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Contingency Plans for Chromium Utilization

Report of the
Committee on Contingency Plans
for Chromium Utilization

NATIONAL MATERIALS ADVISORY BOARD
Commission on Sociotechnical Systems
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C.   1978

NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competence 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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PREFACE

Many elements that possess unique properties or impart
unique properties when added to other materials are scarce
and expensive and, consequently, are used sparingly by
material producers and fabricators. Chromium presents a
different and unusual picture: It is an element that
imparts unique properties to the material to which it is
added, but it is not scarce and its price has been
relatively low until recent years. It plays a vital and
almost irreplaceable role in widely disparate commodities
(e.g., stainless steels, tool steels, wrought alloy steels,
cast iron and steel, superalloys, refractories, coatings and
claddings, pigments and paints, leather tanning chemicals,
metal finishing chemicals, and drilling muds), and chromium-
containing materials are used in a variety of high-
technology military and commercial applications.

Chromium, however, is a completely imported element
with known commercial deposits concentrated in only a few
countries: South Africa, 76.6 percent of deposits;
Rhodesia, 20.6 percent; the USSR, 0.8 percent; Turkey, 0.2
percent; other sources, 1.8 percent. Given the global
political situation, the possibility of forming a chromium
cartel that could produce severe economic penalties and
industrial disruptions by interrupting U.S. chromium imports
is of serious concern.

Realizing the gravity of the situation, the Department
of Energy, U.S. Bureau of Mines, National Aeronautics and
Space Administration, and Federal Preparedness Agency (of
the General Services Administration) sponsored this study by
the National Materials Advisory Board of the National
Academy of Sciences to identify alternative means for
reducing chromium consumption so that contingency programs
for substitution, processing, and product design might be
formulated well in advance of any chromium shortages.

As the Committee sought to identify alternative means
for reducing chromium consumption, it concentrated primarily
on: (1) the substitution of materials containing less or no
chromium for chromium-containing materials (Dr. R. W. Smith,
chairman), (2) the use of various production processes, that
would eliminate or reduce the amount of chromium used and
permit chromium recovery by recycling (Mr. E. L. Pepper,
chairman), and (3) changes in component design that would
eliminate or reduce the amount of chromium used (Mr. D. C.
Goldberg, chairman). In assessing these alternatives, the

Committee assumed the worst possible supply situation (i.e., a total embargo on all foreign sources of chromium ore and ferrochromium). The activities of the Commitee and its Panels are described in detail in chapter 2 of this report and its overview of the chromium supply and demand situation is presented in chapter 3. Chapters 4, 5, and 6 present detailed information on the design, processing, and substitution alternatives.

When the Panel drafts were completed, an overview group consisting of Dr. Earl R. Parker, Mr. Selwyn Enzer, Dr. Robin L. Jones, and the three Panel chairmen met to discuss the overlap of Panel material, to evaluate the results, and to discuss the summary of general conclusions and recommendations, in addition to principal considerations that emerged in the overview. The analyses and inputs of Mr. Enzer and Dr. Jones were particularly valuable in this phase.

In summary, this report is the product of the cooperation and expertise of all the individuals and companies cited in the Acknowledgments and is based on data collected through November 1976.

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- Dr. William J. Harris, Jr., of the Association of American Railroads for his survey on the use of chromium in railroad passenger cars

- Allis-Chalmers, Milwaukee, Wisconsin; American Shipbuilding Company, Lorain, Ohio; Engineering Works Division, Dravo Corporation, Pittsburgh, Pennsylvania; Marathon LeTourneau Offshore Company, Houston, Texas; Sun Shipbuilding & Dry Dock Company, Chester, Pennsylvania; The Boeing Company, Seattle, Washington; and Todd Shipyards Corporation, New York, New York, for information on 1975 chromium consumption and estimated consumption through 1980

- The Technical Advisory Committee of The Refractories Institute, chaired by Dr. J. A. Crookston, for the survey of its members regarding the production and shipment of chrome-bearing refractories to various industries, substitution possibilities, material recycling, and future technological requirements

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ABSTRACT

The United States depends entirely on foreign sources for the critical material, chromium, making it very vulnerable to supply disruptions. This vulnerability results because chromium is essential for the fabrication of corrosion-resisting steels and high-temperature, oxidation-resisting alloys in applications that are vital to the nation's technological well-being; because no substitutes are known for these materials in those applications; and because the known, substantial deposits of chromite ore are only in a few geographical locations that could become inaccessible to the United States as a result of political actions. The effectiveness of programs such as stockpiling, conservation, and research and development for substitutes to reduce the impact of disruption of imports of chromite and ferrochromium are discussed. Alternatives for decreasing chromium consumption also are identified for chromium-containing materials in the areas of design, processing, and substitution.

Chapter 1

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Chromium is an element that imparts unique properties to the material to which it is added. While it is an important ingredient in many commodities, it is irreplaceable in stainless steels and high-temperature-resisting superalloys, two classes of materials that are vital to the technological well-being of the nation. Currently, there are no chromium-free substitutes that can be used in these critical applications nor are any such substitutes likely to be developed in the foreseeable future.

The United States is completely dependent on imported chromium and known commercial deposits are located in only a few countries. The Committee could not identify any technological responses that would eliminate completely U.S. vulnerability to a long-term disruption of chromium imports. Accordingly, contigency plans for chromium utilization are assessed, assuming the worst possible supply situation, that is, a total embargo on all foreign sources of chromium ore and ferrochromium. These contingency plans stem from a technical perspective and the study does not propose measures for coping with chromium contingencies by legal, political, or financial means.

1.1 GENERAL CONCLUSIONS AND RECOMMENDATIONS

1.1.1 Conclusions

These general conclusions and recommendations present the Committee's findings regarding the degree to which the United States can reduce its dependence on imported chromium and recommended programs that might lead to reduction of that dependency.

1. Although important segments of U.S. industry are vitally dependent on chromium, insufficient effort has been made to develop substitutes for or to conserve, reclaim, or recycle chromium-containing materials. Consequently, a drastic curtailment of chromium supply would have serious short- and long-term effects.

2. Known chromium reserves are estimated at about 5 billion short tons and are expected to last for several centuries. On the basis of the currently known information, the quantity and location of proven and potential reserves are such that, at

the current rate of consumption, the geographic concentration of chromium deposits will increase; within 25 to 75 years, the world will depend completely upon South African and Rhodesian deposits.

3. U.S. chromium deposits are small and virtually no prospects exist for the discovery of any significant new U.S. deposits. There is little evidence to suggest the existence of significant chromium deposits outside of those geographic areas presently known. The discovery of additional deposits in producing regions with limited known reserves (e.g., the USSR and Turkey or elsewhere) would be beneficial in maintaining the few alternate sources of supply that currently exist, even if the new deposits were not developed initially.

4. No substitutes exist or are likely to be developed for chromium in the high-strength steels, high-temperature metals, and corrosion-resisting alloys that are essential in the manufacture of jet engines, petrochemical and power plant equipment, and various other critical products. It is highly unlikely that corrosion-resisting or high-strength alloy steels without chromium will be developed for such critical applications, although chromium-free substitutes could be used for decorative stainless steels, automotive trim, flatware, refractories, and some chemicals.

5. Current U.S. chromium consumption could be reduced potentially up to one-third within about five years without creating major economic dislocations by using available technology to substitute alternative materials or processes, to recover and recycle waste chromium, and to design for greater chromium efficiency.

6. A major chromium-conserving research program has the potential of reducing U.S. chromium consumption an additional one-third within 10 years but could involve economic penalties (or disruptions) in some areas.

7. Even if the above measures are taken, however, essential or unsubstitutable U.S. chromium consumption is expected to be at least 180,000 short tons per year (approximately 6 percent of 1975 world chromium production), on the average, in the foreseeable future.

8. Sudden mandatory chromium conservation programs would result in severe economic dislocations even if all needed development work were completed in advance.

9. Chromium conservation is an ineffective response to short-term (about five years) shortages. Moreover, unilateral changes in U.S. consumption will have very little impact on long-term world conditions but would create severe economic penalties for the nation.

10. Conventional stockpiling can provide short-term protection (five years) against chromium shortages; however, the continued use of chromium in easily collected functional products (e.g., hub caps, flatware, and coins) may provide a more cost-effective stockpile for the types of shortages the United States is likely to encounter during the remainder of this century.

11. The criticality of chromium to U.S. industry generally is not appreciated, and this lack of awareness works against the development of long lead-time technologies, stockpiles, or international agreements necessary to avoid supply interruptions.

12. The optimum response to the nation's increasing vulnerability to a disruption of the chromium supply probably would involve a combination of three approaches: some form of stockpiling to provide short-term (about five years) protection, conservation measures to provide medium-term (five to ten years) protection by reducing the consumption rate and thereby extending the life of the stockpile, and exploration for new deposits to provide long-term (more than ten years) protection against a total disruption of supply from existing sources.

1.1.2 Recommendations

1. The criticality of U.S. dependence on foreign chromium should be publicized widely in conjunction with the intention to institute a program to decrease U.S. vulnerability to chromium requirements.

2. A basic research program aimed at developing substitutes for chromium in stainless steels and high-temperature, oxidation-resisting alloys

should be initiated. Although this is a long-term program with little chance for early success, it is the only technical possibility for eliminating U.S. vulnerability to a long-term chromium embargo.

3. The search for new chromium deposits outside of current producing areas should be supported with adequate incentives, particularly on the North American continent.

4. Research into chromium conservation and recycling technology should be pursued vigorously, but only price and the marketplace should be used to control consumption. Detailed examination of this interaction will require further study.

5. A study should be initiated to develop innovative methods for stockpiling chromium to provide up to five years protection against a cessation of supply and improved methods for ensuring that the content of the stockpile is matched properly to changing U.S. needs.

6. The combination of approaches -- stockpiling, conservation, and exploration -- should be explored as a strategy in addressing the chromium problem.

7. A thorough technoeconomic follow-on study (including cost-benefit analyses) should be undertaken to assess the substitution potential of chromium-containing alloys.

1.2 SPECIFIC CONCLUSIONS AND RECOMMENDATIONS

These specific conclusions and recommendations represent the Committee's most attractive approaches for reducing U.S. chromium consumption. However, as indicated earlier, these recommendations will not eliminate U.S. dependence on imported chromium but could reduce by two thirds the quantity of chromium that otherwise would have been consumed. It should be noted that implementing the recommendations below would involve considerable time, money, and effort from development of the alloys through various aspects of metallurgical processing such as heat treatment, fabrication, and testing.

1.2.1 Conclusions

1. The design team (consisting of a designer, materials engineer, processing engineer,

nondestructive evaluation engineer, and maintenance entineer) is the most effective technical approach for using and conserving materials.

2. Bias, available resources, reliability and life expectancy, weight, ease of recycling, aesthetics, corrosion, stress, and alternative materials must be considered in the design process.

3. Significant increases in chromium consumption are anticipated only in three product areas during the next 20 to 30 years: nuclear reactors, synthetic fuel plants, and high-temperature batteries. Decreases in the chromium content of materials used in key components of the petrochemical, nuclear, and aviation industries would drastically affect total life, cost, and performance reliability. However, design innovation and changes in purchasing attitudes in other areas could offset this added demand readily (e.g., automotive components such as hub caps, catalytic converters, and other accessories).

4. Conservative design factors of safety, selected arbitrarily and imposed by design specification, can result in excessive product weight, inefficient design, and increased chromium consumption. Nondestructive testing and evaluation can play an important role in chromium conservation by permitting less conservative design factors of safety.

5. Universities and technical societies have a major role to play in creating an awareness of the proper utilization of chromium in products through curricula changes, handbook revisions, seminars, and publications.

6. Various process changes can result in a total chromium savings of appproximately 100,000 tons per year (see Table 28, chapter 5, Processing, for details).

7. Duplex melting and refining systems minimize the chromium loss in slags during melting and refining, and their use in producing tool steels and high-chromium alloy steels could result in substantial chromium savings. (Major stainless steel producers are practicing duplexing now.)

8. Surface coating of materials offers a good opportunity for chromium conservation; applicable processes include stainless clad plate, surface chromium diffusion (sheet and parts), weld overlays, chemical deposition, and ion implantation. Where economic incentive exists, surface coatings already have been utilized. Further extension is limited by economic barriers, e.g., coated and clad products in thin sections. Protecting the edge and joining thin sections in a manner that will preserve the corrosion resistance of the surface and edge presents technical problems that must be solved.

9. Continuous-strand casting to produce tonnage quantities of semi-finished forms (slabs and billets) of chromium-bearing stainless and alloy steels that subsequently are rolled or forged results in significantly higher yields from molten steel to semi-finished product (about 95 percent as contrasted with 85 percent via conventional ingot pouring practice).

   Ceramic mold and precision investment casting can provide products that require minimal machining and that therefore are material-efficient. Opportunities for chromium conservation in technically proven casting processes include near-net-shape cast preforms and cast hollow preforms for pipe and tube production.

   New processes, such as hot isostatic pressing (HIP) to heal casting defects and to improve mechanical properties of precision cast parts, rheocasting, slush-casting and squeeze casting, require evaluation before their technical and economic feasibility and potential chromium conservation possibilities can be established.

10. More than 95 percent of the raw stainless steel melted and converted into steel mill products either is shipped to customers or is recycled as home scrap indicating that limited opportunity exists for further savings in chromium processing of raw stainless steel to mill products. In chromium-bearing alloy and low-alloy steels, the potential for chromium conservation is greater through better alloy identification, separation, and segregation of recyclable home scrap within the steel mills.

11. Steel and alloy processing operations, normally used to achieve the most economical manufacturing, must be reassessed to minimize generated scrap and to ensure that the generated scrap is in recyclable form.

    Powder metal preforms are promising, particularly for parts requiring a minimum of metal removal. To increase the use of this process, lower-cost metal powders and less expensive sintering operations must be available. Also, the interaction between forging and powder metallurgy must be better to achieve a part finished to precise tolerances and high physical properties.

    Chipless machining (e.g., Gesselschaft fur Fertigungstechnik und Maschinenbau Aktiengesellschaft [GFM] machines) could be developed and applied to manufacturing tubes from hollow cylinder shell castings of specialty and alloy steels -- particularly if it were better demonstrated and if published data on its applicability and production capabilities were made available.

    Isothermal forging, especially for chromium-containing nickel-base superalloys, is well suited to the production of near-net-shaped aircraft engine components and structural forms and should improve and increase in use. The needs for advancing this process are improved die materials, new or improved high-temperature lubricants, improved die heating practices, and better design and preparation of die and preform.

12. Today's methods of joining chromium-containing alloys include welding, brazing, soldering, mechanical fastening, and adhesive bonding. Welding is the most efficient method since no other technique equals it for joint efficiency and strength. Brazing and soldering are commercially significant but few brazed joints match the strength of the chromium-containing alloys being joined. Mechanical fastening using high-strength bolts, rivets, lock-seams, sheet-metal screws and keys results in weight and strength penalties; nevertheless, items that must be disassembled later usually are keyed or bolted. Adhesive bonding is far behind other joining techniques in strength and development.

The use of welding and brazing to replace joints mechanically fastened by bolts, rivets, etc., saves material by eliminating double plates, overlap, rivets and bolts. Autogeneous (no filler metal) welding techniques such as electron beam, electron resistance and friction welding, minimize chromium use and wastage. Narrow-gap welds, made by several semi-automatic and automatic processes, are new, important and emerging chromium-conservation techniques.

The use of new lower-chromium-content alloys may require welding for certain applications. The development of lower chromium electrodes, at least matching the chromium content of the proposed new alloys, is preferred over currently available high-chromium-containing welding electrodes.

13. The U.S. stockpile contains over 750,000 tons of various grades of ferrochromium that contain sulfur exceeding the specification of currently commercial ferrochromium grades. Because duplex melting and refining technology can produce stainless steels economically with a lower sulfur content than conventional electric furnace practice, most of the stockpile could be used with little cost penalty. Without duplexing, this ferrochromium would be too expensive to use for stainless steels and might be unusable for chromium-containing alloy steels, tool steels, and high-performance alloys.

14. Recycling conserves material resources, reduces waste and waste materials, and creates economic and social benefits by better handling and disposition of the waste stream. The lowest life-cycle cost -- initial purchase price plus maintenance and repair costs plus longevity -- should be the motivating force in product selection to achieve maximum conservation of materials, energy, labor, and capital. The amount of generated waste can be reduced by promoting product durability, repairability, and maintainability.

15. Technically, approximately 60,000 tons of chromium can be recovered annually from process wastes in the ferroalloy, stainless steel, refractory and chemical industries but, for economic reasons, very little of this waste is recovered now. An opportunity also exists for increased recycling in user industries where its prompt industrial scrap

TABLE 1   Potential Savings of Chromium-Containing Materials (in million pounds)

Material Designation	Total Chromium Used	Total Chromium Saved	Time Required for Substitution				Irreplaceable Chromium[e]
			Immediately[a]	Within 5 Yrs.[b]	5 to 10 Yrs.[c]	At Least 10 Yrs.[d]	
Stainless Steel	569	332	203	--	129	--	237
Tool Steel	7	--	--	--	--	--	7
Wrought Alloy Steel	123	103	22	35	46	--	20
Cast Iron and Steel	82	54	5	10	35	4	28
Non-Ferrous Alloys	29	2	--	--	2	--	27
Chromium Electroplate	21	17	14	3	--	--	4
Refractories	249[f]	225	110	--	115	--	24
Chromium Chemicals	68	11	6	--	5	--	57
Total	1,148	744	360	48	332	4	404

NOTE: The assigned development times imply a reasonably well-funded and well-staffed investigation -- a crash program supported by government and industry might achieve desired results in much less time, while a poorly funded and under-staffed program might drag indefinitely with no tangible results. The development times estimate only the time required to arrive at a viable technological solution to the substitutability problem involved. The time required to implement the technology depends on economic, political and social factors that are too complex to evaluate in any quantitative way and are beyond the scope of this study.

[a] Amount saved by functionally acceptable chromium-free substitutes currently available. Direct or indirect cost penalties are incurred.

[b] Amount saved by functionally acceptable chromium-free substitutes provided after short development (less than 5 years) with a high probability of success. Direct or indirect cost penalties are incurred.

[c] Amount saved by functionally acceptable chromium-free substitutes provided after intermediate-term (5 to 10 years) research with a high probability of success. Direct or indirect cost penalties are incurred.

[d] Amount saved by functionally acceptable chromium-free substitutes provided after long-term (more than 10 years) research with a high probability of success. Direct or indirect cost penalties are incurred.

[e] Amount considered irreplaceable. No functionally acceptable chromium-free substitutes are identifiable. Basic research and new technology are needed.

[f] Includes refractory types not reported by the U.S. Bureau of Mines

is sold via dealers or directly to steel and alloy producers. Much the same is true for obsolete scrap when the cost of collection and separation is high and recovery is low.

The key problems in recycling today are that primary or virgin chromium is relatively inexpensive and secondary metals in general, and chromium in particular, have a low economic value compared to primary metal. However, increasing energy and disposal costs are expected to foster recycling.

16. Substituting other materials for chromium-containing stainless steel, tool steel, wrought alloy steel, cast iron and steel, nonferrous alloys, electroplate, refractories, and chemicals can result in a total chromium savings of 744 million pounds per year (see Table 1, for details) without seriously affecting quality.

17. An assessment of the end-use requirements of major stainless steel categories indicates that:

 • 10 percent (about 32 million pounds of chromium) could be replaced by existing chromium-free materials without serious degradation of service performance.

 • 50 percent (about 160 million pounds of chromium) might be replaced with a high probability of success after a short-term research and development effort.

 • 40 percent (about 125 million pounds of chromium) cannot be replaced without design or process improvements because an unacceptable degradation of service performance would result.

Economical chromium-free substitutes are unavailable for use in chemical processing when corrosion or elevated temperature resistance is required. In a chromium cut-off, these applications must be supplied by allocation or abandoned until new technology is developed.

Alternative copper- and nickel-base alloys also are subject to serious scarcities and are produced in limited quantities. Titanium and titanium-clad steels might be viable substitutes for chromium-containing materials in chemical

tanks and piping where service temperatures are relatively low. Coatings, clad materials, aluminum alloys, and plastics need more research and evaluation before qualifying as substitutes in many applications.

18. The primary contribution of chromium to wrought and cast steel is its influence on hardenability. Several other elements that influence hardenability can eliminate or reduce chromium usage but at a significant economic penalty. An assessment of the end-use requirements of wrought alloy steels indicate that:

- 50 percent (about 64 million pounds of chromium) of the chromium now used probably could be replaced with little difficulty.

- 30 percent (about 39 million pounds of chromium) more might be replaced after a short-term research and development effort.

- 20 percent (about 20 million pounds of chromium) is considered irreplaceable.

Opportunities for substitution are substantial in iron and steel castings and an estimated 50 million pounds of chromium could be saved. Chromium is essential in high-alloy steel castings and the 32 million pounds of chromium used in this application are irreplaceable.

19. Chromium in tool steels is considered irreplaceable in view of the relatively small amount of chromium used (less than 1 percent of total U.S. consumption), the importance of tool steels to the national economy, and the high cost of replacement materials.

20. Although the number of non-ferrous alloy compositions containing chromium is large, the amount of chromium consumed represents only about 2 to 3 percent of total U.S. consumption.

In aluminum-base, titanium-base and copper-base alloys, chromium primarily alters phase relationships to produce specific and preferred microstructures. Although lead times of several years might be required to qualify a substitute alloy for a critical application, reducing or

eliminating chromium consumption in aluminum-, titanium-, and copper-base alloys would not cause major difficulties.

The chromium content of nickel-base, iron-nickel-base, and cobalt-base alloys ranges from 10 to 25 percent, and no other alloying elements confer the same degree of oxidation and corrosion resistance. Although further research and development, especially in the areas of coatings and engineering ceramics, eventually may decrease chromium dependence, it is not now possible to reduce chromium consumption significantly in these alloys by material substitution. For the foreseeable future, it will be necessary to ensure the availability of chromium for these alloys.

21. The largest use of chromium in ceramic products is as chromite refractories in basic steel plants and as facing sands in steel foundries, and to a great extent, non-critical materials may be substituted at some cost/performance penalty. About 50 percent of the chromite could be replaced with little trouble by using magnesite-chrome refractories instead of chrome or chrome magnesite. The refractory industry is not geared to producing promising chromium-free substitutes such as spinel, fosterite, and dolomite in suitable form and quantity. Considerable research, development, and evaluation of these materials is warranted. With favorable cost incentive and chrome scarcity, the potential for salvage and reuse of chrome-bearing refractories is considerable in all consuming industries.

22. Electroplating uses about 4 percent of total U.S. chromium consumption, and the chromium chemicals used are made from chemical-grade chromite ore that generally has been unacceptable for metallurgical processing.

