synthetic rutile, or titanium slag containing about 85 percent titanium dioxide to make the intermediate compound, titanium tetrachloride. (One firm uses a mixture of ilmenite, leucoxene, and rutile.) Feed materials needed for metal production are the same as those for chloride-process pigment since formation of titanium tetrachloride is required in both cases. Rutile is the only titanium raw material used for metal production in the market economy countries.

The United States mines about one-third of its titanium raw material requirements. The balance is imported mainly from Australia in the form of rutile, synthetic rutile, and ilmenite and from Canada in the form of titanium slag. For economic reasons, U.S. producers of titanium metal have relied almost entirely on imported natural rutile, mainly from Australia. This dependence could be eased or eliminated in an emergency, probably at somewhat higher cost, by making synthetic rutile from domestic ilmenite, or by using titanium tetrachloride made from domestic ilmenite. Figure 6-2 outlines the conversion process from ore to metal. Figure 6-3 shows the location of domestic ore bodies of lower concentration that could be used in an emergency.

A major problem affecting the titanium metal industry is the wide fluctuation in demand resulting from changes in military and commercial aircraft programs. In 1981, about 60 percent of U.S. titanium metal consumption was for use in aerospace applications, 20 percent was for other industrial uses (e.g., chemicals, power generation, and marine and ordnance applications), and 20 percent was used in steel and other alloys. Producers of titanium sponge, the primary form of titanium metal, have repeatedly increased capacity in response to anticipated demand and have then been left with excess capacity when programs were cancelled or cut back (National Materials Advisory Board, 1983). Possible ways to help stabilize this situation include better long-range planning and forecasting of aerospace industry requirements, increased use of multiyear military procurement contracts, and further diversification of titanium into nonaerospace industrial applications. The buildup of production capacity following the shortages that developed in 1979 and 1980 seems to assure an adequate supply of titanium at competitive prices at least for the next few years. Today, domestic sponge capacity is relatively flat even though total use has increased. The Japanese industry, however, has been rapidly expanding its sponge capacity so that it now is equal to that of the United States.

It is estimated that by the year 2000 U.S. titanium metal demand, including primary metal and old scrap, will be about 40,000 tons, equivalent to an approximate annual growth rate of 5 percent from 1980. The forecast range of total domestic titanium metal demand in the year 2000 is 40,000 to 83,000 tons. U.S. nonmetal demand for titanium in 2000

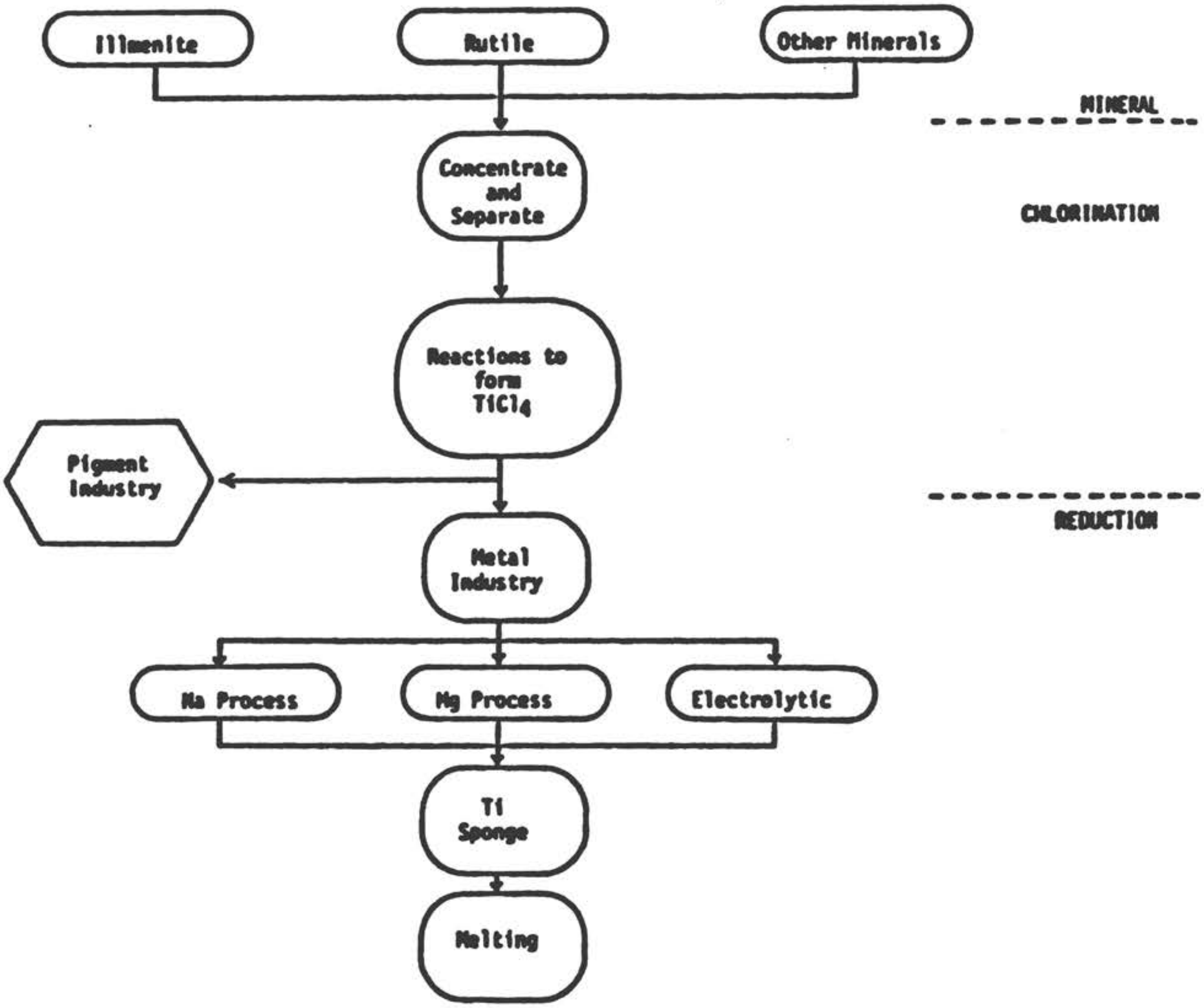


FIGURE 6-2 Titanium melt process.

FIGURE 6-3 Location of important titanium ore bodies in the United States. From Battelle Metals and Ceramics Information Center.

is estimated to be in the range of 650,000 to 1,200,000 tons with a probable demand of 830,000 tons, which represents an average annual growth rate of 2.4 percent from 1981. Rest-of-world titanium metal demand in 2000 is forecast to be in the range of 140,000 to 320,000 tons, with nonmetal demand estimated at 1.4 million to 2.5 million tons (Lynd, 1983).

Forging capacity also must be taken into consideration in assessing national needs in an emergency situation--namely, handling the FEMA stockpile inventory in a 3-year national emergency. Serious disagreement exists on this point between the forging industry and the U.S. Air Force, the major consumer of large-billet forged titanium. During the period of 1979 to 1981, difficulty was encountered in obtaining titanium forgings and mill products. At least part of the difficulty was associated with the lack of sponge caused by the diversion of Japanese sponge to the European market. Currently, over 20 percent of the sponge used in the United States is Japanese. These factors make it difficult for domestic producers and fabricators to establish a healthy and responsive total national capability for this strategic metal. Close cooperation between the producer, fabricator, and user is needed to minimize the impact of such a bottleneck.

USES

In a national emergency of three years' duration (the basis for the stockpile goals), titanium metal would first be directed to military applications. Today's engines, including those that power the most advanced aircraft in the U.S. military inventory, use the largest quantity of the metal in the compressor portion of the engine and some in structural members; e.g., the Navy F-18 fighter aircraft uses as-HIPed titanium parts in engine mount supports. There currently is no substitute for this metal, though aluminum, high-strength steels, and certain nickel-base superalloys could be used as substitute materials along with composite materials, but not without major design changes and significant performance reductions. It is assumed, however, that in an emergency there would be no time to introduce the significant design changes needed to switch to another metal family. Indeed, just qualification testing and certification is a very time-consuming and costly process.

Several of the most advanced U.S. aircraft use considerable amounts of titanium in structural applications requiring forgings and plate and sheet fabrication. The advanced aircraft now being considered for production in the 1990s involve the use of titanium alloys in critical structural components. Although the use of sheet and plate may be reduced somewhat by the introduction of composite materials, the fact remains that the military still will be dependent on titanium at least through the year 2000.

CONDITION OF THE INDUSTRY

The process for producing titanium sponge is basically the same today as the originally developed Kroll Process. Attempts to develop an electrolytic process were undertaken in the early 1980s but have been shelved for economic reasons. TIMET, RMI, Oremet, and ITI currently are the major domestic suppliers of sponge. A DOD development program at Albany Titanium, Inc., involving the "Occidental Petroleum Process" claims to reduce the cost of titanium sponge made from domestic ilmenite using the zinc and aluminum reduction process (Rogers, 1985). The Japanese supply considerable sponge current to the U.S. market especially to melters that do not have their own sponge-making facilities. It is estimated that the domestic sponge suppliers currently are operating at 50 percent capacity. At full production these domestic sources are capable of supplying approximately 28,000 tons of sponge per year to the marketplace, an amount that would meet most of the current U.S. demand. Various reasons have been given for the shortage of titanium metal during the period 1979 to 1980. At that time sponge from Russia and China was purchased for aerospace use, but at least one of these sources probably would not be available in an emergency. In addition, the quality of the sponge from these sources was not up to U.S. and Japanese standards and was allocated to mainly nonrotating applications.

Recently, the number of those converting sponge to mill products has increased. Initially, TIMET, RMI, Howmet, Oremet, Martin-Marietta, and Teledyne-Allvac were the principal converters of sponge to mill products. Wyman-Gordon and Allegheny Steel have since entered the marketplace. Thus, approximately 36,000 tons per year of ingot product can be generated domestically. No major investments are contemplated at this time that would affect significantly the sponge-making capacity, and barring any government action, there is no stimulant in the marketplace to prompt investment for additional capacity. IMI in England could supply material to the U.S. marketplace. The British industry is currently operating at approximately 55 to 60 percent of capacity, about the same as the U.S. industry.

The process of converting titanium sponge to ingot involves compacting the sponge, adding alloying elements and titanium scrap, and welding these pieces together to form an electrode. This is then melted into ingot form by the vacuum consumable-electrode process. The resulting ingot is always remelted and sometimes melted a third time (triple melt) to produce ingots that are suitable for some critical jet engine applications. Titanium alloy for airframe applications is for the most part only double melted. The purpose of the third melt for jet engine rotating parts is to minimize the presence of melt-related defects that have been found to adversely affect service life. Some argue that a good second melt results in an equivalent or better product than that resulting from a poor third melt operation. In an emergency, the melt capacity of the industry probably could be increased, with a commensurate power requirement reduction, if the third melt were eliminated; however, this probably would result in increased component maintenance and lower service life, especially since the aircraft probably would be performing beyond the normal designed life.

Usable mill product is 60 to 65 percent of the ingot product produced. This indicates that between 23,000 to 25,000 tons would be available annually to meet emergency needs without expansion of present facilities. History indicates that the industry will not expand beyond present capacity limits as long as the present industrial climate persists. Since it is estimated that it would take approximately one year to add an additional furnace or two to an already operating melt facility, it must be assumed that the supply of mill product would be limited during an emergency and that steps would have to be taken to better utilize the available metal. Approximately 35 to 40 percent of the scrap generated returns to ingot product; it generally is composed of in-house generated and well-segregated scrap. It is estimated that only 20 to 25 percent of an ingot of titanium actually gets into the final shape used in aircraft applications because of the cutting and shaping operations employed. Therefore, efforts should be made to better utilize this scrap metal since (depending on application) up to 75 to 80 percent scrap is often used for ingot makeup (25 to 80 percent being new sponge) of material currently being used by the industry. Some titanium suppliers do use a high percentage of machine turnings; yet, over 80 percent of such material currently ends up in iron and steel furnaces, thus constituting a major loss to the titanium industry.

RECENT ADVANCES

Recycling

A definite effort is being made to correct the low scrap recycling situation. Machining chips are being recycled by several techniques including plasma arc and electron beam melting. The resulting material is being tested for suitability for engine and airframe applications and other less critical nonrotating applications. It seems that within three to five years rotating-grade forging or casting material made from this material will be approved for usage. In a national emergency, approval could come very quickly.

Shaping Processes

Assuming that the goal in an emergency situation is to maximize the material available, attention should be focused on those processes that produce the "near-net-shape" parts where there is minimum machining involved and the best "buy-to-fly" ratios are achieved, namely, isothermal and hot die forging. A small number of forgers (about six) are operating or would be technically capable of operating such equipment. Round parts (rotating engine components), in the 600 to 700 sq in. plane view area (pva), are currently produced for both military and commercial engine applications. This forging equipment is utilized at about 25 percent of capacity, and currently only 10 percent of the time to make titanium parts (Bergstrom, 1984). More superalloy engine components are made by the process. If materials are upgraded for advanced engines as predicted, this capacity would be more effectively utilized. In such a case, titanium alloys would have to compete with nickel-base superalloys for the use of this equipment, but, fortunately, most of the titanium parts could be produced by conventional processing but in a less efficient manner.

A definite effort is being made to expand the use of hot die forging, which involves considerably less expenditure of funds than adding to existing press capacity; however, only a small number of forgers are doing this. This does not mean there will be an immediate shortage of fabricators that can produce titanium forgings but just a probable shortage of those capable of making components by the most material-efficient processes. Today's forging industry is capable of supplying military needs and is functioning at approximately 50 percent capacity. There is room to handle an emergency. In addition, government edict could direct other forging companies not currently forging titanium to be brought on stream via a directed transfer of the skills needed.

Remarkable progress also has been made in the area of titanium castings. The casting process has benefitted immensely from the microporosity healing capability observed in materials made by the hot isostatic pressing (HIP) process. Complex vane and shroud assemblies, as well as castings which were formerly ring and sheet metal weldments, now are being used in more advanced engines. Two major precision casting companies are producing these components--Precision Cast Parts (PCP) and Howmet Turbine Components Corporation. It is quite probable that in an emergency it would be difficult to significantly increase the production of these precision parts. In any event, weldments could be produced to supply needs beyond those that the precision casters could fill even though there would be an increase in cost.

Not stated explicitly, but implied throughout this discussion, is the fact that the major portion of the titanium used in military applications is titanium alloy. The alloys of concern are Ti-6Al-4V, Ti-8Al-1Mo-1V, Ti-5Al-2.5Sn, Ti-6Al-2V-4Mo-2Sn, Ti-6Al-6V-2Sn, Ti-6Al-2Sn-4Zr-6Mo, and Ti-17 (5Al-4Mo-2Sn-2Sr-4Cr). There is no major problem associated with the master alloys (containing the alloying metals) that are used to make these alloys. In addition to the above, the AFWAL (Materials Laboratory) is pursuing the development of low-density titanium alloys containing lithium, beryllium, or silicon (Bureau of Mines, 1985).

NEW DEVELOPMENTS

One development that could have a significant effect on extending the service life of titanium engine components, and thus reducing the need to increase metal production, involves the current "clean-metal" efforts of the industry. Elimination of the major causes of the most serious defect in titanium alloys--low-density inclusions (LDIs)--is being pursued vigorously. Low-density inclusions generally are regarded as the limiting factor in designing titanium component life based on fracture mechanics criteria, such as crack initiation and growth. This type of defect involves brittle nitrogen- and oxygen-enriched regions generally associated with burned sponge, contaminated scrap, and welding involving poor electrode fabrication. To correct this, some changes will have to be made in the older titanium melt facilities; it is quite possible that an order of magnitude improvement can be achieved within three years. Technologies currently being explored to eliminate this problem are aimed at producing cleaner sponge by improving sponge-making processes (also electrolytic winning), electron beam and plasma arc melting of scrap, eliminating all out-of-chamber welding associated with electrode fabrication, and improving quality standards throughout the entire processing. As an added incentive for a continuing effort, some of these processes, when adequately developed, should reduce the high power requirements of the processing cycle.

Another new development is the method of producing titanium alloy powder net and near-net shapes by the powder metallurgy hot-isostatic-pressing (P/M HIP) method. This process eliminates many steps in making shaped aircraft components so that machining costs and time to make parts are significantly reduced. Also, buy-to-fly ratios are decreased from about 15:1 to 2:1 in many instances. The process has been demostrated to be feasible by several companies and is in an early stage of implementation. In times of emergency, materials savings and shortened production times could result from application of this technology. Further scale-up to production quantities is required to develop information on dimensional reproducibility. The committee finds that there are some impediments to the immediate wider use of this important technology. An unfortunate experience with an as-HIPed nickel-base superalloy powder component in a military engine failure caused manufacturers to be very cautious about moving rapidly to adopt this technology for critical engine components. As manufacturing process experience enhances the confidence of component reliability, HIPing will be qualified for the manufacture of human-rated critical rotating and airframes components from powders of superalloys, titanium, and other metals and alloys, even nonmetals.

CONCLUSIONS AND RECOMMENDATIONS

Based on the current situation and anticipated changes, it has been concluded that:

1. Titanium and its alloys remain important for military and commercial engine and airframe applications.

2. Direct substitution of other alloys or composites in an emergency does not appear feasible without significant design changes and extended qualification testing.

3. Production at full capacity (50,000 tons of ingot) plus the present stockpile (about 32,000 tons of sponge) would fill estimated military needs (70,000 tons) in an emergency for only one year.

4. In an emergency, all titanium produced would have to be directed to military needs.

5. No major expansion of sponge-producing facilities is expected because of the cyclical nature of the market.

6. U.S. titanium sponge-making and titanium-forging facilities currently are operating at about 50 percent capacity.

7. Improved metal shaping processes (e.g., hot-die isothermal forging and precision casting) provide opportunities to greatly improve materials utilization. These processes currently are underutilized, and, as a result, no investments are being made to increase this capability.

8. Near-net-shape processes used for titanium also are utilized for the production of advanced superalloys; therefore, in an emergency, there would be a bottleneck at this stage of production.

9. The service life of titanium engine and airframe components can be extended for critical titanium hardware if current clean-metal approaches can eliminate low-density inclusion problems.

To mitigate the potential problems that could arise in an emergency, the following steps should be taken:

1. Initiate programs for identifying and qualifying substitute materials and designs for titanium that would be ready for use in an emergency.

2. Encourage research and development efforts in near-net-shape processes to permit more efficient use of available sponge and ingot production capacity.

3. Investigate in more detail the unique requirements for using the titanium-alloy powder metallurgy method for producing near-net-shape components by the HIP process and related powder processes for mill products and components.

4. Continue efforts in clean-metal approaches to more effectively utilize the technical potential of titanium and its alloys in critical applications.

5. Support research efforts aimed at providing for better utilization of all types of scrap instead of downgrading this valuable material for use in non-titanium applications.

REFERENCES

Bergstrom, R. P. 1984. Forging: in the survival mode. Manufacturing Engineering 94(3):53-58.

Bureau of Mines. 1985. Federally Funded Research. Minerals and Materials, A Bimonthly Survey. February/March. Washington, D.C.: U.S. Government Printing Office.

Lynd, L. E. 1983. Mineral Commodity Profile 1983--Titanium. Washington, D.C.: U.S. Government Printing Office.

National Materials Advisory Board. 1983. Titanium Availability: Past, Present, and Future. Washington, D.C.: National Academy Press; NTIS PB83 171 132.

Rogers, J. 1985. Albany titanium wins powder research pact. American Metals Market/Metalworking News, July 22, 1985. P. 19.

U.S. Department of Commerce. 1981. Critical Materials Requirements of the U.S. Aerospace Industry. Washington, D.C.: U.S. Government Printing Office; #1982-360-997/2018.

Wachtman, J. B., Jr., ed. 1981. Proceedings of the U.S. Department of Commerce Public Workshop on Critical Materials Needs in the Aerospace Industry. National Bureau of Standards, NBS IR 81-2305. Washington, D.C.: U.S. Government Printing Office.

