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High-Purity Chromium Metal: Supply Issues for Gas-Turbine Superalloys

Committee on High-Purity Electrolytic Chromium Metal
National Materials Advisory Board
Commission on Engineering and Technical Systems
National Research Council

NMAB-480

National Academy Press
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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 competencies and with regard for appropriate balance.

This 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.

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The committee also thanks Elkem Metals Company for the site visit of their facility and the American Ceramics Society for hosting a meeting of the committee in Westerville, Ohio.

The committee is especially grateful for the assistance of Franklin Ringquist of the Defense Logistics Agency and John Papp of the U.S. Bureau of Mines, who obtained a great deal of information for the committee both in terms of agency reports and legislation and in presentations related to the structure, mission, and programs of their agencies. Finally, the committee acknowledges with thanks the contributions of Robert M. Ehrenreich, Senior Program Manager, and Pat Williams, Senior Secretary, to the project.

Abstract

High-purity chromium metal is a critical alloying element of superalloys for gas-turbine engines. This report discusses the uses and specifications for high-purity chromium metal for aerospace engines; the principal features of the processes for producing chromium metal; the chromium-metal marketplace, including the recent supply and demand trends and the prospects of shortages; and several potential domestic and international scenarios that could result in shortages of high-purity chromium metal and the possible means for resolving such shortages within the framework of the report's recommendations. Overall, the chromium-metal market was found to be operating effectively. There appears to be little or no need for government intervention at this time.

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Preface

Section 3306 of the Defense Authorization Act of 1995 mandated that the National Academy of Sciences prepare a report regarding the need for a domestic source of high-purity electrolytic chromium metal. High-purity chromium metal is a critical alloying element of the superalloys used in aerospace gas-turbine engines. Congress is concerned about the availability of high-purity chromium metal since Elkem Metals Company of Marietta, Ohio, is the only domestic supplier of this material and the only remaining producer of electrolytic chromium metal in the Western world.

The objectives of the study were to determine (1) the health of the domestic chromium-metal industry, (2) the capability and reliability of foreign chromium-metal suppliers, (3) projections of material needs for the future, (4) economic and security benefits that derive from having a domestic supplier base, (5) alternative methodologies (and research and development opportunities) for producing high-purity chromium metal, and (6) suggestions regarding strategies to maintain a core capability. To execute this study, the National Materials Advisory Board of the National Research Council convened an eight-member committee with expertise in metals extraction and processing, high-purity metals, aeronautical turbine engine materials, specialty materials supply, environmental considerations, and materials economics.

The committee met three times between February and May 1995. The first two meetings consisted of briefing sessions to collect the data required for the study. The first meeting was held in Washington, D.C., and consisted of briefings by representatives of the materials suppliers and engine manufacturers to obtain their views on (1) the worldwide sources of high-purity electrolytic chromium metal, (2) the capability and reliability of chromium-metal suppliers, (3) the purity requirements for chromium metal in the superalloy industry, (4) the projections of material needs for the future, and (5) the economic and security benefits that derive from having a domestic supplier base. The second meeting was held in Ohio and consisted of a site visit to the Elkem Metals chromium-metal facility in Marietta, Ohio; briefings on the health of the domestic chromium-metal industry by representatives of Elkem; and

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presentations on the health of the international chromium-metal industry and the alternative methods for producing high-purity chromium metal by representatives of London and Scandinavian Metallurgical Corporation, Shieldalloy Metallurgical Corporation, Delachaux Metals Division, and Niddam, Incorporated. The committee finalized its conclusions and recommendations at the third meeting, which was held in Washington, D.C. This report is the result of the committee deliberations.

William D. Manly, *Chair*

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High-Purity Chromium Metal:

Supply Issues for Gas-Turbine Superalloys

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Executive Summary

This report focuses on the availability of high-purity chromium metal for use in superalloys for aircraft gas-turbine engines. Aircraft gas-turbine engines are used to power military, commercial, and private airplanes and helicopters. The objectives of the study were to determine (1) the health of the domestic chromium-metal industry, (2) the capability and reliability of foreign chromium-metal suppliers, (3) projections of material needs for the future, (4) economic and security benefits that derive from having a domestic supplier base, (5) alternative methodologies (and research and development opportunities) for producing high-purity chromium metal, and (6) suggestions regarding strategies to maintain a core capability.

USE OF HIGH-PURITY CHROMIUM METAL IN SUPERALLOYS

The operating parameters of an aircraft engine are extremely demanding on materials. Metal temperatures within an engine can reach as high as 1200 °C. Materials are subject to rapid oxidation and creep, high centrifugal stresses, high pressures (up to 4 megapascals), and high torque. The alloys used in engines are referred to as superalloys because of their superior combination of low- and high-temperature mechanical properties, as well as their ability to withstand harsh environments. Many of the superalloys contain high levels of chromium metal. Chromium metal limits the coarsening rate of the intermetallic (and usually coherent) precipitates; forms Cr_{23} C_6, which strengthens grain boundaries; plays a critical role in the formation of protective scales; and improves hot-corrosion resistance. Thus a major portion of the gross engine weight consists of chromium-bearing alloys, for which there are currently no substitutes.

High-purity materials must be used in aircraft gas-turbine engines because even low concentrations of oxygen, nitrogen, sulfur, iron, and silicon can cause inclusions, areas of hot cracking, and locations of incipient melting. These flaws can cause failure during aggressive forming operations and limit strength, ductility, fatigue life, and creep-rupture resistance during engine operation. To control the purity of the superalloys, the primary metal manufacturer and alloy

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producer must control the quality of the incoming material. The original equipment manufacturers and the primary-alloy producers have determined specifications for each major additive, with the minimum and maximum values allowed for each intentional alloying element and a maximum allowed for each undesirable impurity. Unfortunately, each original equipment manufacturer and primary-alloy producer devises its own specifications, forcing chromium-metal producers to qualify their material for each customer.

HIGH-PURITY CHROMIUM-METAL PRODUCTION

The production of chromium metal begins with the mining of chromite ore. Chromite ore is then converted either into ferrochromium by smelting or into sodium dichromate by roasting and leaching. Ferrochromium is converted into chromium metal by the electrolytic method. Chromic oxide (made from sodium dichromate) is converted into chromium metal by the aluminothermic process. The metal is then further refined using variations of the vacuum-degassing method. These production methods currently appear to be mature. Although incremental improvements in the efficiencies and economics of the processes are still obtainable and should be pursued, no obvious quantum-leap increase in the purity levels appears likely at this time.

Historically, electrolytic chromium metal was used for those aerospace superalloys that required high-purity specifications, and aluminothermic chromium metal was used for those superalloys that allowed lower-purity applications. The quality of high-grade aluminothermic chromium metal has improved over the past decade, however, and aerospace engine manufacturers have certified this material for some higher-grade superalloys. While aluminothermic material of equivalent quality to the electrolytic material may now be available, changes in such critical applications as rotor-grade materials must be mutually acceptable to producer and user and will have to be subject to extensive qualification studies involving production and testing of alloys, test specimens, final cast and forged products, and possibly engines containing them. Similar constraints are associated with any process changes.

DEMAND FOR HIGH-PURITY CHROMIUM METAL

The major chromium-metal producing countries in the world are France, Russia, China, and the United Kingdom for aluminothermic chromium metal and the United States and Russia for electrolytic chromium metal. World capacity

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is estimated at 38,300 metric tons per year, with aluminothermic metal accounting for all but 5,100 metric tons of this total. World production is substantially less than capacity, averaging only somewhat over 21,000 metric tons in recent years.

World consumption of chromium metal approximates world production. The United States is the largest user, with reported consumption at roughly 4,000 metric tons per year. This is less than actual usage because not all U.S. consumers elect to report their consumption. With net chromium-metal imports into the United States fluctuating between 2,000 and 6,000 metric tons during the 1982-1992 time period and with domestic production averaging about 2,000 metric tons, actual U.S. consumption is more likely to be 6,000 metric tons per year, 2,000-2,500 metric tons of which is aerospace quality. Roughly half of this total is secondarily treated for further refinement.

Four aluminothermic chromium-metal producers and one electrolytic chromium-metal producer have closed down in Western Europe, North America, and Japan over the past six years. The dismantling of the Tosoh facility in Japan as part of an urban renewal program has left Elkem in the United States as the only significant electrolytic producer outside of Russia.

Although closures have reduced the quantity of high-purity chromium metal available internationally, shortages have not occurred for two reasons. First, worldwide demand for high-purity chromium metal has declined due to reductions in military spending, the recession in the commercial airline industry, and the pending changes in U.S. government stockpiling policy. Second, the end of the Cold War has led to an increase of chromium-metal exports from Russia and China. As noted earlier, the recent annual production over the past several years of about 21,000 metric tons requires only 55 percent of the 38,300 metric tons of available world capacity. The 3,000 metric tons of electrolytic chromium metal produced at a domestic plant could cover the U.S. aerospace requirements of 2,000-2,500 metric tons per year by itself. *Thus the international chromium-metal supply appears to be stable and sufficient to satisfy the needs of the domestic aerospace industry.*

GENERAL CONCLUSIONS AND RECOMMENDATIONS

Based on the information presented above, the committee developed three general conclusions and recommendations.

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- Current Status of the High-Purity Chromium-Metal Industry—There is currently not a crisis within the international and domestic chromium-metal industries. Sufficient high-purity chromium metal is being produced domestically and internationally to satisfy the needs of the aerospace industry. The closure of the Tosoh plant in Japan has also made the domestic electrolytic chromium-metal industry even more economically secure. *Thus the committee recommends that the government not take any special action to develop additional domestic suppliers of high-purity chromium metal.*
- The National Defense Stockpile—The National Defense Stockpile is maintained by the Defense Stockpile Center of the Defense Logistics Agency. The purpose of the stockpile has been to provide the United States with a supply of strategic and critical raw material in the event of a national emergency. These materials can only be used for national security purposes. The National Defense Stockpile currently retains 7,700 metric tons of chromium metal, 3,500-4,500 metric tons of which is of aerospace quality. *In the case of a national emergency, the 1994 stockpile inventory is sufficient to provide an approximate two-year supply of metal and sustain the aerospace industry until new aluminothermic and degassing facilities are brought into operation if (1) the metal is totally devoted to the aerospace industry, (2) the demand for chromium metal does not suddenly increase, and (3) the domestic source of metal is no longer in production.* The recent collapse of the Soviet Union has caused the U.S. Department of Defense to reassess the quantities of materials required in the stockpile and to liquidate certain items. All indications suggest that the Department of Defense will most likely find little or no continuing need for any of the materials in the National Defense Stockpile, chromium metal included. *The committee recommends that the National Defense Stockpile maintain and continually upgrade to industry standards a sufficient quantity of high-purity chromium metal to meet the industry's needs in the event of an emergency.*
- Domestic capability—International production capacity of high-purity chromium metal is currently sufficient to supply the needs of the domestic aerospace industry in the event that the domestic chromium-metal industry should fail. *Thus the commit*

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tee concludes that no special action to subsidize the domestic supplier industry of high-purity chromium metal would be required by the government should the industry falter economically. If the foreign supplier market should also collapse, the 1994 stockpile appears sufficient to supply the domestic aerospace industry until new aluminothermic and degassing facilities for high-purity chromium metal are developed.

- High-Purity Chromium-Metal Qualification—Qualification of high-purity chromium metal has historically been linked to the process used to produce the metal. Improvements in the quality of vacuum-degassed aluminothermic chromium metal over the past 10 years have led to its increasing suitability and certification for high-purity aerospace applications. *The committee recommends that chromium-metal specifications be disconnected from production methodology so that any material that meets the required end-product specifications is permissible.*

REPORT ORGANIZATION

This report is divided into six chapters. Chapter 1 presents an overview of the chromium-metal marketplace, including the nature of the market, the recent and pending supply and demand trends, and the prospects of shortages. Chapter 2 reviews the uses and specifications of high-purity chromium metal. Chapter 3 and Chapter 4 discuss the strengths and weaknesses of the main techniques for producing chromium metal. Chapter 5 presents the criteria for judging the reliability of a supplier company and the assessment of the four major international chromium-metal producers. Chapter 6 presents a number of potential economic scenarios that could result in shortages of high-purity chromium metal and the possible methods for resolving such scenarios.

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1

The Marketplace for Chromium Metal

The production of chromium metal begins with the mining of chromite ore.[1] Chromite ore is then converted into either ferrochromium by smelting or sodium dichromate by roasting and leaching. Ferrochromium is converted into chromium metal by the electrolytic method described in Chapter 3.[2] Chromic oxide (made from sodium dichromate) is converted into chromium metal by the aluminothermic process described in Chapter 4.

Chromium metal is used to create a variety of alloys. Large quantities of chromium metal are used in stainless steel, some titanium alloys, specialty iron-base alloys, weld rod, coatings or platings, and aluminum alloys (as a strengthening agent). Most of these uses are not addressed in this report because they are not critical for national defense emergencies and because the chromium metal can, in some instances, be substituted with other materials or lower grades of chromium metal. Ultra-pure chromium metal is also used in the electronics industry, but this represents a relatively small quantity of material that is made in small specialty plants.

The vacuum-melted superalloys, which are largely used in the domestic aerospace industry for the construction of aircraft engines described in Chapter 2, annually consume about 2,500 metric tons of the higher-grade, or *high-purity,* chromium metal, which is the subject of this report. Roughly half of this total is secondarily treated to achieve even higher purity levels.

This chapter examines the marketplace for chromium metal. Specifically, it describes the nature of the market, recent and possible future trends in supply and demand, and the prospects for shortages.

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[1] The sources of chromite ore are beyond the scope of this study and not discussed in this report. This information is available in Information Circular 9337 of the Bureau of Mines (1993).

[2] Ferrochromium is also used in the production of other materials (e.g., steel and stainless steel) for other industries (e.g., automotive manufacturers). The additional uses for ferrochromium are not considered in this report.