About 60 percent of the chromium used in electroplating is for decorative applications; about 30 percent is for engineering (hard) chromium plate; and the remainder is for other metal finishing. Painted steel, aluminum, or plastic could be used to replace decorative chromium plate resulting in an annual savings of about 14 million pounds of chromium.

A promising available substitute for hard chromium plate is electroless nickel deposition,

and about 3 million pounds of chromium could be saved annually if this process were used; however, considerable development would be necessary to provide the needed productive capacity.

More chromic acid is lost or wasted in processing than actually is deposited as chromium metal on the plated parts, and total consumption of chromium could be reduced substantially by successful recycling.

23. Annual U.S. consumption of chromium chemicals is about 10 million pounds of chromium. The primary chemical, sodium dichromate, is made from chemical-grade chromite ore.

Considerable research has been done in all areas of chemical application to find acceptable substitutes. Except for the wood treatment area in which known substitutes for the small amount of chromium chemicals used could result in an annual saving of 6 million pounds of chromium; all major applications would suffer severe cost and performance penalties if known and proven substitutes replaced chromium chemicals. In an emergency, pigments could be eliminated in about half their uses with a drastic limitation of produceable colors and about 14 million pounds of chromium could be saved annually. No practical substitute exists for the chromium used in tanning leather, the chromium lignosulfates used in drilling mud additives, or the chromium compounds used in water treatment additives. At present, economics favors chromium as corrosion inhibitors in aqueous systems. It is expected that federal regulations will eliminate these compounds in open systems because of their hazard to health.

1.2.2 Recommendations

1. The design team approach should be implemented by the highest operating decision makers of both industry and government. To promote chromium conservation, design teams should be encouraged to ensure that:

    • Materials are specified with actual required composition and properties.

    • Data compilations are available that are current, comprehensive and precise concerning

chromium-bearing materials and their potential substitutes.

- Combinations of materials are used that are compatible with current recycle systems.

- Materials consistently have the required quality.

- Processing is adjusted to accommodate material variations as determined by nondestructive testing, evaluation, and feedback during processing.

- Finished products have the highest quality and reliability possible through in-process control and have reduced reliance on final inspection.

- Products in service can be inspected to determine their remaining useful life and safety, and can be disassembled and repaired easily at relatively low cost.

2. Incentives or penalties should be considered by government to stimulate changes in the design of high-chromium-content products so that they may be readily identified, disassembled, and recycled.

3. Research should be accelerated to develop surface coatings with better high-temperature corrosion and oxidation resistance, including very thin coatings high in chromium.

4. Programs for nondestructive evaluation (NDE) should be specified and funds allocated specifically for NDE implementation in order to improve material and product reliability, to reduce in-process waste and labor, and to permit designing to higher limits.

5. Further development should be encouraged in the duplex melting and refining of alloy steels with substantial chromium content.

6. Research and development efforts on coated thin sections should be increased and emphasis placed on providing adequate edge and surface corrosion protection. <u>Particular attention should be given to the fabrication and joining of coated products to ensure continuity of corrosion-resisting surfaces and joint strength at reasonable costs.</u>

7. Research and development in electroless alloy deposition (such as nickel-phosphorus alloy) should be accelerated to make the process competitive with hard-chromium plating on a cost and performance basis.

8. Research on the ion implantation process should continue on a moderate scale.

9. Research and development in the various casting areas should be accelerated since castings potentially can provide high-strength, near-net-shape products at savings in energy, processing, and cost if they are sound and consistently reliable.

10. Welding electrodes containing less chromium or filler metals matching proposed new alloys should be developed concurrent with the alloys.

11. The sulfur content of ferrochromium purchased for the U.S. stockpile should not exceed the limits of current commercial grades.

12. Programs should be expedited to develop stainless steels (alloyed with aluminum, titanium, and silicon) that might be substituted in many current stainless steel applications.

13. Low-alloy, chromium-free steel compositions should be developed and tested to replace those steels in which chromium is used mainly for its hardenability characteristic.

14. Economic incentives should be created to stimulate the development and use of lower chromium or chromium-free refractories.

15. Further research is recommended to develop economic chromium-free water treatment compounds.

Chapter 2

INTRODUCTION

2.1 BACKGROUND

The United States is entering a period of increasing
materials scarcities and the potential for the formation of
material cartels is growing as materials become concentrated
in relatively few countries. While this situation has
resulted primarily because the world is consuming its raw
materials at an ever-increasing rate, inefficiency and waste
contribute significantly, possibly critically, to creating
an environment in which competition for materials is
intense.

Many studies in recent years have emphasized growing
U.S. dependence upon imported materials (National Commission
on Materials Policy, 1973; National Commission on Supplies
and Shortages, 1976; Takeuchi and Varon, 1975). Although
chromium, as a 100 percent imported critical material, has
been included, the fact that the United States is
strategically more vulnerable to a long-term chromium
embargo than to an embargo of any other natural resource,
including petroleum, has not been recognized. This critical
vulnerability results because:

1. Chromium is essential for the fabrication of
    certain materials (e.g., corrosion-resisting
    steels and high-temperature, oxidation-resisting
    alloys) used in applications (including jet
    engines, aircraft, and chemical equipment) that
    are vital to the nation's technological well-
    being.

2. There are no known substitutes for chromium in the
    fabrication of the alloys mentioned above and no
    other chromium-free materials can be used in these
    applications without enormous performance and cost
    penalties.

3. Virtually all of the known substantial deposits of
    chromite ore are in South Africa, Rhodesia, the
    USSR, and Turkey.

The strategic nature of this situation was not detected
by the materials studies mentioned above primarily because
the five indicators generally used as tests of material
criticality do not reveal the true nature of the chromium
situation. These five indicators are: (1) criticality of
applications, (2) U.S. supplies, (3) alternative

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(substitute) materials, (4) size of reserves, and (5) geographic distribution of foreign sources of supply. While the first three of these indicators reveal that chromium is highly critical, the last two deceptively reduce its strategic nature. Chromium is not in short supply in an absolute sense, and it will take several centuries to deplete current deposits at projected world consumption rates. Even more misleading is the signal that comes from the last indicator, a proxy measure intended to include insight into the geographic distribution of remaining deposits. The proxy indicator of statistical data on which foreign sources have supplied the United States previously with chromium disguises the situation likely to evolve in the future.

In the past, the United States imported chromium from more than six sources in widely separated geographic regions. Within the next 20 to 75 years, however, all remaining known chromium deposits of substantial quantity will be in two geographically close regions -- Rhodesia and South Africa. The chromium deposits in other regions (e.g. the USSR, Turkey, the Philippines, and India) that traditionally supplied the U.S. with chromium either will be exhausted or insignificant.

Unfortunately, the unique role that chromium plays in a technological society and the geographic concentration of remaining reserves are not widely appreciated facts among the economists and market specialists who contribute to most reports on materials. For example, in 1973 it was reported to the President and the Congress that the United States depended completely on foreign chromium sources and that few, if any, alternates to chromium exist for many applications (National Commission on Materials Policy, 1973). However, the Commission failed to note that many chromium-containing materials (that have no substitutes) are absolutely critical to the nation's industry and that the geographic concentration of remaining world chromium resources sets the stage for a natural monopoly. In 1975, two World Bank economists assessing prospective market conditions from 1975 to 1985 for some 27 "strategic" commodities did not include chromium in their list (Takeuchi and Varon 1975).

The strategic nature of chromium also was not stressed adequately by the National Commission on Supplies and Shortages (1976); however, the Commission did highlight two other aspects related to mineral supply and demand situations that are important to the formulation of alternative chromium policies. The first is that the quantity of "known resources" can change drastically in a relatively brief time. Particularly relevant is the

Commission's observation that world chromite reserves have increased 675 percent from 1950 to 1970 despite interim consumption. Discoveries of chromium deposits in regions (including under the oceans) geographically separated from those now being exploited would defuse the criticality of the U.S. vulnerability to a chromium embargo. Secondly, the Commission report includes an excellent discussion of mineral embargoes and identifies the key factors that should be considered in evaluating the possibility of these conditions occurring. Unfortunately (because the Commission failed to recognize that there are no substitutes for chromium in the fabrication of corrosion-resisting steels and high-temperature alloys and that remaining chromium reserves are highly concentrated), the Commission concluded that "the likelihood of a total embargo by exporters of any of the nonfuel minerals is very remote," a conclusion unjustified by the known information concerning chromium.

If the exporters of another material like tin (for which the nation completely depends on imports) were to form a cartel and if that cartel were to cease all shipments to the United States, significant cost and performance penalties would result. Many processes would have to change or less effective materials would have to be substituted and costs would be higher. The United States might even do without some of the products that it currently enjoys. If, on the other hand, the United States had to survive without chromium, the impact would be enormously greater. The rate at which remaining chromium reserves are becoming concentrated in Rhodesia and South Africa makes this a possibility that cannot be dismissed casually.

Experts on international trade frequently state that ultimately economic forces prevail and that as long as deposits are plentiful, dislocations tend to be short-lived since the economic needs of the exporters and importers eventually are brought into balance. However, during the period that extends from the perception of a change in the marketplace to the time by which the new balance is realized, many severe problems can, and often do, occur. Failure to appreciate the unique strategic characteristics of chromium to U.S. industry only intensifies the criticality of the situation and works against developing long lead-time technologies, stockpiles, or international agreements that may avoid economic dislocations.

2.2 CHARGE AND SCOPE

It was in recognition of this situation that the Department of Energy, U.S. Bureau of Mines, National Aeronautics and Space Administration, and Federal Preparedness Agency of the General Services Administration

requested the National Academy of Sciences to undertake a
study to identify alternative technical responses to
reducing U.S. vulnerability to a chromium shortage if one
were to materialize. To be included in these responses were
means for reducing chromium consumption and waste and the
development of guidelines for contingency programs for
substitution and processing and product design changes that
might be initiated either in response to a chromium shortage
or in an attempt to reduce the nation's vulnerability to a
possible chromium shortage. The Academy undertook this
effort and assigned responsibility for the project to the
National Materials Advisory Board, which appointed a highly
qualified Committee on Contingency Plans for Chromium
Utilization to conduct the study.

The study's sponsors agreed that the Committee should
assume a worst-case situation in its deliberations. This
worst case is, of course, a total embargo against the United
States by all foreign sources of chromite ore and
ferrochromium. The Committee also explored some of the
economic and political responses to such an embargo when
such responses involved technical considerations.

In considering such options, a distinction must be made
between two alternative forms in which such an embargo may
occur. One form would involve only the United States (such
an embargo may even be self-imposed -- i.e., the nation may
refuse to buy chromium from all producers). The other form
could involve not only the United States but all of our
major trading partners as well -- Western Europe and Japan.
The responses that would be effective under each of these
forms are different, and these differences are noted, where
appropriate, throughout this report.

In conducting its study, the Committee particularly
sought to determine:

1. The extent to which technical innovation, material
    substitution, conservation, and recycling and a
    combination of these technical responses can
    reduce U.S. vulnerability to a total embargo by
    all foreign sources of chromium.

2. How long it would take to implement these
    technical responses.

3. How likely it is that these responses will produce
    the desired reduction in chromium consumption.

4. Who should initiate or provide the incentive for
    these programs.

5.   The extent to which U.S. reliance on stockpiling
     as a response to a chromium embargo would be
     affected by technical considerations.

Technical alternatives in design, recovery and
recycling, and substitution all have cost and performance
considerations, and cost and performance were important
factors in the Committee's study. However, the Committee
was not charged with evaluating these factors in detail and
its evaluation was concerned with alternatives that appeared
likely to result in "acceptable" options in both performance
and cost. When possible, changes in costs were estimated,
but only on a relative basis. In addition, the Committee
did not evaluate the secondary consequences of changes in
costs so it was not possible to determine how they, in turn,
might affect consumption patterns. Instead, only
conditional judgments were made and generally are reflected
in this report in the following form: If chromium were to
increase in price by a factor of K, then process Y would be
more economical and would result in a saving of Z tons of
chromium per year. These conditional statements assume that
only the price of chromium rises and that there is no
concurrent increase in the cost of other materials or
processes.

This study addresses aspects of contingency planning
other than policy, which is outside the scope of this
Committee. The implementation of many of the approaches
discussed herein also may depend on legislative and
regulatory actions whose aspects or interactions are outside
the Committee's charge.

This report is based on data collected through November
1976.

2.3 STUDY APPROACH

To compile much of the data it needed to make its
overall assessment, the Committee organized into three
panels to focus on design, processing, and substitution.
Each of these panels was concerned both with current
consumption patterns and with expected changes in chromium
consumption in the future. These future changes included
prospects for both reductions and increases in the demand
for chromium.

Even though the panel approach separated the major
issues involved in chromium fabrication and use, many areas
of overlap were encountered. These areas of overlap were
resolved to a great degree by arbitrarily placing
overlapping considerations in one area (e.g., all recycling
aspects were assigned to the Panel on Processing); however,

this did not eliminate the overlaps entirely (i.e., recycling still was treated by the Panel on Design from the perspective of what might be done to "design for recyclability," to collect waste products, etc.). Thus, the division was not as crisp as was desired.

The lack of definitive data concerning the breakdown of chromium usage by application presented a significant difficulty that the Committee attempted to circumvent in part by adopting one set of figures for current and projected consumption. It was recognized that the accuracy of forecasted consumption is uncertain and that recordkeeping variations make historical data uncertain; however, the Committee did not deem this to be an important problem since the major issue is relative changes in consumption that may occur in the future and, for this purpose, any reasonable data base would suffice. It was not possible to deal in the same manner with the lack of consumption data concerning the specific alloys and their applications. Such breakdowns are important if the possibilities for substitutions are to be evaluated accurately and double counting[1] is to be avoided. Thus, the Committee's Panels were forced to estimate such quantities.

The Committee believed that it was important to indicate the probability of success associated with each of the technical alternatives that they identified. These are presented throughout this report with the usual caveats regarding estimates of uncertain outcomes such as technical developments. However, even greater uncertainty surrounds the ability to implement these developments in processes where failure can result in catastrophic losses. Industry is typically reluctant to abandon tried and true materials; thus, the ability to realize the potential savings contained in the Committee's recommendations may depend more on convincing test data and a vigorously implemented information dissemination program than on the technical developments themselves.

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[1]Double counting could occur if, for example, processing changes could reduce the chromium needed to produce a certain alloy by k percent and design changes permitted a reduction in the use of that same alloy by, say m percent. In such a case, the actual amount of chromium saved is k+m-km. However, these quantities cannot be identified accurately without detailed data describing consumption patterns by both alloy and application.

In order to identify alternative technical responses to
a potential shortage of chromium, the Committee developed an
overview of worldwide trends in the supply and demand for
chromium. This overview served to evaluate: (1) the impact
of a change in consumption on available chromium supplies,
(2) the rate at which such supplies are being concentrated,
and (3) the effectiveness of a stockpile as a means of
protection against short-term shortages of chromium. The
overview was not concerned with short-run details, such as
the modifications that might be required by a particular
process to permit one ore to be substituted for another or
the economic consequences associated with such a transition.
While these latter considerations are of critical importance
in actual operations, they mask the macro aspects of how
much ore is left in each region, the importance of possible
technical substitutions, etc. However, the Committee was
concerned with the details involved in the high payoff
technical options for reducing chromium consumption
including their economic considerations, performance
penalties, and time delays. Descriptions of these technical
opportunities comprise the bulk of this report.

The accuracy of the macro results depends heavily on
the Committee's ability to anticipate possible technological
developments and changes in patterns of consumption. This
is a very difficult task even when such analyses are
confined to U.S. consumption as this study is. However, it
is necessary to extend this information to worldwide
conditions in order to appreciate the rate at which chromium
in certain geographic regions is being exhausted. While
this extrapolation of results may be more uncertain than the
impact of the specific technical changes identified in the
body of this report, it is believed that greater
quantitative precision would not alter the basic conclusions
and recommended actions. As will be seen, even if the
actual amount of chromium reserves is considerably different
than currently believed, the time to realize the
consequences presented below would vary only slightly.

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Chapter 3

ALTERNATIVES FOR REDUCING THE VULNERABILITY OF THE UNITED STATES TO FUTURE SHORTAGES OF CHROMIUM SUPPLY

3.1 INTRODUCTION

In view of the present total dependence of the United States upon chromium imports, an assessment of its current and future vulnerability to chromium supply shortages should permit comparison of the effectiveness of several approaches that might reduce this vulnerability. To this end, the past and projected future supply and demand trends are analyzed in this chapter for the United States alone and the entire world. U.S. vulnerability to shortages depends on:

- Changing domestic and world demand that is in competition for the supply controlled by the few producing countries

- Changes in global supply as determined by the composition of the ore deposits of the supplying countries, and the quantity and grade of chromium produced.

The Committee was charged with the task of examining contingency plans for the use of chromium in the event of a drastic future shortage. The detailed deliberations of its Panels on Design, Processing, and Substitution (presented in chapters 4-6 of this report) focus primarily on methods of conserving chromium. In this chapter, conservation opportunities identified by the Panels are quantified using a consistent framework of assumptions so that the overall effectiveness of conservation as a response to shortages of chromium supply may be judged. Conservation is not, of course, the only approach that could be used to reduce the vulnerability of the United States to chromium shortages. Two other possibilities, stockpiling and exploration for additional ore deposits, are discussed briefly together with some combined approaches.

3.2 THE EXTENT OF U.S. VULNERABILITY

3.2.1   U.S. Chromium Consumption

Data showing the apparent U.S. consumption of chromium from 1950 to 1976 are plotted in Figure 1 (U.S. Bureau of Mines, 1950-1976). The chromium metal content of the chromium ore consumed by each of the three major demand segments (metallurgical, refractory, and chemical) are plotted separately in addition to total U.S. consumption.
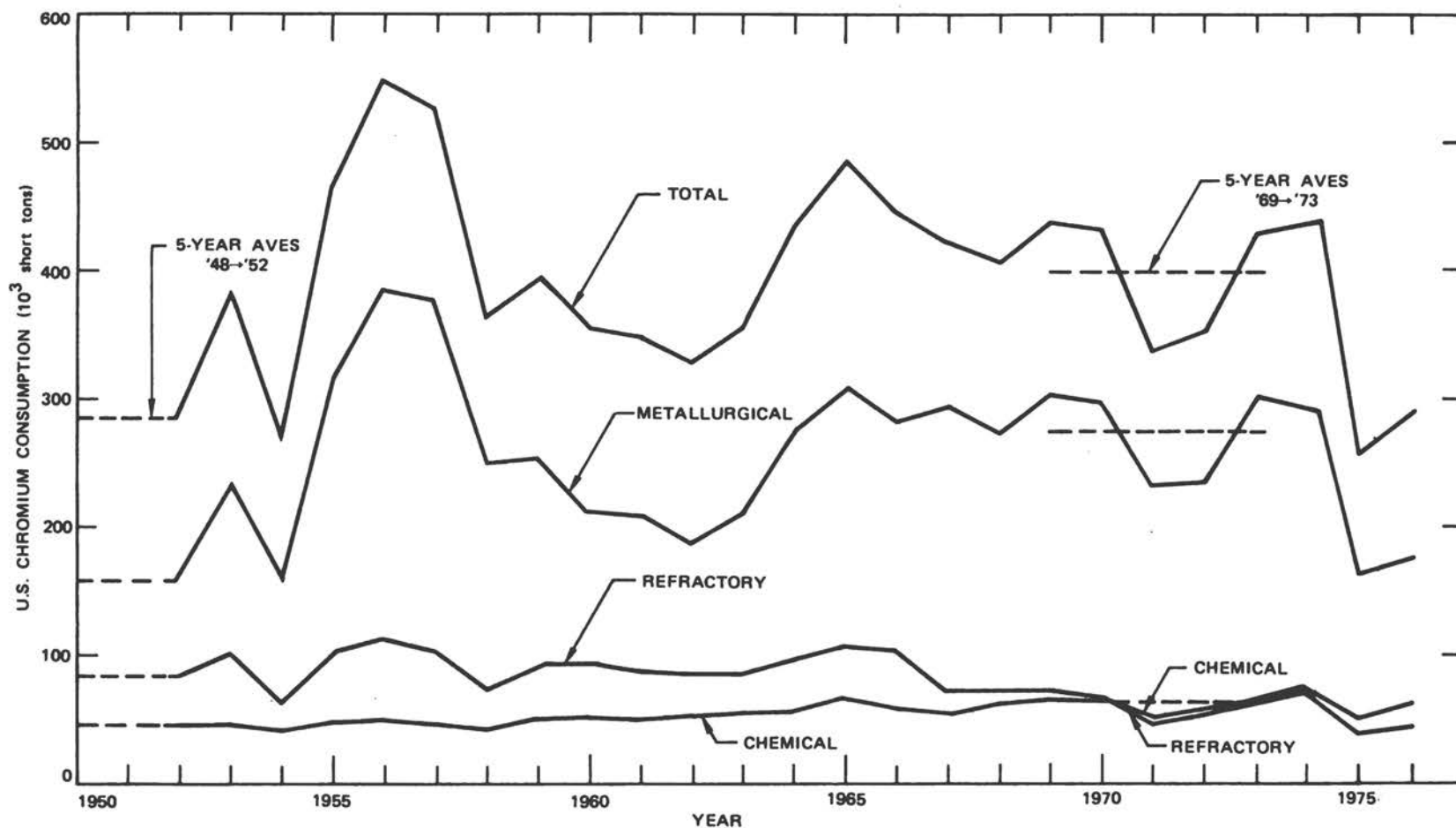
FIGURE 1 Historical Data on U.S. Chromium Consumption (based on data from the U.S. Bureau of Mines 1950-1974, 1975, 1976)

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The same data were used for Figure 2, which illustrates the relative consumption by the three major demand segments over the same time period.

Although the absolute U.S. consumption data are fairly erratic, the trend indicated by Figure 1 is generally one of modest growth. The exception to this behavior is the use of chromium in refractories, which has declined slowly. Comparisons of the average consumptions during the 1948-1952 and 1969-1973 periods indicate the following average rates of growth in U.S. demand over the 21 year period:

Consumption	Percent per year
Total	+1.6
Metallurgical	+2.7
Chemical	+1.6
Refractory	-1.5

Figure 2 confirms that the relative consumption for refractory applications has declined whereas that for metallurgical applications has increased. Chemicals accounted for an almost constant 15 percent of U.S. consumption throughout the period studied.

The use of chromium by type of metal produced has not changed much in the United States during the past decade as indicated by Table 2. The contained chromium consumed in steelmaking as a proportion of contained chromium consumed in all metals utilizing chromium declined modestly between 1964 and 1976, but the absolute amount consumed in steelmaking remained almost constant.

The relative proportions of the major physical forms in which chromium is consumed in the production of metals, refractories, and chemicals in the United States are compared in Table 3 for 1964 and 1976. The table indicates the shift from low-carbon ferrochrome to the more economical high-carbon ferrochrome and the declining absolute and relative use of chromium in refractories.