7

THE SUPERALLOYS INDUSTRY

The term "superalloy" is used in this study to denote a class of vacuum-melted alloys that are either nickel-, cobalt-, or iron-based and that contain significant amounts of alloying additions such as chromium, aluminum, titanium, molybdenum, tungsten, tantalum, and columbium as well as other trace elements.

Approximately 80 percent of the superalloys produced in the United States are used in the aircraft and aerospace industries, specifically in the hot sections of jet and turbofan engines. Thirteen percent of the alloy production is used in power generations and six percent in chemical processing equipment.

As one might expect, since the highly cyclic aircraft industry accounts for most of the superalloys sales, the volume of superalloy shipments is also highly cyclic. Figure 7-1 shows the cyclic demand for superalloys in terms of the volume of primary superalloy shipments. Primary shipment weight, also known as delivery weight, is the weight of material processed and machined to result in a much lower component weight (flyweight). Some shipments also go into inventories, while some remelt (recycled) material (controlled by specifications) is used during primary production. In the 1976 industrial downturn, superalloy shipments were estimated at 45 million lb. They climbed to a peak of over 80 million lb in 1979 and 1980, and then dropped to a lower level in 1982. No doubt the peaks and valleys are exaggerated by hedge buying, as will be discussed later.

The characteristics of the superalloy industry that has evolved to meet the demands of the aircraft industry are discussed below. In addition, the consequences of the highly cyclic demand for superalloys and production overcapacity are considered, as are the threat of internationalization of superalloy production, feedstock insecurities, and the effect of advanced materials to the current industry.

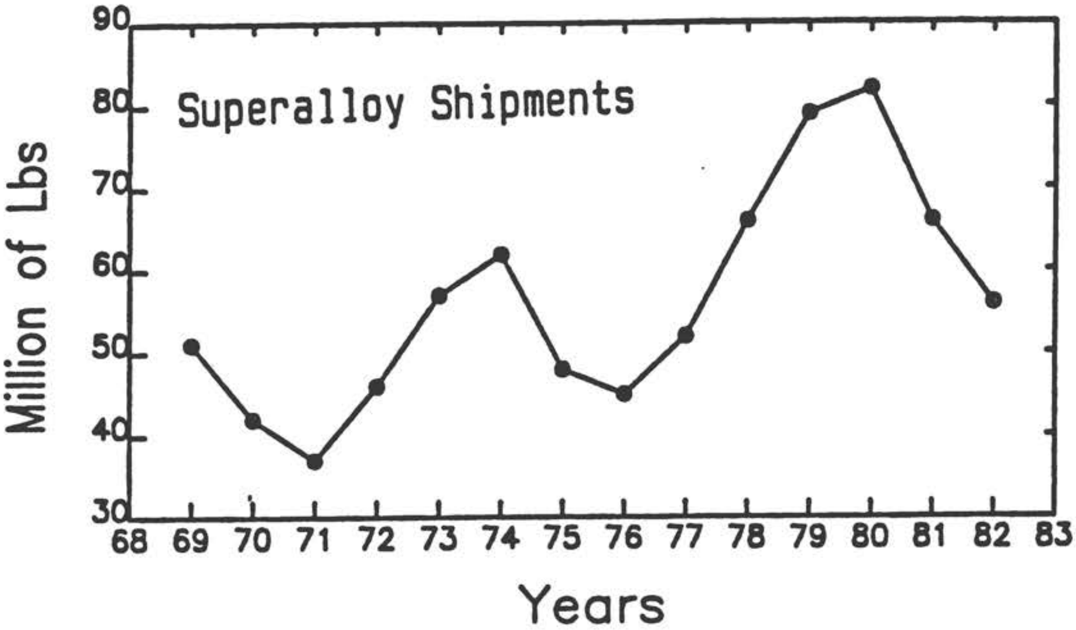


FIGURE 7-1 Superalloy shipments.

SOURCE: J. K. Tien.

SUPERALLOY TECHNOLOGY

As the major end use of superalloys, the gas turbine has been a consistent driving force for the technical requirements of the superalloy industry. The term "gas turbine" as used here is a generic term that includes the pure jet, turbofans, turboprops, and all other gas turbines that have internal combustion chambers and do work such as generating electricity or pumping. The gas turbine producers have an insatiable need for higher stress and temperature capabilities and for more reliable and durable materials. The development of the producing and processing aspects of the superalloy industry has been intimately tied to these demands. In modern gas turbines, the vane, blade, and disk materials (i.e., the hot sections) are made of superalloys.

Since superalloys are used for critical and strategic defense applications, reliability is of the utmost concern. To meet stringent reliability requirements, the first step common to the production of most superalloys is the vacuum induction melting (VIM) of a superalloy charge (Figure 7-2). Melting and alloying in vacuum minimize contact and reaction of the alloying elements with oxygen and nitrogen, produce melts with a minimum of inclusions, and allow superior compositional control. The vacuum also accelerates the refining process by removing dissolved gases from the melt (Pridgeon et al., 1981).

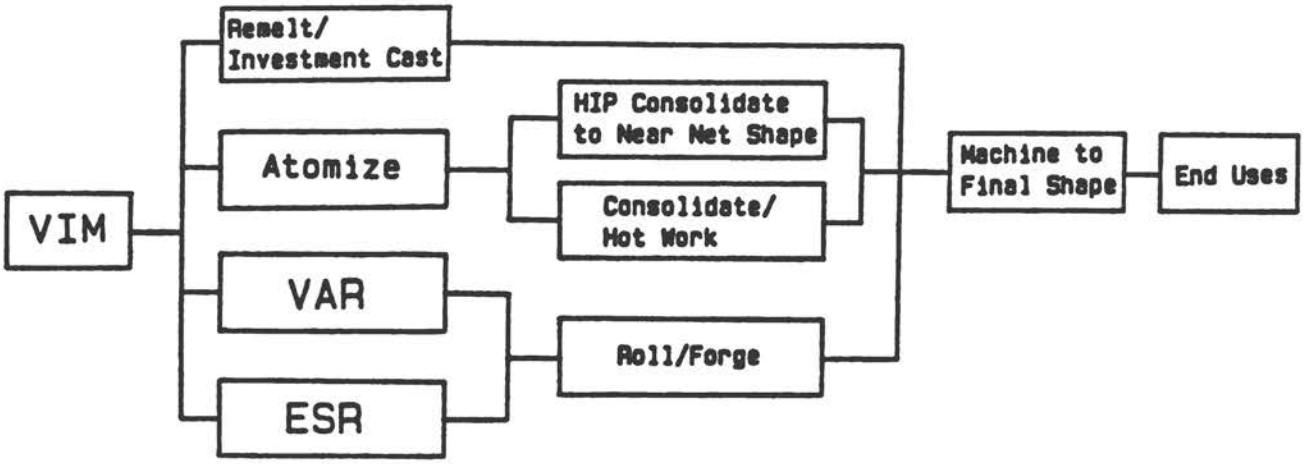


FIGURE 7-2 Summary of the various superalloy processing steps.

SOURCE: J. K. Tien.

Minimizing inclusions and superior compositional control of the VIM ingot go a long way towards satisfying reliability requirements. Because ceramic oxide crucibles are used, however, some nonmetallic inclusions can result for which new filter technology is being developed, and the electron beam refining of VIM ingots is being pursued (Tien and Schwarzkopf, 1983). Beyond the inclusion problem, there are other major limitations with respect to the internal cast structure produced. The cast VIM ingot generally has some segregation and contains large grains of nonuniform size and shape (Pridgeon et al., 1981). A nonhomogeneous microstructure is undesirable, and to make the VIM ingot workable, another processing step generally is necessary. One means of enhancing workability is vacuum arc remelting (VAR), which uses the VIM ingot as a consumable electrode (Pridgeon et al., 1981). During VAR processing the volume of material that solidifies is small compared to the VIM process. This and other VAR process characteristics result in a smaller, more uniform grain size distribution with less segregation. Also, electroslag remelt (ESR) is sometimes used to remelt VIM ingots for grain control and further purification (Gao et al., 1980); however, the practice of using ESR-prepared material for jet engine rotating hardware is just beginning in the United States. The superalloy producer usually hot works the VIM/VAR or ESR ingot into such forms as billet, bar, or sheet.

The VIM/VAR processing route provides the feedstock for another processor in the superalloy industry, the forger. Forgers take the billet material and hot work it into near final form; a typical final form for a wrought superalloy would be the turbine discs or the larger blades of a gas turbine engine. The amount of machining depends on how close to near net shape the material is brought by the preceding processing steps.

In the past 20 years, the VIM/VAR processing route has served the superalloy industry well for a host of applications. However, superalloy users continuously demand higher strength and operating-temperature capabilities; in general, the temperature increase is 8 or 9°F per year (Dreshfield et al., 1981). To meet these demands, alloys richer in alloying additions have been developed as shown in Table 7-1. Increased alloying, however, is accompanied by renewed problems of melt segregation and poor hot workability even when VAR or ESR is used. The poor hot workability of the higher strength (more richly alloyed) superalloys can be circumvented by remelting the VIM ingot through precision or investment casting. The investment casting process allows production of polycrystalline components (i.e., vanes and blades) that can be machined to final shape. Although this processing route allows production of high-strength superalloys, grain morphology can be a problem. The cast structure also is susceptible to segregation and precracked carbide problems. In addition, the presence of carbides and voids, even in the absence of unintentional inclusions, will impair fatigue properties. Subsequent hot isostatic pressing (HIP) of the cast material can be performed to help eliminate porosity problems (Antony and Radavich, 1980).

Current state-of-the-art investment casting allows for the production of columnar grain and single crystal turbine blades through directional solidification (Gell et al., 1980). Directionally solidified (DS) and single crystal (SC) blades are the most heat resistant superalloys now commercially available. In addition, current precision casting techniques allow for the production of various large near-net-shape cast components other than blades.

Although casting technology has made substantial advancements over the years, the basic problem still exists: how to produce high-strength superalloys that are also capable of being hot worked. Superalloy powder metallurgy (PM) processing was developed in the past decade in the hope of attaining this goal and to produce near net shapes. The superalloy powders are produced by atomizing the vacuum-cast ingots and, in turn, are generally consolidated by either hot extrusion or HIPing. The consolidated PM microstructure has fine equiaxed grains and very little segregation, even with respect to VAR or ESR processing. This refined PM-produced microstructure is more suited for hot working. In general, the PM superalloys have intermediate strength, being stronger than conventional wrought superalloys, but are not as heat resistant as the high-strength cast superalloys.

Another advantage of PM processing is the option of producing near net shapes without investment casting and, thus, of producing little scrap relative to conventional forging techniques. The principal problems with near-net-shape PM processing are the complexity and cost of

TABLE 7-1 The Composition (wt.%) of Various Superalloys

Alloy	Ni	Fe	Co	Cr	Mo	W	Ta	Cb	Al	Ti	C	B	Zr	Other
Alloy 901	42.5	36	---	12.5	5.7	---	---	---	0.2	2.8	0.05	0.015	---	0.10 Mn, 0.10 Si
B1900	64	---	10.0	8.0	6.0	---	4.0	---	6.0	1.0	0.10	0.015	0.10	---
Inconel 718	52.5	18.5	---	19.0	3.0	---	---	5.1	0.5	0.9	0.04	---	---	0.2- Mn, 0.2 Si
Inconel MA 754	78	---	---	20.0	---	---	---	---	0.3	0.5	0.05	---	---	0.6 Y_2O_3
IN 738	61	---	8.5	16.0	1.7	2.6	1.7	0.9	3.4	3.4	0.17	0.010	0.10	---
MAR-M246	60	---	10.0	9	2.5	10.0	1.5	---	5.5	1.5	0.15	0.015	0.05	---
MAR-M509	10.5	---	55	23.5	---	7.0	3.5	---	---	0.2	0.60	---	0.50	---
Merl 76	54.1	---	18.5	12.4	3.1	---	---	1.6	5.0	4.4	0.02	0.020	0.06	0.75 Hf
Nimonic 115	60	---	13.2	14.3	3.3	---	---	---	4.9	3.7	0.15	0.160	0.04	---
Rene 95	61.3	---	8.0	14.0	3.5	3.5	---	3.5	3.5	2.5	0.15	0.010	0.05	---
SC Alloy 454	62.5	---	5	10	---	4	12	---	5	1.5	---	---	---	---
Udimet 700	53	---	18.5	15.0	5.2	---	---	---	4.3	3.5	0.08	0.030	---	---
Udimet 720	---	---	14.7	18.0	3.0	1.3	---	---	2.5	5.0	0.03	0.033	0.03	---
Waspaloy	58	---	13.5	19.5	4.3	---	---	---	1.3	3.0	0.08	0.006	0.06	---
WI-52	---	2.0	63.5	21.0	---	11.0	---	2.0	---	---	0.45	---	---	0.25 Mn, 0.25 Si

NOTE: Company trademarks and trade names are: Waspaloy—United Technologies Corporation, Udimet--Special Metals, Inc., Rene--General Electric Company, Mar-M--Martin Marietta Corporation, Inconel--International Nickel Company, Nimonic--International Nickel Company, MA--International Nickel Company, Merl 76—Pratt and Whitney Group of United Technologies Corporation, SC Alloy 454—(see M. Gell et al., 1980).

producing clean powders and subsequent powder compacts and the elimination of reactive defects and prior-particle boundary carbides (Tien and Kissinger, 1984). The problems can be reduced by redundant hot working, such as forging. However, P/M HIP near-net-shape components are currently used in several military engines, as are engine discs formed from superalloy powders by the "Superplastic Gatorizing" process (a Pratt and Whitney development). In addition, the capability for using the "Gatorizing" technology for titanium gas turbine parts is under commercial development at a number of companies.

Higher strength superalloys are extremely prone to defects under cyclic- and impact-loading conditions (Tien and Schwarzkopf, 1983). Currently, the leading edge of superalloy melt process development is in the production of clean metal. In particular, the goal is to produce alloys that are free of ceramic inclusions, whether these are from the ceramic crucibles used in VIM processing or the ceramic nozzles used in PM atomizing. Sophisticated filtering, especially VIM, followed by electron beam (EB) refining can be expected to become standard operating procedures (an added box after VIM in Figure 7-2).

Another technology under development for achieving workable high-strength superalloys is vacuum-arc double-electrode remelt (VADER) processing (Tien, 1983b). VADER is an isothermal remelt cast process that has the potential of producing fine, uniform microstructures that are well suited for hot working. Also, primary hot working of superalloys is done primarily by hot forging and rolling. Lately, the introduction of rotary forge presses has led to the more efficient production of primary wrought structures that lend themselves to improved subsequent secondary breakdown or forging operations.

It should be noted that there may be potential problems associated with the availability of elements currently used in superalloys (see Table 7-2). Availability problems for these various alloying elements can result from resource depletion or geopolitical factors (Tien, 1983a). If superalloy producers are minor users of an imported element relative to other U.S. users, allocation from the major users in times of national emergency may provide relief during a supply shortage (e.g., superalloys require only a small fraction of the chromium used primarily for stainless steels). If, however, superalloys are a major user of an imported metal, no easy solutions exist. Superalloys are major users of cobalt and columbium, and significant users of nickel, molybdenum, and tantalum, but, as shown in Table 7-2, the United States produces no cobalt, columbium, or tantalum, and relatively little nickel. The superalloy industry would be especially vulnerable to a disruption in the supply of these elements such as occurred in the late 1970s (Tien et al., 1980). Element and alloy substitutions are metallurgical alternatives, of course, but institutional barriers to the introduction of new alloys into the "human-rated" gas turbines make superalloys very inelastic with respect to substitution in the short term (Stephens and Tien, 1983). It

TABLE 7-2 Illustration of the U.S. Reliance on Imports for Elements Used in Superalloys

Element	1980 U.S. Apparent Consumption (million pounds)	1980 World Mine Production (million pounds)	1980 U.S. Apparent Consumption as a Percent of World Mine Production	1980 U.S. Mine Production (million pounds)	1980 U.S. Imports[a] as a Percent of U.S. Consumption
Ni	446.0	1,700	26	29.3	93
Co	17.1	65.9	26	0	100
Fe (Iron ore)	184,200	1,747,200	11	139,200	24
Cr (Chromite)	1,936	21,450	9	0	100
Al	10,144	33,880 (plant production)	30	10,260 (plant production)	0
Bauxite	35,772	198,266	18	3,437	90
Ti (Metal)	53.9	187.7 (sponge production)	29	50 (sponge production)	7
Mo	60.8	293.2	25	150.7	0
W	21.8	119.3	18	6.0	72
Cb	7.5	32.3	23	0	100
Ta	1.2	2.1 (Includes tin slags)	57	0	100
V	13.2	79.1	17	9.6	73

---

[a] Excludes recycled material.

is normal, even with a fixed need, for five to ten years to elapse before a new alloy is qualified for jet engine use at a total cost exceeding $5 million (Stephens and Tien, 1983).

CONDITION OF THE INDUSTRY

As seen in Figure 7-2, the production of superalloy components follows a long and complex processing route. The superalloy industry that has evolved to perform these various tasks over the past 30 years (since the beginning of the jet travel era in the mid-1950s) is one with very little integration. Indeed, there is currently no single company that does the producing, processing, and assembling of superalloy components. However, as discussed below, there is some movement in this direction.

This nonintegrated superalloy industry can be divided into three general categories:

1. The producers of superalloy remelt, billet, bar, and sheet material;

2. The alloy processers; and

3. The engine manufacturers.

The major producers of superalloy remelt, billet, bar, and sheet material have the melt shop facilities for VIM/VAR or ESR processing and perform the primary working of wrought (hot workable) superalloys.

Bar and billet material account for the majority of the wrought superalloy production (Tien and Nardone, 1984). Some representative companies with major VIM, VAR, ESR, and primary breakdown facilities for producing bar and billet are: Special Metals Corporation (SMC), Teledyne Allvac, Carpenter Technology, Universal-Cyclops Specialty Steel, Cabot Corporation, and International Nickel Company. Cabot Corporation, the International Nickel Company, and Universal-Cyclops produce sheet superalloys in addition to these forms. With few exceptions, these companies share a common characteristic: they are either small companies or profit centers of companies whose superalloy sales represent a relatively small fraction of total sales.

Another major type of superalloy material is the remelt stock that is used for investment or precision casting. All companies with superalloy VIM facilities can supply superalloy remelt stock. Since remelt stock does not need to undergo secondary melting or primary and secondary working prior to sale, many smaller commercial units also are able to produce it. These companies, or divisions of companies, include Cannon Muskegan and Certified Alloys, both of which also can supply the larger producers with master alloys.

In addition, there are producers that make superalloys by the P/M processing route. P/M superalloy production is currently relatively small. Companies currently producing superalloy powders include Special Metals Corporation, Carpenter Technology, Universal-Cyclops Specialty Steel, Homogeneous Metals (United Technologies, Inc.), Crucible Compaction Metals Operation (Colt Industries, Inc.), and Cameron Iron Works. The powder producers consolidate the superalloy powders by either hot extrusion or HIP. This is a source of workable superalloy material. Current demand for the P/M material is small relative to the ingot metallurgy billet and bar stock that goes through VIM/VAR processing and primary breakdown. Also, near-net-shape or as-consolidated P/M superalloy usage would be increased if the P/M process were able to produce cleaner powders and the existing defect problems were further resolved (Tien and Kissinger, 1984).

The billet, bar, sheet, and remelt stock producers supply materials to feed the second general division of the superalloy industry, the alloy processors. There are two principal types of processors: (1) the companies that take the billet and bar stock and forge it into near final shape (e.g., disks and blades) and (2) the companies that take the remelt stock and cast it into near net shape. The hot workers of the wrought superalloys, in particular the forgers, include Wyman-Gordon Company, Ladish Company (division of Armco), Cameron Iron Works, and Kelsey-Hayes. The companies that investment-cast blades to near net shape include Howmet Turbine Components Corporation, TRW, and several others. Many of these casting companies also produce their own superalloy VIM remelt stock. Precision Cast Parts Corporation, for one, has developed the ability to produce, in addition to blades, various larger near-net-shape and finer-grained castings. Howmet Turbine Components Corporation, TRW, and the Pratt and Whitney group of United Technologies Corporation are among the few companies that currently possess the high technology necessary to produce directionally solidified and monocrystalline-cast blades or vanes, a technology originally developed by Pratt and Whitney. The large engine companies also developed, along with the producers and processors, such modern hot-working technologies as superplastic-type forming, which uses hot dies and controlled strain rates.