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NATURE OF THE MARKET

Chromium metal is produced by a handful of firms around the world and consumed by a large number of alloy manufacturers. This section examines the heterogeneous nature of the chromium-metal market, the current producers and consumers, and the importance of international trade.

Heterogeneous Nature of the Market

Chromium metal is produced to meet stringent specifications, as described in Chapter 2. Historically, chromium metal produced by the electrolytic method was used for those aerospace superalloys with higher purity specifications, and chromium metal produced by the aluminothermic method for those superalloys with lower purity applications. The quality of the high-grade aluminothermic chromium metal has improved over the past decade, especially with the introduction of the double-degassing treatment described in Chapter 4. Pratt & Whitney certified this material in 1987 for some higher-grade superalloys (Chapter 4; Papp, in press). As a result, the prevalent perception that only electrolytically produced metal is appropriate for high-purity applications is no longer valid. Thus the high-purity chromium-metal market encompasses the aluminothermic as well as the electrolytic producers.

Producers

As Figure 1-1 illustrates, the major chromium-metal producing countries are France, Russia, China, and the United Kingdom for aluminothermically produced chromium metal and the United States and Russia for the electrolytically produced chromium metal. World capacity is estimated at 38,300 metric tons per year with aluminothermic accounting for all but 5,100 metric tons of this total. The U.S. Bureau of Mines (Papp, in press) estimates that world production is substantially less than its capacity, averaging only somewhat over 21,000 metric tons per year in recent years.

Elkem Metals Company, located in Marietta, Ohio, is the sole producer of electrolytically manufactured chromium metal in the United States for aerospace applications and produces approximately 2,000 metric tons of high-purity chromium metal each year, in addition to lower-purity chromium metal and other high-purity materials. Despite the termination of government contracts to convert ferrochromium into high-purity chromium metal for the strategic stockpile, Elkem reports growing demand and a high level of capacity utilization for this material. The company is planning to increase the proportion of its total high-purity chromium-metal production as demand increases. Thus the overall health of the company—and therefore the health of the U.S. industry—seems sound at the present time.

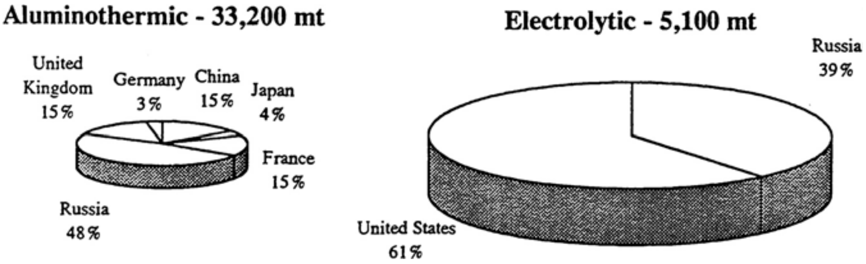

FIGURE 1-1 Worldwide production percentages for the major aluminothermic and electrolytic chromium-metal producers.

Tosoh in Yamagata, Japan, was the only other Western producer of chromium metal by the electrolytic method and had an annual capacity of about 4,000 metric tons. The Tosoh plant was recently dismantled as part of an urban renewal program, however, and no longer produces chromium metal.

Russia possesses an additional 18,000 metric tons of capacity at two separate facilities, of which some 2,000 metric tons is electrolytically produced and suitable for aerospace applications. The London and Scandinavian Metallurgical Corporation, Limited (LSM), produces chromium metal by the aluminothermic method in Rotherham, United Kingdom, some of which is suitable for aerospace applications. Delachaux Metals Division produces double-degassed, aluminothermically manufactured chromium metal in Pau, France, all of which could be made suitable for aerospace applications. These two firms are reported to possess 5,000 metric tons of capacity each. Gesellschaft für Elektrometallurgie (GfE) produces modest quantities of special grades of aluminothermically manufactured chromium metal at its Nürnberg plant, some of which are used in titanium aerospace alloys. GfE currently has a large unused capacity. Little is known about the production capacity in China.

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LSM and GfE are both subsidiaries of the U.S. chromium-metal company Metallurg, Incorporated. Another subsidiary of Metallurg, Incorporated, is Shieldalloy Metallurgical Corporation, which produced aluminothermic chromium metal and chromium oxide in New Jersey until 1991, when environmental consideration led to the closure of those activities.

Consumers

World consumption of all chromium metal approximates world production, which, as noted earlier, the U.S. Bureau of Mines estimates at somewhat over 21,000 metric tons per year in recent years. The United States is the largest user, with reported consumption at approximately 4,000 metric tons per year. This is less than actual consumption because not all U.S. consumers elect to report their consumption. With net chromium-metal imports into the United States fluctuating between 2,000 and 6,000 metric tons during the 1982-1992 time period and with domestic production averaging about 2,000 metric tons, actual U.S. consumption is more likely to be approximately 6,000 metric tons per year, or about 30 percent of total world consumption. Other significant consuming countries include Japan, France, Germany, the United Kingdom, Russia, and China.

As noted earlier, chromium metal is used to produce a large number of different nickel, cobalt, aluminum, titanium, and copper alloys. Chegwidden (1993) cites a 1990 study by Bob Bebbington of LSM, who estimates that 44 percent of all chromium metal is used for superalloys, 16 percent for aluminum alloys, 15 percent for welding and hard-facing alloys, 9 percent for corrosion-resistant alloys, and 16 percent for other uses. In the United States, superalloys are an even more important source of demand. According to Chegwidden (1993), 62 percent of the chromium metal consumed in this country during 1991 went into superalloys.

As stated above, superalloys require high-purity chromium metal. Figure 1-2 shows the range of products and the major producing companies that comprise this end of the quality spectrum. The castings, forgings, rings, and mill products made by the consumers of high-purity chromium metal (e.g., Howmet, Special Metals, Carpenter Technology, Wyman Gordon, and others) are then used by companies such as GE, Pratt & Whitney, Rolls Royce/Allison, and SNECMA to produce jet engines.

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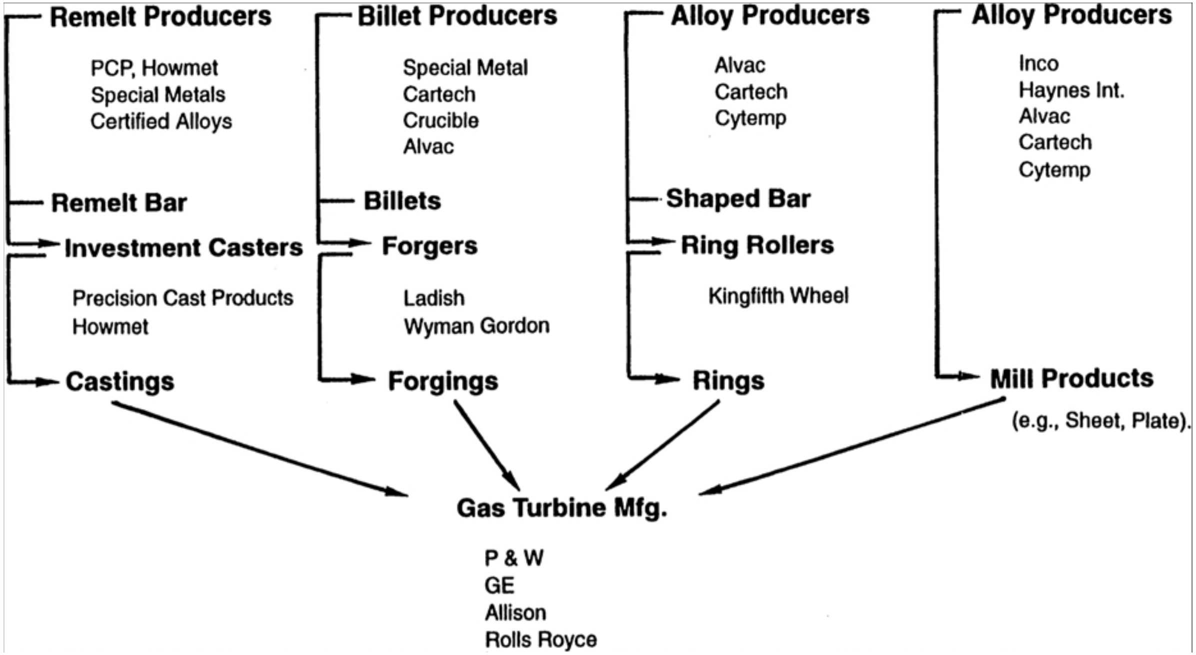

FIGURE 1-2 Schematic showing the range of products and the major producing companies that use high-purity chromium.

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International Trade

According to the U.S. Bureau of Mines (Papp, in press), 8,000 of the estimated 21,000 metric tons of the world's production of all chromium metal enters international trade, or about 40 percent of the total supply. The United States is by far the biggest importer. As noted earlier, net imports for the United States have varied in recent years from 2,000 to 6,000 metric tons. Germany places a distant second. The major exporting countries are currently Japan, the United Kingdom, France, China, and Russia, more or less in that order.

Two implications flow from these figures. First, as the Bureau of Mines has noted: "The United States is unique as the largest chromium-metal consuming country and the only major world consumer that clearly consumes in excess of domestic production" (Papp, in press). Second, the large amount of production entering international trade means that the relevant market for chromium metal is global in scope.

RECENT AND PENDING SUPPLY TRENDS

Both the supply and the demand for chromium metal are changing dramatically. The two major developments on the supply side are the closure of a number of Western firms and the integration of Russian and Chinese producers into the international marketplace.

Closures

Four chromium-metal producers have closed in Western Europe and North America over the past six years: Continental Alloys, S.A., in Luxembourg in 1989; Metal Alloys Limited in Britain in 1990; Shieldalloy Metallurgical Corporation in the United States also in 1990; and Murex Limited in Britain in 1992. Nippon Denko in Japan is also rumored to have reduced or ceased its production and has begun purchasing metal from China (Chegwidden 1993).

As previously stated, Tosoh, the other Japanese producer, has ceased production over the past year. At the time of its closure, this company accounted for about 20 percent of the world chromium-metal capacity and about 40 percent of world electrolytic chromium-metal capacity. Tosoh's shutdown leaves Elkem in the United States as the only electrolytic producer outside of Russia. Tosoh possessed about 1,500 metric tons of high-purity chromium metal in 1995, which it was negotiating to sell.

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Russia and China

The end of the Cold War has led to an increase of chromium-metal exports from Russia and China to the West. Russia began shipping chromium metal to the West in 1988 and has accounted for some 10 percent of the chromium metal entering international trade in recent years (Papp, in press). As noted above, Russia possesses an estimated 18,000 metric tons of capacity, which is the world's largest national production capacity. Of this capacity, 2,000 metric tons is electrolytic and aerospace quality.

Although China has supplied metal to the West for some time, it has sharply increased its shipments in recent years. It accounted for over 10 percent of total world exports in 1991 and for over 20 percent in 1992 (Papp, in press). All of the Chinese material is aluminothermic chromium metal, but none of it is of aerospace quality.

RECENT AND PENDING DEMAND TRENDS

Three important developments are reducing the demand for chromium metal: the decline in military spending, the recession in the commercial airline industry, and the ongoing changes in U.S. government stockpiling policy.

Military Spending

In addition to allowing Russian producers to participate in the international chromium-metal marketplace for the first time, the end of the Cold War has led to a reduction in military spending in the United States and the former Soviet Union. This, in turn, has resulted in a drop in both the new orders for military aircraft and the demand for high-purity chromium metal.

The Commercial Airline Industry

The commercial airline industry has experienced poor growth in passenger traffic and depressed profits throughout much of the world for the past several years. As a result, expansion plans have been curtailed, and new aircraft orders have been cut back or cancelled. This situation has caused a slump in the production of new aircraft engines and a further decline in the worldwide demand for chromium metal.

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Government Stockpiles

A review in the mid-1980s of the U.S. strategic stockpile found that none of the available chromium metal met the most stringent purity specifications. To rectify this situation, the government began a program in 1989 to convert ferrochromium to electrolytic chromium metal. This conversion was undertaken by Elkem, the only U.S. producer of electrolytic chromium metal, and required about 40 percent of the company's capacity over the past five years. This program is scheduled to be completed by October 1995.

PROSPECTS FOR SHORTAGES

On balance, the recent changes occurring in the supply and demand for chromium metal have resulted in excess capacity and depressed prices. As noted earlier, the recent annual production over the past several years of about 21,000 metric tons requires only 55 percent of the 38,300 metric tons of available world capacity. Yet some of these changes (e.g., the continuing closure of capacity and the growing reliance on Russian and Chinese producers) may be sowing the seeds for shortages 5 or 10 years in the future. This section examines the prospects for shortages but not the appropriate policy responses. The latter are considered in Chapter 6 of this report.

Nature of Shortages

There are different concepts of a shortage, although all imply that there is not enough of a commodity. One common and rather narrow definition requires that the market demand at the prevailing price exceeds the available supply. Rent controls, for example, often give rise to a shortage of apartments in the sense that the available supply at the rent the government allows does not satisfy the market demand. This type of shortage may be referred to as a "price-control-induced shortage." Such a shortage could also arise as a result of price-fixing by a monopoly that wishes to keep supplying its loyal customers at the previous price as it engages in expansion of capacity to satisfy a rise in demand.

In markets where the government does not impose price controls and where there is enough competition to prevent firms from maintaining stable producer prices, price-control-induced shortages will not arise. Instead, prices will rise until the available supply is sufficient to satisfy the market demand. In such situations, however, a very large increase in price may be required once

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output approaches the limit imposed by existing capacity. This outcome is likely to be the case for many metals in the short run once production approaches capacity for two reasons. First, metal demand does not change much as price changes—that is, demand is price-inelastic—both because the substitution of alternative materials takes time and because metal prices typically account for only a small percentage of the total cost of the final product. Second, the construction of new metal capacity often requires several years and is not possible in the short run.