Figure 3 projects U.S. chromium demand to the year 2000. Metallurgical uses are projected to continue to grow at the historical rate of 2.7 percent per year from a hypothetical 1971 consumption of 275,000 short tons (the average consumption for 1969 through 1973). Similarly, chemical uses are projected to continue to grow at 1.6 percent per year from a hypothetical 1971 consumption of 62,000 short tons. (This projection did not consider changes that may result from pending government regulations restricting the use of toxic chromium compounds, e.g., for water treatment and pigments.) A survey of the refractories
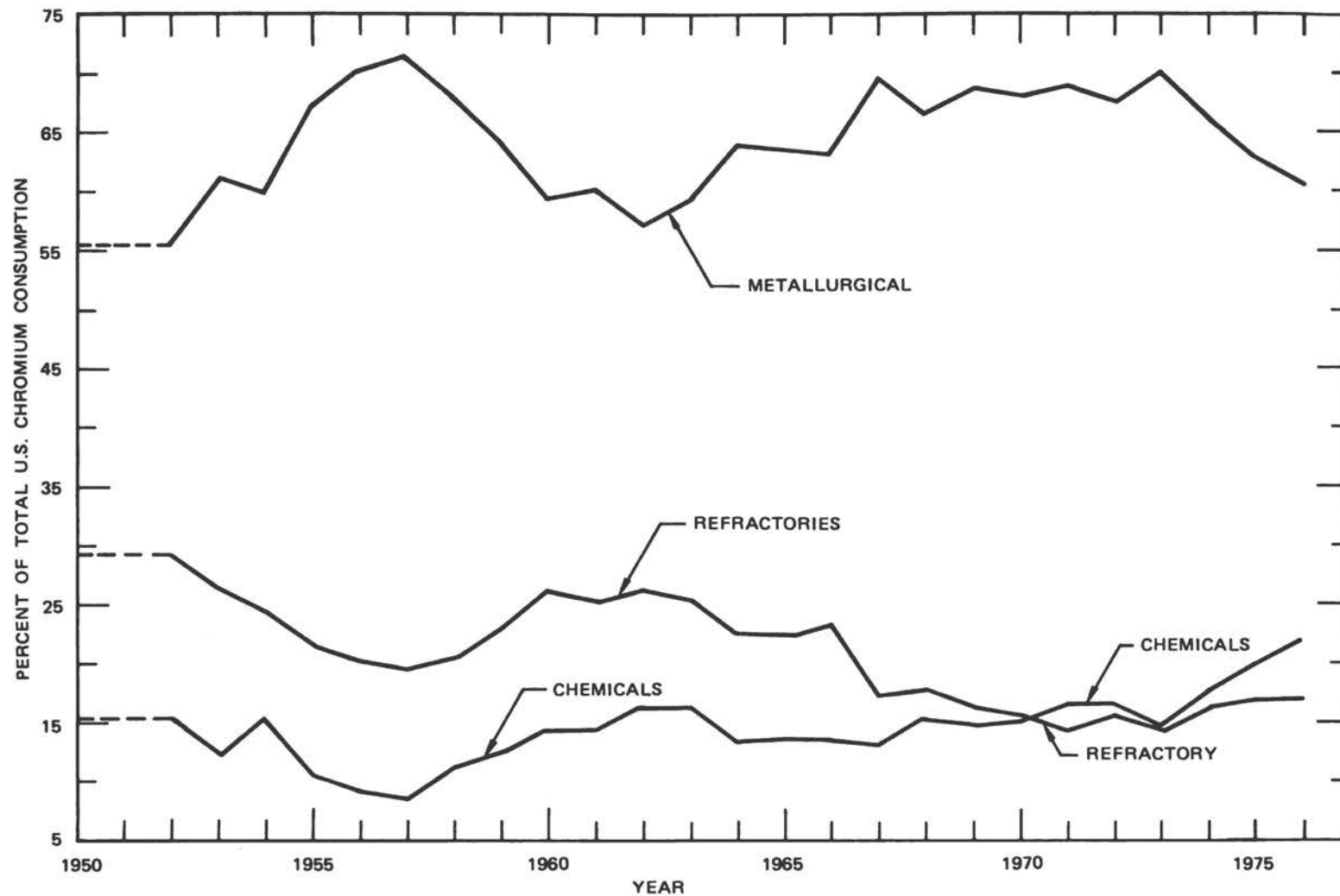
FIGURE 2   Historical Trends in the Relative Importance of Chromium Usage in Metallurgical, Chemical, and Refractory Applications (based on data from the U.S. Bureau of Mines 1950-1974, 1975, 1976)

TABLE 2   Relative Importance of Metals Utilizing Chromium in 1964 and 1976

1964		1976	
Metal	Percent[a]	Metal	Percent[a]
Steel		Steel	
Stainless	70.9	Stainless	69.8
Other alloys	24.2	Tool	1.2
Subtotal	95.1	High-strength low-alloy and electric	3.7
		Other alloy	16.2
		Carbon	1.4
		Subtotal	92.3
		Iron castings	2.6
Iron castings	1.7	Superalloys	2.5
High-temperature alloys	2.2	Other alloys	1.7
Nickel and other alloys	1.0	Miscellaneous	0.9
Total	100.0	Total	100.0

NOTE: Data from U.S. Bureau of Mines, 1964 and 1976.

[a] Contained chromium as a percentage of U.S. metallurgical consumption.

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TABLE 3 Chromium Consumption in the United States by
Physical Form in 1964 and 1976 (1,000 short tons
contained chromium)

	1964		1976	
Metal Production				
High-carbon ferrochrome	83	(21%) [a]	159	(44%)
Low-carbon ferrochrome	104	(27%)	54	(15%)
Ferrochrome silicon	32	(8%)	26	(7%)
Other	10	(3%)	9	(3%)
Subtotal	229	(59%)	248	(69%)
Refractories	114	(29%)	46	(13%)
Chemicals	45	(12%)	64	(18%)
Total	388	(100%)	358	(100%)

NOTE: Data from U.S. Bureau of Mines 1964 and 1976.

[a] The figure in parentheses indicated the percentage of
total U.S. chromium consumption.
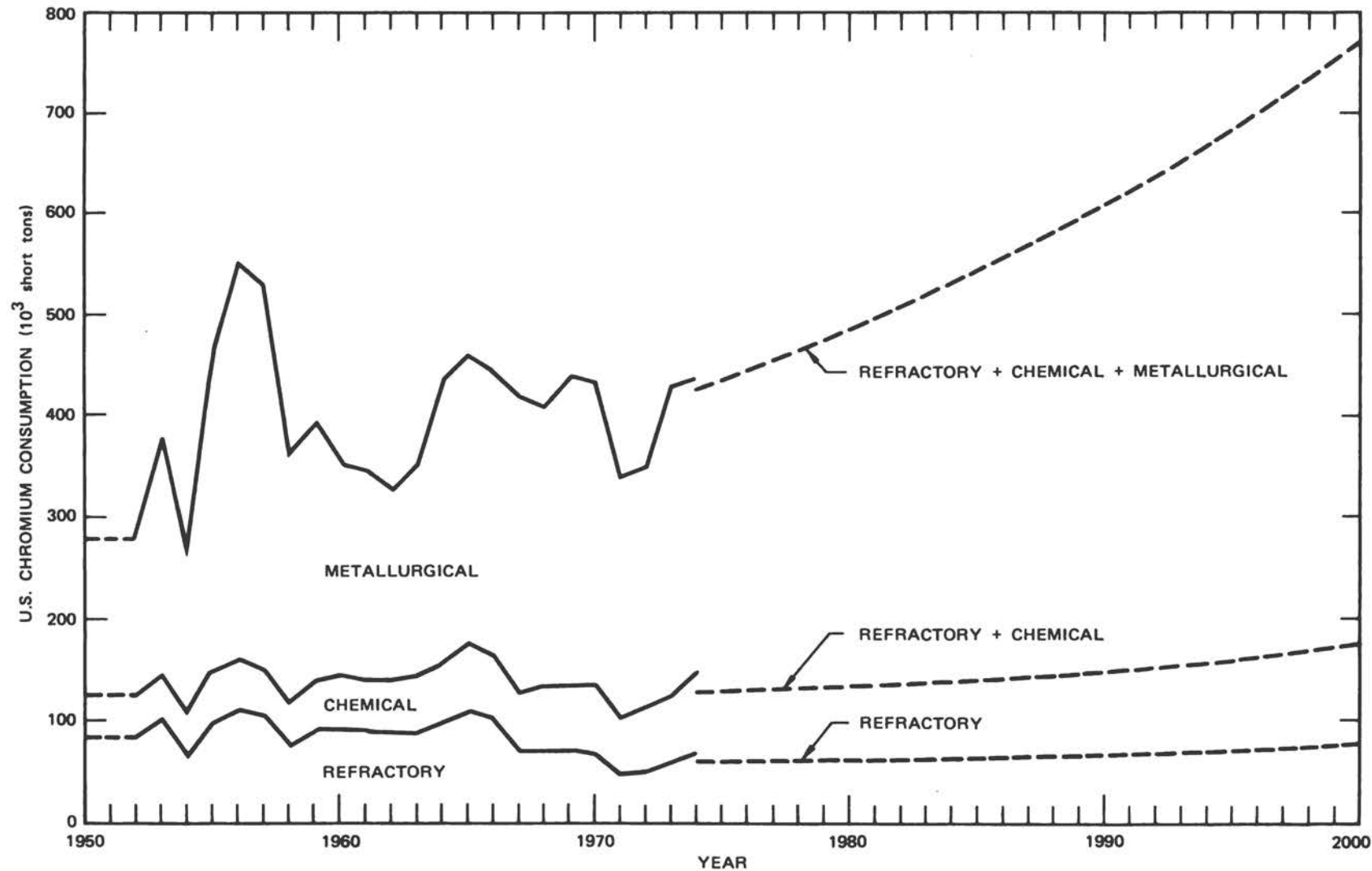
FIGURE 3 Projections of U.S. Chromium Demand (based on data from the U.S. Bureau of Mines 1950-1974, 1975, 1976, and the Committee).

industry undertaken by the Panel on Substitution indicated that chromium consumption in refractories is unlikely to fall much below present levels and may in fact recover somewhat. Therefore, it is projected that refractories consumption will remain static at the average 1969-1973 level through 1982 and will grow at 1 percent per year thereafter. Together, these projections lead to the prediction of a growth in U.S. chromium demand of about 2.3 percent per year through 2000. As shown in Figure 3, annual U.S. chromium consumption is expected to reach about 770,000 short tons by the end of the century.

3.2.2   Sources of U.S. Supply

The United States depends completely on foreign sources of supply to satisfy its demand for chromium. As shown by historical U.S. Bureau of Mines data in Figure 4 and Table 4, the United States has obtained chromium (in the form of chromite and ferrochromium) mainly from five countries: the USSR, Turkey, South Africa, Rhodesia, and the Philippines. Apart from the perturbation in the late 1960s and early 1970s due to the boycott of Rhodesia, the pattern of supply has been fairly stable in the past decade. The largest sources of supply have been South Africa and the USSR, and the remaining imports have been split roughly equally between Turkey, Rhodesia, the Philippines, and other sources.

Chromite ores have been classified into several grades. The definition currently acceptable to the U.S. Geological Survey and the Bureau of Mines is:

"Chromite consists of varying percentages of chromium, iron, aluminum, and mangnesium oxides. Historically, chromite has been classed into three general grades associated with end use; namely, metallurgical, chemical, and refractory. During the past decade, technological advances have allowed considerable interchangeability among the various grades, particularly for the so-called chemical grade, which can be utilized in all three consuming industries. A more definitive classification is high-chromium (metallurgical grade) for chromite containing a minimum of 46 percent chromic oxide (Cr_2O_3) and with a chromium-to-iron (Cr:Fe) ratio greater than 2:1; high-iron (chemical-grade) chromite containing 40 to 46 percent Cr_2O_3 and with a chromium-to-iron ratio of 1.5:1 to 2:1; and high-aluminum (refractory-grade) chromite containing more than 20 percent aluminum oxide (Al_2O_3) and more than 60 percent Al_2O_3 plus Cr_2O_3." (U.S. Bureau of Mines 1975).
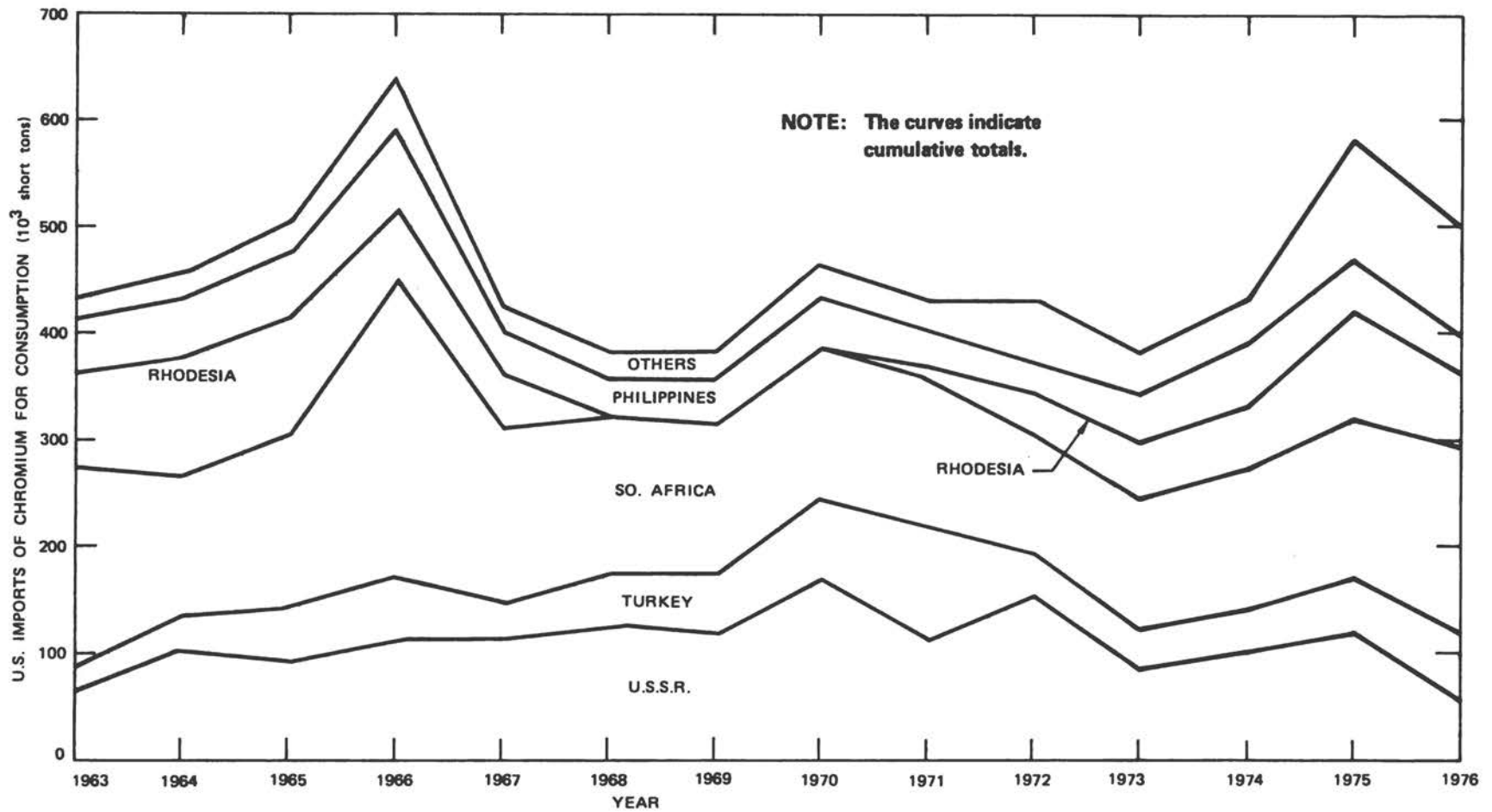
FIGURE 4   Sources of U.S. Chromium Imports (based on data from the U.S. Bureau of Mines 1950-1974, 1975, 1976)

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TABLE 4 U.S. Chromium Imports from Various Sources, 1963-1976 (1,000 short tons)

Year	USSR	Turkey	South Africa	Rhodesia	Philippines	Other	Total
1963	64	25	186	89	47	23	434
1964	103	32	134	110	51	29	459
1965	91	51	163	110	61	29	505
1966	112	59	280	65	77	48	641
1967	113	35	164	49	43	23	427
1968	125	49	147	--	38	23	382
1969	118	56	141	--	44	24	383
1970	170	79	137	--	48	35	469
1971	112	107	141	8	36	27	431
1972	154	40	109	40	29	59	431
1973	82	41	126	51	44	44	388
1974	103	40	142	47	58	42	432
1975	120	53	147	101	48	111	580
1976	61	61	172	67	37	101	499

NOTE: Based on data from U.S. Bureau of Mines 1963-1975 and 1976.

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3.2.3   World Supply and Demand

Figure 5 shows past and projected world production
(apparent consumption) of chromium. Historical data
suggested the 3 percent annual rate of growth that is used
for the projection, and on this basis, world chromium
consumption is expected to reach about 3.8 million short
tons by 2000 -- roughly double present demand (the Institute
of Geological Sciences, 1955-1975). Thus, U.S. consumption
as a percentage of the world total should decline slightly
from its present level of about 24 percent to about 20
percent in 2000.

Chromium is the twenty-first element in the earth's
crust in order of abundance, ranking with zirconium,
vanadium, zinc, nickel, copper, and tungsten as being
moderately abundant. Chromite is the only commercial
mineral of chromium and varies compositionally within wide
limits permitted by the formula:

$$(Mg, Fe^{2+}) (Cr, Al, Fe^{3+})_2 O_4$$

The Cr_2O_3 content of chromite ranges from about 15 percent
to 64 percent, but directly usable ores that are mixtures of
chromite and silicate minerals range from about 33 percent
to 55 percent Cr_2O_3.

Of the three variations of chromite ore recognized,
high-chromium ores are used mostly for metallurgical
purposes, principally for making ferrochromium. High-iron
ores are used in the production of chromium-based chemicals
and are finding increased use in the manufacture of lower
quality ferrochromium. High-iron ores also are used for
refractory purposes and foundry sands. High-aluminum ores
are used mostly for refractory purposes, principally in the
manufacture of magnesite-chrome and chrome-magnesite bricks.

In the following discussion, chromium ore deposits are
classified in two broad categories: reserves (ores
considered exploitable under existing economic and
technological conditions) and potential ores (deposits that
demand more favorable conditions for exploitation). The
term "resources" is used to designate the total of reserves
plus potential ores.

Known world chromium ore resources are summarized in
Table 5 (U.S. Bureau of Mines and other sources). Known ore
resources total about 5 billion short tons and are estimated
to contain about 1.2 billion short tons of chromium, more
than a 500-year supply at present demand levels. Thus, the
physical limitations of world primary chromium resources
will not be a consideration by 2000. However, Table 5
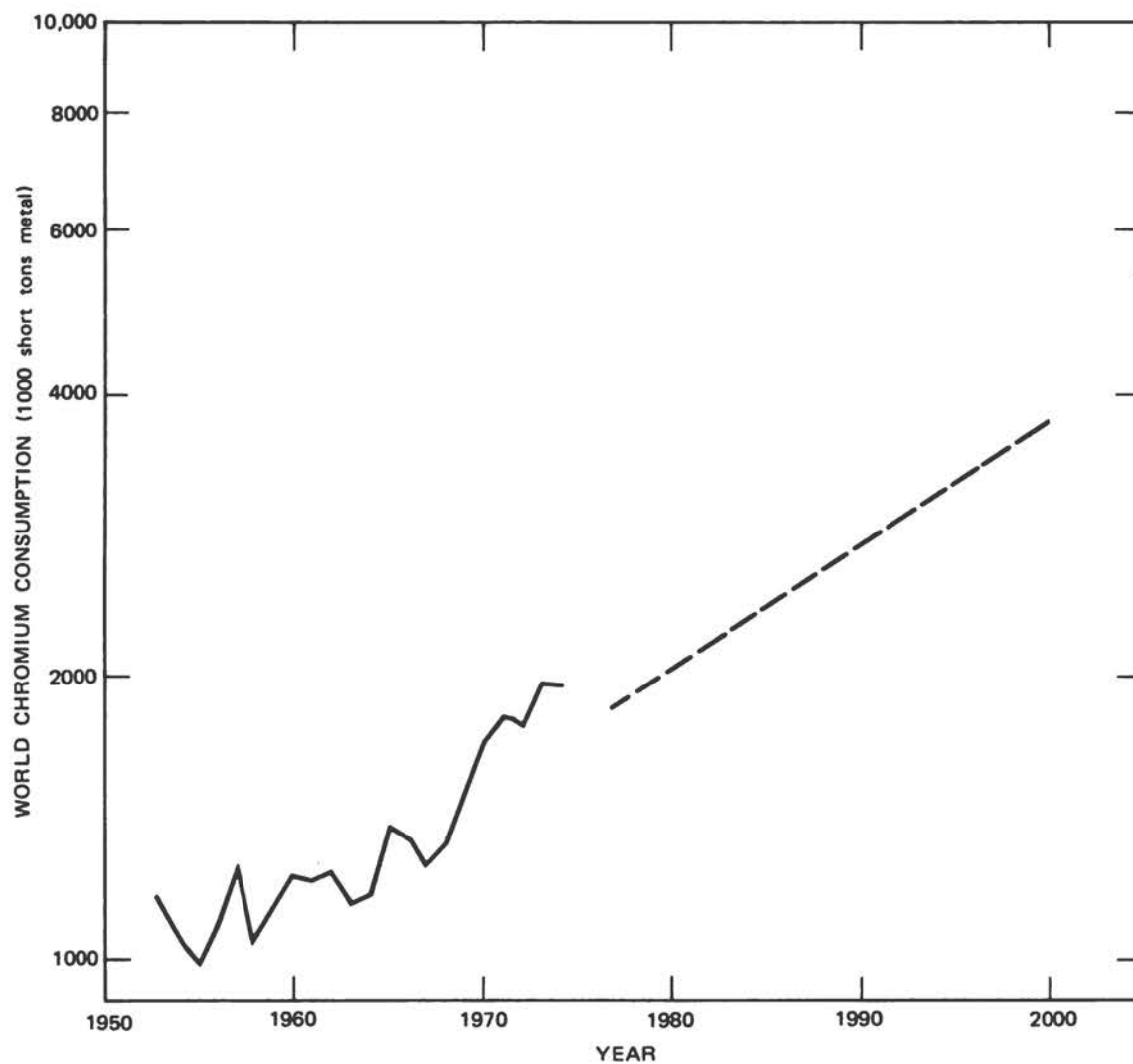
FIGURE 5   Historical and Projected World Chromium Consumption
           (based on data from the Institute of Geological
           Sciences 197)

Table 5   World Chromium Ore Resources

Country	Known Ore Reserves Million Short Tons Ore	% World	Known Potential Ore Million Short Tons Ore	% World
South Africa	1,194	62.4	2,333	76.5
Rhodesia	626	32.7	626	20.5
USSR	24	1.2	25	0.8
Philippines	5	0.3	< 1	< 0.05
Turkey	2	0.1	6	0.2
All other	63	3.3	58	2.0
Total	1,914	100.0	3,049	100.0

reveals a remarkable geographical concentration of the world's chromium ore resources. Two countries, South Africa and Rhodesia, together have nearly 95 percent of the known world reserves and about 97 percent of the known potential ore.