The current demand for the cast superalloys, in terms of volume, is small relative to the demand for wrought superalloys. This situation may change, however, as large-size casting technologies develop further. Current wrought hardware production may be replaced by cast hardware production as cast property reliability is enhanced by improved cast-structure control. In addition, as the cast hardware displaces wrought hardware, the primary shipments of superalloys for the same end-use market will decrease significantly because of improved materials-use efficiency of cast or PM near net shapes. Currently, the ratio of flyweight (weight of the finished wrought product) to the initial VIM stock weight in some cases may be as low as one to eight. The losses are due to inspection, forging, and machining of the wrought material. It should be noted before proceeding further, however, that the distinction between producer and processor is not clear cut. Cameron Iron Works, for example, has VIM/VAR capacity while Wyman-Gordon Company has integrated backward with respect to titanium-base alloys.

The engine manufacturers make up the third and largest general division of the superalloy industry. They provide the engines for use in aircraft for the commercial airlines and for the U.S. and certain other military forces. The other substantial engine companies are the land-based turbine producers that mainly supply the power-generation industry (utilities). The two major U.S. engine producers are Pratt and Whitney Aircraft of United Technologies, Inc., and General Electric Company. In contrast to the superalloy producers and processors, the jet engine companies, or divisions, are large and their engine sales represent a significant fraction of total sales. The large size of these companies is to be expected since the cost of developing a new engine may be as high as $1 to $2 billion.

In addition to the very large engine companies, there are the comparatively smaller companies that supply the business (civilian) aircraft sector with small engines, military tank engines, helicopter engines, shipboard engines, and power generating engines. Among these companies are Garrett Turbine Engine Company, Avco Lycoming Stratford, Detroit Diesel Allison (General Motors Inc.), and Pratt and Whitney of Canada. There are also the producers of rocket engines, which include Teledyne CAE and Rocketdyne (space shuttle main engine) of Rockwell International Corporation.

A significant user of superalloys is the power-generation industry. The principal producers of these land-based turbines are Westinghouse Electric Corporation and General Electric Company. This market segment is similar to the airline segment in that large end-user companies require materials from the smaller producer companies. Also, as a consequence of the stabilization of U.S. electric power demands, much of the recent sales of large utility gas turbines has been to foreign buyers, especially to Near and Far East countries.

An inevitable consequence of the small producer and processor companies is the limited amount these companies can afford to spend on research and development. If new processing techniques are to be developed into commercially feasible ones, the superalloy suppliers will need outside support. The principal potential funding source is the U.S. government, which provides R&D funds directly to the smaller companies or provides cost-share funding to the end users to develop new or improved processes. The government has the unique ability to fund several companies for an integrated R&D effort toward the development of a new technology. Coordinating efforts that exploit the expertise of various companies certainly have the potential of accelerating advancements relative to the achievement from a single company. The U.S. superalloys industry will be seriously impaired if government funding, especially for IR&D in manufacturing technology and for technology modernization, in addition to the more basic research-type funding, is curtailed.

THE FUTURE OF THE INDUSTRY AND FOREIGN COMPETITION

The superalloys industry, as outlined above, is somewhat unstable. This instability reflects the nonintegrated industry structure coupled with the smallness of the producing and processing companies as well as highly cyclic demand and current overcapacity. An example of this instability recently surfaced when Special Metals Corporation, one of the principal producers of superalloy billet and bar material, was almost purchased by Nippon Steel Corporation (National Journal 1983). If this had occurred, one of the principal U.S. producers of superalloys, and its know-how, would have been owned by an economically-aggressive competitor country, which wishes to become a major superalloy, engine, and aircraft producer.

Integration and Diversification

The corporate trend in the industry is to integrate backwards and to diversify. An example of backward integration occurred when the United Technologies Corporation set up an automated single crystal hardware production facility in Connecticut. The corporation also established a modern, automated forge shop in Georgia and acquired Homogeneous Metals as a source of superalloy powders. Another example is the establishment by Cameron Iron Works of vacuum melt facilities, and Wyman-Gordon Company's recent backwards integration into titanium-base alloys (the major alloy system in the compressor stage of jet engines). It is believed that backwards integration has one serious disadvantage: the action makes the integrated company even more vulnerable to the highly cyclic demand for superalloys. During a down period, the entire line of subsidiary facilities will feel the same depressed condition while the inevitable fixed costs remain.

Mention should be made of the fact that the magnitude of cyclic demand swings for superalloys is not solely a function of the business cycle of the aircraft (Weiler, 1983), aerospace, and utilities industries; it also can be aggravated by hedge buying (Andrews, 1983). This results when, during an upswing in demand or during real or perceived feedstock shortages, companies anticipate shortages of certain materials or components and overpurchase for their inventories. Stockpiling during times of increasing demand only serves to increase the demand further. The subsequent downturn in the business cycle causes the normal decrease in demand to become more acute as companies siphon-off existing stockpiles they created during the upswing. The net result is to amplify the business cycle. An estimate of the hedge-buying effect on the cyclic demand for superalloys is given in Figure 7-3, which is the same as Figure 7-2 except for the estimated hedge buying shown as the hatched area.

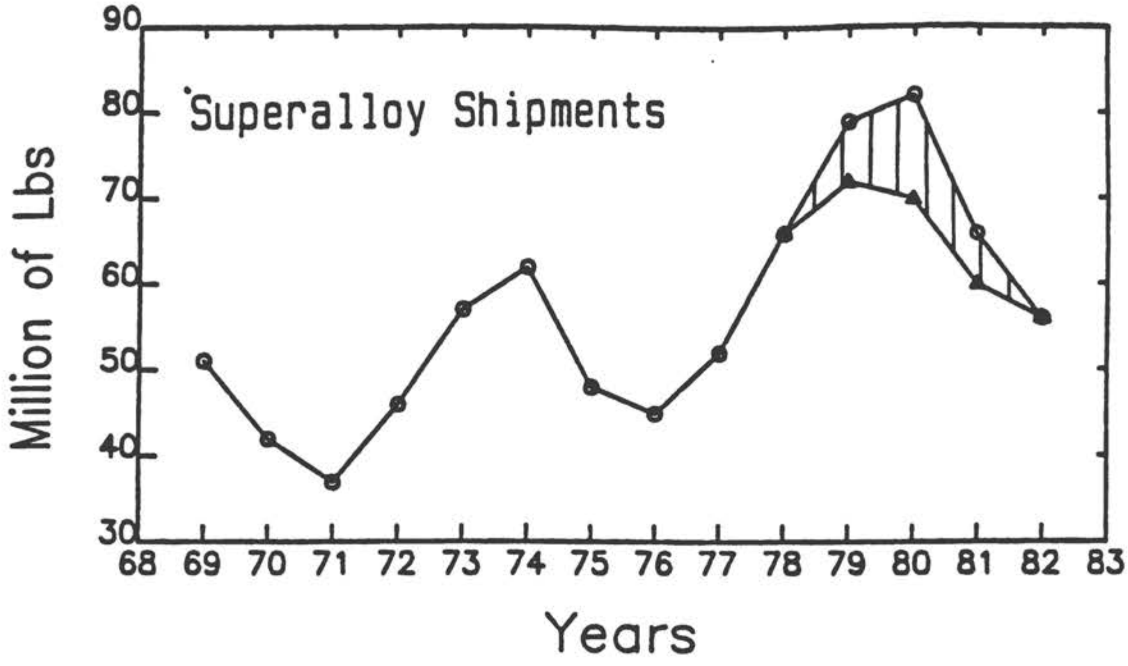


FIGURE 7-3 The effect of hedge buying on the cyclic demand for superalloys. (See Figure 7-2).

Another way a company can minimize the destabilizing effect of the business cycle is through diversification. The less dependent a company is on a particular portion of the economy, the less susceptible it is to its usual fluctuations. Except for a general economic downturn, the company will be insulated from the cyclic demands experienced by any single industry. An example of such a diversified company is United Technologies Corporation, which has acquired the electronics firms of Mostek Corporation and Essex Group, the Carrier Corporation, and Otis Elevator. General Electric Company is a well-known diversified conglomerate, and SMC has diversified into dental and shape memory alloys. A potential danger of diversification to U.S. superalloy production is that the company can become so diversified that it may cease to be a dedicated producer of superalloys and an expert in the required technology.

Perhaps the most pressing destabilization force is the large excess of primary superalloy production capacity. This tends to cause low prices and low return on investments, making it difficult for the primary producers to recapitalize and modernize. The situation may change as the weaker producers leave the business and the profit margins of the remaining producers improve even during the down cycles.

Advanced Materials

Higher and higher operating temperatures are continuously being sought to improve the operating efficiency of jet engines. This demand for enhanced heat resistance can be met by developing and testing new alloy systems. Advanced high-temperature materials under development include oxide dispersion strengthened (ODS) superalloys, rapid solidification rate (RSR) alloys, fiber reinforced superalloys (FRS), eutectic superalloys, intermetallics, and structural ceramics (Tien and Nardone, 1984).

The advanced materials will be used primarily in the high-temperature and highly stressed parts of the engine, e.g., first-stage (hottest) blades. These parts currently are made from the most heat-resistant superalloys, and a question arises concerning the effect the new materials may have on the superalloy industry. As first-stage inlet temperatures increase so will temperatures in the rest of the engine. This should result in high-strength superalloys displacing some less heat-resistant superalloys or other alloy systems, such as titanium-base alloys, rather than the superalloys themselves. Thus, in general, the development of new high-temperature materials should not pose a threat to the superalloy industry. In addition, the companies currently developing these advanced materials are generally the current superalloy producers and users.

Import Reliance for Feedstock

Another potential source of instability in the U.S. superalloy industry is the U.S. reliance on imports for many of the superalloys feedstock elements. The U.S. government has played a principal role in trying to reduce this reliance on imports and two of its actions in this regard have been the procurement of imported elements for the National Defense Stockpile and the sponsorship of research on suitable substitutes for elements currently being imported. The peak in such government activity occurred shortly after the disruption in the supply of cobalt from Zaire (1978-1979). When the situation stabilized, the price of cobalt fell and so did the government's efforts to find replacements for the element (Tien and Jarrett, 1983). A long-term commitment must be made if significant substitution accomplishments are to be expected.

In terms of the U.S. strategic stockpile program, two points should be noted. First, it is not sufficient to simply stockpile quantities of strategic raw materials required to produce superalloys without considering the high quality and form required. Second, even if high-quality materials are stockpiled for a national emergency, the industry should know more clearly when and how they can be released. In other words, what conditions constitute a "national emergency" that warrants the release of stockpile materials by the President or by the Congress? Does it require that an engine manufacturer cease commercial production before the stockpiled materials could be released for military engines? At the very least, the answer to what constitutes a "strategic emergency" situation should be reviewed and more clearly defined as a guide for the industry involved.

Import reliance generally is as much an emotional and political issue as it is a business issue. It is recognized that, although industry desires to pay as little as possible for imported materials, the developing and resource-rich countries must receive a fair price for their minerals. What is fair can never be established. Nevertheless, it will benefit everyone, producer and consumer nations alike, for mining and mineral processing capacities to be kept elastic. The practice of stable pricing and purchasing policies also will help equilibrate the situation; however, the best intentions will be disrupted by political instabilities and actions.

Foreign Participation in the Superalloy Industry

The high cost and risk associated with the development of new engines and airplanes are now catalyzing foreign interactions and participation, especially with respect to such economically aggressive countries as Japan. As mentioned above, the development of a new engine may cost between $1 and $2 billion, which certainly is a significant investment for the engine manufacturer. An even more precarious situation exists for the aircraft producers. In 1982, McDonnell Douglas Corporation and Boeing Corporation and Boeing Company had total sales of about $9 and $7 billion, respectively (Fortune, 1983), and the development cost of a new aircraft can equal these numbers.

The point to note is that development costs are so high that even large companies are reluctant to make the investment. There are generally two alternatives open to a company to minimize development cost and risk.

First, the company may seek financial aid from the government. Since the U.S. military is a major purchaser of advanced-performance aircraft, the government has a vested national security interest in funding industrial research and development of new engines and aircraft. An additional government concern should be the movement off-shore of the U.S. superalloys industry. If government funding levels diminish for superalloys process development, this relocation can be expected to accelerate.

The second alternative is for companies to seek joint ventures. U.S. anti-trust laws are such that a joint venture generally can be made only with a foreign producer or with a consortium of foreign producers. Joint ventures with overseas partners to produce superalloys, along with the large-volume aircraft sales to foreign countries, obviously can lead to an internationalization of the superalloy industry. Development costs are high and the final product (i.e., the aircrafts themselves) costs are high, and such large capital outlays will not be made by countries without getting something in return. A number of countries (e.g., France, Belgium, and Japan) have already sought and are assembling, under U.S. license, engines and aircraft that they ultimately will purchase. The increased internationalization of the aircraft and engine industry is leading to the increased production and processing of engine materials, including superalloys, overseas. This is occurring in spite of current domestic overcapacity. It appears that the foreign market will become more and more important to U.S. producers, but recent U.S. government commerce export restrictions are expected to affect this situation.

Many countries are already producing superalloys for general sale and export (Tien and Jarrett, 1983). France, the United Kingdom, the Soviet Union, and China possess superalloys industries that support and supply their own domestic jet engine production. In addition, West Germany and Japan are currently developing superalloy science, technology, and production self-sufficiency. Western Europe and Japan, however, depend heavily on U.S. technology and technology transfer. The superalloys technology in the United Kingdom rests with Henry Wiggin Limited and Rolls-Royce (Aeroengines) Limited. Wiggin is owned by the International Nickel Company of Canada, which also owns Huntington Alloys in West Virginia. The International Nickel Company has developed many superalloys used today in U.S. engines, including the cobalt-free IN 718 and IN 713 alloys. It also developed, with National Aeronautics and Space Administration funding and involvement, very advanced mechanically-alloyed, oxide-dispersion-strengthened alloys (Tien et al., 1980), and these alloys are also being produced and sold by Wiggin. Accordingly, high-temperature alloy development in the United Kingdom enjoys synergistic interactions with similar major U.S.-based efforts.

With the purchase of the Hawker (Bristol), Siddeley, and De Haviland engine companies in the 1960s, Rolls-Royce became the major jet engine manufacturer in the United Kingdom. In 1972, the British government took over the financially troubled jet engine division of Rolls-Royce, whose difficulties were caused, in part, by materials problems associated with the production of engines for wide-body aircraft. Hence, Rolls-Royce's needs are now the U.S. government's needs. In theory, the United Kingdom should not experience the problems that arise in the United States related to public versus private needs, funding incompatibilities, and research and development coordination. Materials development at Rolls-Royce Aeroengines is managed by a staff committee, and subcontracts are often awarded to U.S. superalloys producers, U.S. export control regulations permitting. It is interesting that Rolls-Royce developed its own monocrystalline superalloy technology. Perhaps better known is the larger joint venture (including materials development) of Rolls-Royce with Japan (Ishikawajima-Harima Heavy Industries), Pratt and Whitney, and others to share the billions of dollars in funding necessary to develop advanced engines.

The major superalloys end user in France, SNECMA, is also a state-related enterprise. The recent growth business at SNECMA involves the licensed production of what are basically U.S. engines, notably the larger engines for European Airbus aircraft. France has a superalloy producer in the Aubert et Duval Company, a specialty metals company that is still privately held. U.S. superalloys technology was initially transferred to Aubert et Duval 20 years ago. Belgium's Fabrique Nationale is also involved in the licensed production of U.S. engines as are some Israeli companies with respect to engine components and spare parts.

Japan's largest jet engine manufacturer is the Ishikawajima-Harima Heavy Industries. Its advanced engine technology apparently was learned from the licensed production of U.S. engines, and the company now aims to become a leading producer of engines and of superalloys and other high temperature materials. The formidable Ministry of International Trade and Industry (MITI) has taken the leadership role in organizing and, when necessary, funding the stable development of Japan's comprehensive high-temperature materials and gas turbine industry. In contrast to the United States, which up to now has offered antitrust immunity only to small businesses, competing corporations in Japan are encouraged by the government to share research results and technology, at least in the development stages. For structural high-temperature ceramics development efforts, the Japanese government funding at government laboratories alone now exceeds $10 million a year. Japanese superalloy producers are small but growing, and two of the larger ones are divisions of multinationals. Lately Japan's heavy industries also have become involved in the construction of superalloys processing equipment for newly emerged industrial countries.

Joint research and information sharing also is practiced in Western Europe, especially with respect to high-temperature materials development and process development. COST-50 is an ongoing European collaborative program on materials for gas turbines that was initiated in the 1970s and supported by the Commission of the European Communities. Despite long-established developments in France and the United Kingdom, high-temperature materials development efforts in West Germany are just beginning. Outwardly, at least, it appears that the German industries are reluctant to enter the high-temperature materials area. It should be noted, however, that Heraeus of West Germany is a major manufacturer of superalloy EB, VIM, VAR, ESR, and PM equipment.

SUPERALLOYS PRODUCTION CAPACITY

Current VIM capacity, including superalloys processing standards and technology, is estimated to be 110 million lb per year; this is based on 3 shifts, a 5-day work week, and a 65 percent yield (J. W. Pridgeon, Special Metals Corporation, private communication, 1984). The recent peak in superalloys shipments was about 80 million lb per year. Assuming that military use accounts for 40 percent (a radical estimate) of these shipments, a doubling of military consumption without cutting into commercial use is possible due to present overcapacity. Further, if a seven-day work week were activated, military use could triple without affecting commercial consumption. In an extreme emergency, the U.S. superalloys industry would be capable of providing the military with about five times the volume of superalloys used during the peak years of 1979 and 1980; this assumes a seven-day work week and no commercial consumption. Thus, <u>if the domestic superalloy industry remains intact</u>, no supply problems are foreseen for military needs during a national emergency.

CONCLUSIONS AND RECOMMENDATIONS

Based on the current situation and anticipated changes, it has been concluded that:

1. The major consumer of superalloys is the aircraft gas turbine (jet engine) industry. Growth of superalloys use in other applications is not expected in the foreseeable future.

2. Consistent with the United States being the major producer of aircraft, the U.S. superalloys industry is by far the Western world's leading producer of superalloys.

3. Science and technology developments in superalloys processing and use are still centered in the United States and often are funded by U.S. government sources.

4. The U.S. superalloys industry is not integrated; it is comprised of numerous small producing and processing companies that have limited financial resources.

5. Even during the peak years of demand, 1979 and 1980, the industry's superalloy production was 30 to 50 percent below capacity.

6. The highly cyclic demand for superalloys superimposed on the nonintegrated industry structure results in considerable instability. Current corporate trends are toward diversification out of the aerospace industry or backwards integration.

7. Another potential source of instability in the U.S. superalloys industry is reliance on imports for many of the feedstock elements (e.g., cobalt, chromium, tantalum, niobium) used in production. The industry requires sustained commitment from the U.S. government in order to find suitable substitutes for elements currently being imported.

8. The high cost and risk associated with the development of new engines and aircraft, along with the high purchase price of the aircraft and increased sales of U.S. aircraft overseas, are stimulating international interactions and participation. These interactions include the licensed production of U.S. engines and aircraft by foreign countries.

9. It is essential that the U.S. superalloys industry, with its overcapacity, participate in the growing international market for superalloys. Current U.S. government information-control regulations, however, can severely curtail the U.S. industry's efforts in the international marketing of superalloys.

10. With respect to meeting U.S. military needs, no superalloys supply problems are forseen, assuming that the current domestic industry remains intact.

Based on the above conclusions, it is recommended that consideration be given to the following actions:

1. The U.S. government should re-examine the effect and potential effects of its information-control actions on the international competitiveness of the U.S. superalloy industry.