The steep slope of the short-run demand curve DD in Figure 1-3 reflects the unresponsiveness of demand to changes in prices in the short run. The steep slope of the short-run supply curve SS as it approaches the initial capacity constraint reflects the impossibility of expanding capacity in the short run. The figure illustrates that an increase in demand (a shift to the right of the demand curve from DD to D'D') will cause a dramatic rise in the market-clearing price, from point A (where DD and SS intersect) to point B (where D'D' and SS intersect). Once the rise in price brings about an increase in capacity, a new short-run supply curve SS' comes into effect (which is also the long-run supply curve relative to the previous capacity). The new equilibrium will be at point C where D'D' and SS' intersect. Assuming the supply curve SS' to be flat at and to the left of C (reflecting constant long-run unit costs), prior to the addition of the new capacity one might say that there is a shortage equal to the distance AC, in the sense that it will be made up for in the long run when the new capacity is installed. This concept of shortage may be referred to as "short-run capacity-constrained shortage." A similar dramatic rise in price could be caused by a decrease in supply (a shift to the left of the supply curve from SS' to SS) caused, say, by a producer ceasing its operations and closing its plant for environmental or other reasons, resulting in a movement from point C (where DD and SS' intersect) to point B (where DD and SS intersect).

Thus a broader definition of shortages, and the one that is used here, includes not only price-control-induced shortages but also short-run capacity-constrained shortages that are typically characterized by the market price rising rapidly and sufficiently to cause serious dislocations. These dislocations can arise for three reasons: a surge in world demand, a contraction in world production (and capacity), or an interruption in international trade. Each possibility is considered below for chromium metal.

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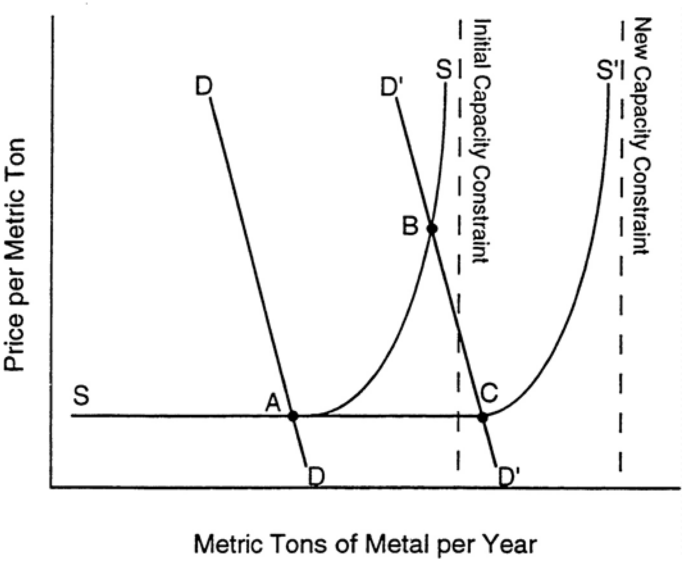

FIGURE 1-3 Illustrative short-run supply curves (SS and SS') under two capacity constraints and two short-run demand curves (DD and D'D').

Surge in World Demand

The demand for high-purity chromium metal has contracted over the past several years with the decline in military spending and the slowing of growth in the commercial airline industry. A reversal of either of these trends could increase the world demand for high-purity chromium metal, and a reversal of both certainly would increase it. Excess capacity exists at the present time, and the committee estimates that demand would have to increase by about a third from 1994 levels before new capacity would be needed.

Contraction in Production and Capacity

The contraction in production and capacity over the past several years has resulted primarily from a response to declining demand and depressed prices. (While the Tosoh plant in Japan was forced to close on account of an urban renewal program, its initial plans to respond to this closure by opening up a new plant in South Africa were abandoned because of the state of the market.) Such contractions are normally considered appropriate responses to changing market conditions and not a cause for alarm. As more and more of the world's capacity

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is concentrated in a few plants, however, the possibility increases that an industrial accident, environmental regulation, strike, political turmoil, or some other event might produce an unexpected contraction in supply that causes the market price to jump. The increase would not last long—only until the problem was rectified or alternative sources of supply became available—but could create short-run problems for chromium-metal consumers.

Interruptions in Trade

The chromium-metal market, as noted earlier, is international in scope with the United Kingdom, France, China, and Russia supplying U.S. and other consumers. Consequently, interruptions in trade could produce rather severe local shortages in the United States and other importing countries. The likelihood of such interruptions is probably slight. Governments have restricted trade for political reasons or to keep domestic prices from rising during a boom in world demand. For instance, the United States has prohibited trade with Cuba since the 1960s for political reasons. Also, trade friction with foreign countries could result in disruptions. For instance, trade friction with Russia over metals has resulted in several countries placing penalty duties on Russian materials, and the United States has repeatedly threatened China with trade sanctions over the past decade.

The preceding discussion suggests that shortages of chromium metal in the future are possible, if one defines shortages broadly to include short-run capacity-constrained shortages, resulting in situations where the market price rises significantly and causing disruption and other problems in the process. Little, however, has been said about price-control-induced shortages. Such shortages could arise with any of the situations described above, but they require government-imposed price controls or firm-imposed price ceilings to keep prices from rising to the market equilibrium level. Such intervention is most likely during wartime, although it has occurred in the United States and elsewhere on other occasions as well.

While chromium-metal shortages may occur in the future, appropriate public policy for dealing with this possibility should take into account several considerations. First, the figures for chromium-metal capacity assume some facilities operate at two shifts a day for five days a week. If necessary, production could actually exceed capacity by 50 percent by operating three shifts a day for five days a week with maintenance and service being conducted during weekends (FitzGibbon, 1995).

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Second, while it takes several years to build new electrolytic chromium-metal capacity, it is technically feasible to increase or redirect aluminothermic capacity within a matter of months. Although there are currently no aluminothermic chromium-metal production plants extant in the United States, aluminothermic production plants do exist that produce other high-purity metals (e.g., Bear Metallurgical produces ferrovanadium; Reading Alloys produces columbium and vanadium; and Cabot Corporation produces columbium). These plants could be converted to produce chromium metal, if required and so long as demand for these other materials does not also dramatically increase. Thus the short-run capacity constraint and short-run supply curve shown in Figure 1-3 pertain to a much shorter time interval than for most other metals. This means that any potential future chromium-metal shortage will not cause extended difficulties for consumers and can be mitigated by consumer, producer, and government inventories until added aluminothermic capacity becomes available, so long as the shortage is not accompanied by a sudden, sharp increase in demand. An exception to this assessment, however, is that for the highest-grade chromium metal needed for high-pressure turbine blades and vanes in aircraft gas-turbine engines (see Chapter 2), the needed secondary treatment of the aluminothermic material by the double-degassing method requires construction of vacuum-degassing furnaces, which, the committee estimates, would require about two years (see Chapter 4).

Finally, it is important to stress that shortages, should they arise, would be ultimately self-correcting and persist only over the short run (a period that the committee estimates to be about two years). This is because the surge in market price or the existence of short-run capacity-constrained shortages encourages producers to develop new capacity. It is also possible that such shortages will encourage chromium-metal consumers to employ alternative materials and to develop new technologies that reduce the need for chromium metal (i.e., that the long-run demand curve is more elastic than the short-run one depicted in Figure 1-3). While these efforts may take time, they will eventually reduce demand and increase supply, thus causing the market price to fall and short-run capacity-constrained shortages to disappear. The short-run nature of the shortages suggests that stockpiling can be an effective antidote, a possibility that is considered more fully in Chapter 6.

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2

Specifications for High-Purity Chromium Metal

This chapter focuses on the need for high-purity chromium metal for aircraft gas-turbine engines. Aircraft gas-turbine engines are used to power military, commercial, and private airplanes and helicopters. Additional applications include ship propulsion, natural gas transmission, and electrical power generation. Aircraft engines are well known for their rapid evolution while maintaining a high degree of reliability. This reliability was achieved through careful design, attention to service problems, and detailed specification of alloy chemistry and metal processing for optimal microstructure and mechanical properties. This chapter describes the operation of an aircraft engine, the chromium-metal-containing alloys used in engines, the reasons for the need for high-purity chromium metal, and the future demand for high-purity chromium metal based on estimates from the aerospace industry.

AIRCRAFT ENGINE OPERATION

The operation of an aircraft gas-turbine engine consists of compressing air, mixing it with fuel, combusting the mixture, and extracting the power from the rapidly expanding gases. To accomplish this task, a gas turbine consists of a fan, low-pressure compressor, high-pressure compressor, combustor, high-pressure turbine, and low-pressure turbine (Figure 2-1). The compressors and turbines consist of several stages, each of which is composed of alternating stators and rotating blades attached to disks (or drum rotors). The disks are attached to one of two or three concentric shafts, which are supported on bearing structures. Additional components of a gas-turbine engine are thrust reversers, afterburners, fan shrouds, seals, cases (including containment structures), pumps, hydraulic tubing, sensors, and controls.

The operating environment of an engine is extremely demanding on the materials used. Metal temperatures within an engine can reach as high as 1200 ° C. Materials at these temperatures are subject to rapid oxidation and creep. Parts are also subject to high centrifugal stresses, high pressures (up to 4 megapascals), and high torque. Furthermore, parts are subject to fatigue due

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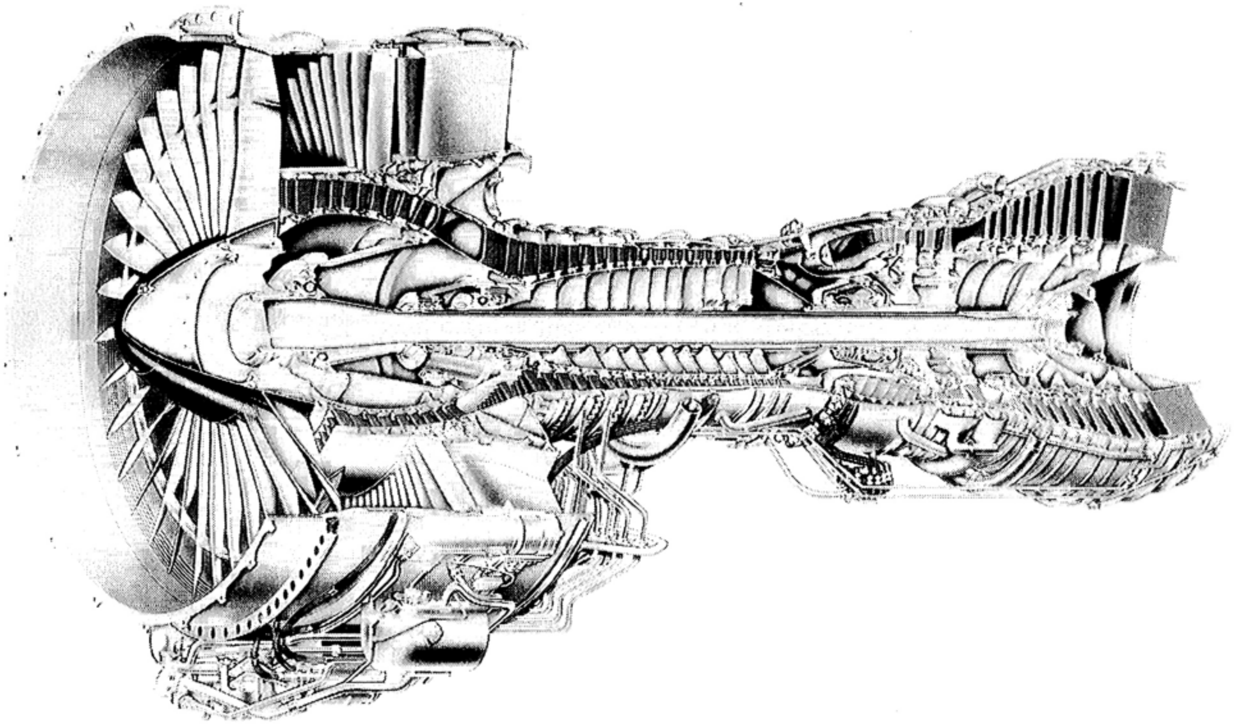

FIGURE 2-1 Schematic of a typical aerospace gas-turbine engine, Reprinted courtesy of Pratt & Whitney (PW2000 turbofan engine).

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to localized stresses at the attachment of blades to disks and the cyclic stresses associated with repeated takeoffs and landings. A general description of parts, exposure temperatures, specified materials, and limiting properties of an aircraft engine is given in Table 2-1.

AIRCRAFT ENGINE MATERIALS

The alloys used in engines are referred to as superalloys because of their superior combination of low- and high-temperature mechanical properties and environmental stability. An aircraft engine typically consists of titanium-alloy fans, drum rotors, and compressors, nickel-base-superalloy turbines and burners, and specialty-steel shafts and bearings. In some cases, specialty steels are also used for the final compressor stages, cobalt-base superalloys are used for the first-stage turbine vanes, and cobalt- or iron-base alloys are sometimes used for the last few stages in the low-pressure turbine.