3.2.4   Discussion and Conclusions

Any country that depends entirely on foreign sources for the supply of a strategically important raw material is potentially vulnerable to economically or politically motivated shortages. In the past, the United States reduced its chromium vulnerability by obtaining its supplies from sources that differed widely in both geographical location and political ideology (see Table 4 and Figure 4); however, it seems clear from Table 5 that this approach will become increasingly difficult in the future. Because South Africa and Rhodesia completely dominate known chromium ore resources, they eventually also must dominate world chromium supply. It might be argued that additional ore discoveries in other parts of the world would tend to reduce the future dominance of southern Africa; however, the known ore resources in South Africa and Rhodesia are so vast that there is little incentive for additional exploration in other areas. Thus, it is probable that a natural chromium supply monopoly will evolve and that the United States will depend increasingly on South Africa and Rhodesia for its future chromium requirements. As a consequence, U.S. vulnerability to chromium shortages will increase greatly.

It is important to examine the time scale over which this conclusion is likely to become reality. A crude method of quantifying the period involved is shown in Table 6 which compares the longevities of the major known deposits of chromium ore (assuming continuing ore production at 1973 levels). Although depletion time estimates of natural resources are notoriously unreliable, the data suggest that South Africa and Rhodesia will reach a monopolistic situation within 25 to 75 years. Clearly, the projected increase in world consumption (Figure 5) will tend to decrease this period, and any major new ore discoveries in other parts of the world will tend to increase it.

Another way to state this situation is to treat world chromium resources as if they consisted of just two sources of supply: South African and Rhodesian, and the rest of the world. If the South African and Rhodesian sources were disrupted and the rest of the world provided the entire demand for chromium, the depletion time at the 1975 level of 8.74 million short tons of ore would be 21 years. Furthermore, even if the United States reduced its consumption level to zero during this disruption period, the

TABLE 6 Depletion Times for Known Chromium Ore Resources

Country	Known Chromium Ore Resources (million short tons)	1973 Chromium Ore Production (million short tons)	Depletion Time at 1973 Production (years)
South Africa	3,527	1.85	1,906
Rhodesia	1,252	0.61	2,052
USSR	49	2.13	23
Philippines	6	0.65	9
Turkey	8	0.63	13
All Other	121	1.58	77
Total	4,963	7.45	666

NOTE: Based on data from the Institute of Geological Sciences, 1975.

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time to depletion would increase only to 27 years. These
data indicate not only the limited longevity of known
chromium deposits outside of Africa but also their relative
insensitivity to U.S. consumption. Indeed, concentration of
world chromium reserves is not exclusively a U.S. problem
and the problem cannot be solved by reduced U.S. consumption
alone.

3.3 CHROMIUM CONSERVATION

One response to a shortage of chromium supply would be
to attempt to reduce consumption, and identification of the
opportunities that exist to do so was the major topic
addressed by the Committee. This section presents
quantititive estimates (based on the detailed considerations
presented in chapters 4-6) of the reductions in chromium
consumption that could be achieved by conservation programs
in the areas of substitution, recycling and improved
processing practice, and design. Two types of conservation
opportunities are distinguished and are considered
separately:

- Category 1 -- Technically feasible with currently
available technology

- Category 2 -- Potentially feasible with future
technology but requiring up to 10 years research
and development

Using these definitions, chromium uses may be viewed as
being of three types:

(1) Those that could be eliminated by using existing
substitutes or by making other state-of-the-art
technological adjustments

(2) Those that could be eliminated if a conservation
research program were initiated and proved to be
successful

(3) Those that could not be eliminated using either of
the above approaches

Before the amounts of chromium that fall in each of these
three classes can be calculated, a forecast of the U.S.
consumption pattern must be made. Projections of chromium
consumption in metallurgical, refractory, and chemical uses
were presented earlier (Figure 3); however, a more detailed
breakdown of U.S. consumption is required to quantify
specific conservation opportunities. A breakdown of the
amounts of chromium expected to be used during 1977 in 21
end-use areas is presented in Table 7. This forecast, which

TABLE 7 Trend Forecast of U.S. Chromium Consumption Pattern in 1977

Use	Quantity Consumed [a] (1,000 short tons)	Percent of U.S. Consumption
Metallurgical		
Wrought stainless and heat-resisting steels	232	51.3
Tool steels	6	1.3
Wrought alloy steels	43	9.5
Cast alloy steels	14	3.1
Alloy cast irons	8	1.8
Nonferrous alloys	14	3.1
Other	6	1.3
Subtotal	323	71.4
Refractories		
Chrome and chrome-magnesite	10	2.2
Magnesite-chrome brick	14	3.1
Granular chrome-bearing	27	6.0
Granular chromite	10	2.2
Subtotal	61	13.5
Chemicals		
Pigments	18	4.0
Metal finishing	15	3.3
Leather tanning	11	2.4
Drilling muds	3	0.7
Wood treatment	4	0.9
Water treatment	4	0.9
Chemical manufacture	5	1.1
Textiles	2	0.4
Catalysts	< 1	< 0.3
Other	5	1.1
Subtotal	68	15.1
Total	452	100.0

[a] Exclusive of scrap.

is based on data obtained by the Panel on Substitution, has
been scaled to match the 1977 trend projections for
metallurgical consumption (323,000 short tons), refractories
consumption (61,000 short tons), and chemical consumption
(68,000 short tons) shown in Figure 3.

3.3.1 Quantification of Opportunities to Reduce Chromium Consumption

Opportunities for chromium conservation by improved
recycling of industrial wastes are discussed in detail in
Chapter 5. Combining the chromium recovery opportunities
identified by the Panel on Processing with the projected
1977 chromium consumption pattern presented in Table 7
allows the potential chromium savings to be estimated as
shown in Table 8. All the potential chromium savings fall
into Category 2 (considered potentially feasible with future
technology but requiring up to 10 years of research and
development). By far, the most important recycling
opportunities are in the refractory uses of chromium where
recycling of about 40,000 short tons of chromium per year
(65 percent of the projected 1977 consumption of chromium in
refractories) is considered potentially feasible. Recycling
of metallurgical and chemical wastes does not offer any very
exciting opportunities for chromium conservation. It is
estimated that only 4.5 percent of the projected 1977
consumption of chromium in metallurgical end uses and only
about 6 percent of the chemical consumption potentially
could be recovered from industrial wastes. Moreover, a
considerable number of recycling technologies would have to
be developed to achieve even these modest recoveries because
of the diversity of wastes involved.

The Panel on Processing also considered the prospects
for chromium conservation by improving the metallurgical
processing of chromium-containing alloys. Four processing
steps were identified in which the potential exists for
significant chromium savings. Table 9 presents estimates of
the potential chromium savings scaled to the 1977
metallurgical consumption pattern shown in Table 7. About
21,000 short tons of chromium per year (6.8 percent of 1977
metallurgical consumption) could be saved by employing
existing advanced technology for melting, refining, and
casting operations. It is estimated that an additional
annual savings of about 16,000 short tons of chromium would
become technically feasible if research and development
directed toward processing improvements were undertaken and
proved to be as successful as expected.

Chromium conservation opportunities associated with
materials substitution are considered in detail in
chapter 6. In most cases, the effective use of a substitute

TABLE 8 Prospects for Chromium Savings by Recycling of Industrial Wastes

Source of Waste	Potential Chromium Savings [a]	
	1,000 Short Tons per Year	Percent of 1977 Segment Consumption
Metallurgical		
Ferroalloy slags	1.0	0.3
Stainless steel furnace dusts	2.5	0.8
Stainless steel grinding swarfs	2.0	0.6
Stainless steel mill scale	3.6	1.1
Stainless pickel liquor	0.8	0.2
Ferroalloy flue dusts	3.5	1.1
ECM and EDM sludges	1.3	0.4
Subtotal	14.7	4.5
Refractories		
Foundry sand	21	34
Chrome-bearing refractories	19	31
Subtotal	40	65
Chemicals		
Etching wastes	1.0	1.5
Plating wastes	2.0 [b]	2.9
Catalysts	0.7	1.0
Chromate and dichromate, leather tanning, paint pigments, and textiles	0.4	0.6
Subtotal	4.1	6.0
Total	58.8	13.0

[a] All the potential chromium savings fall into Category 2 (considered
potentially feasible with future technology but requiring up to 10 years
of research and development).

[b] At present, 1,000 short tons are recovered from plating wastes.

TABLE 9 Prospects for Chromium Savings by Processing Improvements

Processing Step	Potential Savings — Category 1[a]		Potential Savings — Category 2[b]	
	1,000 Short Tons Chromium Per Year	% of 1977 Metallurgical Consumption	1,000 Short Tons Chromium Per Year	% of 1977 Metallurgical Consumption
Melting and refining	19	5.9	0	0
Casting	3	0.9	6	1.9
Mill product fabrication and manufacturing processing	0	0	9	2.8
Joining	0	0	1.4	0.4
Total	22	6.8	16.4	5.1

[a] Technically feasible now.

[b] Potentially feasible after 10 years of research and development.

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material containing less or no chromium would require some
redesign of the product, as discussed in chapters 6 and 4.

By combining the conservation opportunities identified
in chapter 6 with the projected pattern of U.S. consumption
in 1977 (Table 7), the estimates of potential chromium
savings shown in Table 10 have been obtained. It is
estimated that potentially one-quarter of the metallurgical
and chemical consumptions of chromium and one-third of the
refractory consumption can be substituted using existing
technology. If suitably directed research and development
programs are undertaken, it is estimated that substitution
of an additional one-third of metallurgical consumption and
one-half of refractory and chemical consumption would become
technically feasible.

The estimates of chromium savings presented in Tables 8
through 10 all refer to the same projected 1977 consumption
pattern. It is valid, therefore, to combine them to obtain
estimates of the total potential impact of technically
feasible conservation measures on the U.S. consumption of
chromium. Table 11 presents the summary of estimates of the
percentages of metallurgical, refractory, and chemical
consumption that could be saved by taking advantage of
Category 1 and Category 2 conservation opportunities in the
areas of substitution, processing, recycling, and design.
The table also lists the sum of the Category 1 and 2
percentages that represent the maximum savings considered
technically feasible for each combination of conservation
approach and chromium consumption segment. For example,
substitution using existing technology (Category 1) is
estimated to be capable of saving 25 percent of the
metallurgical consumption of chromium. As a result of
research and development, it is anticipated that
substitution of an additional 36 percent of the same
metallurgical consumption base would become technically
feasible. Therefore, the maximum technically feasible
savings of metallurgical consumption that can be achieved by
substitution is 61 (25 + 36) percent.

The percentages in Table 11 can be added horizontally
but not vertically (because of the problem of double
counting). Thus, in Table 11, the total Category 1 plus
Category 2 savings that can be achieved in metallurgical
consumption is not 78 (= 61 + 12 + 5) percent but rather is
more closely approximated by:

$$67 = 100 - \frac{39 \times 88 \times 95}{10,000} \text{ percent}$$

This results because the application of recycling to obtain
a 5 percent savings would permit conservation by processing

TABLE 10 Prospects for Chromium Savings by Materials Substitution and Redesign (1,000 short tons)

End Use	Consumption Forecast for 1977	Potential Chromium Savings	
		Category 1 [a]	Category 2 [b]
Metallurgical			
Wrought stainless and heat-resisting steels	232	69.6 (30%) [c]	69.6 (30%)
Tool steels	6	0 (0%)	0 (0%)
Wrought alloy steels	43	6.5 (15%)	30 (70%)
Cast alloy steels	14	1.4 (10%)	8.4 (60%)
Alloy cast irons	8	0.8 (10%)	4.8 (60%)
Nonferrous alloys	14	0 (0%)	0.7 (5%)
Other	6	1.8 (10%)	1.8 (50%)
Subtotal	323	80.1 (24.8%)	115.3 (35.7%)
Refractories			
Chrome and chrome-magnesite brick	10	7.5 (75%)	2.5 (25%)
Magnesite-chrome brick	14	4.0 (28%)	8.0 (56%)
Granular chrome-bearing materials	27	5.0 (18.5%)	20.0 (74%)
Granular chromite	10	4.0 (40%)	4.0 (40%)
Subtotal	61	20.5 (33.6%)	34.5 (56.6%)
Chemicals			
Pigments	18	4.5 (25%)	9.0 (50%)
Metal finishing	15	7.5 (50%)	2.3 (15%)
Leather tanning	11	0 (0%)	11.0 (100%)
Drilling muds	3	0 (0%)	0 (0%)
Wood treatment	4	2.0 (50%)	2.0 (50%)
Water treatment	4	0 (0%)	2.0 (50%)
Chemical manufacture	5	0 (0%)	2.5 (50%)
Textiles	2	1.0 (50%)	1.0 (50%)
Catalysts	< 1	0 (0%)	0 (0%)
Other	5	1.0 (20%)	3.0 (60%)
Subtotal	68	16.0 (23.5%)	32.8 (48.2%)
Total	452	116.6 (25.8%) [d]	182.6 (40.3%) [d]

[a] Technically feasible now.

[b] Potentially feasible after 10 years of research and development.

[c] Number in parentheses indicates percent saving of consumption forecast for each end use category.

[d] Percent saving of total for all categories.

TABLE 11 Overall Summary of Potential for Chromium Savings

Conservation Approach	Consumption Segment	Percent of Segment Consumption That Can Be Saved		
		By Category 1[a]	By Category 2[b]	By Categories 1 and 2
Substitution with materials containing no (or less) chromium coupled with redesign as necessary	Metallurgical	25	36	61
	Refractories	34	57	91
	Chemicals	24	48	72
Use of improved processing methods for alloys containing chromium	Metallurgical	7	5	12
Recycling of wastes containing chromium	Metallurgical	0	5	5
	Refractories	0	65	65
	Chemicals	0	6	6

[a] Technically feasible now.

[b] Potentially feasible after 10 years of research and development.

improvements, and substitution would only be applied to the remaining 95 percent of the original metallurgical consumption. Similarly, if the 12 percent processing saving is taken on the remaining 95 percent, only 95 x 88/100 percent of the original metallurgical consumption will be available for substitution savings. When the 61 percent substitution savings are taken, the remaining consumption will be reduced to:

$$\frac{95 \times 88 \times 39}{10,000} \text{ percent}$$

of the original metallurgical consumption, which leads to the 67 percent overall savings quoted above.

With the above approach, the 1977 chromium consumption was estimated for metallurgical, chemical, and refractory uses for three cases:

- Business as usual (BAU), i.e., the trend forecasts from Figure 3 and Table 7

- Business as usual less the savings from Category 1 conservation opportunities

- Business as usual less the savings from Category 1 and Category 2 conservation opportunities

The consumption estimates are tabulated in Table 12 and suggest that U.S. chromium consumption potentially could be reduced by 30 percent by conservation based on existing technology. An additional 40 percent reduction in consumption could become technically feasible if research and development related to chromium conservation were pursued vigorously. The remaining 30 percent of current U.S. chromium consumption cannot be eliminated by the conservation measures identified by the Committee.

3.3.2   Consumption Projections at Two Conservation Levels

The impact that conservation could have on the future consumption of chromium in the United States now can be projected. Two cases will be considered: The first examines the impact of technically feasible conservation measures based on existing technology (i.e., Category 1). The second case shows the impact of the maximum level of conservation considered technically feasible (i.e., Category 1 + Category 2).

Because the metallurgical, chemical, and refractory consumption segments are projected to grow at different rates in a business-as-usual situation (Figure 3), they were

TABLE 12 Overall Impact of Potential Conservation Opportunities on
Chromium Consumption Forecast for 1977 (1,000 short tons)

Consumption Segment	Present Consumption (BAU [a])	Projected Net Consumption	
		BAU - Category 1 [b]	BAU - Categories 1 and 2 [c]
Metallurgical	323	225 (70%) [d]	105 (33%)
Chemical	68	52 (76%)	18 (26%)
Refractories	61	40 (66%)	2 (3%)
Total	452	317 (70%)	125 (28%)

[a] Business as usual.

[b] Business as usual less the savings from Category 1 conservation opportunities (technically feasible now).

[c] Business as usual less the savings from the conservation opportunities from Category 1 (technically feasible now) and Category 2 (potentially feasible after 10 years of research and development).

[d] Numbers in parentheses indicate percent of 1977 segment consumption.

treated separately in preparing the projections that follow. However, it was assumed that the pattern of chromium use within each of the three segments would change little during the remainder of this century. This assumption permits use of the percent business-as-usual data listed in Table 12 for the three segments to estimate the impact of conservation on future U.S. consumption.

Figure 6 summarizes the trends in chromium consumption that would result if the United States reduced its chromium consumption by implementing conservation measures based on currently available technology. The several scenarios included in Figure 6 assume that no supply constraints exist. Curve ABC is the business-as-usual projection from Figure 3. Curves ADH and AEH are projections of consumption following initiation of Category 1 conservation programs in 1977. The consensus of the Committee was that a period of five years might be needed to implement Category 1 conservation measures in an orderly manner but that implementation probably could be accomplished in about half that time in a national emergency. The 5-year and 2.5-year implementation periods result in curves AEH and ADH, respectively. (For convenience, it has been assumed that consumption falls linearly as the Category 1 conservation measures are implemented.) Curves BGH and BFH depict the effect of initiating an equivalent conservation program in 1987 for 5-year and 2.5-year implementation periods, respectively.

Figure 6 shows that implementation of the Category 1 conservation measures leads to a transition from the business-as-usual consumption growth curve to a second growth curve at about a 30 percent lower level of consumption. However, because implementation of the conservation measures requires a significant amount of time, the minimum consumptions reached when the conservation program has been fully implemented are always greater than 70 percent of the consumption at the time the program was initiated. For example, the consumption at E, the low point on curve AEH, is about 78 percent of that at A because of the anticipated continuing growth during the implementation period in those end uses not affected by the conservation measures.

If Figure 6 is considered in the context of a chromium supply shortage, it is apparent that the effectiveness of conservation as a response increases as the implementation time decreases. Thus, the shaded triangles ADE and BFG in Figure 6 represent chromium consumption that is eliminated by implementing the Category 1 conservation measures over a 2.5-year period rather than a 5-year period.
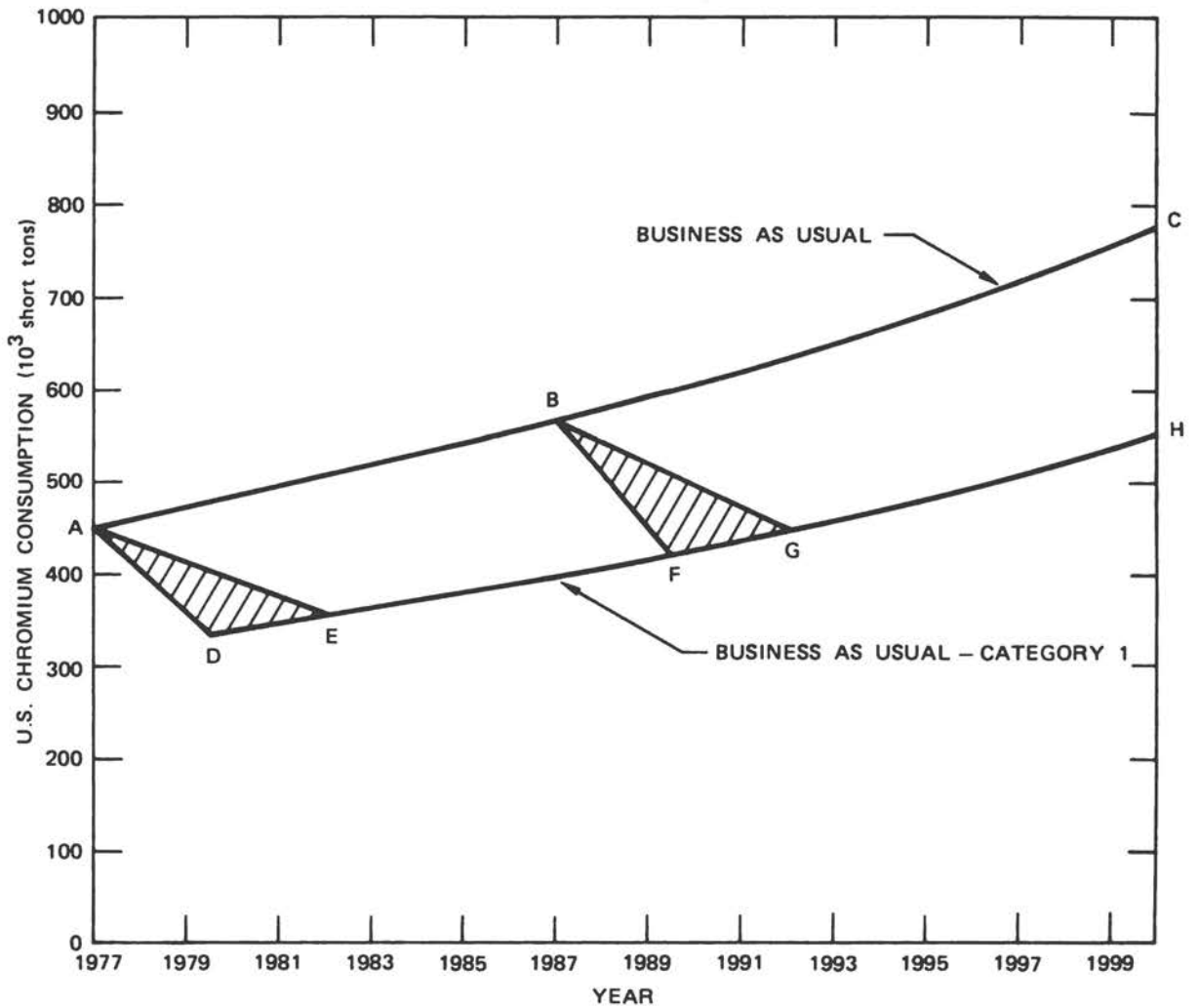
FIGURE 6 Projections of U.S. Chromium Consumption Showing
the Impact of Implementing Conservation Measures
Based on Currently Available Technology

Figure 7 summarizes the expected trends in chromium consumption if the United States were to implement all the conservation measures considered by the Committee to be potentially technically feasible. Curve ABC again shows the business-as-usual consumption projection from Figure 3. As before, implementation of the conservation measures results in a transition from the business-as-usual curve to a lower consumption growth curve that, in the present case, is at about 30 percent of the business as usual consumption level. Curve ADEH projects the consumption expected if the U.S. were to implement Category 1 and Category 2 conservation measures over a 12.5-year period (considered the minimum practicable in view of the 10-year research and development period required before implementation of some of the Category 2 measures could begin) beginning in 1977. Segment AD, replotted from Figure 6, reflects the impact (assumed linear) on consumption of implementing the Category 1 conservation measures as quickly as possible. Segment DE, (again assumed linear) is attributable to implementation of the Category 2 measures as they become available. At E, the low point on the curve, the consumption is about 170,000 short tons per year or about 37 percent of the consumption level at which the conservation program was initiated. However, a long lead time of 12.5 years is required to fully implement the conservation measures.