2. The U.S. government should continue to play a pivotal role in funding R&D of superalloys processing and use, including substitution research leading to minimizing the reliance on imports for superalloys feedstock such as cobalt, chromium, tantalum, and niobium.

REFERENCES

Andrews, J. V. 1983. Consumption of superalloys: the five year outlook. Titanium and Superalloys: Scaling the Peaks. Metal Bulletin Survey. Souderton, Pennsylvania: DMS Information Processing Systems.

Antony, K. C., and J. F. Radavich. 1980. The metallurgical aspects of hot isostatically pressed superalloy castings. P. 257, Superalloys 1980, J. K. Tien et al., eds. Metals Park, Ohio: American Society for Metals.

Decker, R. F. 1980. Superalloys--does life renew at 50. P. 257, Superalloys 1980, J. K. Tien et al., eds. Metals Park, Ohio: American Society for Metals.

Dreshfield, R. L., H. R. Gray, S. R. Levine, and R. Signorelli. 1981. Advanced Aircraft Engine Materials, National Aeronautics and Space Administration TM 82626.

Fortune 500. 1983. May.

Gao, L., J. Fu, and C. X. Chen. 1980. Recent advances in understanding electroslag remelting metallurgy of superalloys. P. 99, Superalloys 1980, J. K. Tien et al., eds. Metals Park, Ohio: American Society for Metals.

Gell, M., D. N. Duhl, and A. F. Giamei. 1980. The development of single crystal turbine blades. P. 205, Superalloy 1980, J. K. Tien et al., eds. Metals Park, Ohio: American Society for Metals.

National Journal. 1983. Vol. 15, July/August.

Pridgeon, J. W., F. N. Darmara, J. S. Huntington, and W. H. Sutton. 1981. Principles and practices of vacuum induction melting and vacuum arc remelting. Metallurgical Treatises, J. K. Tien and J. F. Ellicott, eds., Warrentown, Pennsylvania: American Institute of Mining, Metallurgical, and Petroleum Engineers. p. 261.

Stephens, J. R., and J. K. Tien. 1983. Considerations of Technology Transfer Barriers in the Modification of Strategic Superalloys for Aircraft Turbine Engines. National Aeronautics and Space Administration TM 83395.

Tien, J. K. 1983a. Government and industry efforts to substitute and replace critical metals in superalloys. p. 50, Titanium and Superalloys: Scaling the Peak. Metal Bulletin Survey. Souderton, Pennsylvania: DMS Information Processing Systems.

Tien, J. K. 1983b. Will the force be with VADER? American Metal Market, 91(53):9.

Tien, J. K., T. E. Howson, G. L. Chen, and X. S. Chen. 1980. Cobalt availability and superalloys. Journal of Metals, 32(10):12.

Tien, J. K., and R. N. Jarrett. 1983. Potential for Development and Use of New Alloys to Reduce the Consumption of Cr, Co, and Mn for Critical Applications. [Submitted to the Office of Technology Assessment, Congress of the United States; to be published.]

Tien, J. K., and R. D. Kissinger. 1984. Consolidation Science of P/M Superalloys. International Powder Metallurgy Seminary, to be published.

Tien, J. K., and V. C. Nardone. 1984. The State of Heat Resistant Alloy Design. Proceedings of the Symposium on Synergism of Microstructure, Mechanisms and Mechanics in Fracture, to be published.

Tien, J. K., and V. C. Nardone. 1984. The superalloys industry--status and outlook. Journal of Metals, 36(9):52.

Tien, J. K., and E. A. Schwarzkopf. 1983. Assessing the needs for EB refining of superalloys. In Proceedings of the Conference on Electron Beam Melting and Refining-State of the Art, R. Bakish, ed., Englewood, New Jersey: Bakish Materials Corporation.

Weiler, D. 1983. Profile of free world aircraft production: the changing international mix. P. 22, Titanium and Superalloys: Scaling the Peaks. Metal Bulletin Survey. Souderton, Pennsylvania: DMS Information Processing Systems.

8

COBALT, CHROMIUM, TANTALUM, AND COLUMBIUM: AVAILABILITY AND ECONOMIC ISSUES

The United States relies exclusively on foreign sources for elements needed in superalloy production: cobalt, chromium, tantalum, and columbium. This chapter discusses the future supply of these important elements from their primary sources, the trends that are affecting their availability from secondary sources, and the overall demand issues that are changing the patterns of end-use dependency.

The chief sources for each of these metals are concentrated within only a few nations but supplies are abundant. In the existing economic climate of somewhat reduced consumption and lower metals prices, there is little incentive to explore for additional sources. The supply and demand trends for each metal are discussed along with projections of future production and consumption in the United States and other market economy countries. A more extensive discussion of some of these strategic metals is given in an Office of Technology Assessment report (1985).

COBALT

The most strategically important applications for cobalt are in superalloys (principally used in jet engines), permanent magnets, and chemicals. Production is concentrated in a small number of countries, most notably Zaire. There is no U.S. mine production. Total U.S. consumption has ranged from 20 million lb in 1978 to 10 million lb in 1982. Market economy countries' production of cobalt is generally in the range of 15,000 to 25,000 metric tons annually, about 10 percent of which is exported to the planned economy countries.

Supply Picture

Cobalt, unlike the other important nonferrous metals, is almost exclusively obtained as a by-product of copper and nickel mining and refining operations. The major sources are the bedded copper deposits of Zaire and Zambia, the sulfide nickel-copper ores of Canada and Australia, and the laterite deposits of Asia and Oceania.

Zaire supplies about half the world's cobalt, but internal economic problems in 1982 and 1983 have caused concern about the continuity of supply. With stagnant world economic activity and low copper prices, Gecamines, the Zaire state mining company, found it even more difficult to purchase spare parts and fuel to maintain its copper and cobalt production. These difficulties and the weakness in the markets for Zaire's other major exports, including diamonds, exacerbated Zaire's economic problems. As a result of these factors, cobalt production fell from 11,124 metric tons in 1981 to about 5,800 metric tons in 1982, and in 1983 it was at about the same low level. Production was reduced to prevent stocks (probably cobalt hydroxide) from growing beyond the 20,000-metric-ton level. A recovery in Zaire's economy will hinge on a recovery in copper demand and price.

Zambia's cobalt production resembles Zaire's in many ways. The mineralization of the ores, the processing technology, and the economic and technical problems facing Gecamines and Zambia Consolidated Copper Mines (ZCCM) are similar. Zambia's output fell in 1981 and again in 1982, but stabilized in 1983 at 3,400 metric tons. Zambia's effective cobalt production capacity stands at about 5,000 metric tons. No major technical problems have been encountered, but the ZCCM did not push production and stockpiled some cobalt concentrates. A shortage of foreign exchange added to normal production problems because of a lack of spare parts and replacement equipment.

Compagnie de Tifnout Tiranimine, which operated the cobalt arsenide mines near Bou Azzer, Morocco, halted production at the end of 1982 because reserves were exhausted. This had been the only ore body in the world mined primarily for cobalt. As a result, Speciaux Metaux, the subsidiary of Pechiney that had processed the concentrates from Morocco, no longer has enough refinery feed to produce cobalt metal. It produces cobalt chemicals from other feed materials, including cobalt chloride solution from the Sandouville, France, nickel refinery of Société Le Nickel (SLN).

In 1983, Outokumpu Oy in Finland began selling a full range of cobalt salts, supplementing its hydrogen-reduced cobalt power. Outokumpu has a U.S. sales office in Detroit.

INCO commissioned its new Canadian (Port Colborne, Ontario) 900-metric-ton electrolytic cobalt refinery in the fourth quarter of 1983, and by the end of the year, it was operating at two-thirds of its rated capacity, producing cobalt cathodes for the market. This has increased INCO's cobalt production capacity to about 1,800 metric tons annually, but production is likely to remain well below capacity until the nickel market shows some signs of recovery. INCO shut the Port Colborne refinery for five weeks, starting December 26, 1983, and plans further four-week summer shutdowns at all its Canadian operations.

Sherritt Gordon produces hydrogen-reduced cobalt powder at its ammoniacal-leach nickel refinery in Fort Saskatchewan, Alberta. Output was 787 metric tons in 1982 and 1983. Cobalt raw material sources for Sherritt Gordon's refinery include nickel concentrates from INCO, mixed nickel-cobalt sulfides imported from Western Mining in Australia, and, since May 1983, cobalt hydroxide which is toll-refined for AMAX from its plant in the United States.

Falconbridge has not been able to operate the cobalt circuit at full capacity in its Norwegian nickel refinery since expanding its annual capacity to 1,800 metric tons. In 1981, production was 1,444 metric tons, including toll-refined material for INCO, but output fell to 992 metric tons in 1982. Output probably was also low in 1983 with much of this decline due to nickel production cutbacks.

Cobalt refiners in Japan were forced to operate well below capacity in 1983 with a similar prospect for 1984. Nippon Mining purchases mixed nickel-cobalt sulfides from the Australian Greenvale lateritic nickel project. With Greenvale operating at reduced levels, Nippon Mining can use only about half of its annual capacity of 1,250 metric tons. Sumitomo Metal Mining depends on Marinduque Mining and Industrial Corporation in the Philippines for similar mixed nickel-cobalt sulfides to feed its cobalt refinery. However, Marinduque has been shut down indefinitely.

All the cobalt projects in the United States are either on hold or are moving ahead slowly. Anschutz has suspended work on reopening its old Madison mine in Missouri, and Noranda has likewise halted work on development of the old Blackbird Mine in Idaho. At present, neither project is likely to proceed without some form of U.S. government financial assistance since both mines would require a cobalt price substantially above current levels because of the complexity of the ores and the expensive mining methods required. California Nickel reports that it is moving ahead slowly with its Gasquet Mountain project. The project is aimed at exploiting a low-grade lateritic nickel deposit with low cobalt content and is expected to require a cobalt price equivalent to or higher than those of the other two U.S. mines mentioned above. The last U.S. source worth mentioning is the Cornwall mine in Pennsylvania. This mine, worked to exhaustion by Bethelehem Steel up to 1972, has cobalt-bearing tailings on the site that may contain as much as 5 million lb of cobalt.

Government Activities

The U.S. Air Force considered funding, under Title III of the Defense Production Act, the construction of a pilot plant for processing domestically mined cobalt ores. Presumably such a plant would demonstrate the feasiblity of recovering cobalt from domestic ores so that the plant could be scaled up quickly during a supply crisis. The draft request for proposals contained an option for building a 2-million-pound-per-year production-scale plant backed with purchase guarantees. No fiscal 1984 money is available for the project, so funding could not begin before fiscal 1985. Air Force spokesmen have indicated that the project may be cancelled, in part because costs are likely to be greater than expected. Industry spokesmen have indicated that any cobalt produced from U.S. domestic sources would cost an estimated $18 to $70 per lb, depending on the raw material being processed.

Demand Picture

The end use breakdown of cobalt consumed in the United States is shown in Table 8-1. Superalloys are the largest application for cobalt in the United States. As noted in Chapter 7, the major use of superalloys is in gas turbines for either jet aircraft engines or industrial applications. The demand for cobalt in superalloys is expected to remain slack until the recovery of the aerospace market, an event that is likely to be at least one year away. However, total cobalt consumption in superalloys is likely to grow somewhat more slowly than the demand for superalloy components because of near-net-shape processing and lower cobalt levels in the new cast alloys for jet engine turbine blades and vanes, developments that tend to reduce the total cobalt requirements for superalloys production (Charles River Associates, 1983).

TABLE 8-1 U.S. Consumption of Cobalt by Use (1983)[a]

Application	Consumption (Million Pounds)
Superalloys	3.74
Permanent Magnets	1.71
Salts and Driers	1.58
Catalysts	1.03
Cutting and Wear Resistant	0.53
Welding and Hardfacing	0.39
Tool Steels	0.19
Other Metallurgical	0.28
Other	1.15
	10.60

NOTE: Apparent consumption in the United States normally exceeds reported consumption by about 10 percent.

[a] Estimates developed by Charles River Associates using data published by the U.S. Bureau of Mines.

Permanent magnets made with cobalt have been important for decades, but the high cobalt prices of 1978-1979 caused a permanent shift to cobalt-free ceramic (ferrite) magnets in many applications. The most commonly used cobalt-containing magnetic materials are aluminum-nickel-cobalt-iron alloys, collectively known as Alnicos. The most important of these, Alnico 5, contains 24 percent cobalt. Rare earth-cobalt magnets are typically about 65 percent cobalt and 35 percent samarium. Alnicos typically have energy products in the range of 5.5 megagauss-oersteds (MGOe), ferrites about 4 MGOe, and samarium-cobalt magnets about 18 to 22 MGOe. Powerful magnets, like the samarium-cobalt family, seem promising for totally new applications, including various computer devices and powerful, lightweight electric motors.

The future for rare-earth-cobalt magnets is now less promising than it seemed in early 1983. In the last half of 1983, General Motors, along with other U.S. companies and Japan's Sumitomo Special Metals, publicly announced new magnetic materials that might undercut potential markets for samarium-cobalt magnets and possibly the existing markets for Alnicos as well. The composition of the new cobalt-free magnetic alloys is typically 35 percent neodymium (a rare earth metal) and 6 percent boron with the balance being iron. Their energy products are in the range of 30 to 40 MGOe with values of 45 to 60 MGOe reported for experimental alloys.

General Motors has announced that it expects to use the new magnets in starter motors for 1986 model cars and light trucks. The powerful light magnet will replace the traditional copper coil and reduce the size and weight of the motor by 40 to 50 percent. Some developers of the alloys have discussed the possibility that these magnets could make electric cars economically feasible. There are also plans for using the new magnetic material in the next generation of nuclear magnetic resonance medical-imaging systems. Crucible Research Center in Pittsburgh has announced a powder metallurgical process that yields the highest energy product yet reported. Crucible intends to begin marketing this material under the trade name "Crumax" by late 1984 or early 1985.

One of the major limitations of this new magnetic material is its low Curie temperature (the temperature where ferromagnetic response ceases), which is only 585°K (312°C) compared to 1000°K (727°C) for the samarium-cobalt magnet. This limits its use to temperatures below the 100°C ambient temperature that would be encountered in the starter motor of an automobile. Further research indicates that additions of small amounts of cobalt (10 to 20 percent) or use of heavy rare-earth metals would raise the Curie temperature, permitting higher temperature applications.

In the future, ceramic ferrites are expected to be used in applications that are not limited by size, weight, or temperature stability. Alnicos probably will be used in applications that require temperature stability and have no size or weight limitations.

Neodymium-iron-boron magnets will be used in most applications in which either size or weight is important, including most of the applications for which samarium-cobalt magnets have been considered heretofore. The samarium-cobalt magnets will be used in the more specialized applications in which operating temperatures would preclude the use of the neodymium-iron-boron magnets.

The amount of cobalt in surgical implant alloys, currently about 1 million lb annually in the United States, is expected to increase 15 to 20 percent per year for the next decade. In 1983, about 200,000 joint replacement operations were performed in the United States, half of them for hips. Several factors could slow the growth of cobalt in these applications, because more extensively used cobalt-based superalloys compete with titanium and stainless steels that are also used. Improvements in their properties (e.g., ion implantation to improve surface wear and corrosion of titanium) could permit expanded use of these implants; however, advances in medical techniques also might reduce the need for joint replacements.

Cobalt use in floppy disks for computers and in new miniature video cassettes could expand enormously in the next five years. Technology in both applications is changing very rapidly, which makes forecasting inexact. Cobalt demand for cemented carbides will depend to some extent on the strength of the oil market; high oil prices mean substantial drilling activity with a strong demand for drill bits. In all other uses, including chemicals and catalysts, cobalt demand is likely to keep abreast of industrial production. As the world economy recovers, cobalt demand will accelerate as industrial stocks of cobalt-bearing materials are built up in all stages of the consumption cycle.

The projected U.S. and market economy country demand for cobalt to the year 1995 is presented in Table 8-2. Capacity and supplies are expected to exceed demand for several years, which will maintain downward pressure on prices. On the other hand, expected continued U.S. government stockpile purchases, at least through the early 1990s, should cause prices to remain in the $10 to $15 per pound range through the end of the century.

TABLE 8-2 Projected Cobalt Demand Through 1995

Year	United States (Metric Tons)	Market Economy Countries (Metric Tons)
1984	5,800	15,300
1985	6,600	16,960
1990	8,100	20,230
1995	9,800	24,260

Substitution Potential During an Emergency

The high prices that occurred in 1978 and 1979 stimulated significant research and development activity in all sectors aimed at reducing cobalt import reliance (Reddy and Loreth, 1984). In superalloys, an estimated 10 percent reduction was achieved in the prime use area of jet engines and industrial gas turbines. The time and expense required to certify a new superalloy for use in a jet engine, however, has limited the extent of substitution.

Despite the availability of substitute alloys, Tien and Jarrett (1983) have reported that little if any further cobalt substitution will take place even at 1978 to 1979 price levels, since all major substitutions have already been done. Major alloy development takes 10 years and typically testing and certification procedures are time-consuming and very costly. The cost of the contained cobalt as a percentage of total jet engine cost is very small so the effect of high metal prices on overall system cost is almost insignificant. Since there is a great deal of alloy development work yet to be done, ceramics cannot be considered to be viable substitutes for superalloys in an emergency.

Cobalt-containing powders used in hardfacing applications are not recycled and there is no recovery of cobalt from obsolete hardfaced parts. Government stockpile cobalt, however, is expected to be sufficient for this strategic use. A reduction of up to 70 percent in cobalt use might be achieved in this application in a disruption scenario.

Cobalt-containing magnets during the 1978-1979 period were displaced by ceramic ferrite magnets, accounting for about 70 percent of the Alnico magnet market and about 40 percent of all the cobalt in magnets. During a supply disruption, with sharply higher cobalt prices, a further 50 percent reduction would require one or two years to complete.

Catalyst and chemical needs for cobalt have been reduced by the development of new substitutes (e.g., the use of nickel-molybdenum catalysts for recovering sulfur and heavy metals during oil refining, the use of nickel and manganese for cobalt in ceramic frits, and the use of manganese or zirconium for cobalt in paint driers. The NMAB (1983) study of cobalt conservation indicated that a 20-percent cut in chemical cobalt use could be made without much difficulty and, under severe emergency conditions, up to 60 percent of normal consumption (2.2 million lb in 1980) could be eliminated.

Overall, total U.S. cobalt consumption could be reduced by an estimated 40 percent if all possible reductions were made in each end use. Based on 1983 U.S. consumption of 10.6 million lb, such savings could amount to approximately 4 million lb per year.

CHROMIUM

Although chromium ore and major ferroalloy production are concentrated in just a few countries, the industry consists of a fairly large number of countries and the market is reasonably competitive. There is no indication that, under normal market circumstances, the supply sources would become cartelized. About 70 percent of the market economy countries' chromium is used for metal alloying, particularly in stainless steels. About half the remainder is processed into chemicals and the rest is used in refractory products, primarily for the metallurgical industry.

Supply Picture

Chromium is obtained from primary ores, with the largest supplies coming from the Republic of South Africa and Zimbabwe. The Soviet Union was the second largest supplier to the West (after South Africa) until the late 1970s when it curtailed exports. Recently, it has begun again to export chromium ore. Exports from Albania have expanded sharply, and other sources include Turkey, Brazil, the Philippines, India, Madagascar, and Finland. The United States imports most of its chromite ore from South Africa and the Philippines.

About 98 percent of all known reserves in the market economy countries lie in South Africa and Zimbabwe. Together they could supply any conceivable demand for many decades. Identified reserves outside these two countries represent less than a 15-year supply. The three most important supply developments that have occurred recently are: (1) the emergence of Albania as an exporter to the West, (2) the re-emergence of Zimbabwe as a major source of supply, and (3) the significant shift in ferrochromium production since the early 1970s to the major ore-producing nations, particularly South Africa. Reasons for this shift include cost advantages for labor, power, transportation, and pollution control. South Africa's vast reserves, low mining costs, good infrastructure, and low power will be major determinants of chromium ore and bulk ferroalloy prices in the future. The resulting increase in imports of ferrochromium into the United States has harmed the U.S. ferrochromium industry. Most U.S. ferrochromium plants are either shut down or operating under Chapter 11 bankruptcy procedures.