Many of the iron, cobalt, and nickel alloys contain high levels of chromium metal (Table 2-2). The superalloys obtain their strength from carbides or intermetallic precipitates based on nickel and aluminum (or titanium). Some solid-solution strengthening is obtained from refractory metals, such as molybdenum, tungsten, niobium, tantalum, or rhenium. Chromium metal can play a role in limiting the coarsening rate of the intermetallic (and usually the

TABLE 2-1 Parts, Maximum Exposure Temperatures, Specified Materials, and Limiting Properties of an Aircraft Engine

Part	Temp. (°C)	Material	Limiting Property
Fan/Drum Rotor	50	Ti or Al	Foreign object damage, low-cycle fatigue
Compressor Blade	600	Ti or Ni	High-frequency fatigue
Combustor	1100	Ni or Co	Melting, oxidation
Outer Air Seal	1250	ZrO_2	Melting, erosion
Turbine Vane	1200	Co or Ni	Melting, oxidation
Turbine Blade	1100	Ni	Creep, thermal mechanical fatigue, low-cycle fatigue, high-frequency fatigue, oxidation, hot corrosion
Turbine Disc	600	Ni	Low-cycle fatigue
Shaft	250	Fe	Stiffness
Bearings	250	Fe	Wear resistance
Case	600	Ni	Toughness, thermal mechanical fatigue

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coherent) precipitates. Chromium also form, $Cr_{23}C_6$, which strengthens grain boundaries. *Thus a major portion of the gross engine weight consists of alloys containing chromium.*

The required oxidation resistance of the cobalt- and nickel-base alloys is also obtained through either the development of alumina or chromia scales on the alloy or the application of a coating on the alloy (NRC, 1995). *Chromium metal plays a critical role in the formation of these protective scales.* Even if alumina is the final scale, chromium metal minimizes transient oxidation (NiO or spinels) and promotes the early formation of alumina. In addition, chromium metal provides hot-corrosion resistance to attack by such impurities as salts in the air and sulfates in the fuel. There are possible substitutes for many elements (e.g., tantalum for molybdenum, tungsten for rhenium) but not for chromium metal.

TABLE 2-2 Some Major Gas-Turbine Alloys with Significant Chromium-Metal Content

Alloy	Weight percent chromium
WI-52®	21.0
IN-100®	9.5
IN-718®	19.0
Hastelloy-X®	22.0
Mar-M 200®	9.0
Mar-M 247®	8.4
Udimet-700®	15.0
Stainless Steels	17-25
Waspaloy®	20.0
B-1900®	8.0

NEED FOR PURITY

There are three reasons why high purity levels are needed for the chromium metal used in aircraft gas-turbine engines. First, these alloys are normally vacuum-melted, and the final form is either a cast or wrought product. *The success of a forging (or other aggressive forming) operation requires the avoidance of hot cracking or incipient melting, which is dependent on the quality of the starting materials, especially the iron, oxygen, and silicon contents.* The components with the most demanding combinations of temperature and stress are the single-crystal superalloys, which are used for high-pressure turbine blades and vanes. These materials are dependent on very low impurity levels in order to avoid incipient melting, fatigue crack initiation at oxides, and oxide spallation in the cyclic temperature environment of engine operation.

Second, inclusions are one of the limiting microstructural features for ductility, fatigue life, or creep-rupture. There are high- and low-density inclusions (based on radiographic appearance), but a particularly insidious type is dross (i.e., large stringers of oxide; see Figure 2-2). These stringers can be

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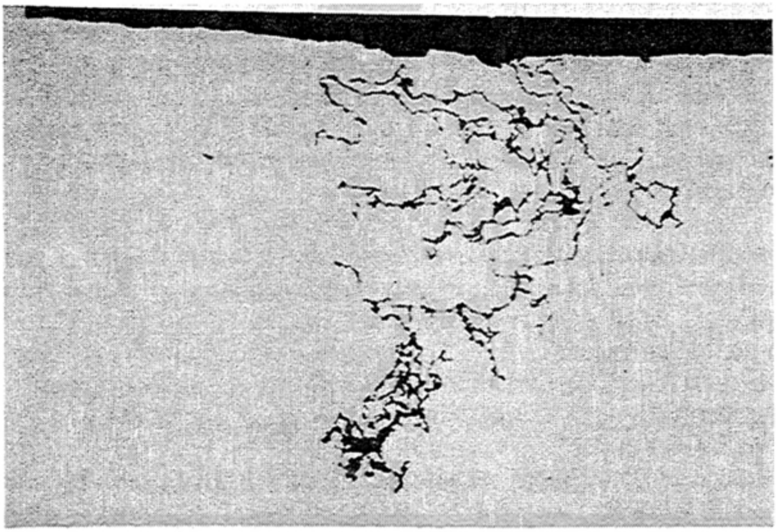
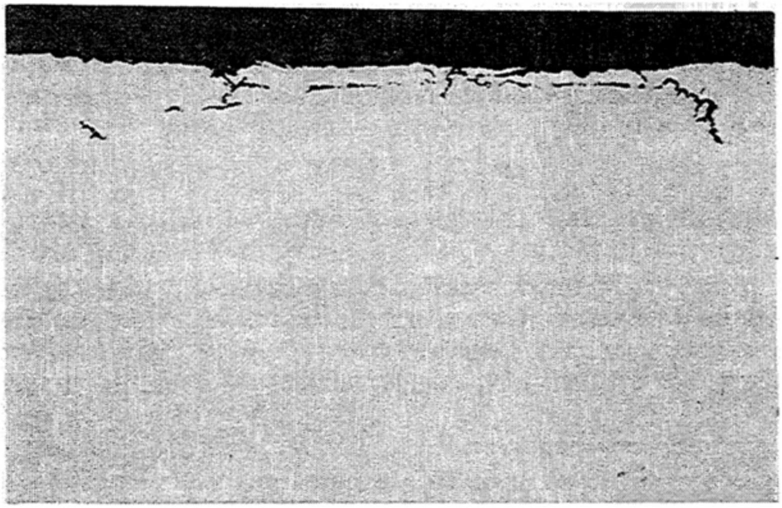


Deep Lacy Dross



Shallow Surface Dross

FIGURE 2-2 Photomicrographs depicting deep lacy and shallow surface dross. Reprinted courtesy of Pratt & Whitney.

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as large as 0.5 mm, have aspect ratios much larger than one, and act as crack initiators. These inclusions are formed by a combination of reactive elements (e.g., aluminum, zirconium, and hafnium) with impurities (e.g., oxygen, nitrogen, and sulfur). Many of these parts are found and rejected during inspection, but this process is imperfect, especially in thicker sections or complex shapes. *Impure chromium metal can be a major source of such particles and stringers.*

Third, other impurities (e.g., lead, selenium, bismuth, and silver) have caused major component failures and recalls due to a loss of strength or ductility at grain boundaries. An example of intergranular cracking due to lead is shown in Figure 2-3. Many of these effects occur at extremely low levels of impurity. *Based on the aerospace industry's experience with such problems, chemical compositions have been specified for the metals to be used in superalloys to prevent recurrence of this failure type.* Some examples of such compositions are given in Table 2-3.

To control the purity at the alloy level and attain the compositions specified in Table 2-3, the primary metal manufacturer and the alloy producer must control the quality of the incoming material (as well as crucibles and furnace atmosphere). The original equipment manufacturers and the primary-alloy producers have determined stringent specifications for each major additive, with the minimum and maximum values allowed for each intentional alloying element and a maximum for each (known) undesirable impurity. An example of a specification for chromium metal is given in Table 2-4. Of particular concern are the levels of oxygen, nitrogen, sulfur, iron, and silicon.

FUTURE DEMAND FOR HIGH-PURITY CHROMIUM METAL

Estimating the future demand for chromium metal in aircraft engines is difficult for three reasons. First, several thousand aircraft engines are made or refurbished each year, most weighing between 1.8 and 6.4 metric tons. Second, the alloys used consistently contain approximately 60 percent revert.[1] Third,

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[1] Revert is recycled scrap that originates from many sources. Melters recycle gates, risers, turnings, and crop ends. Aircraft engine builders and their subcontractors generate significant quantities of scrap, such as forge ends, turnings, and parts. This material is then processed through a network of specialized scrap dealers. Very few parts are retired and then offered for conversion, however. Airlines frequently refurbish parts or save them for possible rejuvenation. Aircraft engine builders do not recycle used parts because the material tends to be contaminated with impurities (e.g., oxides, salts, or sand) and traceability would be very complicated.

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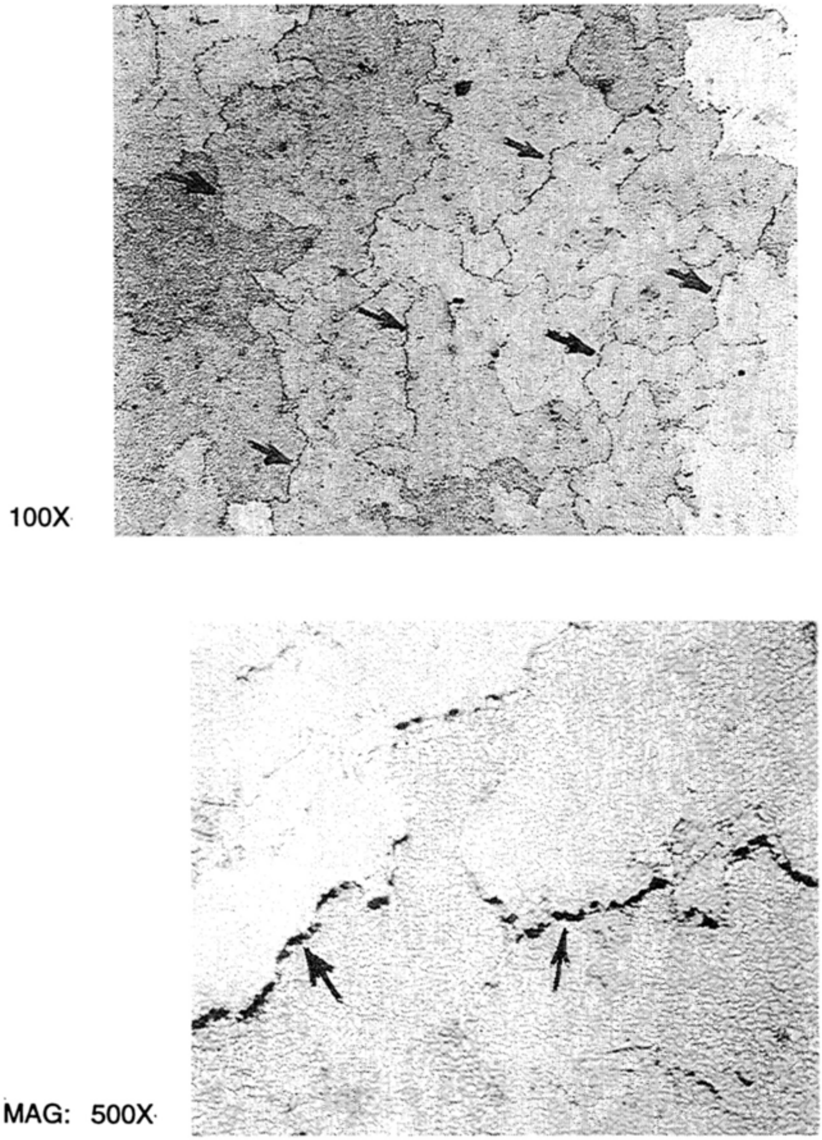

FIGURE 2-3 Photomicrographs of jet engine turbine blade showing intergranular stress-rupture cracks. Blade contained 8ppm lead and bismuth. Reprinted courtesy of Pratt & Whitney.

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TABLE 2-3 Nominal Compositions of Nickel-Base Heat-Resistant Casting Alloys (percent by weight)

Alloy	C	Ni	Cr	Co	Mo	Fe	Al	B	Ti	W	Zr	Others
B-1900®	.1	64	8	10	6	—	6	.015	1	—	.10	4Ta[a]
Hastelloy X®	.1	50	21	1	9	18	—	—	—	1	—	—
IN-100®	.18	60.5	10	15	3	—	5.5	.01	5	—	.06	1V
IN-736X®	.17	61.5	16	8.5	.75	—	3.4	.01	3.4	2.6	.1	1.75Ta; .9Nb
IN-792®	.2	80	13	9	2.0	—	3.2	.02	4.2	4	.1	4Ta
Inconel 713C®	.12	74	12.5	—	4.2	—	6	.012	.8	—	.1	2Nb
Inconel 713LC®	.05	75	12	—	4.5	—	6	.01	.6	—	.1	2Nb
Inconel 718®	.04	53	19	—	3	18	.5	—	.9	—	—	.1Cu; 5Nb
Inconel X-750®	.04	73	15	—	—	7	.7	—	2.5	—	—	.25Cu; .9Nb
M-252®	.15	56	20	10	10	—	1	.005	2.6	—	—	—
MAR-M 200®	.15	59	9	10	—	1	5	.015	2	12.5	.05	1Nb[b]
MAR-M 246®	.15	60	9	10	2.5	—	5.5	.015	1.5	10	.05	1.6Ta
MAR-M 247®	.15	59	8.25	10	.7	.5	5.5	.015	1	10	.05	1.5Hf; 3Ta
NX 188(DS)®	.04	74	—	—	18	—	8	—	—	—	—	—
René 77®	.07	58	15	15	4.2	—	4.3	.015	3.3	—	.04	—
René 80®	.17	60	14	9.5	4	—	3	.015	5	4	.03	—
René 100®	.18	61	9.5	15	3	—	5.5	.015	4.2	—	.06	1V
Udimet 500®	.1	53	18	17	4	2	3	—	3	—	—	—
Udimet 700®	.1	53.5	15	18.5	5.25	—	4.25	.03	3.5	—	—	—
Udimet®	.13	55	18	15	3	—	2.5	—	5	1.5	.08	—
Waspaloy®	.07	57.5	19.5	13.5	4.2	1	1.2	.005	3	—	.09	—
WAZ-20(DS)®	.20	72	—	—	—	—	6.5	—	—	20	1.5	—

NOTES: Nominal weight percent of alloying additions. Actual specifications would contain ranges (e.g., 9-11 percent chromium). Trace or *tramp* elements may be specified with tight upper limits (e.g., < 3 parts per million lead).

[a] B-1900 + Hf also contains 1.5% Hf

[b] MAR-M200 + Hf also contains 1.5% Hf

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there are a multitude of yield considerations, including the losses associated with primary melting, secondary melting operations, casting gating, oversized forging shapes, and yield losses following inspection of parts.