Curve ABIGH is based on the same assumptions as curve ADEH except that program initiation is assumed to occur in 1987 rather than in 1977. Here again, implementation of the Category 1 and Category 2 conservation measures drives consumption down to about 37 percent of the level at which the program was initiated but only over a long period of time. In contrast, curve ABFH shows the projected consumption if the research and development needed for the Category 2 conservation measures had been completed in advance (i.e., if the required 10-year research and development program had been initiated in 1977 and had been brought to a successful conclusion before the initiation of the conservation program). It is estimated that implementation of the Category 1 and Category 2 conservation schemes then could be completed within five years. The consumption at the end of this period would be about 180,000 short tons or about 32 percent of the consumption at the initiation of the program. If the conservation program was undertaken in response to a supply shortage, curve ABFH would represent a much stronger response than curve ABIGH because it would allow reducing the cumulative U.S. chromium consumption to be decreased by an amount equivalent to the shaded area in Figure 7.
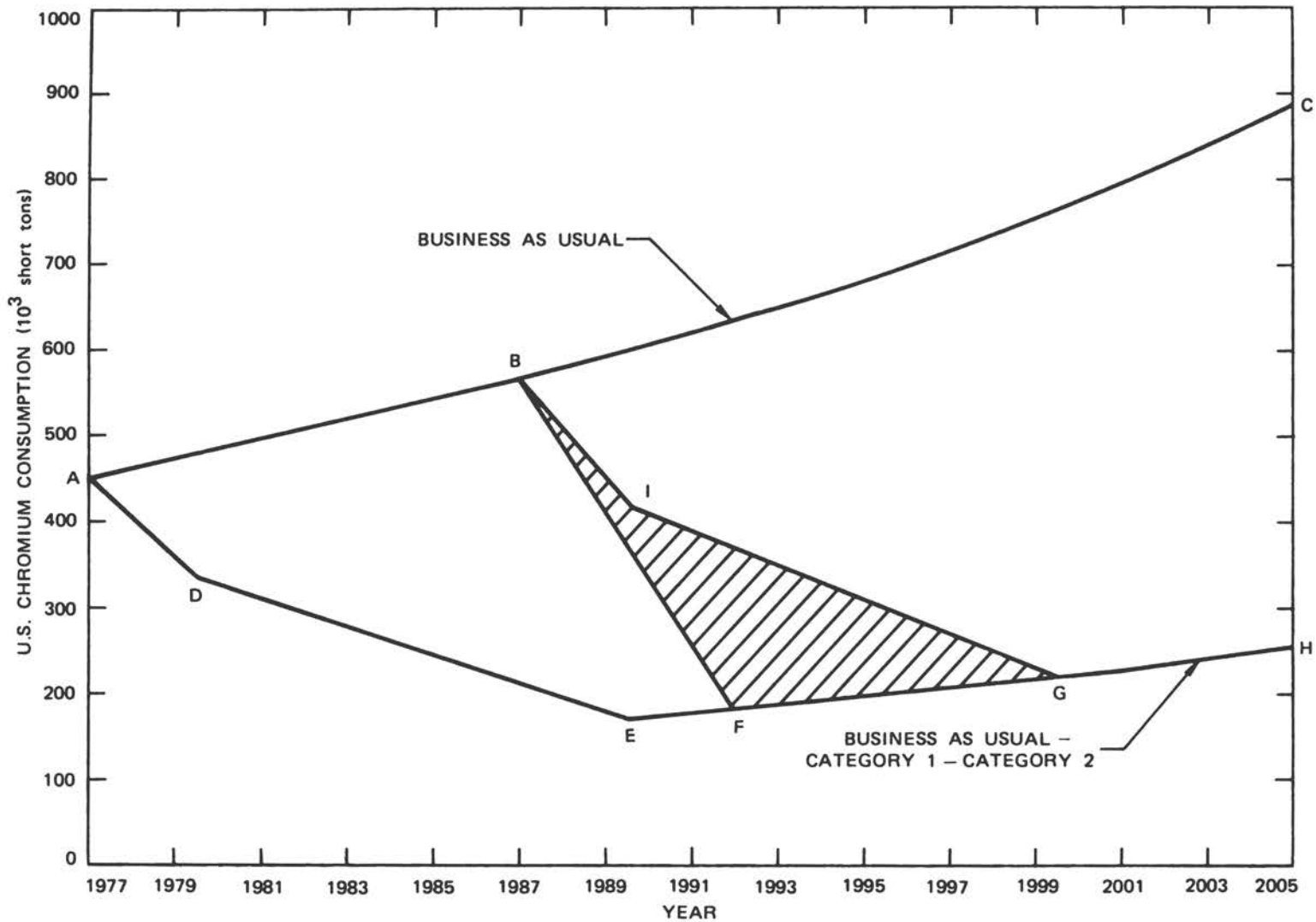
FIGURE 7   Projection of U.S. Chromium Consumption Showing the Impact of
Maximum Technically Feasible Conservation

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The quantitative estimates of chromium savings and lead times embodied in Figures 6 and 7 are subject to considerable uncertainty and very few accurate data exist for improving the present estimates. Moreover, further refinement of the quantitative data probably would not have much effect on the conclusions reached since the consumption rate is offset only temporarily.

3.3.3   Impacts of Conservation

In this section, the following question is considered: If an intensive program of chromium conservation is implemented by the United States in response to a chromium supply shortage, what would be the foreseeable impacts, other than the desired decrease in consumption? Chromium is irreplaceable for some applications and the amounts used for them are small compared to total U.S. consumption. Hence, the available chromium would be allocated preferentially to these end uses. Examples of industries that would be affected little by drastically reduced chromium availability and strong efforts to conserve it are:

- Tool steels, which use chromium for metal cutting and forming

- Superalloys, which use it for jet engines and gas turbines

- Chromium chemicals, which are used in closed systems for water treatment additives and in leather tanning.

Some industries would benefit by drastically reduced availability of chromium and by strong efforts to conserve it. Examples are manufacturers of substitute materials such as titanium, tantalum, aluminum, zinc, plastics, porcelain enamel, coatings, and metal paints. A lack of chromium because of high prices or government taxes to restrain its use and enforce its recycling would strongly encourage substitute materials. Many industries would benefit by recapturing old markets previously lost to chromium-containing materials or by creating new markets. As no one material could substitute across-the-board, the impact on any given material would be modest but always positive.

Other industries, likely to benefit, are associated with recycling efforts. Examples are:

Industry	Application
Scrap sorting	Metals
Crushing and grinding	Refractories and foundry sands
Chemical processing	Chemical waste and effluents
Beneficiation	Stockpiled material and low-grade ore

An immediate demand by chromium-consuming industries to use state-of-the-art recycling equipment and technology in the above applications would be expected as well as incentives to develop more efficient and less costly new processes.

Still other industries likely to benefit are associated with the production of clad and coated materials and their subsequent testing and processing. In the event of a requirement to reduce chromium demand substantially, the use of stainless clads and coatings on less corrosion- and oxidation-resisting materials would increase and would require new technology and increased production capacity. More importantly, demand would arise for equipment to form, join, and edge-seal such composite materials. New nondestructive testing procedures and equipment also would be required to ensure the integrity of the protective surface layer when initially formed and after subsequent in-plant processing.

Many industries would be affected unfavorably by drastically reduced availability of chromium and strong efforts to conserve it. Examples are:

Industry	Use
Refractories	Steel producers and foundries
Nonferrous alloys	Broad spectrum of users
Stainless steels	Fabricated metals, machinery other than electrical, transportation
Alloy steels	Primary metals, machinery other than electrical, fabricated metals

The greatest impact would be on stainless steel producers and users because the opportunity to apply or develop low-chromium stainless alloys is limited. In a truly drastic supply situation, it would be necessary to live with less stainless steel. The consequences for some user industries would be modest or only economic in nature, but the effects would devastate others, such as the nuclear power industry.

Very few of the chromium conservation opportunities identified in chapters 4 through 6 are cost-effective at present; therefore, implementing an intensive program of

chromium conservation would involve substantial costs as well as sacrifices in service performance. These added costs may arise from more complex designs, additional processing steps, additional testing or from the use of more expensive substitute materials. As a consequence, the overall impact of a chromium conservation program on the U.S. industry and economy is certain to be negative. Just how negative would depend critically on the extent to which conservation was implemented. Although the Committee was unable to generate any meaningful quantitative estimates, it is considered likely that achievement of a 70 percent reduction in consumption, while technically feasible, might be potentially crippling to the economy but that a 30 percent reduction might be attainable without serious economic consequences or industrial dislocations.

3.3.4 Discussion and Conclusions

It would be technically feasible to reduce U.S. chromium consumption by about one-third by implementing existing conservation technology and by about two-thirds by supplementing existing technology with the new developments expected to result from a 10-year program of research and development related to chromium conservation. The effectiveness of conservation as a response to a chromium shortage depends strongly on the time required to implement the chromium conservation programs -- a much stronger response to a hypothetical supply shortage in 1987 would be possible if, in the interim, the 10-year research and development program, mentioned above, had been completed successfully. Even so, the lead times required to fully implement chromium conservation programs are so long that conservation would not become effective as a response to a shortage of supply unless the shortage were to last for several years.

The Committee does not believe that the reductions in chromium consumption discussed in this section will be self-initiating in the U.S. market-oriented economy. Rather, the reductions represent what could be expected from a planned program. In the Committee's view, if the United States were faced with a shortage of chromium supply, the need for a planned program would be imperative. If the marketplace were the sole determinant for allocating limited supplies of chromium, automobile bumpers might win out over chemical tanks.

The industrial dislocations and economic penalties associated with an intense national effort to conserve as much chromium as is technically feasible would be severe but might be acceptable in a national emergency. However, if the United States attempted to pursue chromium conservation

unilaterally in anticipation of a possible supply shortage rather than in response to a real situation, the substantial penalties involved would not be justifiable. In fact, unilateral conservation by the United States as a hedge against a possible future shortage makes very little sense except for the relatively few conservation opportunities that do not entail cost-performance penalties. Since most of the conservation measures are not currently cost-effective, they would not be implemented voluntarily but would have to be legislated. The effect of such legislation would be poorer quality and more expensive products than could be produced with the normal use of chromium. Aside from the reduction in societal benefits, these legislated changes would have a substantial economic impact on the competitive position of these U.S. products relative to foreign products that would be made using the normal chromium practice. For example, if the United States decided unilaterally to substitute silver plate for stainless steel in domestically produced flatware, foreign suppliers of stainless steel flatware would attempt to satisfy the U.S. market with their less expensive products. If the United States truly wanted to conserve the chromium used in stainless steel flatware, it would be necessary to embargo imports. This solution is not very practical considering the vast number of products for which a comparable situation would exist.

On the other hand, a reduction in chromium consumption on a worldwide basis (if such an agreement could be reached) might be justifiable if it provided the time necessary to develop durable agreements regarding the management of remaining chromium resources. This aspect is part of a much larger issue concerning world mineral resources in general and is beyond the scope of this Committee's deliberations.

Although in the United States it is difficult to justify initiating any chromium conservation programs that are likely to produce adverse economic consequences, research aimed at the development of alternative materials, process improvements, design efficiencies, and recovery and recycling of spent chromium should be accelerated. As seen in Figure 7, the developments that result from this research would be of considerable value if a shortage of chromium supply occurred in the future. This research also may produce new methods for reducing chromium consumption that are economically attractive, particularly if chromium prices rise. However, under present economic conditions, the required research is not likely to be undertaken by industry without government incentives.

Finally, although conservation may reduce the vulnerability of the United States to chromium shortages, it

cannot eliminate it. About one-third of U.S. chromium
demand cannot be saved by conservation measures based on
present or projected future technology. Much of this
chromium is consumed in uses that are absolutely vital to
U.S. industry. Approaches other than conservation,
therefore, are required to assure that enough chromium is
available to satisfy these needs. Moreover, because of the
long implementation times required, conservation alone would
be of little value in the event of an abrupt disruption of
chromium supply. To respond effectively to this situation,
stockpiles could make up larger deficits while conservation
measures are being implemented, in addition to providing the
substantial amounts still required on a continuing basis.

3.4 ALTERNATIVES AND SUPPLEMENTS TO CONSERVATION

3.4.1 Stockpiling

One of the traditional approaches to the problem of
providing protection against potential cartelization of raw
materials has been the use of stockpiles and, indeed, the
U.S. Government has a stockpile of chromium. A summary of
the content of the stockpile is presented in Table 13.

The time to deplete this stockpile depends on the rate
at which the United States is consuming chromium and the
makeup of the stockpile. Figure 8 shows a projection of the
approximate number of years to use up the entire stockpile
as a function of time, assuming that all of the material in
the stockpile inventory at present could be used and that
U.S. consumption follows the business-as-usual growth curve
depicted in Figure 3. (The question of whether the present
content of the stockpile is optimum is addressed in
chapter 5.) As can be seen, the stockpile offers more than
three years of protection at present consumption rates;
however, this protection would dwindle to less than two
years by 2000 if no conservation programs are initiated and
the stockpile itself is unchanged.

The key issue regarding stockpiling of chromium
concerns the type of protection sought. If protection is
sought against a cartel trying to maximize its economic
returns and if that cartel has the resources to hold out
long enough, no feasible stockpile can suffice. If, on the
other hand, the United States is seeking protection against
temporary supply dislocations, such as might occur due to
short-term instabilities, it is necessary to define an
appropriate protective time period. For any such decision,
Figure 8 indicates the protection that would be realized
from the current stockpile. Changes in the stockpile would
produce proportionate shifts in protective times.

TABLE 13 U.S. Government Stockpile of Chromium-Based
Materials (1,000 short tons) [a]

Description	Inventory	Estimated Contained Chromium
Ores		
Metallurgical	1,984	651
Chemical	254	76
Refractory	406	86
Nonstockpile grade	561	172
Ferroalloys		
High-carbon	409	266
Low-carbon	304	198
Silicon	57	23
Nonstockpile grade	25	13
Chromium metal	4.5	4.5
Total		1,489.5

NOTE: Based on data from U.S. Bureau of Mines 1975.

[a] As of September 30, 1975.
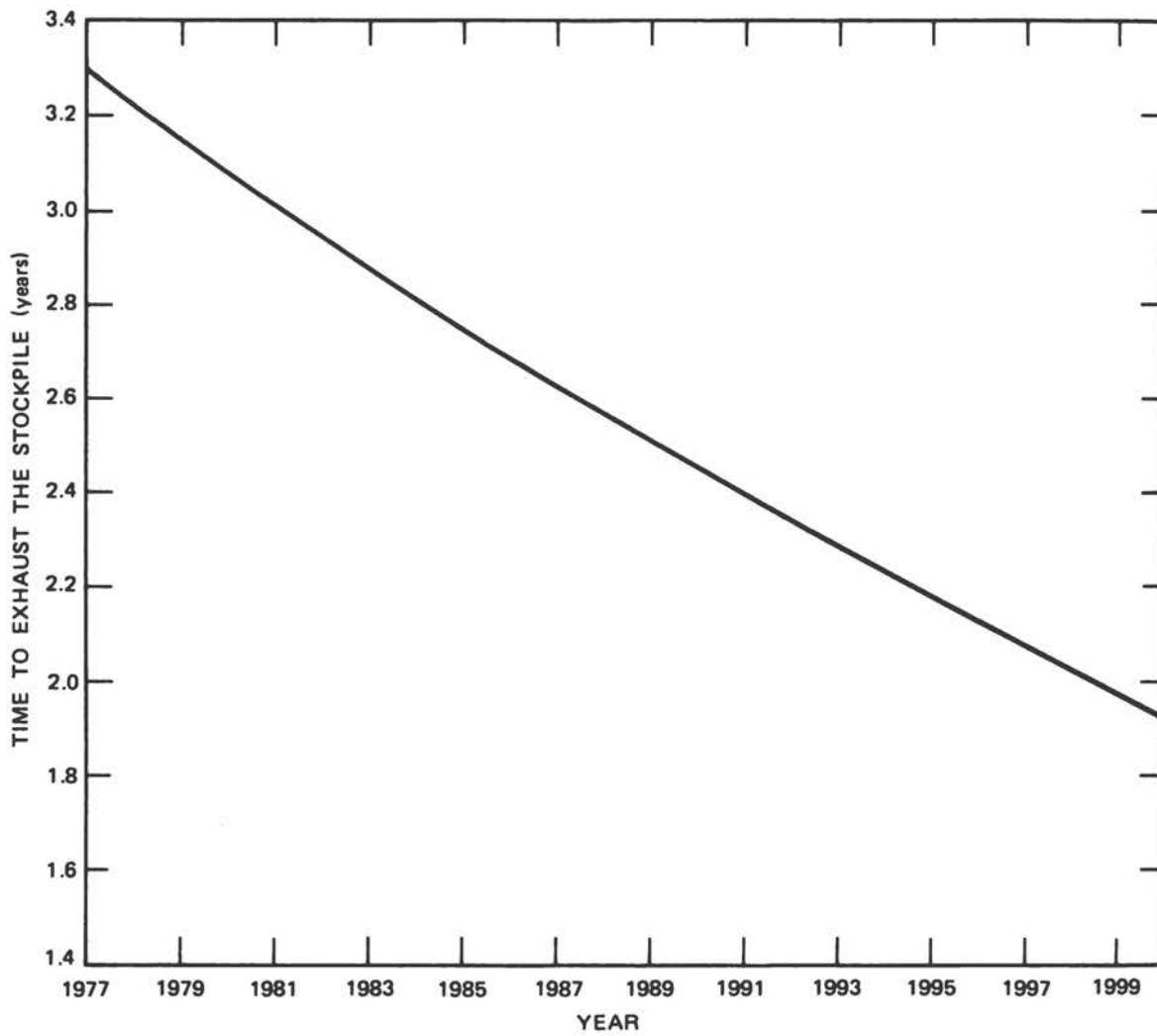
FIGURE 8   The Protection Offered by the U.S. Chromium
           Stockpile on a Business-As-Usual Basis

The U.S. strategic stockpile of chromium is part of a program concerned primarily with wartime protection. During such emergencies, the causes of shortages and the natural demand patterns are considerably different from those normally encountered. Should the United States wish to increase its stockpile as assurance against "economic warfare," politically induced embargoes, etc., innovative approaches to stockpiling may be appropriate. For example, if all the new automobiles sold in the United States contained 10 pounds of chromium in an easily recoverable form (e.g., hub caps made from a standard high-chromium alloy), within about 10 years, a "stockpile" of about 500,000 short tons would have been established -- enough to satisfy the demand for about one year. This suggestion would require study by government and a government policy decision, and would have to be implemented by the end-use industry involved.

Although the maintenance of a strategic stockpile of chromium-containing materials generally is accepted as a necessary and effective strategy, the desirability of a separate economic stockpile is a controversial subject being debated in and out of Congress. An economic stockpile might benefit from the cyclical nature of world industry by accumulating excess stocks of minerals and metals when times are slack, providing a buffer from severe economic dislocations in an emergency and a little more time for research and development on alternative responses to minerals shortages.

3.4.2   Exploration

Another method of reducing the vulnerability of the United States to future shortages of chromium would be to attack directly the developing problem of increasing geographic concentration of chromium ore resources. As mentioned earlier, the United States has reduced its vulnerability in the past by obtaining its chromium needs from a diverse group of suppliers. This policy could be continued if additional exploration resulted in the discovery of new, high-quality ore deposits in areas of the world remote from southern Africa. It would not be necessary to develop these deposits. The mere fact of their existence would provide excellent protection against a long-term supply embargo (but not against a short-term supply disruption).

However, as mentioned earlier, the size of the Rhodesian and South African reserves essentially eliminates any incentive for additional exploration on the part of private industry. Thus, any additional exploration probably must be financed by the U.S. government, either directly or

indirectly. The involved exploration costs could be considerable, and high capital costs would be incurred if the new deposits had to be developed hurriedly in an emergency. Moreover, there is absolutely no assurance that additional exploration would uncover new, economically exploitable ore deposits. Thus, although additional exploration might aid in reducing U.S. vulnerability, exploration alone would not provide a solution to the problem.

3.4.3   Combined Approaches

Up to this point, the Committee considered the separate use of conservation, stockpiling, and exploration to reduce U.S. vulnerability to future shortages of chromium. However, an optimum solution to this situation probably would be to combine two or, possibly, all three of these approaches.

For example, if exploration were undertaken and proved successful, these new sources could reduce the vulnerability of the United States. However, in the interim, the stockpile must provide adequate supplies for the time needed to develop the newly discovered ore deposits. An alternative approach (that would avoid the element of uncertainty involved in exploration and might also prove to be less expensive) would be to combine conservation and stockpiling. Figure 9 shows the way in which the stockpile would be depleted following a hypothetical complete cessation of chromium imports at the beginning of 1987. If the present stockpile were used to supply the entire U.S. consumption and consumption continued unchecked (i.e., consumption followed the business-as-usual curve in Figures 6 and 7), the stockpile would be exhausted by mid-1989 (curve 1). Implementation of the Category 1 conservation measures over a 2.5-year period (curve ABFH in Figure 6) would increase the depletion time only by about 7 months. Even if the maximum technologically feasible conservation response was implemented (curve ABFH in Figure 7), the stockpile would still be exhausted by mid-1990.