Except for a small amount in 1976, the United States has produced no chromium ore since 1961. U.S. chromium resources, located in Montana, Oregon, Washington, California, and Alaska, are estimated at 22.5 million tons of low-grade ore containing 1.8 million tons of chromium. Collectively these deposits could yield 6.8 million tons of ore or concentrate averaging 38 percent Cr_2O_3. The most promising domestic deposits lie in the Stillwater Complex in Montana at the Mouat and Benbow mines (22.4 percent Cr_2O_3). Second in importance are the beach sands in Oregon (3-5 percent Cr_2O_3). Deposits in Alaska range from 15 to

45 percent Cr_2O_3. In California, nine areas have important chromite occurrences ranging from 5 to 10 percent Cr_2O_3 and up to 38 to 48 percent in some very small deposits.

Until the 1970s, chromite ore was classified into three grades according to normal industrial use. The metallurgical industry consumes about 70 percent of the world's chromium production, almost all of which is used to produce ferrochromium for the manufacture of stainless and alloy steels. A small portion goes into making high purity chromium metal for specialty alloys. In the late 1960s and early 1970s, the development of the argon-oxygen decarburization (AOD) process and other processes for making stainless steel permitted the use of ferrochromium with chromium contents as low as 50 to 55 percent and carbon contents as high as 4 to 6 percent. These new ferrochromium grades can be produced from a wider range of ores, including ore fines with lower Cr:Fe ratios. Taken together, these technological developments have revolutionized the supply side of the chromium market and have made a wider range of ores acceptable for metallurgical processing.

Purified chromium metal used in specialized metallurgical applications (e.g., superalloys) is produced in the United States by two plants that must use imported ore. These companies supply about half of U.S. consumption, the remainder being imported from Japan and Western Europe. Worldwide capacity for chromium metal production currently exceeds demand by almost two to one; unless some of it is retired, this excess capacity will persist through the 1990s.

South Africa has the potential for almost infinite expansion of its chromium ore and ferroalloy production. Other producers, whether of ore or of bulk ferroalloys, must be prepared to compete with South Africa. Albanian exports of chromium ore to the West are expected to continue to increase. Zimbabwe's exports of chromium are likely to be increasingly in the form of ferroalloys, which reduce transportation costs and bottlenecks. Exploration and development of new deposits in India and the Philippines is likely to continue although perhaps at a slow pace. Ore production in other countries during the 1980s is unlikely to increase much if at all. Ferroalloy production, at least for bulk alloys, is likely to become increasingly concentrated in ore-producing countries, but specialty alloy production is likely to remain concentrated in the consuming countries. The industry's present low capacity utilization, between 60 and 70 percent for both ore and ferroalloys, is expected to improve only slowly.

Demand Picture

The major end uses for chromium ore are: metallurgical applications (including stainless steels, alloy steels, and superalloys), chemical applications (including pigments, salts for electroplating, tanning compounds, and drilling muds), and refractory applications (particularly in chrome-magnesite bricks for lining sections of electric arc and open-hearth furnaces for steel production). U.S. consumption of chromium products by end-use is given in Table 8-3.

TABLE 8-3 U.S. Consumption of Chromium in Ferroalloys, Metal, and Ore by Use in 1982 (short tons)

	Consumption
Ferroalloys and Metal	
Steel:	
Carbon	6,394
Stainless and heat resisting	191,370
Full alloy	40,827
High-strength low-alloy	8,240
Electric tool	1,979
Cast irons	7,057
Superalloys	7,574
Welding materials	1,279
Other alloys	2,186
Miscellaneous	1,164
TOTAL	268,070
Net chromium content	157,211
Chromite Ore	
Refractories (36.4% Cr_2O_3 Ore)	80,000
Chemicals (44.9% Cr_2O_3 Ore)	195,000

SOURCE: Bureau of Mines (1982).

Stainless steels, in which chromium provides unique corrosion resistance, account for about 50 percent of world ferrochromium demand and 70 percent of U.S. demand. Chromium consumption for stainless steel production is expected to grow slightly faster than overall industrial production because of a strong demand for stainless steels in many chemical and energy-related areas (e.g., pollution control, oil and gas well-drill casings, and chemical-processing corrosion-resistant tubing and fabricated parts).

Chromium in alloy steels and tool steels is presently used at much lower concentration levels than before and its main purpose is to act as a relatively cheap hardening and strengthening agent. Because the uses for these alloys are so diverse, increased chromium use is expected to follow industrial production. The United States uses about 5,000 metric tons of high-purity chromium metal in a variety of specialty alloys, particularly in superalloys, corrosion-resistant alloys, welding and hard-facing alloys, aluminum alloys, and electrical resistance alloys. Overall growth is expected to follow industrial production.

In chemicals, about 180,000 metric tons of 45 percent Cr_2O_3 ore are consumed annually. The major growth areas lie in wood preservatives and oil drilling muds; however, overall growth across all uses will likely be equal to or less than industrial production growth. Refractory use, which has been declining due to the closing down of open hearth steelmaking furnaces, consumes about 73,000 metric tons of 36 percent Cr_2O_3 ore annually. The trend is toward a continual decline at the rate of about 1 percent per year at least through the 1980s.

Future U.S. demand estimates are given in Table 8-4 for chemical grade ore, refractory grade ore, and contained chromium in metallurgical uses.

TABLE 8-4 Chromium Ore and Metal Demand Projections (1000 metric tons)

	Metallurgical (chromium)	Chemicals (ore)	Refractories (ore)
1984	369	340	410
1985	378	350	410
1990	424	380	390
1995	474	405	370
2000	524	430	350

Because chromium is relatively cheap despite its unique properties and despite the dependence of U.S. users exclusively on foreign supplies, there has been essentially no incentive to seek substitutes for chromium. No equivalent low-cost materials are known that offer the same degree of corrosion resistance that chromium imparts to stainless steels and superalloys. Some potential exists for reducing dependence on chromium by using more coatings, polymers, and new chromium-free stainless steels or grades with lower chromium contents. However, no sustained move in this direction is expected to occur without a substantial price increase, an event believed to be unlikely in the near future. The chromium supply industry generally has a severe excess capacity that is expected to continue at least into the 1990s, resulting in very stable prices for the foreseeable future.

Substitution Potential During an Emergency

As noted above, since chromium is one of the least expensive strategic metals and is readily available from foreign sources, there has been little economic incentive for companies to try to find substitutes for it. In stainless steels, there is essentially no viable substitute for chromium that can impart the same degree of corrosion protection. The most the industry can do is ensure against overdesign of a given alloy (e.g., a 9Cr-1Mo steel could be used in place of stainless steel for tubes in boilers and superheaters).

There are a number of areas, however, where stainless steels can be replaced, including many consumer and construction applications where aluminum alloys, plastics, fiberglass, and coated or clad plain steels can be used effectively. Alternative stainless grades are being developed that would utilize more manganese and nickel to make up for reduced chromium availability. Armco has developed several low-chromium (6 to 12 percent) stainless steels, called the SR grades, to replace the ferritic stainless grades; these are the only grades available that are cheaper than those they are designed to replace. Manganese-aluminum stainless steels also are being developed that contain no chromium or nickel and show enhanced high-temperature strength and corrosion resistance compared to the existing chromium-nickel grades. They present an economically viable alternative to the austenitic stainless grades. Development work on these alloys is continuing, but it could be five years or more before a commercial grade appears on the market.

Chromium-free alloy steels have been designed, but their use requires American Iron and Steel Institute (AISI) certification as experimental alloys. At present, Ni-Mo and Ni-Mo-V steels are the existing certified substitutes for the chromium-bearing steels used in such applications as shafts and gears. In superalloys, the use of electrolytic chromium metal is critical to the high-temperature, corrosion-resistant performance required for alloys in the hot section of the jet engine. Chromium is not essential for mechanical properties but is critical at the surface for corrosion and oxidation resistance. A thin surface coating of chromium alloy would be sufficient for this application and, thus, the chromium requirement could be reduced significantly. At present, however, there is no desire or incentive for these users to attempt to substitute or save on chromium.

Stainless steel scrap is an important source of chromium for stainless steel and alloy steel production. The chromium added as primary ferroalloy accounts for only about 10 percent of the 17 percent chromium content with the remainder coming from scrap added to the melt. A total of about 1 million metric tons of stainless scrap is consumed per year. About 60 percent is home scrap, which is immediately recycled by the producer, and about 30 percent is prompt industrial scrap, which is generated during product fabrication and recycled to the producer on a regular basis. The remaining 10 percent is old scrap that comes from used products; its supply responds to changing prices.

A 1978 study on chromium (NMAB, 1978) estimated that, with existing technology, chromium consumption could be reduced 25 percent in metallurgical uses, 34 percent in refractory uses, and 25 percent in chemical uses. With 10 years of addition research and development, chromium consumption could be reduced by an additional 33 percent in metallurgical uses and 50 percent in refractory and chemical uses. Table 8-5 summarizes the potential chromium savings.

TABLE 8-5 Summary of Potential Chromium Savings (percent)

Conservation Approach	Consumption Segment	With Present Technology	After 10 Years R&D	Totals
Substitution	Metallurgical	25	36	61
	Refractory	34	57	91
	Chemical	24	48	72
Improved processing	Metallurgical	7	5	12
Improved recycling of wastes	Metallurgical	0	5	5
	Refractories	0	65	65
	Chemicals	0	6	6

SOURCE: National Materials Advisory Board (1978)

In the short term, therefore, a reduction of about 25 percent in U.S. consumption of chromium ferroalloys could be accomplished through a combination of fabrication advances, recycling, and substitution where alternative lower chromium alloys are available. Savings of 34 percent of the chromite used in refractories and 24 percent of that used in chemicals also could be possible.

TANTALUM

Tantalum is a special metal used in several very narrow and dissimilar markets--namely, electronic capacitors, cemented carbides, mill products for the process industries, and superalloys for jet engines. Electronic capacitor production is the most important of these markets, consuming over 50 percent of the world supply of the metal and about 65 percent of the U.S. supply; therefore, trends in tantalum use are very much tied to events in the rapidly changing electronics industry.

Tantalum is relatively scarce, and its supply is concentrated in the hands of only a few. Traditional sources are declining and future tantalum prices, which have fluctuated widely in recent years, will have to be high to encourage the development of additional supplies while remaining low enough to avoid significant major end-use substitution.

Supply Picture

Commercial quantities of tantalum are known to exist in only a few areas of the world. Where the metal does occur, it is found in very low concentration and usually in association with other metals such as tin and columbium. Tantalum is largely produced as a by-product of the extraction of tin and columbium mining. Tanco's Bernic Lake property in Canada is the only hardrock mine that produces tantalum for its own value. Tanco's production has usually been about 10 percent of total world production. The major sources of tantalum are the hardrock tantalum and columbium deposits of Canada, Brazil, Zaire, and Nigeria; the alluvial tin-tantalum deposits in Australia and Southeast Asia; and the low-grade tin smelting slags accumulated and stockpiled by the tin-producing countries in Southeast Asia.

Tantalum is in transition from being produced mainly in small quantities from alluvial ores and as a by-product to being increasingly derived directly from hardrock and primary sources. The high price of tantalum after 1978 revived exploration activity in Australia, Brazil, Africa, and Canada and led to the discovery of several new deposits that are expected to be of future importance to the tantalum industry. Most of the new sources, however, are of lower grade than major existing sources so future tantalum prices must remain high enough to encourage bringing such deposits on stream to replace declining by-product capacity. Such a threshold price level has been estimated to be between $80 and $100 per pound of tantalum pentoxide, compared with the current market price of about $30 to $35 per pound.

By the late 1980s production is expected to decline as the ore grades and reserves decline at Tanco's Canada operation and as the old tin slags in Southeast Asia are depleted. The key developments for replacing this production are expected to be associated with the new Australian Greenbushes tantalite deposit (potential output 630,000 lb of tantalum pentoxide at full capacity), the Manono deposit in Zaire (potential of 500,000 lb per year), and the continued maintenance or growth of 1980 production levels in Brazil. The new Greenbushes deposit will not by itself be sufficient to meet future demand; for this an additional 600,000 to 700,000 lb of capacity will be needed. No significant or potentially exploitable resources of tantalum are known to exist in the United States.

Demand Picture

The major U.S. tantalum-consuming sectors are electronic capacitors (64 percent), cemented carbides (18 percent), mill products (6 percent), and superalloys (10 percent). U.S. consumption accounts for almost 65 percent of the market economy countries' consumption, which amounted in recent years to about 1.2 to 1.4 million lb in the form of tantalum pentoxide.

Capacitor production will dominate the future market for tantalum. Tantalum became an important capacitor material in the late 1960s when the superior dielectric properties of its oxide were identified and its importance increased with the rapid technical advances that were made in the quality and capacitance value of tantalum powders during the 1970s. The severe price escalation that occurred in 1978-1979, however, induced significant substitution away from tantalum to ceramic and aluminum capacitors as well as successful attempts to downsize the components and so reduce the tantalum powder input per capacitor unit. Together these trends slowed dramatically the increase in tantalum use despite the still rapid growth of the capacitor market. The future increase in tantalum use is expected to average only 1 to 2 percent per year; in fact, capacitor demand may take a long time to reach the peak levels seen in 1979-1980.

During the recent recession, the market for cemented carbides fell some 30 percent from the 1979 peak level. Although demand recently has been recovering, some important developments will combine to lower the growth rate of primary tantalum demand for this use. First, the market share for coated carbide cutting tools will continue to increase from 37 percent of all tools in 1979 to 51 percent by 1985 and is expected to reach 65 percent by 1990. Second, increased substitution of cheaper columbium carbide will lower the Ta:Cb ratio in cutting tools from today's 90:10 to approximately 70:30 by 1990. Third, the recycling of used tools will continue to increase from 10 percent of consumption today to an estimated 25 percent by 1990. These factors are expected to keep future demand growth for primary tantalum in cemented carbides at a relatively low level.

The tantalum mill product market is very price sensitive and has fluctuated widely in the past few years. Substitute materials (e.g., columbium or titanium) can be used in many situations where compromises can be made concerning the superior corrosion resistance of tantalum. For this reason, long-term growth in this market is expected to be slower than the growth of general industrial production.

Tantalum content in superalloys in the latest single-crystal cast alloys for jet engine turbine blades and vanes has been about 12 percent. This application is insensitive to the price of tantalum, but after a doubling in consumption from 1981 to 1985, growth should slow and follow the future trends of the aircraft market.

U.S. tantalum pentoxide demand is expected to reach 1.7 million lb in 1985, 2 million lb in 1990, 2.3 million lb in 1995, and 2.7 million lb by 2000. Prices in constant dollars will rise substantially above the present $40 per pound level because of the decline of existing primary and by-product supplies and the depletion of old slags inventories. New mining resources will have to be found and brought on stream by the end of the 1980s to replace this lost production capacity, and a pentoxide price in the $80 per pound range (in 1984 dollars) will be required to sustain this new capacity.

Substitution Potential During an Emergency

Tantalum use in electronics has been reduced by the substitution of aluminum electrolytics and monolithic ceramics, the use of smaller sizes and lower voltages for tantalum capacitor applications, and advances in tantalum powder production. These advances have increased the surface area per unit volume of material that provides a much higher capacitance while using less tantalum. Additional reductions in tantalum use in capacitors could still be achieved without sacrificing too much performance; indeed, a reduction of as much as 25 percent can be achieved during a supply emergency by using existing technology. U.S. capacitor makers believe they can reduce further the quantity of tantalum powder used per unit and there is further room for substitution of alternative capacitor materials.

With respect to cemented carbide tools, the use of coated carbide cutting tools, which reduce the need for tantalum in the carbide matrix, is increasing. New ceramic tools based on silicon nitride, alumina, and sialon are being used as substitutes and lower-cost columbium carbide is being substituted for tantalum in the matrix. These efforts potentially could reduce the primary tantalum requirements of cemented carbide production by 10 to 20 percent.

Recently motivated by both economic and strategic considerations, the reclamation of scrap carbide cutting tools has been increasing steadily. Recycled carbide scrap presently makes up at least 10 percent of U.S. consumption and by 1990 is likely to grow to 25 percent. Manufacturers of cutting tools also are able to reduce tantalum needs by 3 to 5 percent by using more efficient production techniques (e.g., hot isostatic pressing). Together, these tantalum savings currently amount to some 20 to 25 percent of the cemented carbide market's requirements. During an emergency, an additional 10 to 15 percent of consumption could be saved by more efficient use of recycled material.

In many areas of mill product use, tantalum could be replaced by titanium, columbium, zirconium, nickel-base superalloys, stainless steels, or clad steels. A cutback of as much as 30 percent possibly would result if tantalum prices moved above $100 per pound, especially during an emergency situation.

In superalloys, an emergency situation could cause the replacement of new high tantalum alloys by alloys such as Mar M 200 and 509. Nickel-cobalt-base alloy substitution would not be achievable in a short time, however, and would be done only if there were an extremely serious problem with availability of tantalum. A dramatic increase in price alone is not a prime factor for such a changeover.

In total, U.S. tantalum usage could be reduced in the short term by approximately 20 percent from existing levels in the event of a supply disruption emergency.

COLUMBIUM

Columbium is used almost exclusively as an alloying element in steel and superalloys. Although it is a relatively new additive in many of these applications, its use is growing rapidly. The supply side of columbium is dominated by Brazil and, in particular, by Cia Brasileira de Metalurgia e Mineração (CBMM). The market will continue to have surplus production capacity for the foreseeable future, mainly as the result of CBMM's large production capability.

Supply Picture

Columbium is mainly derived from pyrochlore ores in Brazil, East and Central Africa, and Canada. A small quantity also comes from placer tin mining in Southeast Asia. Although it is sometimes found associated with tantalum in ores, most columbium is produced from deposits that do not produce tantalum. Total market economy countries' production in recent years has reached about 50 million lb of Cb_2O_5 in concentrate. Brazil has a very large, high-grade reserve base, and its three active mining operations produce two-thirds of the world's supply. A new Brazilian deposit also was discovered recently. To realize the full potential of its resources, Brazil plans to increase production of higher value-added products (e.g., ferrocolumbium and high-purity oxide) and reduce sales of pyrochlore concentrate. CBMM is the world's major force in the columbium market and is actively engaged in market development research. The company is increasing the production of all products to gradually bring prices down and thereby encourage expanded use of columbium.

Canada is the second largest producer, providing about 15 percent of world supply. Nigeria currently produces columbium as a by-product of tin mining at a rate of 800,000 lb of Cb_2O_5 per year, but this production is expensive and will disappear in a competitive market. The need for Nigerian columbites to produce high-quality columbium oxides today has been rapidly supplanted because CBMM and Teledyne Wah Chang in the United States now process pyrochlore directly to high-quality oxide.

CBMM not only has the largest capacity (55 million lb of the total world capacity of 73.7 million lb) but also by far the lowest costs. Thus, CBMM could at any time cut prices and effectively drive its competitors out of business. However, its current strategy is to let competitors survive and to integrate downstream into the production of high-purity oxide and ferrocolumbium. CBMM's stable pricing policy should allow current producers to operate profitably but will preclude any significant entry into the market by new higher-cost producers.

The economics of starting a new columbium operation provide little margin for profit in a new investment for a primary-producing mine unless it is extremely low cost. As testimony to this, there are major deposits of columbium ore in a number of African countries, notably in Kenya, Tanzania, and Uganda, that have been known for years but remain undeveloped. CBMM itself could supply the entire world demand for columbium for decades without putting a strain on its reserve base. In addition, the Uapes deposit, recently discovered in northern Brazil by Cia de Pesquisa e Recursos Minerais (CPRM), has increased Brazil's reserve base by some 75 percent. CPRM is planning to bring the deposit into commercial production but the timetable is yet unknown. New columbium production, as evidenced by the Uapes deposit, is likely to result from new discoveries of columbium-rich areas such as those found in Brazil, from expansion of current mines, or from by-product production such as tantalum recovery from the Thor Lake deposit in Canada. The United States has no significant columbium resources that offer any commercial potential in the future.