TABLE 2-4 Example of Typical Specification for Chromium Metal

Element	Maximum Percent
Chromium[a]	
Carbon	0.05
Manganese	0.03
Silicon	0.10
Phosphorus	0.005
Sulfur	0.010
Copper	0.01
Iron	0.35
Columbium	0.05
Tungsten	0.05
Zirconium	0.005
Boron	0.003
Hafnium	0.005
Lead	10.0[b]
Bismuth	0.5[b]
Selenium	1.0[b]
Tellurium	0.5[b]
Thallium	1.0[b]
Oxygen	0.05
Nitrogen	0.01

[a] Chromium is specified at a *minimum* of 99.4 percent by weight.

[b] Concentrations are in parts per million.

All other concentrations are by weight.

Source: Pratt & Whitney.

The aircraft engine business has been in modest decline for several years; however, this trend has ceased and is expected to reverse over the next few years. In addition, the need for heat-resisting alloys for large land-based gas turbines may increase substantially over the next decade. It appears that the hot section of these new machines will also require vacuum-grade superalloys.

The type of chromium metal used for aircraft gas-turbine engines was traditionally electrolytically produced. More recently, double-degassed, aluminothermically produced chromium metal has made significant inroads into aircraft engine applications. However, the precedent that electrolytic chromium metal must be used continues to be followed for some critical uses (e.g., rotor-grade materials), which account for approximately 10-15 percent (roughly 125 metric tons) of the aerospace-grade chromium metal domestically consumed. While aluminothermic material of equivalent quality to the electrolytic material may now be available, changes in such critical applications must be mutually acceptable to producer and user and would require extensive qualification studies involving production and testing of alloys, test specimens, final cast and forged products, and possibly engines containing them. Similar constraints are associated with any process changes.

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3

Electrolytic Chromium-Metal Production

The previous chapter focused on the use of high-purity chromium metal for high-performance alloys in jet-engine applications. Technical emphasis in this chapter focuses on the two main variations of the electrolytic process that have traditionally produced high-purity chromium metal: the trivalent chrome-alum electrolyte method and the chromic-acid electrolyte method. Also discussed are the final vacuum-degassing process that is used to refine electrolytic chromium metal further for aerospace applications and the environmental and occupational health considerations of these methods. Other potential methods for producing high-purity chromium metal are detailed in Chapter 4. An overview of possible treatment schemes available to produce metallic chromium metal is presented in Figure 3-1.

TRIVALENT CHROME-ALUM BATH ELECTROLYTE METHOD

The main electrolytic method used for the production of large tonnages of chromium metal is the chromium (III) or trivalent chrome-alum bath electrolyte method. This process was developed by the U.S. Bureau of Mines in 1950, following a long-term study on chromium-metal electrowinning.

Solutions suitable for producing chromium metal can be derived from ore by oxidative roasting in alkali or dissolution of chromite in sulfuric acid. However, the preferred starting material is milled high-carbon ferrochrome that is leached in recycled anolyte and make-up H_2SO_4. A simplified flow sheet showing the essential steps in the process is given in Figure 3-2. The 20-mesh ferrochrome (67 percent chromium) is leached at about 90 °C in roughly 3-metric-ton batches without agitation. Approximately 95 percent of the solids dissolve.

The hot-acid leach solution is clarified, and the undissolved solids, such as silica, are separated by filtration. The filtrate is cooled using mother liquor from the ferrous ammonium sulfate circuit and the mixture is conditioned at 80 °C, causing the transformation to the green, non-alum form of chromium. Upon further cooling, the crude iron sulfate crystals form, are separated for

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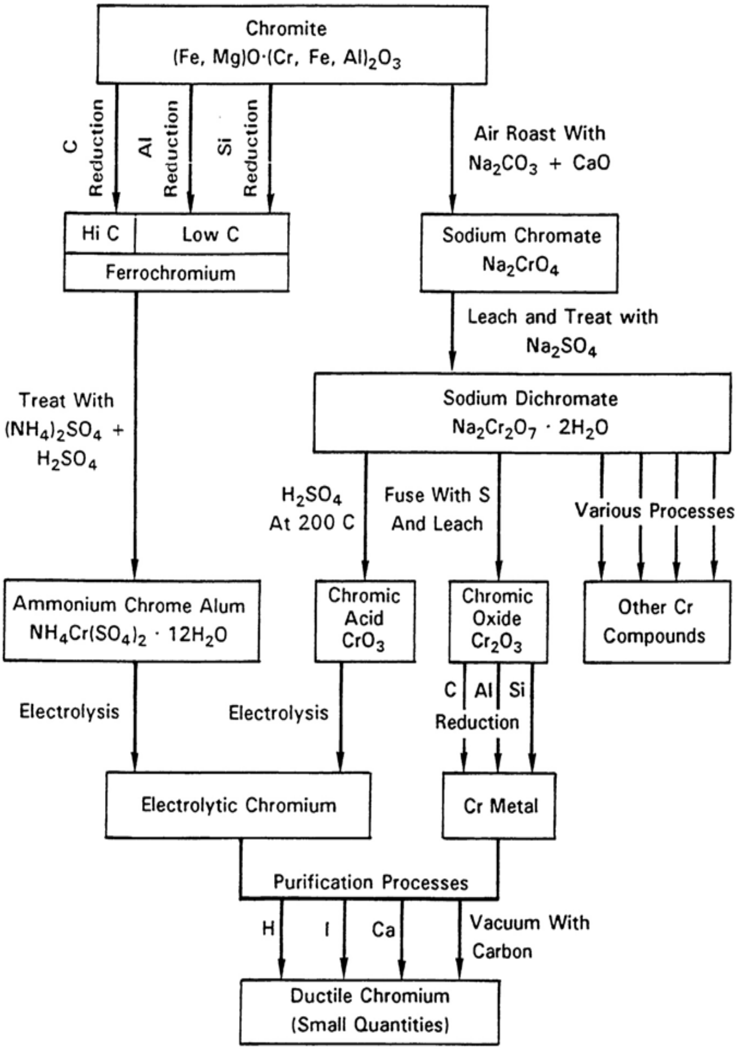

FIGURE 3-1 Simplified flow chart for the production of metallic chromium and chromium compounds. Reprinted courtesy of Grayson (1985) and Elkem Metals Company.

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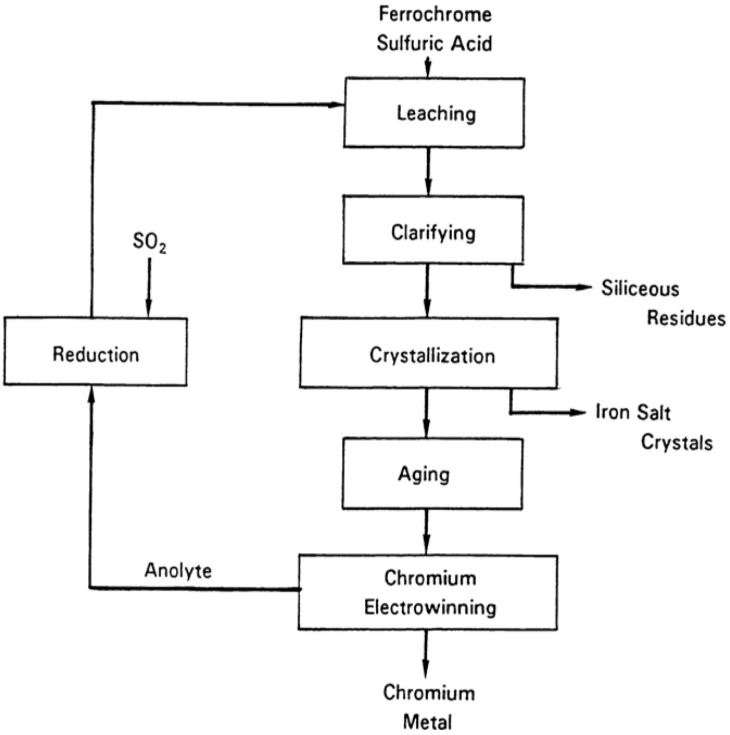

FIGURE 3-2 Flow sheet for chromium electrodeposition from chrome-alum solutions. Source: DeBecker et al. (1993).

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further conditioning, and are recrystallized as ferrous ammonium sulfate.

The mother liquor from the crude ferrous sulfate crystallization contains the bulk of the chromium metal that is then sent to the aging circuit. Aging and crystallization are conducted at relatively low temperatures. The kinetics are rather sluggish, but the desired purple ammonium chromium alum eventually forms. The crystal slurry is then filtered, washed, and pumped to the leach circuit. The washed chromium-alum crystals are dissolved in hot water and filtered to produce cell feed.

The key to successful, efficient electrodeposition of metallic chromium is ensuring that the proper chemistry is maintained at the cathode. This requires using a diaphragm cell, which separates the anolyte and catholyte, to minimize the migration of chromium (VI) to the anode and assist in controlling the pH. If chromium (VI) is present, its reduction to Cr^{+2} is detrimental to current efficiency. If the Ph is too low, hydrogen evolution causes low current efficiency. If the Ph is too high, however, the undesirable precipitation of $Cr_2O_3 \cdot xH_2O$ occurs. Thus, control of electrolyte composition and Ph at about 2.1–2.4 is essential. The current efficiencies obtained are usually about 45 percent.

Figure 3-3 shows the desired reactions during electrolysis; these reactions are listed below.

At the cathode:

$$Cr^{+3} + 1e- \rightarrow Cr^{+2}$$

$$Cr^{+2} + 2e- \rightarrow Cr^{0}$$

$$2H^{+} + 2e- \rightarrow H_2$$

At the anode:

$$2H_2O \rightarrow 4H^{+} + O_2 + 4e-$$

$$2Cr^{+3} + 7H_2O \rightarrow Cr_2O_7^{-2} + 14H^{+} + 6e-$$

The approximate electrolyte composition in both compartments of the diaphragm cell and typical electrode reactions are shown in Figure 3-3. Other operating data are listed in Table 3-1.

After 72 hours of plating, the brittle chromium metal is removed in pieces from the cathode blanks by hammering. The metal at this point contains a number of impurities and must be refined by vacuum reduction before final use. A more complete flow sheet for producing electrolytic chromium metal by the chrome-alum process is given in Figure 3-4.

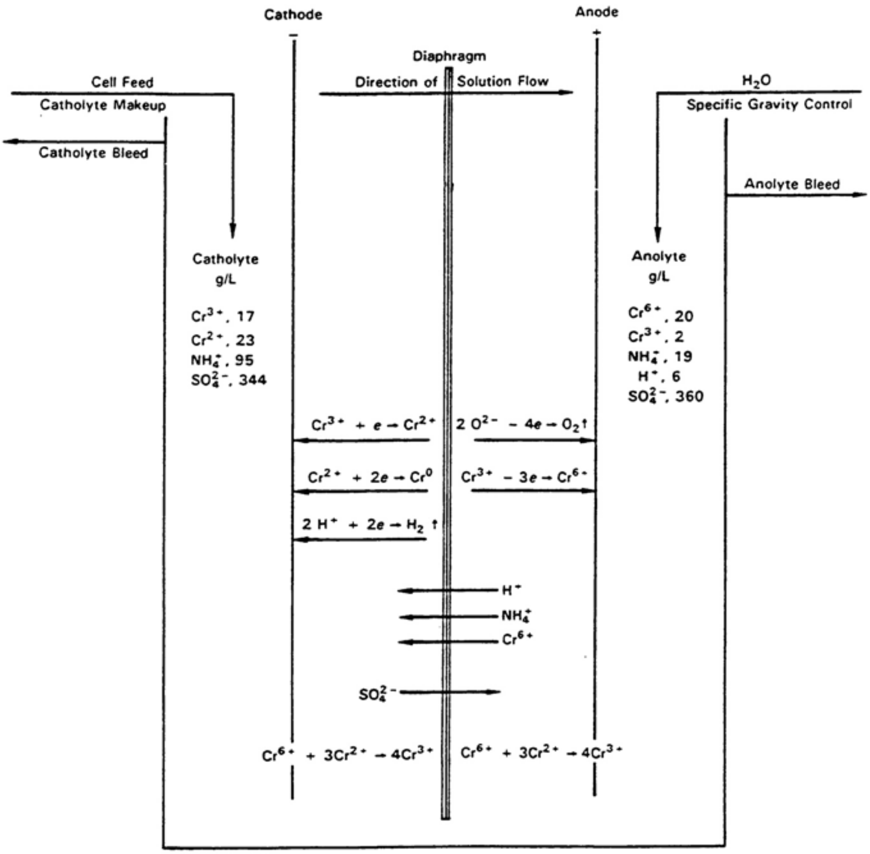

FIGURE 3-3 Principal electrolytic cell reactions in chromium production by the chrome-alum process. Reprinted courtesy of Grayson (1985) and Elkem Metals Company.

CHROMIC-ACID ELECTROLYTE METHOD

Referred to as the chromium (VI) or hexavalent process, the chromic-acid electrolyte method is used primarily for surface finishing and electroplating applications. Chromium trioxide, CrO_3, is obtained from sodium dichromate. Small, catalyzing additions of halogens or sulfate are essential for electrolysis. The current efficiency of the process is very low (e.g., in the range of 10 percent) because of the low hydrogen overpotential on chromium. The excessive hydrogen evolution may result in the precipitation of chromium hydroxides

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TABLE 3-1 Operating Data for Electrowinning of Chromium Metal from Chrome Alum

Cathode Current Density (A/M^2)	753
Cell Potential (V)	4.2
Current Efficiency (%)	45
Electrical Consumption (MJ/Kg)	67
pH of Catholyte	2.1 - 2.4
Catholyte Temperature (°C)	53 ± 1
Deposition Time (h)	72
Cathode Material	Type 316 stainless steel
Anode Material (wt %)	1.99 Ag-Pb

because of the higher localized Ph at the cathode surface. Passivation of the reactions may then occur, making efficient processing even more difficult. Some of the cell conditions for chromium electrowinning from chromic acid are given in Table 3-2.

The low overall efficiency obtainable with hexavalent chromium makes it nonviable as an alternative method for the production of bulk, high-purity chromium metal for alloys. Thus, this method has not been used when large tonnages are required.