The ineffectiveness of the conservation measures in the case illustrated in Figure 9 is due to the comparatively long lead times required to implement the conservation programs. Obviously, protection can be improved by adjusting the stockpile size to obtain a better match between the stockpile depletion time and the time required to implement the conservation measures. Figure 10 illustrates what happens if the available stockpile is doubled to 3 million short tons of contained chromium and if chromium imports cease in 1987. In this case, unchecked consumption (curve 1) would exhaust the stockpile in five
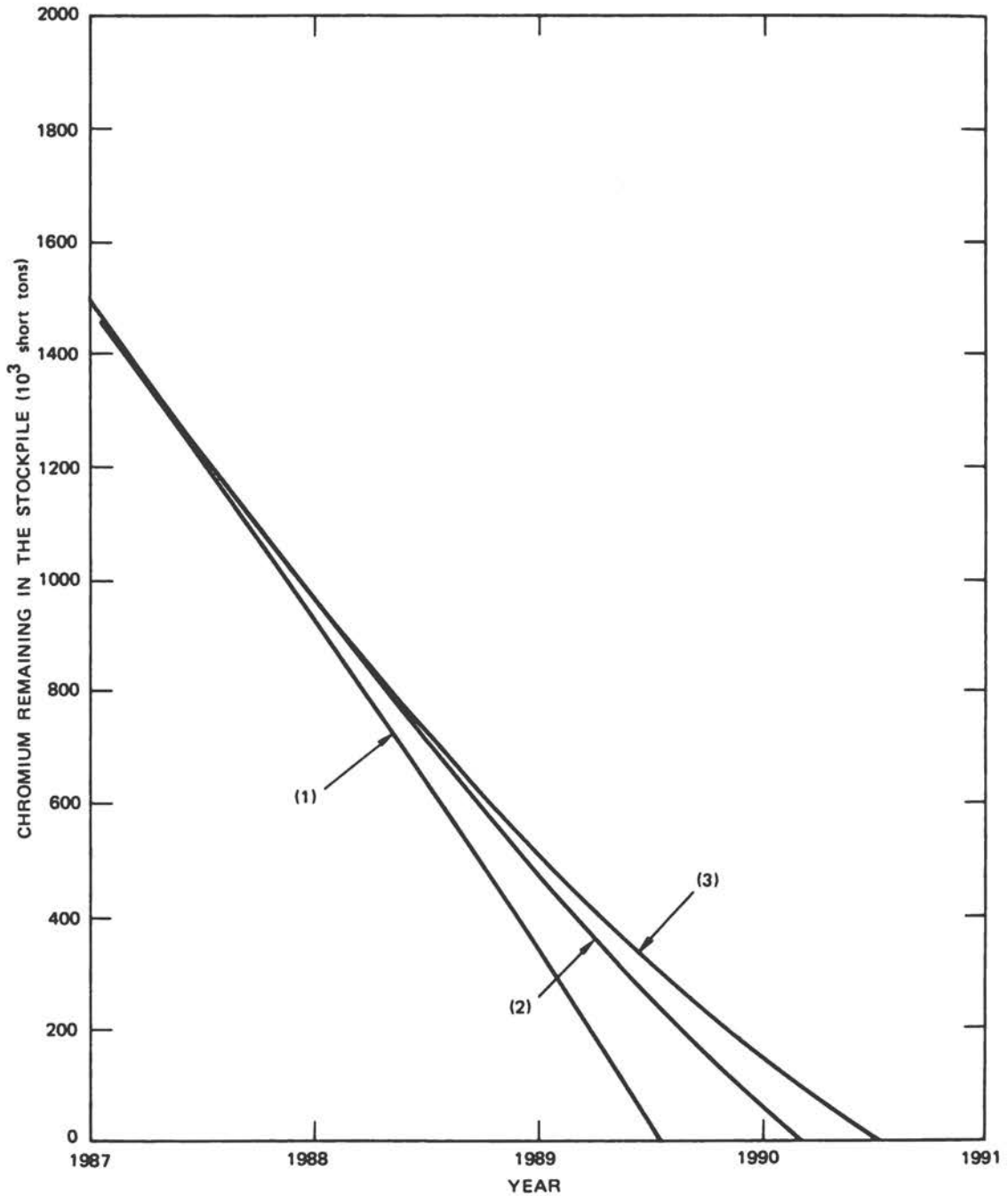
Depletion Curves
1 - Business as usual.
2 - Using currently available conservation methods.
3 - Using maximum technologically feasible conservation.

FIGURE 9 Depletion of the Present Chromium Stockpile
Following a Hypothetical Cessation of Supply in
Early 1987
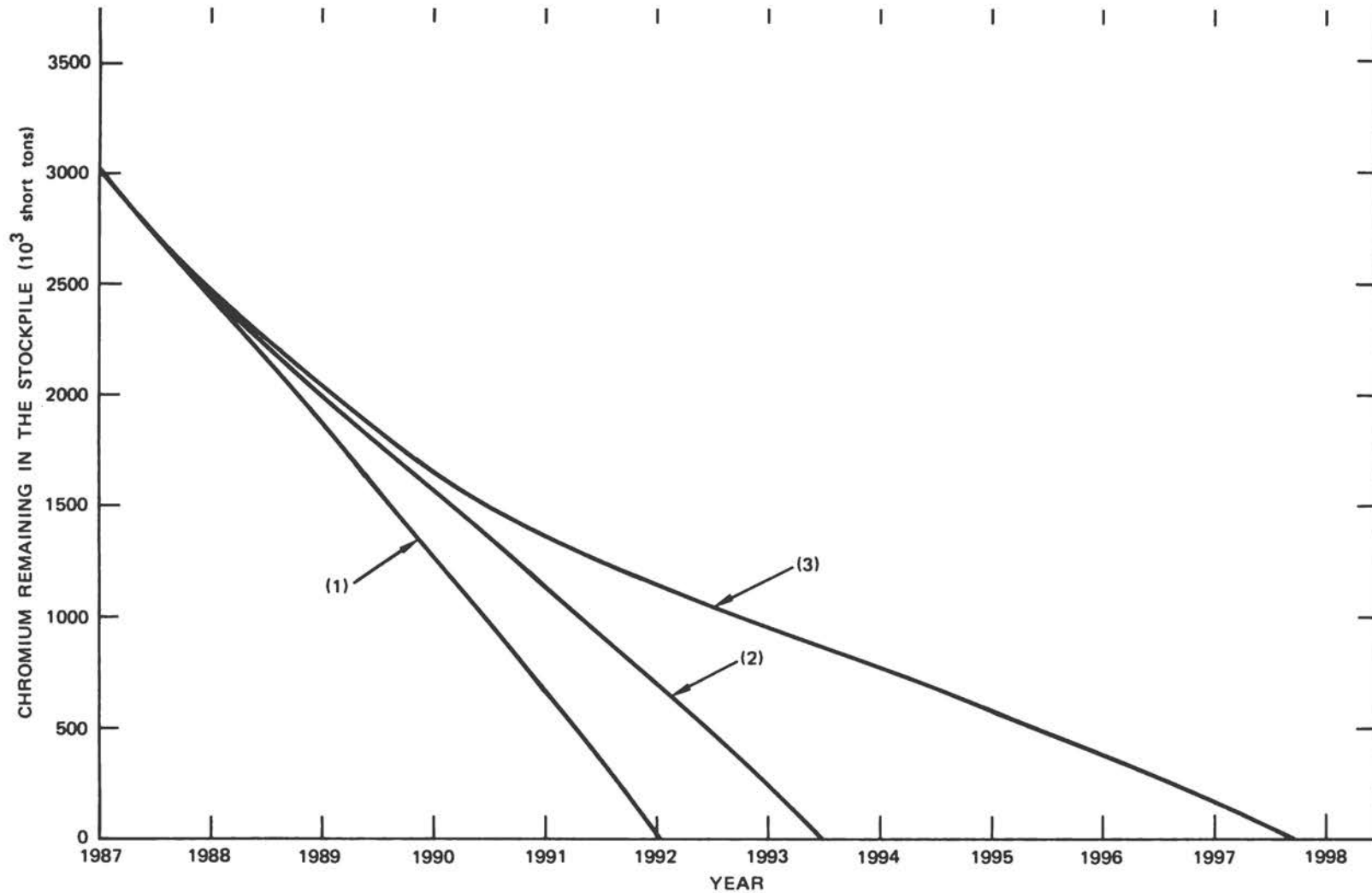
Depletion Curves

1 - Business as usual.
2 - Using currently available conservation measures.
3 - Using maximum technologically feasible conservation.

FIGURE 10   Depletion of an Enlarged Chromium Stockpile Following a Hypothetical
            Cessation of Supply in Early 1987

years; implementation of Category 1 conservation measures is again relatively ineffective (curve 2), but implementation of Category 1 plus Category 2 conservation measures would more than double the effective life of the stockpile (curve 3). However, curve 3 is based on the assumption that the research and development required for the Category 2 conservation measures had been completed prior to the cessation of imports in 1987.

A final possibility is to develop a three-pronged approach to reducing U.S. vulnerability. Consider the situation if over the next 10 years the United States: (1) increased its chromium stockpile to 3 million short tons of contained chromium, (2) undertook a successful program of research and development aimed at chromium conservation, and (3) undertook a successful program of exploration to locate additional ore deposits. The United States then would be in an excellent position to respond to any subsequent supply interruption. As shown in Figure 10, the combination of the larger stockpile and an intensive conservation program could satisfy the chromium requirements of the country for more than 10 years, providing ample time to bring ore production from the new deposits up to the required level.

3.5 CONCLUSIONS AND RECOMMENDATION

1. Over the years, the unique properties, low cost, and plentiful supply of chromium-containing materials have made important segments of U.S. industry vitally dependent on chromium. These same factors have inhibited, almost entirely, research on possible substitutes for chromium and serious efforts to conserve, reclaim, or recycle chromium-containing materials. Now, a drastic curtailment of the availability of chromium would have serious consequences in both the short and long term.

2. The present situation regarding worldwide chromium ore resources appears to favor the development of a Rhodesian/South African supply monopoly over the next 25 to 75 years. Thus, the United States, which is completely dependent on imports for its substantial chromium requirements, will become increasingly vulnerable to politically or economically motivated interruptions of supply as alternative ore resources dwindle in the future.

3. The strategic role that chromium plays in U.S. society and the unique geographic concentration of known ore resources are not widely known or appreciated even among many materials experts, and

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failure to appreciate this role only can work
against developing the long lead-time
technologies, stockpiles, or international
agreements necessary to avoid economic
dislocations.

4. None of the three approaches considered here
(conservation, stockpiling, and exploration) can
protect the United States completely against the
possibility of a future disruption (or drastic
shortage) of chromium supply. Although
conservation technically may be capable of
reducing U.S. consumption by as much as 70
percent, the lead time to implement the program
needed to achieve this level of savings is
substantial, probably as much as 12.5 years at
present. While this lead time could be reduced to
perhaps 5 years following completion of a suitably
directed 10-year research and development program,
conservation will remain an ineffective response
to short-term (< 5 years) supply interruptions.
Moreover, chromium conservation involves economic
penalties that, although difficult to quantify,
would be severe if attempted reductions of
consumption approach the limits of technical
feasibility. Because of these costs and because
the rate at which the world's ore resources are
expected to concentrate are not likely to be very
sensitive to changes in U.S. consumption,
conservation is only appropriate as a response to
an actual shortage of supply (i.e., nothing will
be gained by unilaterally implementing a policy of
chromium conservation in the United States in
anticipation of a possible future shortage of
supply).

5. Stockpiling can provide the United States with
effective protection against short-term
interruptions of supply but its protection is
finite and could be overcome by sufficiently
determined action by the suppliers. Obviously, if
a supply monopoly develops, Rhodesia and South
Africa will be in a position to wait out any
conceivable stockpile should they choose to do so.
The general issue of stockpiling policy lies
outside the charge of this Committee. However, it
is apparent that for stockpiling to be most
effective, the material in the stockpile must be
optimally matched to U.S. needs. Thus, the
content of the stockpile must be adjusted at
fairly frequent intervals to compensate for
trends, such as the decreasing domestic

ferrochrome productive capacity. A further observation pertinent to the present study is that a substantial buildup of the size of the U.S. stockpile is unlikely to be viewed with much enthusiasm by the chromium suppliers and might actually trigger a reaction such as the formation of a cartel.

6. Exploration, if successful in finding exploitable new chromium reserves, would provide protection against a long-term interruption of supply even if the new deposits were not developed initially. However, there is no current incentive for exploration so the costs (which might prove to be considerable) would have to be borne by the U.S. government. Furthermore, the probability of success is unknown and, even if success were achieved, little protection against short-term supply shortages or disruptions would be provided because of the long lead time required for the development of the deposits. This lead time could be reduced if the deposits were developed as, and when, they were found but the costs involved would be very high and probably are not justifiable in view of the known size of the deposits that are already in production.

7. An optimum response to reducing the vulnerability of the United States probably would be to combine all three approaches. Stockpiling in one form or another could be used to provide short-term protection (< 5 years). Medium-term protection (5-10 years) would be achieved by using conservation to extend the life of the stockpile, while exploration would provide insurance against a truly long-term interruption of supply (> 10 years).

The Committee recommends that the U.S. government consider the following three actions:

• Plan and fund a 10-year research and development program aimed at the development of advanced chromium conservation technology and focused on the specific opportunities for chromium conservation by recycling, substitution, and processing improvements identified in chapters 4 through 6 of this report.

• Develop and implement a program of incentives to encourage exploration for additional high-quality

chromium ore deposits in nearby parts of the world such as South America and Canada.

Fund studies on innovative methods of stockpiling chromium to provide up to 5 years of protection against a cessation of imports and on improved methods of ensuring that the content of the strategic stockpile is matched properly to the changing needs of the United States.

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Chapter 4

DESIGN

4.1 INTRODUCTION

The present raw material cost of chromium will not spur the designer to substitute alternate materials or to "design around" chromium; therefore, he must be educated to use the minimum amount of chromium consistent with conservation and recycling philosophies. Thus, a design philosophy for chromium conservation is presented in this chapter to make available to the designer some of the information that he needs to perform his function efficiently. Also presented are initial systems design criteria that can minimize the nation's dependence on chromium imports. Examples from the energy, transportation, marine, and process industries are used to illustrate barriers and incentives to change and innovation.

4.2 DESIGN CONSIDERATIONS

During the recent industrial growth era, the designer has been the arbiter in establishing customer preference with respect to shape, aesthetics, and style as well as materials of construction. The major impact for future chromium conservation may be initiated by his using trade-off studies that weigh operating efficiency and life-cycle cost against the amount of chromium incorporated. To perform effectively in the future, the product designer must consider the factors discussed below.

4.2.1 Bias

The designer often selects a particular material or mill form based on his prior experience. Since this experience was gained when first cost and aesthetics rather than chromium conservation were the design motivators, specific guidelines, indoctrination, training, and a unified policy must be developed to tell the designer which processes have the greatest potential for using chromium efficiently (e.g., least losses in melting and recycle), which forms (casting, forging, or weldment) are most effective, and which materials can meet the requirements of the product. These points are discussed in greater detail below.

4.2.2 Available Resources

A basic guideline of the designer is the short-term and long-term availability of mineral resources. If major

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elements of an alloy are considered critical, unavailable or not stockpiled, the designer normally will not use them in a product. Because of its geopolitical sensitivity, chromium falls into the critical category.

4.2.3 Reliability and Life Expectancy

When the function or performance of a product is defined, the product must be analyzed in sufficient detail to establish minimum design criteria to ensure that it functions properly and achieves desired goals of reliability, maintainability, cost, and aesthetics. The selection of candidate construction materials, another key aspect of the design process, involves effecting the best compromise and considering such design factors as product life, initial and total cost, and efficiency of operation as well as environment (corrosion, oxidation), temperature, requisite strength properties, weight, and form. For example, if the operating temperature of a nuclear reactor were reduced, stainless steel would not be needed and a significant chromium saving would be achieved but efficiency would be sacrificed. The customary questions in design practice are: Is this desirable? Is it economical? Can performance objectives be met?

Another major design consideration that affects chromium conservation is selecting criteria for life and maintainability. Generally, the designer must choose between finite and long life design (i.e., should he aim for a product that will have finite life and be replaced rather than maintained by using minimal critical materials and low-cost processes or should he strive for infinite product life by using the most corrosion- and wear-resisting materials and the highest quality form and process needed to achieve good maintainability -- commensurate with reasonable cost). There probably always will be a middle ground in which material and energy can be conserved by selectively applying wear-resisting coatings to key wear areas, using design techniques that minimize corrosion (coatings, drain holes, galvanic couplings), relying on careful corrosion and stress analyses that permit use of the lowest chromium alloy content material for the job, and permitting ease of replacement or repair of the failure-sensitive critical components.

To achieve full and responsible chromium conservation, the full range of quality assurance techniques -- including specifications, standards, in-process inspection, inspectability, and feedback from these inspections to the designer -- must be used. Defective hardware found during inspection can be accepted as deviant material and repaired and used or recycled. However, once a defective component

is integrated into the finished system, recalling for
recycling, repair, or replacement becomes more difficult.
Thus, the initial design should facilitate nondestructive
testing and evaluation. Judicious use of quality assurance
can be a powerful tool for chromium conservation since
excessive application of too high a standard for the
intended product can be wasteful.

Examples of application of each of these design
considerations exist in most industries. The aerospace
industry provides convenient examples for each of the
extremes and the compromise conditions -- the expendable
drone airplane, the Apollo space vehicle, and the cost-
conscious commercial airplane, respectively.

4.2.4 Weight

A reduction or increase in product weight can be
another design tool to conserve chromium. Reduction in
total weight obviously introduces less chromium into a
product particularly if the reduction can be traced back to
the mill. Not only is less chromium present in the finished
hardware (and therefore not available for ready recycling)
but less energy is consumed in the process and possibly less
energy will be used in moving the product during its life.

On the other hand, increasing product weight could mean
operating at a lower stress, using lower chromium-containing
alloys that have a longer oxidation and corrosion life-time,
and permitting the use of coatings or claddings on carbon
steels. Once again, the designer must decide which route is
the best for a particular application.

4.2.5 Ease of Recycling

The designer should provide for the recycling of
chromium-containing products by designing to permit ready
disassembly for recall, repair, or replacement and by using
a marking system and part numbers that would permit ready
identification and location of chromium-containing parts.

4.2.6 Aesthetics

Aesthetic considerations enter into the design of many
chromium-plated and stainless steel components ranging from
automobile bumpers to kitchen sinks and building exteriors.
The aesthetic appeal of these parts may be associated with
the impression of newness, cleanliness, and durability
created although some chromium-plated parts may have been
introduced as inexpensive substitutes for traditional brass
parts.

Because of these considerations, public acceptance of
various possible substitutes is impossible to predict except
in instances where past marketing experience exists
(presentation by S. Gratch to the Panel on Substitution,
June 7, 1976). For example, the public generally has not
noticed the replacement of most interior automotive
chromium-plated die-cast zinc parts by vacuum metalized
plastics, and color keyed, painted bumpers on many small
sportly cars have been accepted readily in place of the
conventional chromium-plated bumpers. Thus, aesthetics may
not represent any real, long-term barrier to chromium and
stainless steel substitution; however it may become one if
poor judgment is used in effecting substitution.

4.3 DESIGN CRITERIA

4.3.1 Corrosion

4.3.1.1 Sulfidic Corrosion in Hydrogen-Free Environment

Chromium-containing steels have been used extensively
by the petroleum industry and others to control corrosion in
equipment used to process sulfur-containing oil at elevated
temperatures. Below approximately 500 °F, carbon steel is
normally adequate. At higher temperatures, chromium steels
are usually more economical because the added first cost is
offset easily by the extended life. The results of an
American Petroleum Institute (API) survey (McConomy 1963),
reproduced in Figure 11, show that, in the absence of
hydrogen, sulfidic corrosion approximately doubles when
operating temperature is increased from 50 to 100 °F. On
the other hand, the corrosion rate decreases by a factor of
2 for each 2.5 to 3 percent increment of chromium in the
steel.

Unfortunately, no satisfactory substitute for chromium
is known to reduce sulfidic corrosion in steel at high
temperature although several partially successful attempts
during the past 20 years provided sulfur resistance by
"diffusing" aluminum into the outer layer of steel exposed
to a sulfurous environment. In the absence of a hydrogen
environment, however, corrosion is a surface phenomenon and
the corrosion-resisting material may be applied as a surface
coating by using corrosion-resisting linings that are
bonded, loose or spot welded, or weld deposited. While
these techniques can increase the cost of fabrication, they
conserve chromium by eliminating its use in the backing
plate.

In general, it is neither beneficial nor chromium-
conserving to reduce the normal concentration of chromium in
the corrosion-resisting lining (Figure 11). If a vessel is
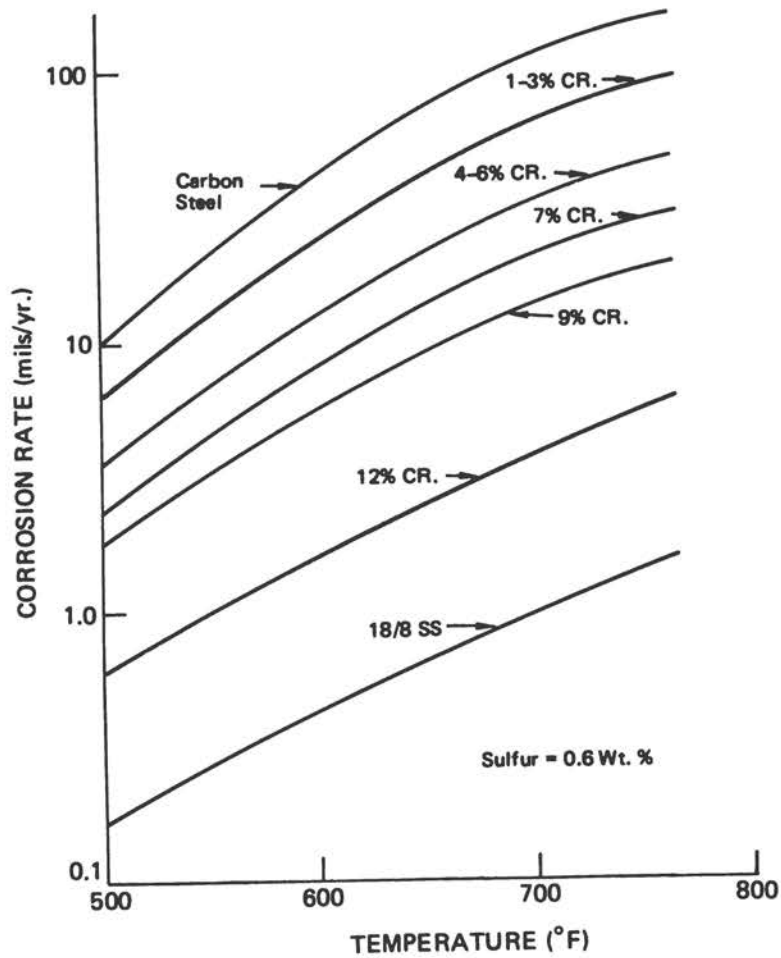
FIGURE 11 Average Corrosion Rates for High-Temperature Sulfur Corrosion in a Hydrogen-Free Environment (McConomy 1963)

NOTE: From H. R. McConomy, "High-Temperature Sulfidic Corrosion in Hydrogen-Free Environment," _Proceedings of the American Petroleum Institute_ 43, III (1963): 78-96; reprinted by courtesy of the American Petroleum Institute. Compiled from 1961 A.P.I. questionnaire data from industry desulfurizing processes and published or reported data on non-desulfurizing processes. Average sulfur is 0.6 weight percent.

designed with a 1/8-inch-thick, 12 percent chromium liner and is operated at 750 °F, the corrosion rate is about 6 mils per year and the expected service life is about 20 years. If the chromium content of the liner is reduced to 9 percent, the corrosion rate increases to about 19 mils per year and the expected vessel life is reduced to about 6.6 years using the 1/8-inch-thick liner. For 20 years of service, a 0.4-inch-thick liner (or equivalent) would be required, and the total amount of chromium used over the 20-year period would be 2.4 times as much as would have been needed if the preferred 12 percent chromium liner were used. Thus, reducing the chromium content of liners designed to resist sulfidic corrosion normally leads to a long-term increase -- not a decrease -- in chromium consumption. This example suggests that chromium would be conserved by using thin linings of high-chromium steel rather than by using thick linings of low-chromium steel. However, minimum thickness is constrained by the fabrication problems.