Demand Picture

Columbium is mainly used as an alloying element in steel and superalloys. U.S. consumption in the past few years declined from 6.5 million lb in 1980 to a low of 3.7 million lb in 1982. About 39 percent of U.S. columbium consumption is in carbon steel, 35 percent is in high-strength, low-alloy steels for oil and gas transmission pipelines; 9 percent is in stainless steel; 7 percent is in full alloy steel; 10 percent is in superalloys, and a small remainder is in sintered carbides.

Columbium use has grown more rapidly than use of other alloying elements because of applications in new areas (e.g., gas turbine engines, oil and gas transmission pipelines, and structural steel shapes and plates). In some of these uses, particularly oil and gas transmission pipelines, the columbium content of these alloys has progressively increased from 0.03 percent to 0.05 percent in order to increase the strength of the alloys. There are a number of possible replacements for columbium in steel--namely, molybdenum, vanadium, or tungsten and steel grades are available that could substitute in an emergency for columbium-containing grades. However, the development of the microalloyed steels using thermomechanical treatments, known as the high-strength low-alloy grades (HSLA), is actually increasing U.S. dependence on imports of columbium as an important alloying element. In superalloys, columbium-bearing alloy IN 718 (5 percent columbium) has replaced some cobalt-base alloys in jet engines and space applications and is also finding increased use as a corrosion-resistant alloy in the chemical process industries.

One of the most important future growth markets for columbium is in superconductors. About 100,000 lb of columbium was consumed in 1980 by the market economy countries for this use, and consumption is expected to grow at about 10 percent per year. In addition, certain classified U.S. government projects could increase future demand.

Generally, columbium demand is expected to grow 5 or 6 percent per year at least through the 1980s and then slow to 1 or 2 percent per year to the year 2000. This growth will be driven by high-strength, low-alloy steel and stainless steel requirements. U.S. consumption is expected to grow from the present 6.5 million lb level to about 7 million lb in 1985, 9.4 million lb in 1990, 12 million lb in 1995, and 14.6 million lb by 2000. The total market economy countries demand is projected at 28.5 million lb in 1984, 30.2 million lb in 1985, 41 million lb in 1990, 52 million lb in 1995, and 64 million lb in 2000. Current capacity for all columbium products, including ferrocolumbium, high-purity columbium, and high-purity nickel-columbium masteralloy, is more than adequate to meet future demand. Brazilian producers have integrated production capacity through to ferrocolumbium. CBMM and Teledyne Wah Chang also have sufficient high-purity oxide capacity to meet anticipated demand.

The projected future market for columbium will depend heavily on CBMM's future strategy regarding pricing and planned output. All the other pyrochlore producers are expected to maintain or increase production slightly over the coming decade. The current price structure objective of CBMM is to promote columbium usage through a stable pricing policy, thus allowing current producers to operate profitably. This will preclude any significant entry into the market by new producers, especially those with products exploiting columbium properties--companies such as Thor Lake in the Northwest Territory of Canada that are potential entrants into the market.

Substitution Potential During an Emergency

In times of emergency, U.S. consumption could be reduced by an estimated 20 percent in the initial phases of a supply disruption. Fortunately, columbium's major use is in various steels for which columbium-free grades are readily available (e.g., the full alloy and high-strength low-alloy types).

GOVERNMENT STOCKPILE CONSIDERATIONS FOR COBALT, CHROMIUM, TANTALUM, AND COLUMBIUM

The General Services Administration cobalt stockpile inventory is 40,802,393 lb, which is 48 percent of the goal of 85.4 million lb. The cobalt is in the form of rondelles and granules with a small fraction as briquettes and no cobalt powder. Most of the cobalt was purchased between 1947 and 1961, but about 5.2 million lb was purchased in 1981 and 1982. All of the pre-1980 material is below the quality required for the vacuum-melted superalloys used in the most critical applications (e.g., aircraft jet engines) and for extra-fine cobalt powder for cemented carbides. This quality of material is sufficient, however, for the less critical uses such as air-melted corrosion-resistant superalloys, hard facing alloys, air-melted high-strength ferrous alloys, and high-speed steels and for even least critical applications such as catalysts, chemicals, and air-melted tool steels.

An American Society for Metals (ASM) study panel (American Society for Metals, 1983) has recommended that the government "establish three quality grades of cobalt for the National Defense Stockpile and define the quantities of each grade required for applications that are critical to defense and industrial production." These grades were designated as Grade 1, where the impurity level is most critical (e.g., jet engines); Grade 2, where composition is less critical; and Grade 3, for the least critical applications cited above. The study further specified the impurity limits by element for controlling the quality of Grades 1 and 2. Finally, the panel recommended that the government accept an industry offer to conduct pilot processing tests at no cost to the government to determine the most expedient procedure for upgrading the pre-1980 cobalt stockpile. The panel also set guidelines for upgrading the cobalt to standards that would be in line with future stringent requirements on impurities, particularly the trade elements tellurium, thallium, and mercury. The panel favored tight specifications on sulfur, carbon, and phosphorus. It was noted that processing by vacuum induction furnace melting is not effective in removing these last three elements.

In addressing the issue of extra-fine cobalt powder, the ASM panel (American Society for Metals, 1983) recommended tests on the chemical treatment of pre-1980 cobalt as feedstock for the Carolmet powder process and evaluation of the powder in carbide cutting tools. It is possible that chemical processing of the feedstock may obviate the need for a special high-purity cobalt for making powder. The powder itself apparently cannot be reliably stored for long periods because of oxidation and nitrogen pickup.

The most critical need is for chromium as pure metal. The chromium metal stockpile contains about 7.5 million lb of material acquired 25 years ago and this constitutes about 9 percent of the stockpile goal of 40 million lb. The chromium in the stockpile is judged inadequate for vacuum-melted superalloys used in jet engine parts. The undesirable element content also precludes its use for producing PH 13-8 Mo stainless steel or as an alloying element in titanium alloys, both of which have important defense uses. In quality, however, it is satisfactory for air-melted heat- and corrosion-resistant alloys, aluminum alloys, electrical resistance alloys, some hard facing alloys, stainless steels, and alloy steels.

An ASM study of chromium metal (American Society for Metals, 1984) has set compositional limits for Grade 1 chromium (for jet engine parts) and for grade 2 chromium (for less critical applications). The report recommended the purchase of Grade 1 chromium for use in the production of high-performance superalloys. It advised not that the existing stockpile be upgraded but that the existing material be classified as suitable for Grade 2 applications on a selective basis. Compositional limits were developed for high-purity ferrochromium used for the nickel-base superalloys containing iron, most notably alloy IN 718, used in jet engines, and the panel recommended the procurement of high-purity ferrochromium to supplement the chromium metal in the stockpile.

The high-carbon ferrochromium stockpile, currently at 402,696 short tons, is adequate for projected applications. The low-carbon ferrochromium inventory of 318,892 short tons is in excess of the current goal, and most of it is at a carbon level too high for use in some superalloys and stainless and alloy steels. It was recommended that an analysis program be initiated to check carbon and nitrogen levels to segregate the higher carbon lots from those of lower carbon (below 0.02 percent) and that reprocessing be considered if insufficient lower carbon material is found (National Materials Advisory Board, 1984). The quality of the ferrochromium silicon inventory was found to be adequate. The ferrochromium silicon inventory of 58,357 short tons is about 65 percent of the stockpile goal. The recently increased goal will permit the upgrading of part of the inventory to meet more stringent needs in critical applications. The widespread U.S. use of the AOD process for making stainless and other types of steels obviates the need for large low-carbon ferrochromium and ferrochromium silicon stockpiles.

The tantalum stockpile consists largely of tantalum minerals and a small quantity of tantalum capacitor powder and tantalum carbide: 2,551,000 lb in minerals, 201,000 lb in powder and ingot, and 29,000 lb in carbide (all values in contained tantalum). The current goal is 7,160,000 lb of contained tantalum--that is, at least three or four years of U.S. consumption--which an NMAB panel thought to be unduly high (NMAB, 1982b).

Tantalum ingot and powder and carbide powder in the stockpile are deemed essentially useless in most applications because of the high impurity content. The only form of tantalum that will not become obsolete is the mineral form since this is furthest from the end product in terms of processing requirements. A better form would be potassium fluotantalate (K-salt), an intermediate product used to make tantalum powder for capacitors. One drawback to stockpiling K-salt is its susceptibility to hydrolysis and the need for extra care in packaging the material for long-term storage; rotation of the inventory would solve this problem. The National Materials Advisory Board (1982b) panel recommended that only tantalum minerals be stockpiled until an effective rotation program is established. Tantalum oxide is not an acceptable form because it can be used only in carbides, which represent a small segment of the market. Metal powder and ingot also are not acceptable because they can rapidly become obsolete.

The columbium stockpile consists of 2.8 million lb of contained columbium, primarily in minerals and ferrocolumbium. The current goal is 4.9 million lb, which appears inconsistent with the much larger tantalum goal since the consumption of columbium is 10 times larger than that of tantalum. Unlike tantalum, however, additional columbium may be easily acquired from Brazil in a rather short time (two years) in the forms of ferrocolumbium and purified columbium oxide in proportion to their relative use.

It can be concluded that the most significant problems in the availability of an adequate quantity of high-quality materials in the stockpile appear to be with cobalt and chromium metal. Reprocessing of some portion of the cobalt stockpile material will be necessary, while purchases of high-purity metal, with no reprocessing of the inventory, will be required for chromium.

CONCLUSIONS

The committee's overall conclusions for each of the four metals are as follows:

1. Supplies of cobalt, chromium, and columbium are expected to be ample in the foreseeable future during nondisruption periods. Since the sources of all of these commodities are concentrated in foreign areas, security of supply will continue to be an issue. Existing sources of tantalum are declining and more than one major new mining operation will be needed by the late 1980s to meet the expected demand, even though demand growth will be fairly slow relative to the past.

2. Long-term demand for cobalt and chromium is expected to grow in proportion to industrial production. New uses of cobalt in surgical implants, floppy discs for computers, and miniature video cassettes potentially could expand at a significant rate. Columbium growth is expected to be more rapid because of increasing penetration in new markets. The potential exists for significant future increased consumption in superconductors, but there is more than enough supply to meet this eventuality. Slower demand growth is projected for tantalum because of past substitution and technical development efforts that have

improved the use efficiency in some areas such as capacitors. Increased recycling also will tend to reduce the quantity of primary tantalum required in cemented carbide cutting tools.

3. Future prices are expected to be very stable for chromium and columbium. Cobalt prices are expected to stabilize near current levels and should remain in the $10 to $15 per pound range. Tantalum prices are expected to become firm at about $80 per pound for the pentoxide as existing supplies decline and real costs of recovery from existing and new mines increase. Price volatility is likely to decline because there has been significant substitutability in the major tantalum end uses. The tantalum market, however, will continue to be more cyclical than most other metal markets. Columbium prices are expected to be stable and may even decline in terms of real dollar over the next few years as a result of the efforts to encourage market penetration by the major supplier, CBMM.

4. In the event of an emergency supply disruption of these metals, appropriate substitution of alternate materials, increased recycling of scrap, and increased use of coatings could be expected to reduce consumption in the short term. Requirements for cobalt could be reduced by as much as 40 percent, chromium by 25 percent in metallurgical and chemical uses and 34 percent in refractory uses, tantalum by 20 percent, and columbium by 20 percent.

5. The U.S. National Defense Stockpile inventories of cobalt, chromium, tantalum, and columbium are not adequate to meet U.S. needs in an emergency. They are not of sufficient quality for use in the most stringent applications, particularly in superalloys for jet engines. Therefore, a significant portion of the cobalt must be upgraded to meet the more stringent standards. Purchases of higher quality chromium metal are required to augment the existing lower grade material. Some of the tantalum stockpile must be in a form closer to the end-use product than the material forms now held in order to be responsive in an emergency. The columbium stockpile only needs some additional purchases of ore and ferrocolumbium to balance the tantalum stockpile in the same proportion as the respective consumption of the two metals.

REFERENCES

American Society for Metals. 1983. Quality Assessment of National Defense Stockpile Cobalt Inventory. Federal Emergency Management Agency, Metals Park, Ohio: American Society for Metals.

American Society for Metals. 1984. Quality Assessment of Chromium Metal for the National Defense Stockpile Inventory. Metals Park, Ohio: American Society for Metals.

Bureau of Mines. 1982. Minerals Yearbook. Washington, D.C.: U.S. Government Printing Office.

Charles River Associates. 1983. The Impact of New Metals Processing Technologies on the Conservation of Cobalt, Chromium, and Manganese. Final Report 741 for the Office of Technology Assessment, U.S. Congress.

National Materials Advisory Board. 1978. National Research Council Contingency Plan for Chromium Utilization. Report NMAB-335. Washington, D.C.: National Academy Press.

National Materials Advisory Board. 1982a. Consideration in Choice of Form for Materials for the National Stockpile. Report NMAB-378. Washington, D.C.: National Academy Press.

National Materials Advisory Board. 1982b. Tantalum and Columbium Supply and Demand Outlook. Report NMAB-391. Washington, D.C.: National Academy Press.

National Materials Advisory Board. 1983. Cobalt Conservation Through Technological Alternatives. Report NMAB-406, Washington, D.C.: National Academy Press.

National Materials Advisory Board. 1984. Priorities for Detailed Quality Assessments of the National Defense Stockpile Nonfuel Materials. Report NMAB-403, Washington, D.C.: National Academy Press.

Office of Technology Assessment. 1985. Strategic Materials: Technologies to Reduce U.S. Import Vulnerability. OTA-ITE-249. GPO No. 052-003-00979-0. Washington, D.C.: U.S. Government Printing Office.

Reddy, B., and M. Loreth. 1984. Cobalt turns the corner. Journal of Metals (April):90.

Tien, J. K., and R. M. Jarrett. 1983. Potential for the Development and Use of New Alloys to Reduce the Consumption of Chromium Cobalt and Manganese for Critical Applications. Final Report for Office of Technology Assessment, U.S. Congress.

Appendix A

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS

NICKOLAS J. THEMELIS received a B.Eng. degree in 1956 and a Ph.D. degree in 1961 from McGill University, both in chemical engineering. He served as an engineer at the Pulp and Paper Research Institute of Canada from 1956 to 1957, a research consultant for the Strategic Materials Corporation from 1960 to 1962, and manager of the engineering division of Noranda Research Center from 1962 to 1972. He became vice president of research and engineering of Kennecott Corporation in 1972 and in 1979 he was appointed vice president of technology. In 1980 he joined the faculty of Columbia University as professor of mineral engineering and he is currently chairman of the Henry Krumb School of Mines. He is the recipient of the ERCO Award and four awards of the American Institute of Mining, Metallurgical, and Petroleum Engineers. He is a member of the National Academy of Engineering. His research specialties include extractive metallurgy, process metallurgy, and management of technical resources.

JAMES C. BURROWS received a B.A. degree from Harvard University in 1969 and a Ph.D. degree from the Massachusetts Institute of Technology (MIT) in 1970, both in economics. He served as a staff member in the U.S. State Department from 1964 to 1965, as a research associate in the U.S. Bureau of Budget from 1965 to 1966, and as an economics teaching fellow at MIT from 1967 to 1968. Since 1970 he has been consultant and research associate at Charles River Associates and presently is vice president of the firm's natural resources group. He also is a member of the American Economics Association, the Econometrics Society, and Phi Beta Kappa. He is a member of the National Materials Advisory Board at the National Academy of Sciences and has served on numerous committees and panels. His fields of specialization are market forecasting for ferrous and nonferrous metals, applications of economic theory, applications of industrial organization and econometrics to models of industries, evaluation of alternative policies, and mineral economics.

JAMES E. COYNE received a B.S. degree from the University of Notre Dame in 1953 and an M.S. degree from Rensselaer Polytechnic Institute in 1957, both in metallurgy. He worked at Pratt and Whitney Aircraft, United Technologies Corportion, from 1957 to 1964 and in 1964 joined

Wyman-Gordon Company, where he is now vice president and technical director. He is a member of the American Institute of Mining, Metallurgical, and Petroleum Engineers and a registered professional engineer in Massachusetts. His areas of specialization are titanium- and nickel-base alloys, microstructural control, and effects of plastic deformation on mechanical properties.

NOEL JARRETT received a B.S. degree from the University of Pittsburgh in 1948 and an M.S. degree from the University of Michigan in 1951, both in chemical engineering. From 1949 to 1950, he worked as a sales engineer, industrial oil sales at Freedom-Valvoline Oil Company. In 1951, he joined the Aluminum Company of America and, after serving in various research and development positions, is now technical director, chemical engineering, at the ALCOA Laboratories. He is a fellow of the American Society for Metals and a member of the American Institute of Chemical Engineers; the American Institute of Mining, Metallurgical, and Petroleum Engineers; the Electrochemical Society; and Sigma Xi. He also is a member of the National Academy of Engineering and has served on a number of National Materials Advisory Board committees. His areas of expertise include electrochemical cell development, optimization of the Hall-Heroult process, coker reactor, Alcoa smelting process cell development, pollution control, and high-purity aluminum via crystallization.

LEMBIT C. KUSIK received a B.S. degree from the Massachusetts Institute of Technology in 1956 and a D.Sc. degree from New York University in 1961 in chemical engineering. He worked as a scientist in operations research at MIT from 1961 to 1962 and as a scientist in gas dynamics at Avco Corporation from 1963 to 1964. Since 1964 he has been with A. D. Little, Inc., and is now senior staff member for energy analysis. He is a member of the American Institute of Chemical Engineers; the American Chemical Society; and the American Institute of Mining, Metallurgical, and Petroleum Engineers. He has worked in the areas of energy assessment, environmental impact, process development, economics, and commercial feasibility studies.

ROGER N. KUST received a B.S. degree from Purdue University in 1957 and a Ph.D. degree from Iowa State University in 1963, both in physical chemistry. He served as assistant professor in inorganic chemistry at Texas A&M University from 1964 to 1965, was a faculty member at the University of Utah from 1965 to 1971, and was on the staff at Kennecott Copper Corporation's Ledgemont Laboratory from 1971 to 1980. He joined the Exxon Minerals Company in 1980 and is now manager of minerals processing research. He is a member of the American Association for the Advancement of Science, the American Chemical Society, the Electrochemical Society, and the American Academy of Arts and Sciences. He has worked in the areas of acid-base reactions in fused salts, electrochemical investigations in fused salts, and chemistry of metallurgical processes.

RICHARD K. PITLER received a B.S. degree from Massachusetts Institute of Technology, an M.S. degree from Rensselaer Polytechnic Institute, and a Ph.D. degree from Massachusetts Institute of Technology in 1949, all in metallurgy. He worked as research metallurgist at Allegheny Ludlum Steel Corporation on titanium, valve steels, and superalloys. He was named technical director at Special Metals Corporation, Inc. (a subsidiary company) in 1965 and then returned to Allegheny Ludlum to work on product development. Presently he is senior vice president and technical director at Allegheny Ludlum. He has been elected a member of Sigma Xi and Phi Lambda Upsilon and has served in numerous professional organizations. He is a member and trustee of the American Society for Metals and a member of the Americal Institute of Mining, Metallurgical, and Petroleum Engineers; the Industrial Research Institute; and the Association of Iron and Steel Engineers. His areas of expertise include titanium metallurgy, special steels, superalloys, and research and development management and technical sales.

BHAKTA B. RATH received a B.S. degree from Utkai University (India) in 1955, an M.S. degree from Michigan Technological University in 1958, and a Ph.D. degree from the Illinois Institute of Technology in 1962, all in metallurgy. He served as an assistant professor and research metallurgist at Washington State University from 1961 to 1965, a research scientist at U.S. Steel Corporation from 1965 to 1971, and a member of the research staff at McDonnell-Douglas Research Labs from 1972 to 1976. Since 1977 he has been at the U.S. Naval Research Laboratory where he is presently superintendent of the material sciences and technology division. He is also an adjunct faculty member of Carnegie-Mellon University. His professional organization affiliations include the American Association for the Advancement of Science; the American Society for Metals; the American Institute of Mining, Metallurgical, and Petroleum Engineers; the British Institute for Metals; and the Physical Society of Japan. He has been involved in many areas of research including metals recovery, recrystallization and grain growth in metals, x-ray diffraction, theory of metals, crystallography, micro-calorimetry, and surface physics.