TABLE 3-2 Cell Conditions for the Chromic Acid Process for Electrowinning Chromium Metal

Bath Composition (g/L)	300 CrO_3, 4 sulfate ion
Temperature (°C)	84-87
Current Density (A/m^2)	9,500
Current Efficiency (%)	6-7
Plating Time (h)	80-90

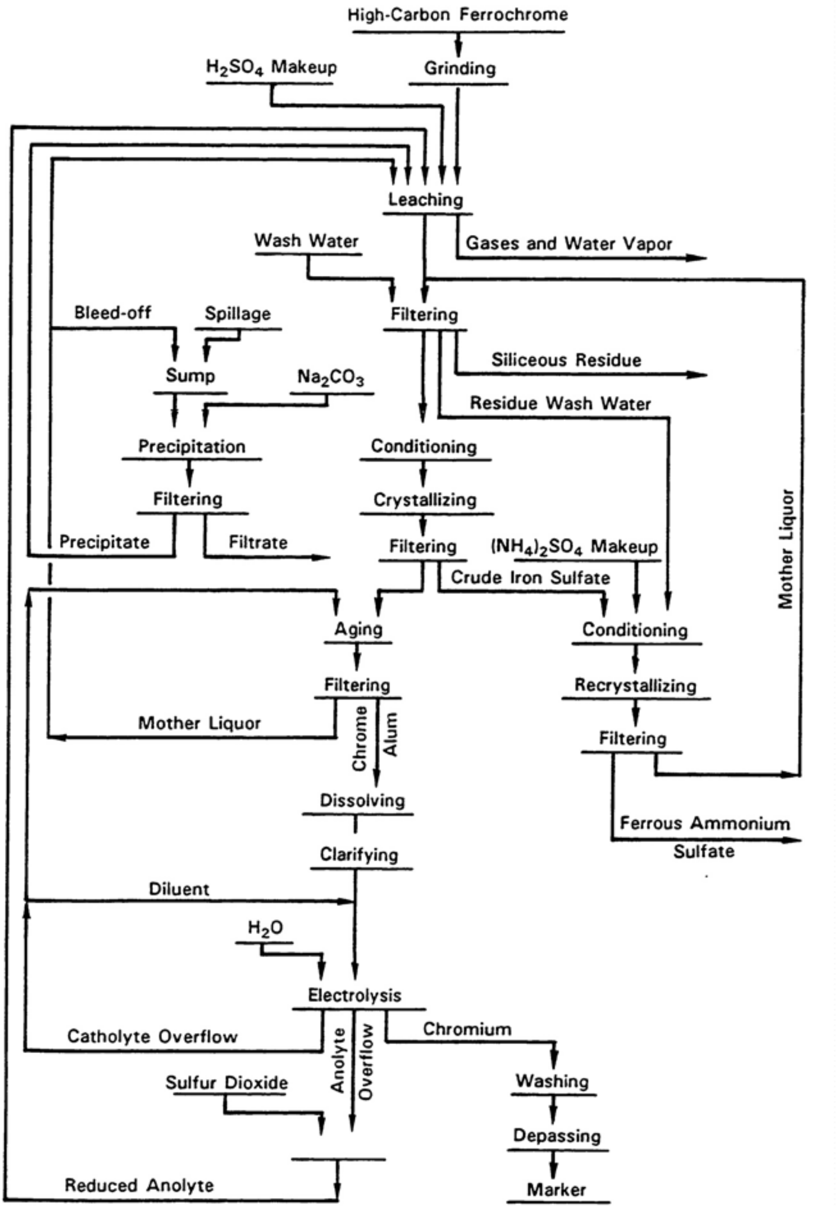

FIGURE 3-4 Flow sheet for production of electrolytic metal by the chrome-alum process. Reprinted courtesy of Grayson (1985) and Elkem Metals Company.

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VACUUM-DEGASSING OF CHROMIUM METAL

The following process is used to produce vacuum-grade chromium metal by the Elkem Metals Company (trade name Elchrome). It is the final refinement step for the production of chromium metal for aerospace applications.

The irregular plates of chromium metal removed from the electrodes are first milled to 100 µm and then blended into a briquetting mixture with finely divided carbon, tin, and a polymeric binder. The quantities of these additives will depend on the composition of the feed chromium metal. This mixture is wetted and formed into small briquets, which are allowed to dry and placed in separate lots on a long flatbed railcar. The railcar is placed in a long, cylindrical, resistance-heated vacuum oven, which is closed and evacuated with a steam extractor. The oven is heated to approximately 1400 °C (2600 °F) at a rate sufficiently slow to accommodate offgassing without excessive increases in pressure. When the maximum temperature is reached, it is held until a constant vacuum of less than 100 µm of mercury can be maintained. It is then allowed to cool while a stream of argon gas is admitted. Final purging is with helium. The briquets are then removed, analyzed, and packaged for shipment in 1-ton boxes.

An entire cycle requires approximately one week. During the process, nitrogen and lead are volatilized, and sulfur is removed as tin sulfide. Oxygen is also removed as carbon dioxide to levels lower than 0.05 percent. The use of carbon as an oxygen getter places lower limits on carbon content. Some chromium metal is volatilized and recondensed on the cooler parts of the oven at the highest temperatures and lowest pressures. Thus there is a tradeoff between the additional purity obtained by continued treatment and the loss of chromium metal. All of the chromium metal produced electrolytically can be refined to aerospace quality by degassing.

ENVIRONMENTAL AND OCCUPATIONAL HEALTH CONSIDERATIONS

Chromium-metal manufacture by any method is energy intensive. Electric power is consumed in both the electrowinning and vacuum-degassing processes. To the extent that this power is generated by the burning of fossil fuels, it contributes a burden to the local environment. In the aluminothermic process, electric power is consumed externally to the process proper (in the smelting of aluminum reductant used in the process) but is nevertheless comparable to the electrolytic process in terms of energy consumption.

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The major direct by-products of electrolytic chromium-metal manufacture are ferrous ammonium sulfate and ammonium sulfate, which are formed during ammonia neutralization of the sulfuric acid leachate of ferrochrome. Ferrous ammonium sulfate is subjected to two recrystallization steps to remove as much entrained chromium as possible and then pumped to settling ponds on site for indefinite storage. Excess ammonium sulfate is discharged to the Ohio River under an EPA permit. Currently, research and development efforts are being made at Elkem to develop an alternative method for removal of iron that does not introduce ammonia into the process stream. While the iron removal step is not needed in the aluminothermic process since it employs chromium (III) oxide rather than ferrochrome as the main feedstock, iron removal must be performed at some point in the path between chromite ore and high-purity chromium metal.

In general, chromium-containing solutions that exit the process stream are mixed with the main process stream at the ferrochrome leaching stage, a practice driven largely by the cost of chromium units. These solutions include mother liquors from ferrous ammonium sulfate recrystallization and anolyte containing chromium (VI) from the electrolytic process, reduced to the chromium (III) state with sulfur dioxide before re-addition to the leach. Thus, there are no significant costs associated with disposal of chromium-bearing hazardous wastes from the electrolytic process.

One concern in the chromium process is in the milling, blending, and briquetting operations that occur prior to the vacuum-degassing step. This generates and releases a considerable quantity of very finely divided particulates. This dust is known to constitute an explosion hazard under certain conditions, and safety precautions are observed. These particulates may cause health and environmental problems as well, but no special efforts are apparently being expended to contain this material. Similar considerations apply to the aluminothermic process. Metallic chromium recovered as floor sweepings can be reintroduced into the process stream at the leaching step.

The vacuum-degassing process itself results in production of gaseous stack emissions, largely consisting of carbon monoxide, although these are insignificant in relation to the initial smelting of chromite ore. This process will be performed in a similar manner in both electrolytic and aluminothermic processes.

In conclusion, the production of electrolytic chromium metal as carried out at the Elkem plant in Marietta, Ohio, appears to have few opportunities for major environmental improvements other than the effort to remove ammonia from the process stream. In addition, neither the electrolytic nor the aluminothermic process offers a significant advantage over the other in terms of its environmental impact.

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4

Alternative Technologies for Chromium-Metal Production

The geologic sources of chromium are essentially mixtures of spinels of the ideal form $RO{\cdot}R_2O_3$ (e.g., chromite is $FeO{\cdot}Cr_2O_3$), although a more accurate representation of an ore source would be $(Mg,Fe)Cr_2O_4$ with silica and alumina gangue materials. The refining processes for chromium metal have been thermodynamically defined by their spinel origins. The two processes of electrolytic deposition, discussed in the previous chapter, and aluminothermic reduction have evolved over time as more efficient than such other processes as carbon and silicon reduction (Sully, 1954). Both the electrolytic and the aluminothermic processes have been successfully improved over time to result in lower levels of impurities so that the requirements of *high-purity* applications have continued to be met, even though purity specifications have become increasingly stringent over time. Improvements in the efficiencies and economics of the processes are probably still possible, but no obvious quantum-jump increase in the purity obtainable appears likely. This chapter discusses the strengths, weaknesses, uses, limits, and possible improvements to alternative processes for producing chromium metal.

PREPROCESSING OF CHROMITE ORE

Chromite ore is processed in preparation for aluminum reduction in a number of different ways, two of which are briefly described below.

In the first method, chromite ore (Na_2CO_3) and a carrier (e.g., limestone) are roasted to produce sodium chromate. This product is then leached, filtered, and acidified to form the dichromate. The dichromate is filtered, crystallized out of solution, and then reduced with a reducing agent (e.g., sulfur or carbon) to produce chromic oxide.

In the second method, the sodium chromate liquor can be treated to reduce impurities (e.g., silicon) and then treated with alkaline hydroxides or ammonium hydroxide to produce a hydrated chrome oxide. This product is then

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heated in a rotary furnace to produce chromic oxide. This method can produce a high grade of aluminothermic chromium.

The by-products of these two methods have environmental liabilities involving the chromium (VI) compounds. The second method has historically produced a purer grade of oxide and chromium metal and may still be in use in some parts of the world today. Improvements in treating the environmentally important waste products are possible with increased costs. Potential future liabilities may promote such considerations.

ALUMINUM REDUCTION METHOD FOR PRODUCING CHROMIUM METAL

The aluminothermic process is a batch process usually carried out in a steel cylindrical container with a basic or neutral refractory lining. The lining may be rammed MgO with an organic binder or alumina from the slag produced in the process. The process can be run in either an autogenous fashion or carefully preheated with good premixing and then ignited with barium peroxide. The reaction then proceeds exothennically as follows:

$$Cr_2O_3 + 2Al \rightarrow 2Cr + Al_2\,O_3.$$

The end-product is a cake composed of metal and slag. The final purity can be adjusted within limits for adaptation to the intended use. Generally, if the product is to be used in aluminum alloys, the aluminum content can remain high. Silicon can be added if lower aluminum is desired. If low content of both aluminum and silicon is required, however, the reaction can be run with a less than stoichiometric amount of aluminum, resulting in a lower yield of metal and residual unreduced chromium oxide. Method one of the previous section has been used to produce chromium metal low in sulfur when the initial ore is low in sulfur. The foregoing general process description is basically relevant to current operations, but there appears to be detailed process variations by the manufacturers to meet specific objectives relating to end usage.

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OTHER METHODS FOR PRODUCING CHROMIUM METAL

The dichromate can be reduced by a number of different methods besides the aluminum reduction process.

- The ore, $(Mg,Fe)Cr_2O_4$, containing 15-65 percent Cr_2O_3 must first be chlorinated by heating to 600 °C:

  $Cr_2O_3 + Cl_2 \rightarrow CrCl_3 +$ Cr oxychlorides.

  Heating the reaction to above 1300 °C then causes the decomposition to metal:

  $2CrCl_3 + \text{heat} \rightarrow 2Cr + 3Cl_2$.

  The volatilization of the chlorides are such that complete separation from the iron chlorides is difficult, however. This process is also possible using iodine. The oxide is treated with iodine to form the iodide, followed by thermal decomposition by heating. However, these processes require heating to high temperatures, whereas the reduction with aluminum is self-propagating.
- Reduction by hydrogen is possible and produces the acceptable by-product water:

  $Cr_2O_3 + 3H_2 \rightarrow 2Cr + 3H_2O$.

  The reduction of the oxide with hydrogen requires extremely high temperatures, however, for relatively low yields. These constraints make the process economically uncompetitive.

Carbon and silicon have also been used as reducing agents, but heat must again be supplied to the process. The availability of aluminum with its high-energy investment, the stability of Al_2O_3 as a reaction product, and the autogenous nature of the process have made the aluminothermic process the second major engineering method of choice for the reduction of chromium metal.

DOUBLE-DEGASSED REFINING

A major improvement to the aluminothermic process involves the refinement of the degassing systems, such as the double-degassed briquette (DDB) treatment of Delachaux. The DDB process shows that chromium-metal products and powder can be produced with lower iron, carbon, oxygen, or sulfur by degassing the purest sections of the chromium-metal buttons with

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possible additions. Unlike chromium metal produced electrolytically, however, the entire button produced by the aluminothermic method cannot be refined to aerospace quality; only roughly one-fifth of the metal is suitable for double degassing to attain higher grades. Thus, to increase the quantity of high-purity chromium metal produced, an aluminothermic producer must also increase the quantity of less pure material manufactured. Alternate uses for this material would have to be found in the marketplace.

Six different grades of double-degassed chromium metal are available from Delachaux with purity levels of 99.81 to 99.89 percent. Iron, silicon, and oxygen are still major impurities in the range of 200 to 1,000 parts per million by weight in these materials, but carbon and sulfur are present in the range of 200 parts per million or less. Consumers of chromium metal currently utilize the higher-purity grades with in-house processes to produce products critically dependent on purity. The details of Delachaux's process, its chemical additions for specific purity objectives, and its possible variations are currently not public.