4.3.1.2 Operating Limits for Steel in Hydrogen Service

Hydrodesulfurization and hydrogenation operations have increased dramatically in petroleum refining operations during the past 20 years and have introduced an additional problem in the design of processing equipment. At high temperature and high pressure, molecular hydrogen dissociates into atomic hydrogen, penetrates into the steel, and reacts with carbon to form methane. This reaction creates high internal pressure that causes the metal to fail by intergranular cracking. With vessels designed to operate at internal pressures of several hundred or thousand pounds per square inch, such failure can be catastrophic and must be avoided at all costs.

Hydrogen attack on steel is decreased by the addition of carbide-forming alloying elements such as chromium, molybdenum, tungsten, vanadium, titanium, and columbium. Safe working guidelines for the design of equipment for use in high-temperature, high-pressure hydrogen service have been developed and published by the API and are reproduced here as Figure 12 (Nelson 1949; American Petroleum Institute 1977). The curves in this figure are based on using chromium and molybdenum as carbide-stabilizing materials and are the largest single collection of reliable data on this subject. In time, guidelines for using other (nonchromium, molybdenum) carbide stabiliziers may be developed, but care must be taken to develop reliable alternatives and to avoid substituting one critical material for another. Reliability in any alternative is a primary requirement because of the catastrophic consequences of failure.
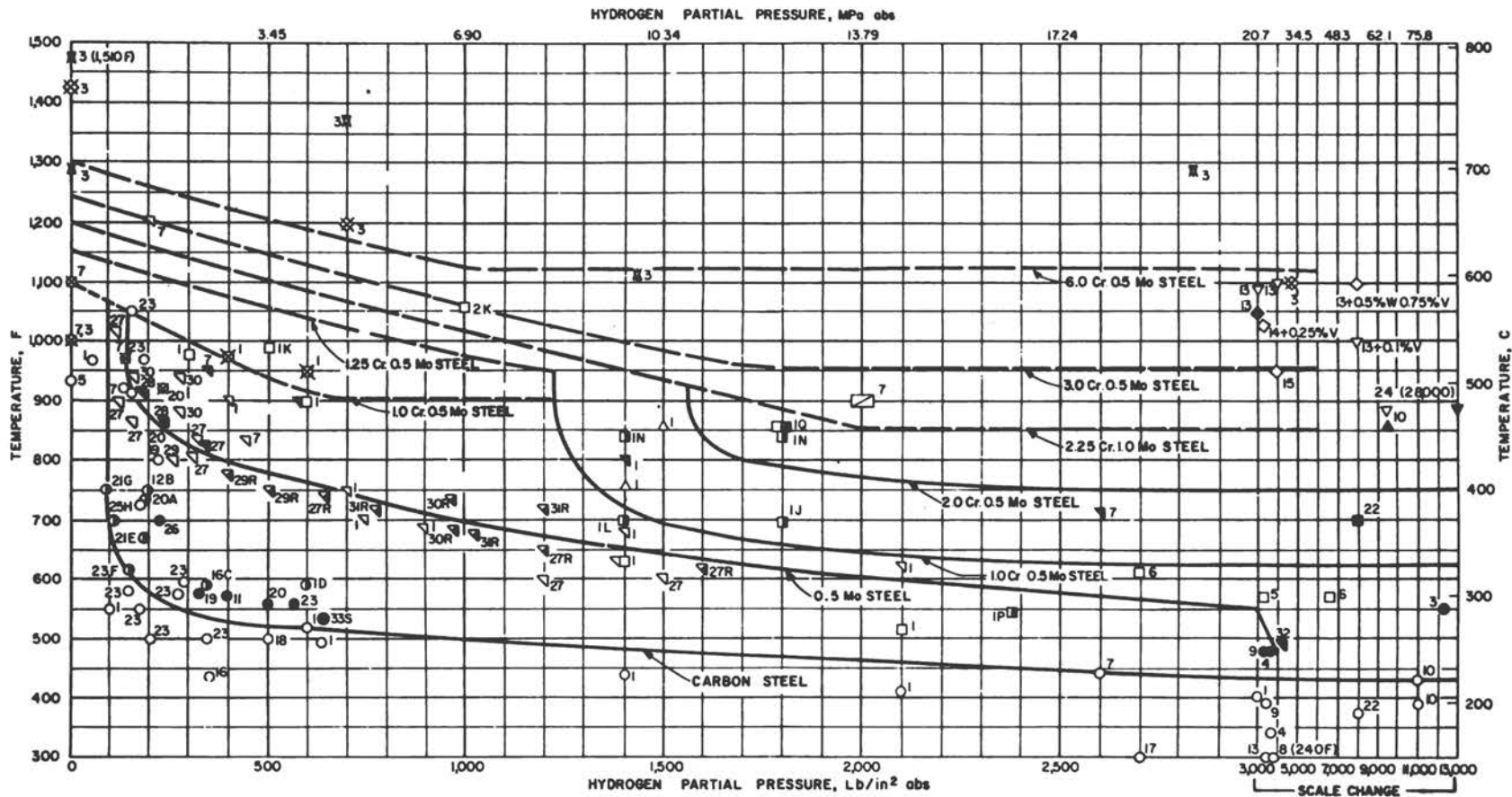
HYDROGEN PARTIAL PRESSURE, MPa abs

6.0 Cr 0.5 Mo STEEL
13+0.5%W 0.75%V
14+0.25%V
13+0.1%V
1.25 Cr 0.5 Mo STEEL
3.0 Cr 0.5 Mo STEEL
24 (28000)
1.0 Cr 0.5 Mo STEEL
2.25 Cr 1.0 Mo STEEL
2.0 Cr 0.5 Mo STEEL
1.0 Cr 0.5 Mo STEEL
0.5 Mo STEEL
CARBON STEEL

HYDROGEN PARTIAL PRESSURE, Lb/in² abs

SCALE CHANGE

NOTE:
Figure 1 of API Publication 941, Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants, 1977 (preprint); reprinted by courtesy of the American Petroleum Institute. Revisions to the 1/2 percent and 1/4 percent molybdenum curves were offered to the API in May 1976. These revisions probably will be adopted at a later date.

Austenitic stainless steels are satisfactory at all temperatures and pressures.

See references and footnotes on following page.

LEGEND

SURFACE DECARBURIZATION
INTERNAL DECARBURIZATION
HYDROGEN ATTACK

	LOW CARBON	0.5 Mo	1.0 Cr 0.5 Mo	2.0 Cr 0.5 Mo	2.25 Cr 1.00 Mo	3.0 Cr 0.5 Mo	6.0 Cr 0.5 Mo
SATISFACTORY	o	◣	□	▲	▭	◇	▽
HYDROGEN ATTACK	●	◥	■	▲	▬	◆	▼
DECARBURIZATION	✕	◥	✕	▬	▱	▤	▬
SEE FOOTNOTES	●	◥	■	▲	▭	◆	▼

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FIGURE 12   Operating limits for steels in hydrogen service   (American Petroleum Institute 1977)

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Footnotes:
A. A section made of A106 pipe was found to be attacked to 27 percent of its thickness after 5,745 hours. Other pieces of pipe in the same line where unaffected.
B. The attack was concentrated in the overheated section of a hot bent steel elbow. The unheated straight portions of the elbow were not attacked.
C. In a series of 29 steel samples, 12 were attacked while 17 were not.
D. After 2-years exposure, 5 out of 6 pieces of carbon steel pipe were attacked. One piece of pipe was unaffected.
E. Attack was concentrated in the weld and heat-affected sections of A106 pipe. Metal on each side of this zone was unaffected.
F. After 11-years service, attack was found in the hot bend section of A106 pipe. Unheated straight sections were not affected.
G. After 2-years service, all parts of carbon steel pipe, including weld and heat-affected zones, were satisfactory.
H. After 4-years service, weld and heat-affected zones of A106 pipe showed cracks.
J. After 31-years service, a steel forging containing 0.3 percent C, 1.3 percent Cr, and 0.25 percent Mo showed cracks 0.007 inch deep.
K. 1.25 percent Cr-0.5 percent Mo steel pipes.
L. After 4-years service, a steel forging containing 0.3 percent C, 1.3 percent Cr, 0.25 percent Mo was unaffected.
M. After 4-years service, a steel forging containing 0.2 percent C, 1.2 percent Cr, 0.35 percent Mo showed cracks 0.032 inch deep.
N. After 7-years service, a steel forging containing 0.3 percent C, 1.52 percent Cr, 0.50 percent Mo showed cracks 0.050 inch deep.
P. After 30-years service, a steel forging containing 0.30 percent C, 0.74 percent Cr, 0.43 percent Ni was unaffected.
Q. After 15-years in ammonia service, a pipe containing 0.15 percent C, 2.25 percent Cr, 1.00 percent Mo showed no hydrogen cracks but was nitrided to a depth of 0.012 inch.
R. Stainless steel cladding on 0.5 Mo steel. No known hydrogen attack.
S. After 8 years carbon steel cracked.

_____

*Private communication to Subcommittee on Corrosion

The broken lines at the top of Figure 12 illustrate the tendency of steels to decarburize by the migration of carbon to the surface and its reaction there with hydrogen. This phenomenon creates a nearly pure iron layer at the surface that has lower tensile strength, hardness, and fatigue strength. Minor surface decarburization is not usually of great concern in refinery equipment design.

The solid lines at the bottom of Figure 12 illustrate the tendency of steels to decarburize internally with resulting cracking caused by methane formation. This phenomenon is of great concern in refinery equipment design. In high-pressure hydrotreaters or hydrocrackers, the practice is to use 2.25 percent chromium/1 percent molybdenum steel, designated by the American Society for Testing and Materials (ASTM) as A-387, Grade 22. As shown, this material is not expected to fail by internal cracking under design conditions in present refinery hydroprocessing. Steels containing less chromium could fail under some service conditions.

Because of the potential for catastrophic failure, chromium and molybdenum currently are considered practically indispensible for use in hot high-pressure hydrogen service. As mentioned above, other suitable alloying materials eventually might be found but, thus far, none have proven satisfactory.

Since about 1940, other designs have been tried or considered with less than phenomenal success. Some designs used either a multilayer or a solid outer shell of carbon steel that was designed to withstand the internal design pressure. A loose-fitting pressure-tight liner of alloy steel is fabricated inside the outer shell. The outer shell has holes drilled through the entire thickness so that any hydrogen, which diffuses through the inner alloy shell, will leak to the atmosphere and not accumulate to build hydrogen pressure against the inside of the carbon steel outer shell. A satisfactory method for installing leak-proof nozzles in the vessel, without providing a diffusion path for hydrogen to penetrate into the carbon steel shell, has not yet been developed.

4.3.2 Oxidation

In petroleum refining and petrochemical plant designs, alloy selections for high-temperature furnace tubes are dictated by the alloy's resistance to air oxidation. Limiting temperatures for low air oxidation rates have been assembled and are presented in Table 14 (American Petroleum Institute 1973). At temperatures above the reported values, oxidation rates become appreciable.

TABLE 14   Maximum Metal Temperatures for
            Low Oxidation Rates of Chromium
            Alloys in Air

Material	Temperature (°F)
Carbon steel	1,050
C-Mo steel	1,050
½% chromium steel	1,075
1¼% chromium steel	1,100
2% chromium steel	1,150
2¼% chromium steel	1,175
3% chromium steel	1,175
5% chromium steel	1,200
7% chromium steel	1,250
9% chromium steel	1,500
12% chromium steel	1,500
18 Cr-8 Ni steel	1,600
25 Cr-12 Ni steel	2,000
25 Cr-20 Ni steel	2,100

NOTE: Data from American Petroleum
        Institute 1973, chapter 2.

When a tube is selected to resist high-temperature sulfidic corrosion on the inside, it usually resists air oxidation adequately on the outside, but when it does not, a higher chromium alloy is selected . If the chromium supply were restricted severely, an attempt probably would be made to diffuse aluminum into the outer surface of a lower chromium alloy or a carbon steel tube.

High-temperature steam also causes severe scaling of carbon-steel and low-chromium alloys because an oxidation process results from the decomposition of steam into hydrogen and oxygen. Table 15 presents the limiting temperatures for the use of chromium steels in steam service which are about 50 to 100 °F lower than those for air oxidation. No satisfactory alternatives are known for the use of the chromium steels in this service.

4.3.3 Stress

The life of many components is controlled by the stress placed on them in service. Design stresses are calculated on the basis of anticipated loads and environment plus the expected life of the product, and stress criteria are available from a variety of sources such as MIL-Handbook 5 (NAVSHIPS 250-008-5) and the American Society of Mechanical Engineers (ASME) Boiler Code. The most reliable stress criteria are those developed on the basis of similar service experience or through statistical treatment of results from a relatively large number of tests and should result in the conservation of chromium as well as other materials and energy by permitting efficient product design. Further conservation of chromium through selection of materials containing less chromium often is hindered because stress criteria are not correlated with chromium content. In the long run, chromium conservation also can be achieved by designing for longer life.

4.3.3.1 Stress Reduction

A reduction in the applied stress generally results in longer service life and may be accomplished by decreasing the stress producing factor (i.e., speed, pressure, load, etc.) or by increasing the section thickness. The increase in service life that will result from a given stress reduction depends to some extent on the original stress. The service life of components such as propeller shafts, axles, crank shafts, and aircraft lower wing skins may be limited by fatigue (i.e., the initiation and growth of cracks caused by repetitive application of tensile stress significantly below the material's ultimate tensile strength).

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TABLE 15   Maximum Metal Temperatures for Low
            Scaling of Chromium Alloys in Steam
            Service

Material	Temperature (°F)
Carbon steel	950
C-Mo steel	975
½% chromium steel	1,000
1¼% chromium steel	1,050
2% chromium steel	1,080
2¼% chromium steel	1,100
3% chromium steel	1,125
5% chromium steel	1,150
7% chromium steel	1,175
9% chromium steel	1,200

NOTE: Data from American Petroleum Institute
         1973, chapter 2.

Data on cycles-to-failure versus stress level for
15-5 PH (15 percent chromium) steel are presented in
Figure 13 (Armco 1976). A reduction in maximum stress level
from 150,000 to 140,000 psi approximately doubles the life
for the H1025 condition while a similar reduction in stress
from 135,000 to 130,000 psi increases the life by more than
50 times. Fatigue life at 10 million cycles (fatigue limit)
for low-alloy steels varies with strength level or hardness
as shown in Figure 14 (American Metals Society 1961) but is
not influenced appreciably by composition.

A chromium content of approximately 1 percent will be
found in the 41XX, 43XX, 51XX, and 86XX alloys. Since
fatigue properties are unaffected by chromium content,
reduced consumption of chromium could be achieved on
fatigue-life-controlled designs without reducing performance
by selecting material from chromium-free alloys when
corrosion and heat resistance are not critical. Other
material characteristics, such as hardenability, also must
meet design requirements and could preclude selection of a
substitute alloy in some cases. (Section 4.4 presents a
methodology for alternate alloy selection.)

Stress concentrations (e.g., changes in geometry,
holes, and fillets; surface roughness produced by
fabrication operations or corrosion; and material defects
such as inclusions) will reduce fatigue life. Figure 15
(American Society for Metals 1961) shows the effect of
inclusion size on fatigue life and emphasizes the need for
quality assurance throughout the processing of the alloy to
ensure optimum usage of the contained chromium.

Shorter-than-expected service life can result when
corrosive action of the environment reduces fatigue life.
Due to variables between specimen tests and operational
hardware, design changes or material substitutions should be
verified whenever possible by tests using actual operational
components and a real or simulated service environment.

Reduction of operating stress can increase the life of
components (e.g., high-strength bolts, actuator bottles, and
helical springs) subjected to sustained tensile stress in
applications where failure is caused by stress-corrosion
cracking or hydrogen-induced cracking. Applied stress
versus time to failure data are illustrated in Figure 16
(Fontana and Greene 1967) for four different stainless
steels that are grouped into two performance ranges.
Greater chromium content is associated with the improved
performance, and the effect of reduced stress on increase in
life is a function of the original stress for each material.

Axial Load Fatigue
15-5 PH, Heat 3W0667
2" X 6" Section, Condition H1025
Transverse, Unnotched Specimens
Stress Ratio = +0.1

Tensile Properties
UTS — 164 ksi
0.2% Y.S. — 160 ksi
% elongation — 16
% R.A. — 56
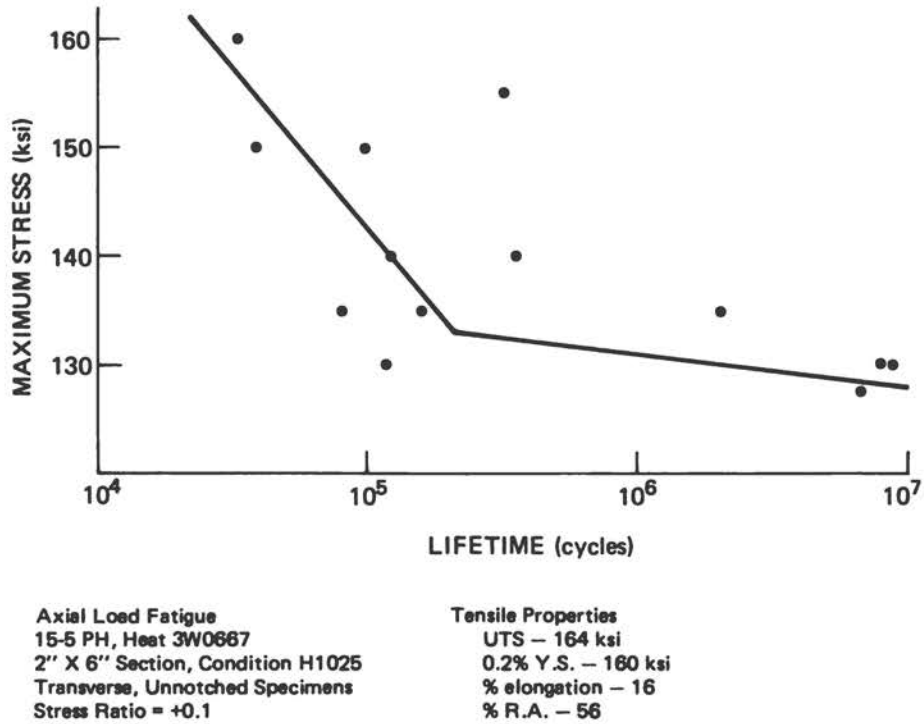
FIGURE 13 Fatigue Strength Curve for 15-5 PH Precipitation
Hardening Stainless Steel (Armco Steel Corporation
1977)
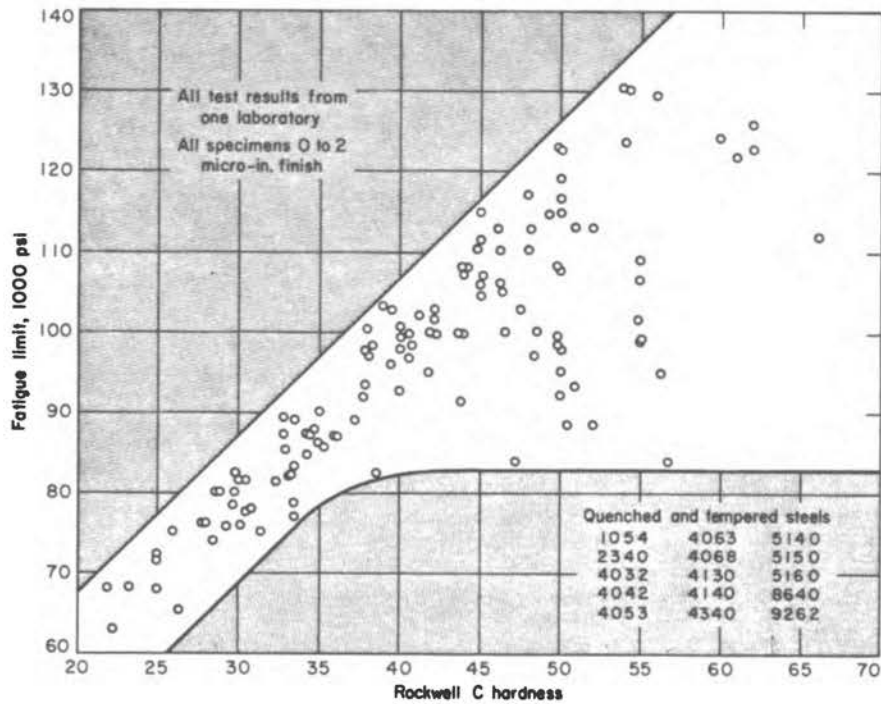
FIGURE 14   Effect of Hardness on Fatigue Limit of
Through-Hardened and Tempered Steel
(American Society for Metals 1961)

NOTE: By permission from <u>Metals Handbook</u>, Volume 1,
p. 217, © American Society for Metals, 1961.
Standard 0.250-in. diameter R. R. Moore
rotating-beam fatigue specimens were tested.
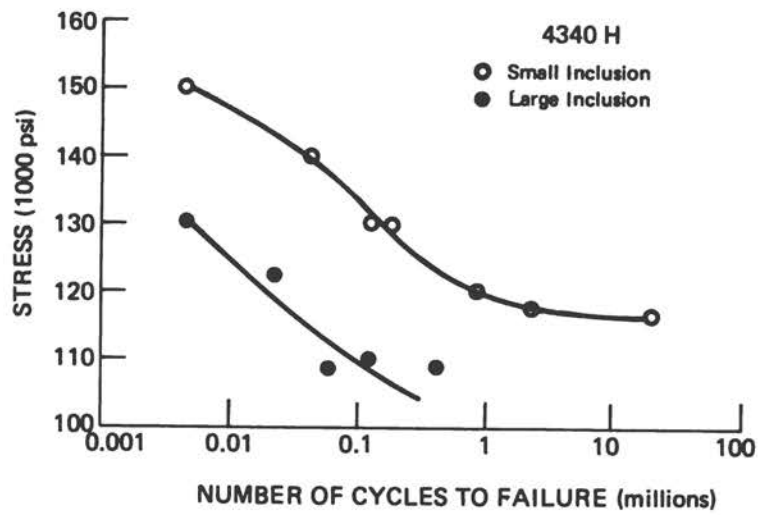
FIGURE 15 Effect of Inclusions on Fatigue
(American Society for Metals 1961)

NOTE: By permission from Metals Handbook,
Volume 1, p. 224, © American Society
for Metals, 1961.
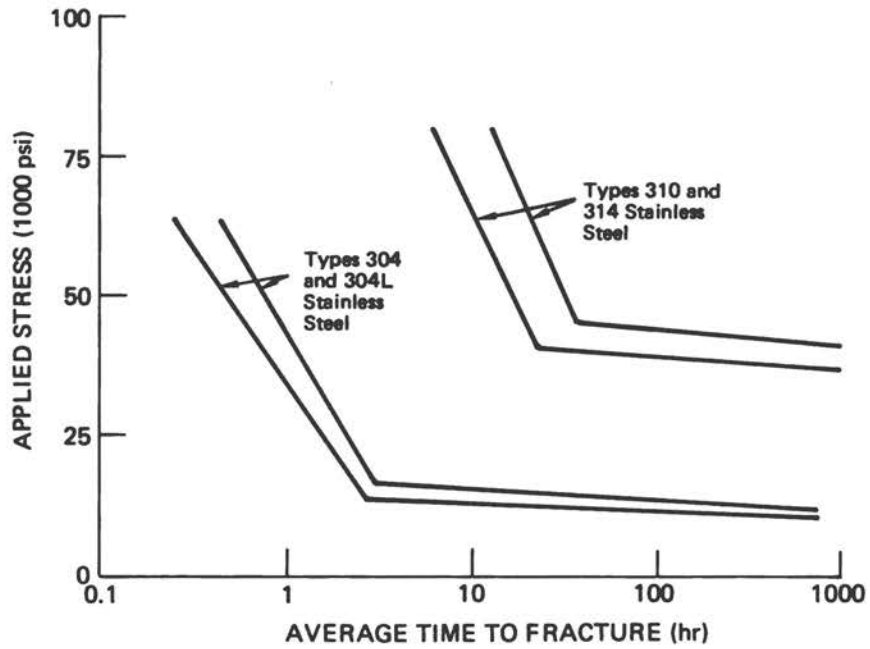
FIGURE 16   Effect of Alloy Composition on Threshhold
Stress (Fontana and Greene 1967)

NOTE: From <u>Corrosion Engineering</u>, Fontana and Greene,
copyright © 1967 by McGraw-Hill, Inc.   Used with
permission of McGraw-Hill book Company.