JOHN B. WACHTMAN, JR. received a B.S. degree in 1948 and an M.S. degree in 1949 from Carnegie Institute of Technology, and a Ph.D. degree from the University of Maryland in 1961, all in physics. He joined the U.S. National Bureau of Standards in 1951, serving in various research positions in the Center of Materials Science and becoming its director in 1978. In 1983, he was appointed director of the Center for Ceramic Research at Rutgers University. He has served on numerous committees and boards and in professional, government, and academic organizations and has received honors and awards including the U.S. Department of Commerce Gold Medal, the American Ceramic Society Sosman Memorial Lecture Award, and the Hobart Krauer Award. He is a member of the National Academy of Engineering. His professional organization affiliations include the

American Ceramic Society (past president), the National Institute of Ceramic Engineers, the Federation of Materials Societies (past president), and the American Society for Testing and Materials. His varied research interests include mechanical properties of materials and effective utilization of inorganic materials.

Appendix B

ATROPHY IN METAL DEMAND*

by John E. Tilton, Professor of Mineral Economics,
The Pennsylvania State University

From the trade press to the halls of Congress, the debate over mineral policy in recent years has focused largely on the problems of imports and the need for secure supplies of strategic and critical materials. Meanwhile, what appears to be a major structural change with serious implications for all of the major metal industries has in many quarters gone largely unnoticed.

This change, which apparently took place about 1974, shortly after the first major oil crisis, involves a sharp break or discontinuity in the growth of world demand for metals. Its magnitude is highlighted by the graphs [below], which show the rise in world consumption, outside the socialist countries, for the major metals since 1950. Indeed, growth in consumption has not only slowed, it has for many metals ground to a halt over the last decade.

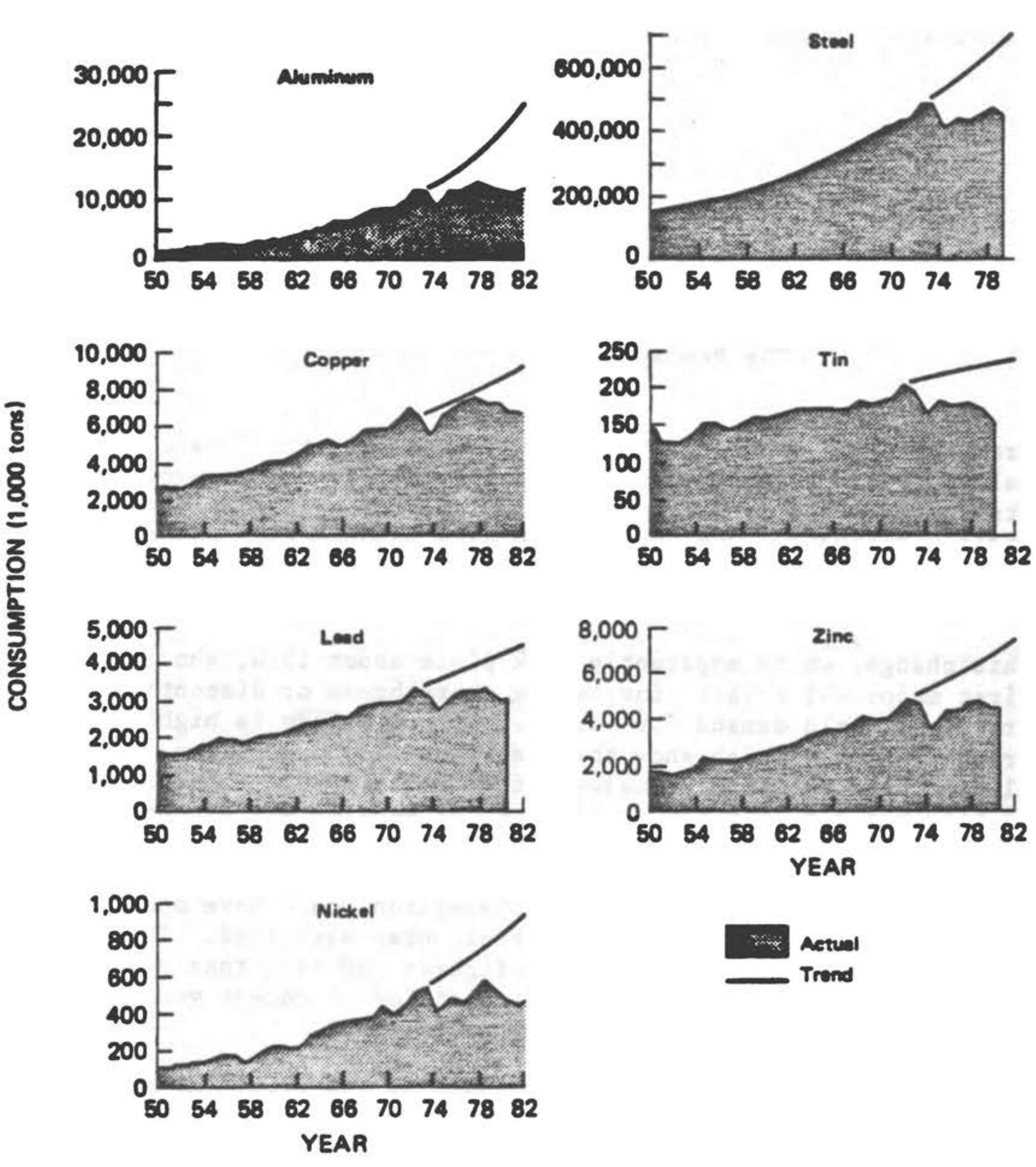
The graphs also illustrate what consumption would have been in the post-1974 period had earlier growth trends been sustained. The large gaps between the actual and the trend figures indicate that much of the distress suffered by the major metal industries in recent years can be attributed to the slowdown in the growth of demand.

The decline in consumption growth could be the result of higher metal prices rather than a change in the growth of demand. In real terms, however, the prices for almost all of the metals examined have fallen since 1974, eliminating this possibility.

It should also be noted that a slowdown in demand, if it is anticipated and the construction of new capacity reduced accordingly, need not depress metal markets and distress producers. The decline in

---

*Reprinted from Earth and Mineral Sciences, Winter 1985, Quarterly Bulletin of the College of Earth and Mineral Sciences, The Pennsylvania State University.



Western world consumption of major metals, actual and trends, in thousands of tons, 1950-1982. Trend figures indicate how metal consumption would have increased in the post-1973 period had growth continued at the 1950-73 rate. Steel consumption figures for a number of years between 1951 and 1972 were estimated by extrapolation. (Sources: References 1, 2, 3, and 4.)

the growth of metal demand after 1974, however, was for a number of years widely assumed to be temporary, a cyclical downturn associated with the decline in world gross domestic product (GDP).

SEARCHING FOR AN EXPLANATION

Just why the growth in world metal demand stalled about 1974 is far from clear. One important factor is the slowdown in world economic growth beginning about that time. Western world GDP, which rose at an average annual rate of 6.2 percent between 1950 and 1974, has since increased by only 1.7 percent a year. This, however, is only part of the explanation. Also important are shifts in the speed at which the intensity of use--the amount of metal consumed per unit of GDP--has been rising or falling over time.

Data on the growth in consumption of aluminum, copper, and nickel for 1950-74 and 1974-82 are shown in the table[1,5] [below], along with the rate of growth in world GDP outside the socialist countries and in intensity of use for the same two periods. With this information, we can separate the influence of changes in economic growth from the intensity of metal use in explaining the slowdown in consumption growth since 1974. For both aluminum and nickel, 44 percent of the decline can be attributed to the change in intensity of use. Before 1974, the intensity of aluminum and nickel use was rising, causing consumption to grow at a faster pace than GDP. Since then, just the opposite has been the case.

The intensity of copper use has been declining sine 1950. In contrast to aluminum and nickel, however, the rate of decline has slowed since 1974. This change has partially offset the adverse effect of lagging economic growth. Without it, the drop in the growth rate of copper consumption would have been some 30 percent more severe.

There are two factors behind these trends in intensity of use--the product composition of income, and the material composition of products. The first reflects the mix of goods and services provided by the economy. As the composition of output shifts away from material-intensive goods, intensity of use tends to decline. It is widely thought that such a shift has taken place in the United States and other developed countries as rising per capita incomes have created greater consumer preferences for services.[6] High interest rates and other macroeconomic policies may also have changed the product mix by depressing the construction and capital equipment sectors. The introduction of new products also alters the composition of income, and can be important. The development and rapid diffusion of the aluminum beverage can during the 1960s and 1970s, for example, contributed to the rising intensity of aluminum use up to 1974.

Western World Growth in Metal Consumption, Intensity of Use, and Gross Domestic Product[1,5]

Metal	Metal Consumption	GDP	Intensity of Use	Contribution of Intensity of Use (%)
Aluminum				44
1950-74	9.3	6.2	2.9	
1974-82	-0.4	1.7	-2.1	
Copper				-30
1950-74	3.8	6.2	-2.2	
1974-82	0.6	1.7	-1.1	
Nickel				44
1950-74	6.3	6.2	0.1	
1974-82	-2.9	1.7	-4.6	

Notes: Since intensity of use is by definition metal consumption per unit of GDP, metal consumption in any year is the product of GDP and intensity of use, and growth over time in metal consumption depends on both the growth of GDP and intensity of use.

The last column shown above indicates the contribution of intensity of use to the change in the metal consumption growth rate between 1950-74 and 1974-82. For example, in the case of aluminum the drop in the growth rate of intensity of use from a plus 2.9 to a minus 2.1 accounts for 44 percent of the decline from a plus 9.3 to a minus 0.4 in the growth rate of aluminum consumption. The remaining 56 percent of this decline was caused by the slowdown in GDP growth from 6.2 to 1.7.

The second factor, the material composition of products, reflects the amount of steel, aluminum, copper, and other materials used in the production of specific goods, such as automobiles or telecommunications transmission systems. Over time, material substitution, technological change, and other factors can decrease or increase the amount of metal required in specific end uses. For example, the quantity of steel used per automobile has declined over the last ten years, due in part to downsizing, and in part to the substitution of high-strength low-alloy steel and other materials for traditional steel sheet. These changes have contributed to the overall decline in intensity of steel use.

As noted earlier, despite the important role of demand in understanding the current problems and future prospects of the metal industries, it has not received a great deal of attention--far less for example than developments on the supply side of the market, such as the impact of imports, new processing technologies, higher energy costs, the rise of state enterprises, environmental regulations, public land policies, and government subsidies for foreign producers.

Still, some interesting research on metal demand does exist. The International Iron and Steel Institute[7,8,9] and the Organization for Economic Cooperation and Development,[10] for example, have published a number of studies focusing on changes in the intensity of steel consumption. The Commodity Research Unit, Chase Econometrics, and other consulting firms have also examined metal demand.

UNANSWERED QUESTIONS

Yet there is still much we would like to know about the demand for metals, and its role in the current depression and the future evolution of metal markets. Among the important outstanding questions are the following:

--How is the current stagnation of metal demand tied to the slowdown in world economic growth? To what extent would metal demand recover if the GDP were to resume the brisk pace of growth the world enjoyed during the 1960s and early 1970s?

--How important are changing trends in the intensity of metal use in explaining the decline of metal demand over the last decade? For aluminum and nickel, we have seen that changing intensity of use has been very imortant. Is the same true for most other metals? Is the slowing of the decline in intensity of use for copper, with its beneficial effects on demand, the exception to an overall trend?

--What are the important factors causing the intensity-of-use trends to change over time? In particular, how significant are changes in the product composition of income compared with the material composition of products? How are these determinants likely to evolve in the future? To what extent are they cyclical, caused by fluctuations in construction and capital equipment sectors over the business cycle? To what extent are they secular, driven by new technological developments and materials substitution? What are the implications for metal demand?

--To what extent has the intensity of metal use fallen because consumers are keeping automobiles and other material-intensive products longer, reducing the replacement demand for such goods?

--How does the intensity of metal use vary among countries? Are there significant differences between the United States, Japan, and Western Europe? If so, are these differences found across all the major metals, or are they specific to individual commodities? Are there important differences in intensity of use between the developed and developing countries? In particular, does intensity of use tend to rise over time in the developing countries, as many believe, thereby offsetting to some extent the adverse effects of the decline in intensity of use in the more developed countries? How does the intensity of metal use in the Soviet Union and other socialist countries compare with that of the developed and developing countries? Have the differences been increasing or decreasing? Are they greater or smaller for metals such as specialty steels that require more sophisticated technology?

--What are the important factors causing the intensity of metal use to vary among countries? How important, for example, is the level of economic development measured by per capita income, as suggested by Malenbaum,[6] or the material intensity of a country's exports and imports, as suggested by Radcliffe[11] and the OECD?[10] Do countries that are saving and investing a large portion of their GDP, and hence growing rapidly, have relatively large construction and capital equipment sectors, and as a result high intensities of use?

--How do the forecasting techniques used by firms, government agencies, international organizations, and other institutions take account of secular changes in metal demand? What are the relative strengths and weaknesses of the available approaches?

--How do expectations about the future and, in turn, investment of new capacity respond to secular changes in demand? When demand declines, is there a response period of five to ten years during which capacity expands faster than necessary, because the downturn in demand is underestimated or presumed to be cyclical or temporary? Conversely, when the long-run growth in demand accelerates, will capacity likely lag behind for a decade, causing shortages and high prices?

--To what extent does the decline in the growth of consumption for steel, copper, and other metals in recent years simply reflect the market penetration of new materials, such as sophisticated metal alloys, polymers, ceramics, and composites? In the first half of the 20th century, aluminum was a new material, and its consumption grew more rapidly than the overall economy as its range of applications expanded and it replaced copper and other materials in many end uses. Now, like steel, copper, and other older metals, it finds itself under attack from even newer materials. This suggests that materials may experience a product life cycle, a possibility investigated by Humphreys,[5] with consumption growing rapidly at first and then more slowly, and that many metals, particularly the older ones, may have reached the more mature stage where they are losing more markets than they are gaining.

--To the extent that demand is shifting from the more traditional metals to newer materials, what are the implications for material trade? Will countries such as the United States and Japan, with their traditional comparative advantage in high technology sectors, find that they are becoming more competitive in the production of the rapidly growing segment of the materials market, and becoming less competitive only in the slow-growth segment? If so, will the industrialized countries, despite growing imports of steel and other traditional metals from abroad, become less dependent over time on foreign countries for their essential materials? Will the United States, for example, become a less important metal producer but a more important material producer, while Brazil and other mineral-rich exporting countries become more important metal producers but less important material producers?

LOOKING FOR ANSWERS

In the hope of providing insight into such questions, the Department of Mineral Economics in the College of Earth and Mineral Sciences will be actively involved in two major research efforts over the next several years. The first is an international conference on the technological and economic forces altering the demand for metals to be held at Penn State, May 20-22, 1986. At this meeting, which is being organized by Dr. William A. Vogely, head of the Department of Mineral Economics, for the journal Materials and Society, experts from around the world will present invited papers on various aspects of the changing nature of metal demand. These papers will then be revised and published along with a summary report of the meeting.

The second effort is an ambitious research program on "Structural Change in World Metal Demand," which the Mineral Economics and Policy Program, in collaboration with the Center for International Business Studies of the University of Montreal and other research organizations abroad, is planning to initiate this summer.

The Mineral Economics and Policy Program (MEPP) was established in 1982 by the Department of Mineral Economics and the Energy and Materials Division of Resources for the Future, a nonprofit research organization in Washington, D.C. The overall goal of the MEPP is to advance education and research on the nonfuel mineral industries, and thereby help rectify the imbalance that has developed in recent years as the energy minerals have attracted an ever increasing share of the research and attention devoted to minerals.

The economics of mineral exploration, structural change in the world aluminum smelting industry, East-West mineral trade, state enterprise in the minerals sector, opportunities for domestic production of strategic minerals, the declining zinc refining industry in the United States, and minerals scarcity and economic growth are among the studies that MEPP has supported over the last several years. More information on MEPP can be obtained from the writer, who is one of the two directors of the Program, the other being Hans Landsberg of Resources for the Future.

As part of the research effort on structural change in world metal demand, a number of complementary studies will be conducted by different authors. One study, for example, will examine past and current trends in the demand for steel, aluminum, copper, nickel, lead, zinc, and tin in the developed countries, particularly the United States, Japan, and the European Economic Community. Patterns of consumption and intensity of use will be compared across countries, metals, and time periods. The effects of material substitution, metal-saving technological change, the decline in economic growth, and the shift in GDP toward services on the demand for metals will be appraised to the extent the available data permit.

Parallel studies covering the developing countries and the Council of Mutual Economic Assistance countries will also be conducted. (Member states of CMEA include the Soviet Union, Bulgaria, Czechoslovakia, German Democratic Republic, Hungary, Poland, Romania, Mongolia, Cuba, and, since 1978, Vietnam.) In-depth studies of metal use in the automobile and packaging industries are also planned. The Department of Mineral Economics several years ago conducted a detailed analysis of material use in beverage containers in the United States over the last several decades.[12,13] The proposed study on the packaging industry would extend this earlier work by considering material usage in other forms of packaging and in other countries.

The case studies of specific end uses should help us discover the more important factors responsible for the general trends and patterns of metal consumption, which the country studies will highlight.

As a result of these and other research efforts, we hope in a few years to understand more fully what is happening to world metal demand. This, in turn, should improve our ability to forecast metal requirements, and to assess the meaning of the recent slowdown in demand growth for the future of the metal industries in the United States and abroad.

REFERENCES

1. Metallgesellschaft Aktiengesellschaft, Metal Statistics (Frankfurt am Main, annual).

2. IISI, Iron and Steel Yearbook, (Brussels: International Iron and Steel Institute, annual).

3. United Nations, Statistical Yearbook (New York: annual).

4. Gerald Manners, The Changing World Market for Iron Ore, 1950-1980 (Baltimore: Johns Hopkins for Resources for the Future, 1971).

5. D. Humphreys, "A Mineral Commodity Life-Cycle?" Resources Policy, September 1982, pp. 215-229.

6. W. Malenbaum, World Demand for Raw Materials in 1985 and 2000 (New York: McGraw-Hill, 1978).

7. IISI, Projections 85: World Steel Demand (Brussels: International Iron and Steel Institute, 1972).

8. IISI, Steel Intensity and GNP Structure (Brussels: International Iron and Steel Institute, 1974).

9. IISI, Causes of the Mid-1970s' Recession in Steel Demand (Brussels: International Iron and Steel Institute, 1980).

10. OECD, Forecasting Steel Consumption (Paris: Organization for Economic Cooperation and Development, 1974).

11. V. S. Radcliffe, L. L. Fischman, and R. Schantz, Jr., Materials Requirements and Economic Growth: A Comparison of Consumption Patterns in Industrialized Countries, report prepared by Resources for the Future for U.S. Bureau of Mines, Washington, D.C., 1981.

12. F. R. Demler, The Nature of Tin Substitution in the Beverage Container Industry, Ph.D. dissertation, The Pennsylvania State University, University Park, Pennsylvania, 1980.

13. F. R. Demler, "Beverage Containers," Material Substitution: Lessons from Tin-Using Industries, ed. J. E. Tilton (Washington, D.C.: Resources for the Future, 1983).

THE AUTHOR

Dr. John E. Tilton received his B.A. in public and international affairs from the Woodrow Wilson School at Princeton University and his M.S. and Ph.D. in economics from Yale University. Prior to joining the Penn State faculty in 1972, he worked as an economist for the Office of the Secretary of Defense and for the Brookings Institution in Washington, D.C. He also taught for two years at the University of Maryland. In 1977, while on leave from the University, Dr. Tilton served for a year as an economic affairs officer for the Minerals and Metals Branch of the United Nations Conference on Trade and Development in Geneva, Switzerland. More recently, he has spent two years at the International Institute for Applied Systems Analysis in Laxenburg, Austria, as the leader of a research project on mineral trade and markets.