ACCEPTANCE OF ALUMINOTHERMIC CHROMIUM METAL

As stated in Chapter 2, the double-degassed aluminothermic chromium metal has now been certified for many aerospace applications. *Recent developments in the processing and secondary treatment of aluminothermic material has led the committee to conclude that there is currently little difference in purity between the chromium products produced by the aluminothermic and electrolytic processes.* However, as also stated in Chapter 2, while aluminothermic material of equivalent quality to the electrolytic material may now be available, changes in such critical applications as rotor-grade materials must be mutually acceptable to producer and user and would have to be subject to extensive qualification studies involving production and testing of alloys, test specimens, final cast and forged products, and possibly the engines containing them.

Overall, the aluminothermic chromium-metal industry does not currently appear to be producing at full capacity. Aluminothermic chromium metal is currently produced in the United Kingdom (London and Scandinavian Metallurgical Corporation, Ltd (LSM)), Germany (Gesellschaft für Elektrometallurgie (GfE)), China, and Russia. The LSM high-grade chromium metal appears nearly comparable to that of Delachaux, with slightly higher (parts per million) iron and oxygen contents and, to a lesser extent, sulfur, silicon, aluminum, nitrogen, and phosphorus. The Delachaux DDB grades are somewhat higher in overall

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purity, and special grades can provide reduced levels of specific impurities. The Chinese and Russian products are not as reliably specifiable at this time.

Additional sources of aluminothermic chromium metal could also be quickly redirected or instigated. As stated in Chapter 1, there are no aluminothermic chromium-metal production plants currently extant in the United States, but aluminothermic production plants do exist that produce other high-purity metals. These plants could produce chromium metal if required. *Also, since producers have indicated that the aluminothermic process is not as capital-equipment intensive as the electrolytic process, the construction of new facilities appears to be a minor factor should the need arise.* As stated in Chapter 3, neither the electrolytic nor the aluminothermic process offers a significant advantage over the other in terms of environmental impact.

The degassing operations are harder to initiate quickly, however, because of the relatively large vacuum furnaces needed. *The committee believes that suchvvacuum-degassing furnaces could be constructed within two years, if the need were sufficiently great.*

POSSIBLE IMPROVEMENTS IN THE PROCESSING TECHNIQUES

The technique of electroslag remelting, utilizing the products of the above processes, could provide a level of purity higher than either high-grade aluminothermic or electrolytic chromium metal. The objective would be to obtain chromium metal in bulk metallurgical form. The process could address the current impurities of iron, silicon, carbon, oxygen, sulfur, and other impurities that, at the parts-per-million level, are still relatively high. The obvious difficulty is to obtain appropriate consumable electrodes from the above sources to run the process. Processes utilizing powder metallurgy, the chloride route, or chemical vapor deposition methods could be adapted to making electrodes. One must still remember that only a small fraction of the chromium-metal market would be involved, and economic factors may very well override the technical considerations in any such venture.

Current processes for producing high-purity chromium metal can provide powder as a possible source material for producing electrodes for an electroslag remelt process. The vapor pressure of chromium even at intermediate temperatures is high enough to promote vapor-phase sintering as a reasonably economic process. The powder might be used in a way similar to the current production of briquettes. A product relatively low in carbon, nitrogen, oxygen, and sulfur is currently produced. The sintering operation might be examined for adaptation

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to producing electrodes suitable for electroslag remelting. Slags high in fluorite, CaF_2, could be examined with the view to producing bulk metallurgical chromium with lower carbon, nitrogen, oxygen, and especially sulfur contents.

The committee considers it possible that a process based on induction plasma technology could use a chromium powder to produce satisfactory electrodes for remelt processing. Induction plasma methods, as opposed to arc plasma methods, can have inherently lower process-induced contamination. The powder could be melted directly with the plasma or injected through the plasma at a suitably arranged target that permits rapid solidification. This may be a feasible method to explore even with the high vapor pressure of chromium at its melting point (8-10 mm at about 1700 °C). The electrodes could then be processed in the electroslag remelt process with the object of obtaining ultra-high purity from elements that promote inclusion contents in later processing.

All of the above processes are energy-intensive and unattractive economically unless the need for the product is great enough.

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5

Reliability of Suppliers of High-Purity Chromium Metal

The reliability of a chromium-metal producer is of utmost importance to a superalloy or engine manufacturer. This is especially true with the recent closures of a number of chromium-metal production companies around the world. This chapter presents criteria by which the reliability of a supplier can be judged and assesses the reliability of the four major high-purity chromium-metal producers in the world. The chromium-metal producers in Japan and China are not discussed in this chapter because both countries currently produce only small quantities of aerospace-quality material for internal consumption.

DEFINITION OF A RELIABLE SUPPLIER

Reliability is simply defined as the ability of a company to consistently supply an acceptable product at the required time. There are seven criteria by which reliability can be judged.

1. Quality—A quality product must be consistently delivered that satisfies the customer's needs. Quality should be guaranteed through documented production practices and defined process controls.
2. Process Equipment—State-of-the-art equipment must be maintained and improved through organized maintenance procedures and capital investment to ensure that quality is maintained on a long-term basis.
3. Research and Development—Initiatives and resources must be continually invested to improve the product in response to market demands.
4. Geography—Plants must be located in countries where economic, political, or naturally occurring phenomena or infrastructure will not inhibit production or delivery.

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5. Financial Health—A solid financial situation must be demonstrated, including good cash flow for flexible operation of the business and strong support for capital investment. The company cannot be financially burdened by either a second-party owner or subsidiary.
6. Management Commitment—Commitment to the future must be evident and supported by long-term business relationships.
7. Raw Materials—Reliable sources of raw materials must be available as well as strategies to maintain them.

RELIABILITY OF THE HIGH-PURITY CHROMIUM-METAL PRODUCERS

This section examines the reliability of the four major high-purity chromium-metal producers (i.e., Elkem Metals Company, Delachaux Metals Division, the subsidiaries of Metallurg, Incorporated, and the Russian manufacturers) based on four of the seven criteria described above. Management commitment, raw materials, and the economics of the industries will not be considered because these areas are outside the technical scope of this study. The committee collected the data for this chapter at a two-day briefing session held in Ohio. The first day of the briefing session consisted of a site visit to the Elkem Metals chromium-metal facility in Marietta, Ohio, and briefings on the health of the domestic chromium-metal industry by their representatives. The second day of the briefing consisted of presentations on the health of the international chromium-metal industry and the alternative methods for producing high-purity chromium metal by representatives of London and Scandinavian Metallurgical Corporation, Shieldalloy Metallurgical Corporation, Delachaux Metals Division, and Niddam, Incorporated.

Elkem Metals Company

Elkem Metals Company, a Norwegian-owned company, currently produces electrolytic chromium metal in the United States that consistently meets the specifications stipulated by the aerospace engine manufacturers. The Elkem plant maintains four full-size, electrically heated vacuum furnaces for degassing. Each furnace has a charge capacity of approximately 80 metric tons of chromium metal and is capable of processing one charge per week, for a plant total of 16 charges per month. Current furnace usage in chromium-metal

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production is approximately two charges per month. Although these furnaces are also used for the production of low-carbon ferrochrome and ferromanganese products, Elkem has easily enough reserve capacity to convert all of its electrolytic chromium metal to vacuum grade, with additional capacity to spare, if demand were sufficient.

Elkem has an ongoing research and development program. Research and development on the vacuum-degassing process is conducted using a small-scale electric vacuum furnace. Current projects are concerned with improving product quality (simultaneously reducing carbon and oxygen), identifying ways to increase throughput, and testing improved binders (lower impurities and higher mechanical stability of briquettes).

Being located in the United States, the plant has an advantage for domestic consumers in terms of geographic location. The chances of disruption of supply because of economic, political, or naturally occurring phenomena are minimal, as long as the supply of raw materials is either secure or present in the United States. The infrastructure of the United States is also sufficiently good to ensure safe delivery of materials within the time constraints required.

The representatives of Elkem who briefed the committee were very optimistic about the company's future in the industry. Elkem is also accepting orders for high-purity chromium metal through 1996. *In conclusion, the information available to the committee indicates that Elkem Metals Company is a reliable supplier of high-purity chromium metal for the foreseeable future, with respect to the criteria of quality, equipment, research and development, and geography.*

Delachaux Metals Division

Delachaux Metals Division, a French-owned company located in Pau, France, currently meets the quality specifications required by their customers. Chromium metal produced by Delachaux has been certified for use in aerospace engine applications by Pratt & Whitney, Howmet, Rolls Royce/Allison, Special Metals Corporation, and others. The total capacity for Delachaux is approximately 3,500 metric tons, 750 of which is currently the double-degassed grade.

The committee was unable to travel to France to tour the Delachaux production facilities and thus could not directly assess the company's equipment and research and development program. The steady improvement in the purity of the chromium metal produced by Delachaux over the past 10 years and the increasing number of certifications for its material by aerospace engine

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companies would indicate that Delachaux possesses and maintains both state-of-the-art equipment and a healthy research and development program.

France is a long-standing ally of the United States and a member of the North Atlantic Treaty Organization (NATO). As allies, NATO forces would probably maintain safe shipping between the two countries in the event of a crisis. The infrastructure within France is also extremely good. Thus the transportation of chromium metal from France to the United States should continue to be reliable.

The representatives of Delachaux Metals Division who briefed the committee were very optimistic about the company's future in the industry. Delachaux is also accepting orders for high-purity chromium metal through 1996. *In conclusion, the information available to the committee indicates that Delachaux Metals Company is a reliable supplier of high-purity chromium metal for the foreseeable future, with respect to the criteria of quality, equipment, research and development, and geography.*

Metallurg, Incorporated

Two wholly owned subsidiaries of the U.S. company Metallurg, Incorporated (i.e., London and Scandinavian Metallurgical Corporation, Limited (LSM), of the United Kingdom and Gesellschaft für Elektrometallurgie (GfE) of Germany), annually produce approximately 2,000 metric tons of high-grade aluminothermic chromium metal that meets some aerospace-engine quality specifications. Their capacity is also scheduled to increase with the opening of a new plant in the United Kingdom in the next few years and the possible full utilization of the capacity of the GfE facility.

The committee was unable to travel to either the United Kingdom to tour the LSM production facility or Germany to tour the GfE production facility. It thus could not directly assess the companies' equipment and research and development program. The steady improvement in the purity of the chromium metal produced by Metallurg subsidiaries over the past 10 years, the establishment of a new plant in the United Kingdom that can produce larger buttons with better process control, and the potential unused capacity of the GfE facility indicate that Metallurg possesses state-of-the-art equipment and maintains a healthy research and development program.

The United Kingdom is a long-standing ally of the United States, and both the United Kingdom and Germany are members of NATO. As allies, NATO forces would probably maintain safe shipping between these countries and the United States in the event of a crisis. The infrastructure within the

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United Kingdom and Germany is extremely good. Thus the transportation of chromium metal from Europe to the United States should continue to be reliable.

The representatives of LSM and Shieldalloy Metallurgical Corporation who briefed the committee were very optimistic about Metallurg's future in the industry. As stated above, LSM is also currently constructing a new plant in the United Kingdom, which is scheduled to open in the next few years. *In conclusion, the information available to the committee indicates that the subsidiaries of Metallurg, Incorporated, are reliable suppliers of high-purity chromium metal for the foreseeable future, with respect to the criteria of quality, equipment, research and development, and geography.*

Russian High-Purity Chromium-Metal Producers

One of the major unanswered questions regarding the international availability of high-purity chromium metal is the future role that Russian technology and production may play. The reports available to the committee on the purity levels of the Russian chromium metal are quite varied. Some analyses find the material to be extremely pure, while others show great variability in the impurity levels. The picture should become clearer in the future as more companies attempt to qualify the material.

The Russian producers appear to use an electrolytic process. Since the committee was not briefed by any representatives of the Russian industry, the committee could not judge the state of either the equipment or the research and development efforts. However, the current economic and political situation in Russia has resulted in minimal finances being available for the support of the infrastructure for the dependable delivery of products, the maintenance of equipment for the consistent production of quality material, and the support of research and development programs (NRC, 1994a, 1994b).

In conclusion, the information available to the committee indicates that the Russian suppliers are currently not reliable based on the fact that the high-purity chromium metal is extremely variable. The material requires further characterization before being considered for the production of vacuum-melted superalloys.

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6

Potential Economic Scenarios for the U.S. Supply of Chromium Metal and the Role of the National Defense Stockpile

Previous chapters indicate that the chromium-metal industry is currently sufficiently healthy to produce the quantities of high-purity chromium metal required by the aerospace industry. This favorable situation, however, could change. This chapter first presents the committee's deliberations concerning the general question of how to balance trade policy with national security issues. The chapter then examines the role of the National Defense Stockpile and its responsibility to ensure that sufficient quantities of critical materials are available in case of a national emergency. It then considers several possible situations that could conceivably give rise to shortages in the future and the need for public policies to cope with such situations should they arise.

FREE TRADE VERSUS NATIONAL SECURITY

Since high-purity chromium metal is an essential ingredient in the production of both military and civilian jet engines, the committee first had to address the general question of how to balance trade policy with national security issues. It is widely agreed among economists that mutual loosening of trade restrictions among countries raises standards of living among all of them, although possibly in different degrees in different countries. This theory was originally forwarded by Adam Smith (1776), but even he believed that a valid argument could be made for protecting those industries that are essential to national security because of the ease by which world trade patterns can be disrupted.

Adam Smith wrote at a time when the chief means of transportation were the stagecoach and the sailing ship; the enormous reduction in transport costs since then has led to a highly integrated international market with countries specializing to an increasingly greater extent in products for which they have a comparative advantage. Thus the current cost of national self-sufficiency is much

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greater than it was in the past. The British Empire, protected by the Royal Navy, formed a fairly self-sufficient unit in the nineteenth century from the point of view of national security. Since what is essential for national security is secure and rapid access to strategic materials, NATO could be regarded as a modern and similarly secure region.

The three main methods of protecting a domestic source of a material are the imposition of import restrictions, the granting of government subsidies, or the establishment of stockpiles. All three of these methods have disadvantages.