Appendix C

MONEY-COST GAP BETWEEN JAPAN, U.S. STILL HUGE*

by Peter Behr
Washington Post Staff Writer

Chikara Hayashi is a Japanese entrepreneur. Like many of his American counterparts, he started with an idea far ahead of its time--in his case, the processing of valuable, high-quality metallic and mineral products within vacuums.

Hayashi's company, Ulvac, in Kanagawa, Japan, now has $300 million in sales, thanks to the explosive demand for vacuum processing of silicon chips.

It took 25 years to get there. Unlike the typical American counterpart, however, Hayashi has had the benefit of years of patient, long-term financing at relatively low interest rates--loan rates much lower than American entrepreneurs could obtain.

> "On the average, we pay 6 percent or 7 percent interest now," Hayashi said in a recent interview here. The figure is roughly half the prime lending rate in the United States. "On top of that, there is as much money as I wish. The banks are happy to lend it."

As he explains it, Hayashi is a prime beneficiary of Japan's closely controlled financial strategy for providing low-cost capital to its industries. His experience, repeated throughout Japan's industrial sector--particularly with large manufacturing and trading companies--illustrates what has been a major competitive advantage for Japanese manufacturers in their rise to the top of the world marketplace, according to many U.S. and Japanese economists and business leaders.

George N. Hatsopoulos, Chairman of Thermo Electron Corp. of Waltham, Mass., has pursued a year-long campaign to highlight the cost-of-capital issue through a series of studies and publications. His major study was prepared in conjunction with the American Business Conference, a Washington-based lobbying organization of mid-sized U.S. growth companies.

---

*From The Washington Post, June 24, 1984, p. G-1.

Hatsopoulos has compared the financial conditions of U.S. Steel Corp. and Japan's No. 1 firm, Nippon Steel, noting that between 1965 and 1980, Nippon spent, on average, two and a half times as much on plants and equipment per employee as U.S. Steel. It could do so because of its ability to obtain--and live with--high levels of debt, at real interest rates that were much lower than those available to U.S. Steel. "The cost-of-capital advantage that the Japanese industry enjoys overshadows other advantages they may have, such as lower labor costs. It also shows that Nippon's competitive advantage stems principally from Japan's financial system . . . ," he said.

The Japanese financial system has begun to change, under pressure from Japanese consumers, a growing class of Japanese entrepreneurs, and from the United States and other trading partners.

But as long as Japan's advantage in the cost of investment capital continues, it represents a serious handicap for many American manufacturers in their competition with Japanese rivals, according to analysts of the trade competition between the two countries. This cost-of-capital issue not only stirs up political tensions between the United States and Japan, it also adds to the growing domestic debate over taxes. Corporate leaders, seeking to offset a Japanese advantage in capital costs, will be campaigning hard next year for a wholesale revision--and reduction--of corporate taxes.

The Japanese financial structure that has produced such favorable borrowing conditions for its industries is as much a reflection of Japan's economic environment as the go-go U.S. venture capital market reflects an American life style.

In Japan's case, the financial system was an indispensable part of its strategy for recovery from the ruins of World War II. Yasusuke Murakami, a Tokyo University economist and highly regarded social commentator, explained that strategy in a 1982 study of the Japanese economy published by the University of Washington.

The goal of the Japanese government was the recovery and reconstruction of industry. It was financed by Japan's consumers, who were faced with a system of financial policies and interest rate regulation that encouraged savings but made consumer borrowing costly if not impossible.

> "A huge amount of money was constantly flowing from the household sector to major leading industries mainly through bank loans . . . Interest rates charged on industrial loans remained favorable in large part because industry did not have to compete with consumers for loans, he notes. "In this sense, the Japanese households were the single most important mainstay of the low interest rate policy."

Nor could Japanese consumers--if frustrated by low regulated interest rates on Japanese investments--turn to foreign investments with higher rates. "Until recently, ordinary Japanese could not acquire any financial assets," writes Murakami.

Finally, Japan's financial system permitted its firms to rely heavily on debt--far more so than have American firms. For Nippon Steel, the long-term debt-to-equity ratio exceeded 250 percent, says Hatsopoulos. For U.S. Steel, it was 40 percent, reflecting American steel makers' far heavier reliance on equity and retained earnings to finance their capital investments, says Hatsopoulos.

As long as Japan's bankers were patient with its industries--and their patience was almost infinite--Japanese manufacturers could pursue the long-range development of new products year after year, and pour investment into modernization, regardless of the rise and fall of annual profits.

The magnitude of Japan's cost-of-capital advantage has declined in the past few years, in part because of the dramatic rise in the U.S. stock market two years ago, which created a capital windfall for many American companies, and in part because of the sharp drop in inflation, which lowers the real, inflation-adjusted cost of capital. The stock market's poorer performance since 1982 is adding to the problem, however.

Last month, Japan announced it had agreed to undertake changes in its financial system designed to make the yen much more like an international currency (no more than 4 percent of international transactions are now conducted in yen). The cautious opening of Japan's financial market a bit to foreigners, and the agreement to a partial deregulation of interest rates, could--in time--contribute to a narrowing of the capital cost gap.

The gap remains for now, however. By Hatsopoulos' calculations, the cost of capital in the United States averaged 16 percent in 1983, while the Japanese average was about 9 percent. The gap is narrower than the peak in 1974, but still substantial, says Hatsopoulos.

If his analysis is right, and the gap remains large, it foreshadows a continuing underdog role for many American firms facing import competition--not only in basic industries like steel, but in high-tech competition as well. "I really believe that what happened to U.S. Steel is going to happen to Digital Equipment or Intel," he said recently. "In fact, it's the semi-conductor industry that will be the next one to feel it."

Hatsopoulos'calculations have been questioned by several academics, and some U.S. corporate leaders see the cost-of-capital problem as far less of a handicap than he does. But he has academic supporters, as well, among them Lawrence Summers, a Harvard University economist and former member of the Council of Economic Advisers in the Reagan administration.

Earlier this year, Summers told a task force on industrial competitiveness appointed by President Reagan that he considers Hatsopoulos' conclusions to be essentially correct, even if there is some debate about the calculations.

> "First, the cost of capital in the United States is high and rose substantially during the 1970s, a period during which net investment and capital per worker also performed poorly," Summers said.
>
> "Second, the cost of capital in Japan, which has grown much more rapidly than we have and which has been much more successful on international markets than we have, has grown much less rapidly than the American cost of capital. It is now at a level between one-third and a half of the American cost of capital.
>
> "Third, the [U.S.] cost of capital differs dramatically on different types of investments," said Summers. (Hatsopoulos' calculation includes not only the manufacturers' costs of raising funds, but also the return from different kinds of investments. Some types of investment are taxed at higher rates than others, and this affects the cash flow from the investment.) [A review of pertinent investment comparisons is shown in the tabulation and plots below.]

The cleanest solution to the problem would be a return to the economic conditions of the 1960s, a time of low real interest rates and low inflation, Hatsopoulos says. But that goal has eluded economic policy makers for nearly two decades. As a piecemeal remedy, Congress could change the tax code to make dividends on preferred stock deductible, reducing the costs of capital, at least for profitable corporations, Hatsopoulos says.

There is another policy alternative, one gaining growing support from business leaders and liberal critics of the current tax structure. By pointing out the great variations in the cost of capital for different kinds of business investments, Hatsopoulos has helped strengthen the argument for the simplification of the corporate tax and a smoothing of the huge variations in effective corporate tax rates on new investment created by the 1981 tax bill.

> "For new investment, the range of effective tax rates has increased from 27.4 percent to 48.4 percent," Brookings Institution economist Robert Z. Lawrence says in his new book, "Can America Compete?"

Ironically, some of the firms penalized by the discriminatory differences in effective tax rates are high-tech firms that offer the hope of the fastest growth and the most rapid creation of jobs.

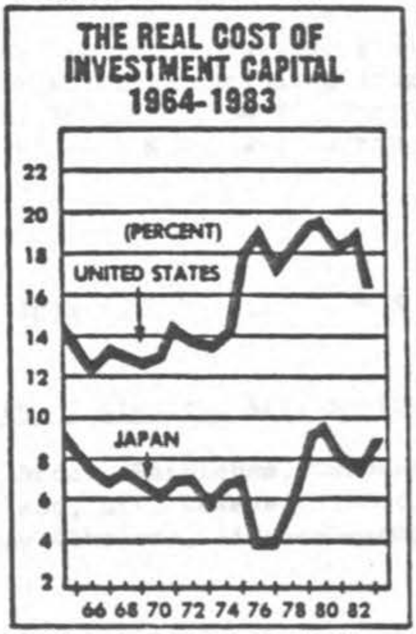
JAPAN'S HIGH SAVINGS RATE, AND LOW INTEREST RATES...

SAVINGS RATES
AVERAGES 1970 TO 1980

FRANCE	13.4
GERMANY	14.7
ITALY	21.5
JAPAN	20.7
UNITED KINGDOM	8.0
UNITED STATES	7.7

SOURCE: DEREK W. BLADES AND PETER H. STURM, "THE CONCEPT AND MEASUREMENT OF SAVINGS: THE UNITED STATES AND OTHER INDUSTRIALIZED COUNTRIES," FEDERAL RESERVE BANK OF BOSTON

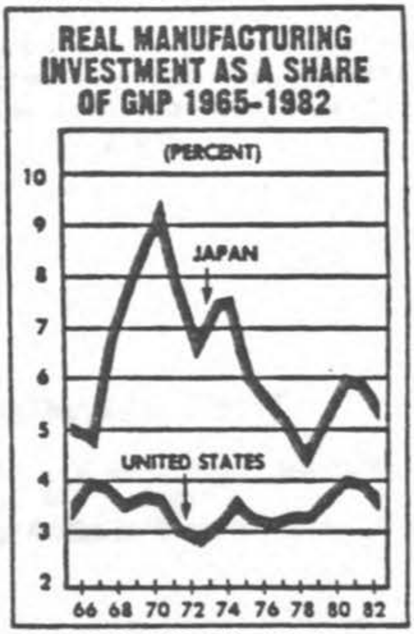
...HELP GIVE ITS CORPORATIONS A LOWER REAL COST OF INVESTMENT CAPITAL THAN U.S....



THE REAL COST OF INVESTMENT CAPITAL 1964-1983

SOURCE: "HIGH COST OF CAPITAL", 1983

...LEADING TO A HIGHER LEVEL OF INVESTMENT IN MANUFACTURING.



REAL MANUFACTURING INVESTMENT AS A SHARE OF GNP 1965-1982

SOURCE: DATA RESOURCES INSTITUTE

By Gail McCrory--The Washington Post

Appendix D

PARTICIPANTS IN AISI COLLABORATIVE RESEARCH

The participants in AISI collaborative research are listed briefly below. A more extensive listing, including program descriptions, appears in the AISI publication, RESEARCH 1984-85, The American Iron and Steel Institute, 1000 - 16th Street, N.W., Washington, D.C. 20036.

Tall Coke Oven Problems

Algoma, Bethlehem, Inland, LTV, Stelco, U.S. Steel

Improvement of Stability of Electric Arcs in Steelmaking Furnaces

Armco, Atlantic, Babcock, Bethlehem, Carpenter, Copperweld, Cyclops, Green River, Hylsa, Inland, LTV, Lukens, McLouth, North Star, Pennsylvania Engineering (Sharon), Sidbec-Dosco, Stelco, Timken, U.S. Steel

Induction Heating for Semifinished Products

Ajax Magnethermic, Battelle, Detroit Edicon, EPRI, McLouth

Basic Research on Steelmaking Refractories

(See AISI publication, RESEARCH 1984-85.)

Rapid In-Process Analysis of Molten Metal

Alcoa, Algoma, Allegheny, Armco, Bethlehem, Carpenter, Cyclops, Dofasco, G. M. Foundry Division, Inland, Interlake, LTV, National Reynolds Metals, Stelco, Timken, U.S. Steel

In-Line Detection of Gross Porosity in Hot Slabs, Blooms, and Billets

Bethlehem, Inland, LTV, National, Timken, U.S. Steel

Rapid Measurement of Temperature Distribution Within a Solid or Solidifying Body of Hot Steel

Armco, Bethlehem, Inland, LTV, National, Timken, U.S. Steel

On-Line Inspection of Surface Defects on Cold Rolled Strip

Alcoa, Armco, Bethlehem, Cyclops, Inland, Kaiser Aluminum, LTV, Reynolds Metals

Detection of Slag in Molten Steel During Teeming

Armco, Babcock, Bethlehem, Carpenter, Inland, LTV, National, Timken

Recycling and Recovery of Waste Acid from Stainless Steel Pickling

Allegheny, Armco, Atlas, Carpenter, Cyclops, Latrobe, LTV

Sludge Dewatering

Armco, Bethlehem, Carpenter, Cyclops, Inland, LTV, National, U.S. Steel

Removal of Hydrocarbons from Iron-Bearing Waste

Armco, Bethlehem, Carpenter, Cyclops, Heckett, Inland, LTV, National, U.S. Steel

Flow Stress for Hot Rolling

Armco, Bethlehem, Inland, LTV, Lukens, National, U.S. Steel

Appendix E

ENERGY CONSUMPTION IN ELECTROLYTIC CELLS

Table E-1 shows the thermodynamic minimum possible energy consumption at Hall-Heroult cell operating temperatures for three different reactions producing aluminum. Reaction 3 is the primary reaction that takes place in the Hall-Heroult cell, yielding a minimum energy consumption of 6.35 kWh/kg of aluminum produced. Some of this CO_2, however, reacts in solution with reduced cathodic species to form CO, reducing current efficiency. A small amount of the CO_2 also back reacts with the carbon to produce CO. These two reactions are equivalent to some of the oxygen introduced as alumina reacting, as in Reaction 2, to form CO at a minimum energy consumption of 7.78 kWh/kg. Since CO in Hall cell off-gases ranges from about 18 to 40 percent, depending on operating conditions, the minimum energy requirement actually ranges between 6.6 and 6.9 kWh/kg Al. If the oxygen added as alumina is simply deposited at the anode and dimerizes to make oxygen, as in the case of an inert anode (Reaction 1), the minimum energy requirement is 9.26 kWh/kg Al. Therefore, to be competitive with the carbon anode with regard to the electrical energy consumed, the inert anode system would seem to have to make up between 2.2 and 2.66 kWh/kg of aluminum through reduced interelectrode spacing or the reduction of other resistances by advanced designs not possible with a carbon anode. The actual penalty, however, is only about 1.76 kWh/kg of aluminum due to lower polarization in the inert anode system.

TABLE E-1 Thermodynamic Energy Consumption

Cell Reactions	Minimum Possible Energy Consumption at 960°C
1. $\alpha\, Al_2O_3 = 2Al + 3/2O_2$	9.26 kWh/kg
2. $2\,\alpha\, Al_2O_3 + 3C = 2Al + 3CO$	7.78 kWh/kg
3. $\alpha\, Al_2O_3 + 3/2C = 2Al + 3/2CO_2$	6.35 kWh/kg

In Table E-2 voltage drops in a typical Hall-Heroult cell are compared to calculated similar drops in inert anode cells at varying interelectrode spacings. Energy consumption and total energy savings are also indicated. The additional energy required for the deposition of oxygen is reflected in the decomposition potential, which is 1 volt higher for inert anode cells than for consumable carbon anode cells. However, the polarization component reflecting voltage drop due to diffusion, reaction rate at the anode, and bubble layer (typically 0.6 V in the Hall-Heroult process) is only 0.15 volt in the inert anode cells, resulting in a penalty of 0.55 volt instead of the 1 volt due to decomposition. If the carbon anode in a Hall cell is simply replaced by an inert anode having the same voltage drop and operated at the same interelectrode spacing, a total energy savings in the production of aluminum would be 5.4 percent, although electrical energy consumption would rise 12 percent. This energy saving is obtained by subtracting the additional energy required at the power plant from the energy saved by not manufacturing petroleum coke-pitch anodes to be burned in the cell.

If the inert anode is operated at an interelectrode spacing of 1.91 cm, as previously described for titanium diboride, the 10 percent electric power savings over a typical Hall-Heroult cell coupled with the carbon fuel and auxiliary power saved in carbon manufacture yields a total energy savings of 23 percent. This interelectrode space reduction is possible using an inert anode because of the utilization of the total anodic surface at all times, the uniformity of that surface, and the ability to configure the surface to reduce bubble polarization. If a properly configured inert anode surface were coupled with a stable titanium diboride cathode surface, interlectrode spacing of approximately 0.60 cm with no shorting should be possible. Current efficiency losses and bubble polarization under these conditions remain to be determined accurately, but if 91 percent current efficiency could be achieved, 32 percent of the electrical energy now consumed in the production of aluminum would be saved.

The corrosive environment, high fluctuating temperatures, and periodic exposure to air add up to the following requirements for a successful inert anode:

1. High electronic conductance
2. Low reactivity with oxygen or bath
3. Relatively low cost, readily available
4. Does not contaminate aluminum
5. Ability to be fabricated into large shape
6. Stable electrical connections to bus
7. Adequate mechanical strength

TABLE E-2 Voltage Drops in Aluminum Smelting Cells Calculated at 91 Percent Current Efficiency

	Hall-Heroult Cell	Inert Anode Cell		
	4.45[a]	4.45[a]	1.91[a]	0.64[a]
External	0.16	0.16	0.16	0.16
Anode connection	0.16	0.16	0.16	0.16
Anode resistance	0.16	0.16	0.16	0.16
Electrolyte resistance	1.76	1.76	0.75	0.26
Decomposition	1.20	2.20	0.20	0.20
Polarization	0.60	0.15	0.15	0.15
Cathode resistance	0.60	0.60	0.60	0.60
Total cell volts	4.64	5.19	4.18	3.68
kWh/kg	15.2	16.96	13.66	12.0
Total energy savings, percent	-	5.4[b]	15.40	26.4

[a] Interelectrode spacing (in cm) with TiB_2 cathode.

[b] Carbon savings is at minimum 12 percent of power requirement.

High electronic conductance, as distinguished from ionic conductance, is also necessary if the electrical contact to the inert anode is not to be destroyed.

BIBLIOGRAPHIC DATA SHEET

1. Report No.

2.

3. Recipient's Accession No.

4. Title and Subtitle

Basic and Strategic Metals Industries:
Threats and Opportunities

5. Report Date
October 21, 1985

6.

7. Author(s) Committee on Science and Technology Implications for Processing Strategic Materials

8. Performing Organization Rept. No. NMAB-425

9. Performing Organization Name and Address

National Materials Advisory Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

10. Project/Task/Work Unit No.

11. Contract/Grant No.
EMW-83C-1350

12. Sponsoring Organization Name and Address

Federal Emergency Management Agency
500 C Street, S.W.
Washington, D.C. 20472

13. Type of Report & Period Covered
Final

14.

15. Supplementary Notes

16. Abstracts

Five strategic metals processing industries (iron and steel, copper, aluminum, titanium, and superalloys) are assessed in terms of their capacity and survival problems in the worldwide competitive marketplace. The availability and economic issues of four critical alloying elements (chromium, cobalt, columbium, and tantalum) are discussed. An overview of the current status of each of these industries is presented in terms of its unique characteristics and needs. Some innovative technologies and processing steps are identified as having merit for improving the competitive posture of these industries.

17. Key Words and Document Analysis. 17a. Descriptors

Aluminum industry
Basic industries
Copper industry
Critical alloying metals
Energy conservation
Import dependence
Industrial maturity
Innovative processing
Iron & steel industry
Metals processing
Retrofittable technologies
Strategic industrial base
Superalloys industry
Technological improvements
Titanium industry

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement

Distribution Unlimited

19. Security Class (This Report)
UNCLASSIFIED

20. Security Class (This Page)
UNCLASSIFIED

21. No. of Pages
164

22. Price

FORM NTIS-35 (10-70)

USCOMM-DC 40329-P71