- Import restrictions can cause an increase in domestic prices, which increase costs for domestic chromium-metal users (i.e., jet engine and aircraft producers) and decrease their competitiveness in the international marketplace.
- Government subsidies strain both the U.S. budget and international relations. Protection of domestic suppliers by either subsidies or import restrictions could create difficulties with the new World Trade Organization and lead to retaliation on the part of European producers.
- Stockpiling can cause initial price increases in a commodity when the government enters the market. The liquidation of stockpiles can also depress prices if supply outpaces demand.

The committee believes that stockpiling is the most benign of the methods of ensuring that a material is available during a period of crisis. *Thus the committee agrees that a reasonable point of departure would be that the disadvantages of taking active measures to protect a domestic industry would probably outweigh any advantages, provided that an adequate stockpile were maintained.*

NATIONAL DEFENSE STOCKPILE

The National Defense Stockpile is maintained by the Defense Logistics Agency to provide the United States with a supply of strategic and critical raw materials in the event of a national emergency. By law these materials can only be used in the interest of national security and cannot be used for economic purposes.

The U.S. Department of Defense mandates the types and quality of materials that are maintained in the stockpile. The requirements are reviewed

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biennially, using input from the U.S. Departments of State, Commerce, and Interior. The most recent report on requirements published in 1993, requires an inventory of 24,344 metric tons of chromium metal. The stockpile currently retains 7,700 metric tons of material, of which the National Defense Stockpile technical staff estimates that between 3,500 and 4,500 metric tons is suitable for aerospace applications.

The collapse of the Soviet Union in 1992 has caused the Department of Defense to reassess the quantities of materials required in the stockpile and has raised the question of whether there is any continuing need to have a stockpile at all. As of this writing, no decision has been made concerning what disposition is to be made of the 7,700 metric tons of chromium metal currently retained. All indications suggest that the Department of Defense will most likely find little or no continuing need for any of the materials in the stockpile, however, chromium metal included. *The committee recommends that the National Defense Stockpile should maintain and continually upgrade to industry standards a sufficient quantity of high-purity chromium metal to meet the industry's needs in the event of an emergency.*

As stated in Chapter 1 and Chapter 2, the domestic aerospace industry requires approximately 2,000-2,500 metric tons of material annually. *In the case of a national emergency, the 1994 stockpile inventory is sufficient to provide an approximate two-year supply of metal and sustain the aerospace industry until new aluminothermic and degassing facilities are brought into operation if (1) the metal is totally devoted to the aerospace industry, (2) the demand for chromium metal does not suddenly increase, and (3) the domestic source of metal is no longer in production.*

POTENTIAL ECONOMIC SCENARIOS FOR THE U.S. SUPPLY

Most U.S. aerospace melters buy chromium metal from a variety of sources, and as a group they buy from all of the world's major producers. The one possible exception is the secondarily treated Russian electrolytic material, which is currently being evaluated.

Given what is now known about the chromium-metal market, chromium-metal producers, and global economics and politics, it is possible to construct scenarios where shortages of high-purity chromium metal could arise. Three such scenarios are presented in this section. The first envisages a worldwide surge in demand for high-purity chromium metal. The second assumes both a surge in demand and the closure of the one significant domestic producer,

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Elkem. The third, building on the second scenario, considers the additional loss of one or more foreign suppliers to the U.S. market. The latter two scenarios are highly unlikely within the foreseeable future but provide worst-case scenarios. These scenarios, it is important to stress, are not predictions by the committee but simply situations that could conceivably occur. They are all based on the data presented above and summarized in Table 6-1.

Scenario 1: A Surge in Demand for High-Quality Chromium Metal

The impact that an increase in the demand for aerospace-quality chromium metal would have on the marketplace depends on its magnitude. If demand suddenly were to jump to 4,000 metric tons per year, existing world capacity would still be capable of meeting demand. The U.S. producer could supply up to 3,000 metric tons per year, the French producer could increase supply to 1,000 metric tons per year, and the German producer could increase supply by at least 1,000 metric tons per year. Material from Russia and the new plant in the United Kingdom would be available as well. Additional sources of aluminothermic chromium metal could also be quickly redirected or initiated. As stated in Chapter 1, there are no aluminothermic chromium-metal production plants currently extant in the United States, but existing aluminothermic production plants that produce other high-purity metals could produce chromium metal if required. Also, since the aluminothermic process is not as capital-equipment intensive as the electrolytic process, the construction of new facilities appears to be a minor factor should the need arise.

TABLE 6-1 Data Used as Basis for Discussion on Scenarios

Chromium-Metal Statistics	Metric Tons per Year
Current world demand (secondarily treated for aerospace applications)	2,000-2,500
U.S. supply	3,000
National stockpile (total)	7,700
National stockpile (aerospace quality)	3,500-4,500

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If demand should dramatically increase to 6,000 metric tons per year, doubling or tripling current levels, the resulting rise in market price would encourage the French, German, British, and Russian suppliers to increase their supply, perhaps to 2,000 metric tons per year from each source. The U.S. producer could supply up to 3,000 metric tons per year operating at two shifts and up to 4,500 tons per year by adding a third shift. Its output might be further increased by vacuum-degassing purchased material and upgrading it to aerospace quality. The vacuum-degassing capacity of the U.S. producer is very large, above any foreseen demand requirement. Again, within a year or so, new production capacity could be added. Finally, defense production can, if necessary, obtain chromium metal either by government allocation or by outbidding other potential uses.

Scenario 2: Loss of the Domestic Industry

This scenario assumes that Elkem, the one significant U.S. producer, closes down as a result of a plant failure, the loss of economic competitiveness, environmental problems, or some other factor. The increases in chromium-metal output for this scenario would not be very different than that described for scenario 1. Prices would rise, providing strong incentives to expand existing sources, to qualify Russian material quickly, and to develop new sources as required. The two predominant differences between the first and second scenarios would be that Elkem customers would be forced to buy high-purity chromium metal from foreign suppliers and that a major vacuum-degassing facility would be lost. As stated in Chapter 4, the degassing operations are harder to initiate quickly because of the relatively large vacuum furnaces needed. A new vacuum-degassing facility could be constructed within two years, however, if the need were sufficiently great.

If Elkem were to go out of business, certain economic and security benefits derived from having a domestic producer would be lost. First, the local economy in Ohio would suffer for several years or even longer. For instance, many of the company's 632 employees would likely require retraining or relocation, and the community would lose part of its tax base. Second, ease of communication between the downstream users of high-purity chromium metal in the United States and their suppliers could be restricted. Unimpeded communication is important for developing improved materials and resolving problems. Third, the security of domestic supplies of high-purity chromium metal could be compromised. Imports are susceptible to restrictions or curtailments imposed by foreign governments. Fourth, the upgrading of the

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National Defense Stockpile of chromium metal might suffer. The chromium metal must be periodically upgraded to maintain the quality standards required by the aerospace industry. This task was previously carried out by domestic producers. Fifth, the United States might lose the technology needed to produce high-purity chromium metal. Domestic production helps ensure that the required technologies are locally available, should the need to expand capacity arise.

While the benefits of domestic production are significant, they do not, in the judgment of the committee, justify the government protecting or in other ways subsidizing domestic production. Local economic benefits, such as jobs and tax revenues, can be claimed by almost any company. Modern technology makes communication between U.S. consumers and foreign producers almost as easy as between U.S. consumers and domestic producers. Foreign governments, out of self-interest, are unlikely to restrict exports of chromium metal and similar commodities where new production capacity can be relatively cheaply and quickly constructed abroad. Such actions call into question the reputation of their own producers as reliable sources of supply and undermine their ability to compete in the international market. For the same reason, foreign producers are likely to be just as eager and able to upgrade the chromium metal in the National Defense Stockpile as a domestic producer. Finally, the technology for producing high-purity chromium metal is well understood and widely available with or without domestic production.

In weighing these benefits of domestic production, one should also consider the costs. Today, Elkem is a competitive producer and needs neither protection nor subsidy. Were this not the case, the costs of domestic production could be substantial, extending far beyond just the financial burden that subsidies and protection entail. Insulation from foreign competition, particularly when there are few if any other domestic rivals, reduces the incentives to innovate and increase efficiency. Vested interests arise and resources are devoted to lobbying and other efforts to keep or extend favorable government policies. Domestic consumers may be forced to pay more for their chromium metal than their foreign competitors, undermining the domestic companies' ability to compete in both the domestic and international marketplace. Also, such efforts to sustain uncompetitive domestic production undermine the leadership role the United States should take in promoting international trade.

Scenario 3: Loss of Foreign Supply

This scenario, presumably the worst-case scenario, assumes the closure of domestic production followed by a surge in domestic demand for high-purity

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chromium metal and a cutoff of part or all of foreign supply. Although highly unlikely, this scenario cannot be completely ruled out, particularly during a global military emergency. In such dire circumstances, releases from government and private stockpiles would provide sufficient chromium metal to sustain the highest priority needs, including those of the aerospace industry, while domestic production capacity was quickly constructed. As stated previously, it is technically feasible to bring new aluminothermic and degassing facilities into operation within 24 months, if necessary. *Thus the existing inventory of high-purity chromium metal in the National Defense Stockpile could currently provide for most domestic requirements, including all military and essential civilian needs, while new aluminothermic and degassing facilities were constructed. During this time period, small experimental furnaces should be used to refine the degassing process and ensure that aerospace-quality chromium metal would be produced once the larger degassing facilities are brought on line.* Since only about one-fifth of the chromium produced by the aluminothermic process is suitable for secondary treatment by the degassing process, unless the surge in demand for high-purity chromium is accompanied by a corresponding increase in demand for lower grades of chromium metal, additional uses for the less pure output would have to be found in the market place.

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Appendix: Biographical Sketches of Committee Members

WILLIAM D. MANLY is a consultant for Technology Transfer at Oak Ridge National Laboratory for Martin Marietta Energy Systems, Incorporated. He joined Union Carbide as director of materials technology in 1964, later becoming vice president and general manager of Union Carbide's Stellite Division. He joined Cabot Corporation when it acquired Stellite in 1970 and later became senior vice president and manager of Cabot's engineered materials group. He retired from Cabot as executive vice president in 1986. He received a B.S. degree and an M.S. degree in metallurgy from the University of Notre Dame. Mr. Manly has served on and chaired numerous committees and boards of the National Research Council. He is a member of the National Academy of Engineering.

JOHN S. CHIPMAN is Regents' Professor of Economics at the University of Minnesota, Minneapolis. He received a Ph.D. from The Johns Hopkins University. He is a member of the National Academy of Sciences and the International Statistical Institute, and a fellow of the American Academy of Arts and Sciences, the Econometric Society, and the American Statistical Association. He has worked extensively in the area of international trade.

ANTHONY F. GIAMEI heads the Computational Materials Science activity at United Technologies Research Center (UTRC). He received a B.E. from Yale and a Ph.D. in materials science from Northwestern University. His research and development activities included studies of X-ray diffraction, phase equilibria, alloy design, high-temperature mechanical behavior, joining, superalloy crystal growth, and prototype casting of single-crystal gas-turbine components. Since joining UTRC, he has worked with process modeling, atomistic modeling, and advanced alloy system design. Dr. Giamei has authored 70 technical publications, 22 U.S. Patents, and three conference proceedings. He is an ASM fellow and has served on several TMS committees, including a term on the Board of Directors. He has won several awards, including the UTRC George Mead Medal for Engineering Achievement.

JEROLD LEIBENSPERGER is manager of Raw Materials for Carpenter Technology. He earned a degree in metallurgy and materials science from Lehigh University. Mr. Leibensperger worked in the melting and primary production areas for 13 years before becoming manager of Carpenter's Premium Melting Units. His current responsibilities include the purchase of all scrap and

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alloys used at Carpenter, the development and assessment of new suppliers, and the management of inventory. Mr. Leibensperger possesses process knowledge of Carpenter's stainless steel, low alloy, tool, electronic, and aerospace alloys and their corresponding raw materials.

THOMAS J. O'KEEFE is Curators' Professor of Metallurgical Engineering, senior research investigator of the Graduate Center for Materials Research, and director of the Institute for Chemical and Extractive Metallurgy at the University of Missouri–Rolla. He received a B.S. from the Missouri School of Mines and a Ph.D. from the University of Missouri–Rolla in metallurgical engineering. His primary technical areas of interest are chemical and extractive metallurgy and deposition of coatings with emphasis in electrometallurgical processing. He has numerous publications and patents in these related areas.

BEN F. OLIVER is a professor of Materials Science and engineering at the University of Tennessee, Knoxville. Dr. Oliver received a Ph.D. in metallurgy from Pennsylvania State University. His research interests include solidification, crystal growth, ultra-high purity materials, composites, thermodynamics, magneto-hydrodynamics, and the solid state. His current researches include ultra-high purity intermetallic compounds and composites.

DAVID C. ROBERTS is a member of the technical staff at the MITRE Corporation, McLean, Virginia, where he is a specialist in environmental chemistry, regulations, and information management. He holds a B.A. in molecular biology from the University of Wisconsin and a Ph.D. in organic chemistry from the Massachusetts Institute of Technology. Before joining MITRE in 1985, Dr. Roberts was on the chemistry faculties of Rutgers and Fordham universities, where he performed research in the areas of peptide and polymer chemistry.

JOHN E. TILTON is the William J. Coulter Professor of Mineral Economics, director of the Division of Economics and Business, and joint director of the Mineral Economics and Policy Program at the Colorado School of Mines. He received a B.A. degree in public and international affairs from the Woodrow Wilson School at Princeton University and M.A. and Ph.D. degrees in economics from Yale University. His teaching and research interests focus on economic aspects of the nonfuel mineral industries, including the shifting pattern of metal mining, East-West mineral trade, economics of exploration, international diffusion of technology, and cyclical instability of mining. He is a former member of the National Materials Advisory Board of the National Research Council and a past president of the Mineral Economics and Management Society.