The data of Figure 16 are not converted readily to design criteria and are of limited value to the designer even though screening of materials is accomplished. Consequently, in recent years many investigators have been developing data applicable to fracture mechanics concepts (Metals Handbook 1975) that permit the reliability of a design to be evaluated in terms of applied stress and the size of defects. Figure 17 (Peterson and Brown 1967) is an example of such data. The lower curve represents conditions above which stress-corrosion cracking will occur. Increased susceptibility with increasing strength, as shown by the data, is a potential hazard to designs enduring sustained tensile stress and should be considered when stress levels are raised in chromium conservation efforts.

Some designs (e.g., lifting equipment and high-pressure gas bottles) are life-limited by the stress level at which rupture occurs from overloading. In these cases, a reduction in design stress criteria would result in longer life, if the component were inadvertently overloaded in service or if a general degradation mechanism (e.g., corrosion, oxidation, creep, and wear) reduced load-bearing sections to thicknesses susceptible to failure at normal working stresses. Section thicknesses generally are increased to reduce the average working stresses for cases involving overloads. Average life improvement is proportional to the increase in degradation allowance, but design changes would be determined on the basis of experience for inadvertent overloads.

Design actions that reduce stress levels by increasing section thickness would increase initial requirements for chromium and product weight when chromium's properties are essential. Added weight also would be undesirable for moving components or mobile products since wear and the energy required for operating the equipment would be increased, and in designing for longer life of such equipment, weight should not be increased.

4.3.3.2 Unchanged Stress

Longer life may be designed into a product without changing applied working stresses by using alloys more resistant to the service environment, by improving control of the service environment, and by inducing favorable residual stresses into selected components. Research and development are required, particularly in the first area, to provide materials with improved environmental resistance. Increases in chromium content are expected for alloys having improved resistance to corrosion and oxidation but, as will be discussed below, are not expected for alloys having improved elevated temperature rupture strength. Figure 16
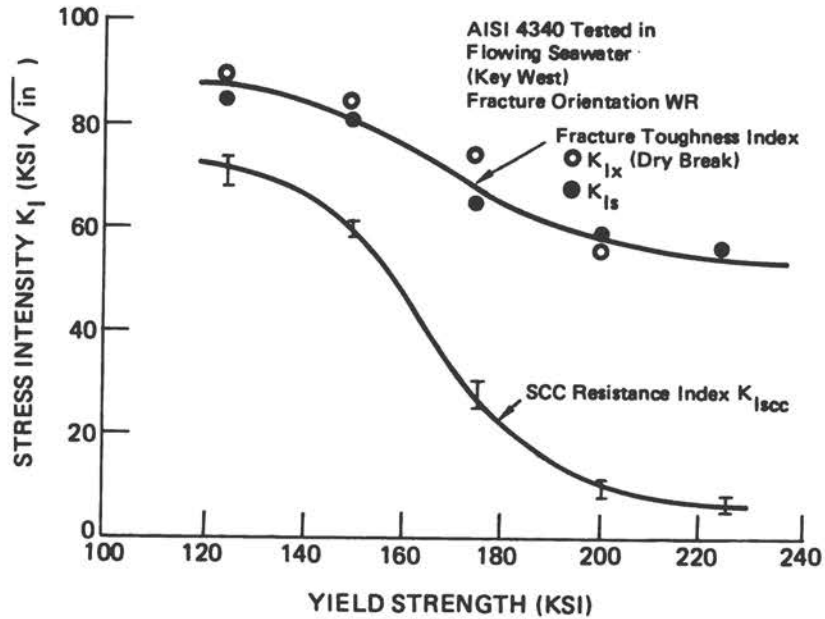
FIGURE 17   Fracture Toughness as a Function of Yield Strength
for AISI 4340 Steel (Peterson and Brown 1967)

NOTE: The fracture toughness indices K_{IX}, K_{IS}, and K_{ISCC} for
AISI 4340 steel plotted as a function of yield strength
show that resistance to stress corrosion cracking (SCC)
is degraded more severely with increasing yield strength
than is the fracture toughness.

illustrates the effect of chromium content on corrosion
resistance and Figure 18 (American Society for Metals 1961)
shows improvements in wear resistance for chromium-
containing steels for two different applications.

Advantageous use of residual stresses effectively
increases the life of components subject to failure by
fatigue or stress-corrosion cracking without changing the
applied stresses. Processes such as shot peening, cold
rolling, prestressing, and surface hardening are employed to
induce favorable residual stresses in a part. The increase
in fatigue life resulting from shot peening of carbon and
alloy steel springs is shown in Figure 19 (American Society
for Metals 1961). For a maximum stress of 90,000 psi,
minimum fatigue life increased approximately 10 times. At
lower stresses, the increase is even greater.

Surface hardening processes such as carburizing,
nitriding, and induction hardening produce residual
compressive stresses in the surface layers. Increases in
service life from these processes probably are due to the
combined effects of residual stress and high surface
hardness. The effect of nitriding on fatigue life is shown
in Figure 20 (Gadd and Ochiltree 1945). The engineering
benefits from these processes are improved fatigue life and
wear resistance. One advantage of carburizing and nitriding
is their applicability to low-alloy-content steels to
improve their engineering capability.

Although the above discussion has been directed to
extending service life without changing design stress
levels, the magnitude of benefits derived from favorable
residual stress and surface hardness permits an increase in
design stress and service life in some cases. Use of higher
design stresses is expected to occur primarily in new
design.

4.3.3.3 Stress Increase

Increasing design stress criteria above current
practice involves one or more of the following: (1) the
development of improved or new materials, (2) greater
reliance on the integrity of supplemental processing such as
shot peening and surface hardening, and (3) more efficient
nondestructive inspection of components.

Design working stress is often a factored value of the
static tensile strength of the material and raising the
tensile strength seems to be a logical method of achieving
higher design stress criteria. This approach is frequently
attempted but has obvious limitations (Figures 14 and 17)
when fatigue life and stress-corrosion cracking are the

Rockwell C hardness

Screen wire material		Vibrating screen for crushed ore
0.30% C — 13% Cr	55	
1095	52	
1095	44	
1080 (austempered)	57	
1080 (cold drawn)	37	
1070 (austempered)	54	
1070	53	
1070	44	(a)

50 wires of each material

0 20 40 60 80 100
Relative weight loss

○● 1018, 65 to 67 R_C Tractor track pins
△▲ 1045, 61 to 64
□■ 4140, 59 to 65

Wear, 0.01 in.

Tractor A

Tractor B

(c)

0   0.5   1   1.5   2   2.5   3
Length of operating time, 1000 hr
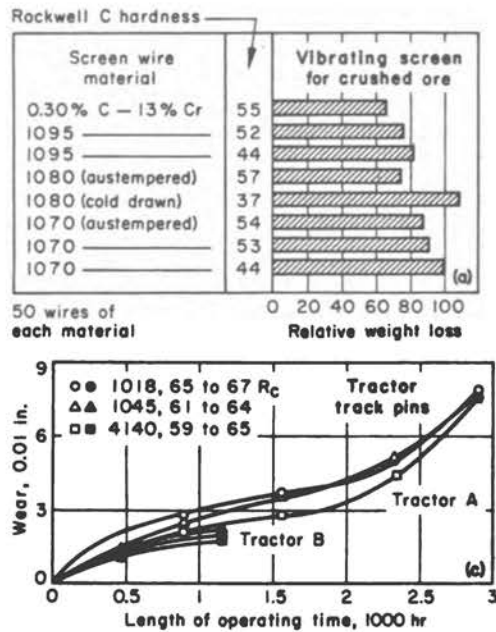
NOTE: By permission from <u>Metals Handbook</u>, Volume 1,
         p. 248, © American Society for Metals, 1961.
         The 10XX alloys contain no chromium and the
         4140 has a chromium content of approximately
         1 percent. Only moderate improvement in wear
         resistance results from chromium additions to
         the steel. Chromium-free steels for these
         applications could reduce performance approxi-
         mately 15 to 30 percent.

FIGURE 18   Effect of Steel Composition and Hardness
             on Wear and Life in Abrasive Applications
             (American Society for Metals 1961)
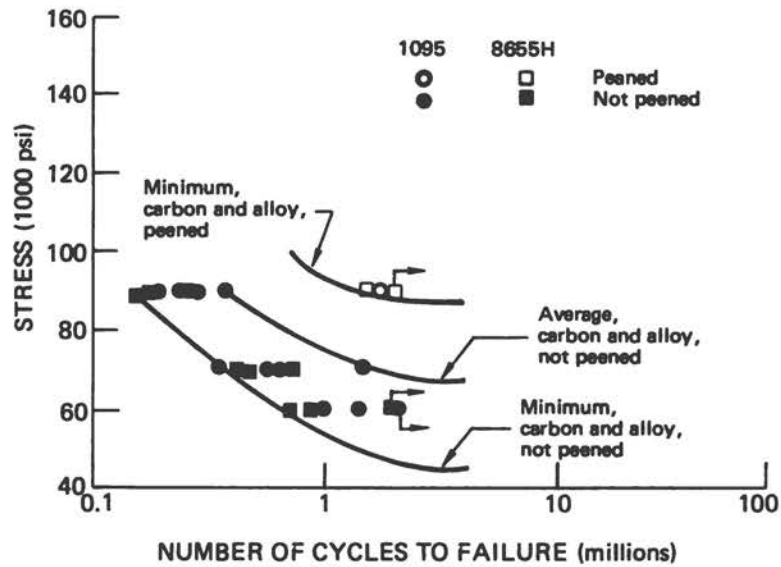
NOTE:
Effect of shot peening on the life of helical compression springs of 1095 and 8655H steel made by hot winding. Bar diameter was 19/32 to 1-1/16 in. Springs ware oil quenched and tempered to 444 Bhn. Tests were discontinued at 2 million cycles. All springs were preset and tested at a mean stress of 60,000 psi. Each point indicated on the chart represents a group of no fewer than eight springs.

FIGURE 19   Effect of Shot Peening on the Life of Helical Compression Springs of 1095 and 8655H Steel Made by Hot Winding (American Society for Metals 1961)
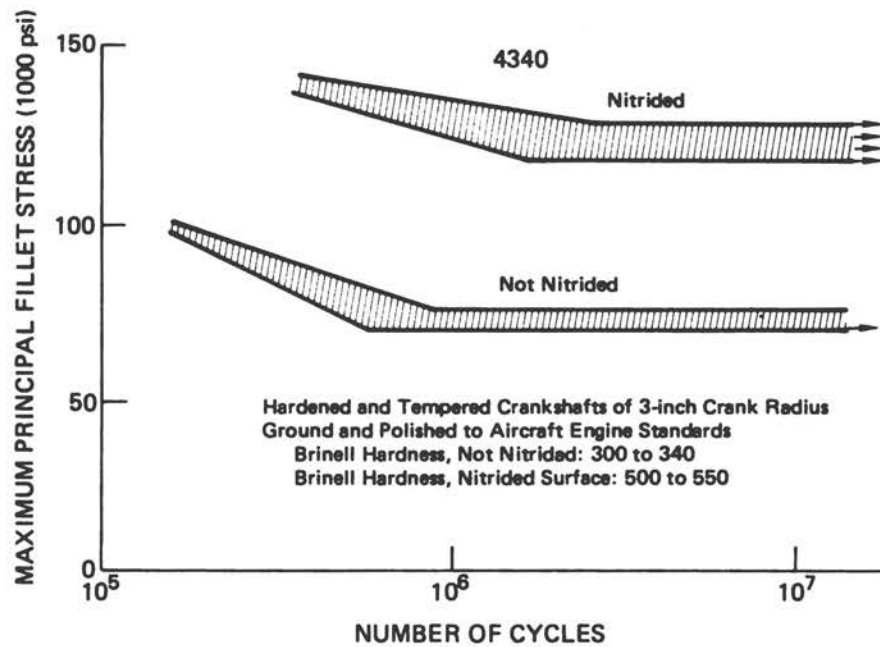
FIGURE 20 Effect of Nitriding on Fatigue Life of 4340 Steel in Full-Scale Bending Fatigue Tests of Individual "Throws" of Crankshafts (Gadd and Ochiltree 1945)

design limiting factors involved. In both instances, at tensile strengths above approximately 180,000 psi, there is a marked degradation for stress corrosion and no significant improvement in minimum capability for fatigue life. Raising tensile strength to obtain higher design stress criteria in such a situation could increase chromium consumption as a result of earlier failures.

The effect of chromium content on the stress capability of stainless steel in a severe corrosion environment was illustrated in Figure 16. An increase in chromium content of approximately 30 percent raises the stress capability of the 310 stainless over 304 by a factor of 3 for a 1,000-hour life. An improvement in performance of this magnitude could result in chromium conservation since the use of higher operating stresses could reduce product weight and the total amount of chromium consumed.

Working stresses are a major design consideration in the planned service life of a product. Efficient successful design allows for degradation mechanisms and utilizes supplemental processing, as appropriate, while minimizing cost. Effective material utilization is the result of efficient design and is achieved most readily on mature products, but it requires comprehensive design study as well as development effort on new products.

4.3.4 Decreasing Chromium Consumption

An overall decrease in chromium consumption while retaining equal life and performance of a component may be accomplished by reducing the weight of the product, using materials containing less (content) chromium, or combining these approaches. As noted above, reducing the weight of a product while employing the same materials of construction results in higher working stresses and increased design complexity and requires that more attention be given to product maintenance. Design complexity could result from supplemental processing to enhance engineering capability, new requirements for application of coatings, use of greater precision, and planned repairability.

Efficient material utilization also may be viewed as a general product weight reduction when the ratio of raw material to finished product weight is reduced. Extrusions, rolled shapes, die forgings, castings, and powder metal compacts are more efficient uses of material than components machined from bar. Castings are considered less efficient because significantly more metal is melted and poured into the mold than is delivered as a finished casting and because the homogeneity of castings is much less than that of wrought material.

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Fusion welding is used as a repair process and joining method to improve material utilization. Components may be joined edge to edge rather than requiring an overlap to accommodate mechanical fasteners. Design efficiency factors often are applied to the weld joint, thereby reducing apparent benefits.

The selection of alloy materials with a lower chromium content is constrained by a number of factors. Less effective performance of alternative materials may preclude their use for critical applications (e.g., where corrosion or oxidation is a major consideration). Hardenability requirements for heat-treating also enter into the alloy selection process, and since nonchromium alloying elements also increase the hardenability of steel, they could be used to decrease chromium consumption. In the competitive economic environment, cost also influences alloy selection.

Nonmetallic materials may serve as a replacement for chromium-containing alloys for nonstructural and structural applications. For some applications, structural components are being fabricated from advanced composite materials (e.g., the high strength and modulus properties of advanced composites are attractive for aerospace applications where minimum weight is a prime design goal).

Design efficiency may be achieved through extensive development testing of components and representative specimens or realistic structural analysis. Availability of accurate design data on loads, flaw size, environment, and materials is a prerequisite for detailed structural analysis, and inadequate design data retention and retrieval procedures are considered a major deterrent to efficient design.

The inability to characterize materials often precludes efficient design. Preliminary data often are obtained by laboratory testing and are adjusted as service data become available. Historically, over 10 years have elapsed between the introduction of a new material and its acceptance by the design community.

Design criteria, such as conservative factors of safety, increase product weight and may result in additional chromium consumption. As design analysis becomes better and more comprehensive and as in-process nondestructive testing and evaluation and feedback improve material and product reliability, factors of safety can be reduced and applied more realistically.

Although the costs of alloying elements and their effects on hardenability have been linked qualitatively

almost since steelmaking began, it was not until the 1940s
that one of the first quantitative attempts to use this
information to devise an optimum steel composition was
published (Grossman 1942). At that time, the relative costs
of the alloying elements chromium, nickel, and molybdenum
were about 1:2:5, respectively. Today, this ratio is about
1:5:9.

A careful and continuing survey of the cost and
availability of the various alloying elements used in
steelmaking is essential for their efficient and cost-
effective utilization in steel design. Quantitative
knowledge of the influence of individual alloying elements
on properties, such as case and base hardenability, permits
the cost of an alloying element to be compared with its
effect on properties. This comparison permits the chemical
composition of a steel to be optimized. Ideally,
hardenability efficiency should reflect the hardenability
contribution of an alloying element with respect to the cost
of the element. Because the contributions to base and case
hardenability (D_{Ib} and D_{Ic}) are both important in designing
a case-hardening steel, the two efficiencies must be
considered for each element; for a through-hardening steel,
only base hardenability efficiency is important.

Recently, the International Harvester Company
introduced a steel selection and alloy design system known
as the computer harmonized application tailored (CHAT)
system (Metal Progress 1972-73). The CHAT concept minimized
the consumption of critical alloying elements during the
1969 nickel shortage when the Equalloy steels (IH SAE EX
grades) enabled International Harvester to reduce its
consumption of nickel. The CHAT procedure could be used to
maintain steel production efficiency in the face of
potential chromium shortages by permitting increased
flexibility in alloy substitution based on available
elements and by broadening the standard chemical analysis
range limits (while maintaining hardenability within the
required range) to new range limits established by CHAT
analysis. More details on such steel selection and design
are given in appendix A.

4.3.5   Standards, Specifications, and Quality Assurance
         Considerations

Certain high technology, high safety, and high
reliability products emphasize the interaction of quality
assurance methodology with the design process. While the
design engineering function imposes the standards,
specifications, and performance criteria for specific
products, the quality assurance procedures monitor and often
enforce the criteria, particularly for nondestructive

testing (NDT) or evaluation (NDE). NDT methods are tools to evaluate material properties, structural integrity, and product reliability without destroying the material or items being evaluated, and, by its very nature, NDT plays an important role in conserving materials, equipment and capital resources. NDE saves materials by permitting their use under higher stress conditions. It increases reliability and makes property measurement easier by providing for the screening of materials for flaws before commitment to processing and the sorting of mixed or salvageable materials; it also provides a means for in-process control and for determining when useful life is questionable or safety is compromised (Federation of Materials Societies 1973). Furthermore, materials conservation is extended through the capabilities of NDT (or NDE) to substitute for destructive testing and possibly extend a product's useful life through in-service testing or maintenance. These conservation opportunities are applicable not only to chromium but to all engineering materials. To reap fully the benefits of properly used quality assurance technology, all aspects of quality assurance must be planned from the earliest design stages of a product and sufficient money must be allocated specifically for the necessary testing and evaluation.

4.3.5.1   NDE Design Considerations

Nondestructive evaluation is a phrase used to describe noninjurious methods for testing and evaluating properties and for detecting and measuring discontinuities and defects in materials or parts. Quantitative values are obtained for the properties and defects measured by these tests when they are correlated by destructive testing and service experience. NDE generally has been applied qualitatively as a mechanism for acceptance or rejection of finished parts.

Testing per se generates raw data that must be translated into the language of the materials and design engineers before the data can be useful (National Materials Advisory Board 1969). However, the design engineer also must be aware of the appropriate applications and limitations of NDT if it is to be used effectively to conserve materials and lower life-cycle costs. He must learn about NDT and its potential for conserving materials through all stages of the product's life cycle including the manufacturing process and the in-service phase (NATO 1976, Federation of Materials Societies 1973, National Materials Advisory Board 1969).

Since 1969, much has been done to popularize the fracture control approach in structural design. This approach has caused many design engineers to focus upon the

applications and limitations of NDE methods. Prior to the imposition of fracture control structural design criteria in recent military aircraft and NASA spacecraft programs, the design approach to NDE results asked: How small a flaw can be detected? Now the question is: How large a flaw is likely to go undetected? In evaluation programs aimed at answering the latter question, much attention has been drawn to the aspects of inspectability as is illustrated by the following excerpts from recently published papers on the subject:

> For a structure of short life operated under adverse conditions or for a long life structure justifiably operated under "kid glove" conditions, reduction in initial flaw size and consequent reliance on sophisticated nondestructive inspection procedures may be a legitimate alternative. Available inspection procedures and estimates of detectable flaw sizes and types are summarized in Table II [not included in this report]. It should be emphasized that flaw detection capability is not absolute, varying with product form, accessibility, test conditions and human factors. The designer is thus well advised to ask guidance from an inspection expert for aid in the parametric studies. (Krupp and Walker 1974).

> The interface between structural analysis and quality and reliability assurance (Q&RA) starts with the determination of initial crack length, continues with determinations as to which structures are inspectable and which are not, and how to change the latter into the former and thereby gain weight reduction. (Tupper 1974).

The relationship between design and inspection requirements is summarized in Figure 21 (Wood 1974), which further illustrates the intertwined roles of design and inspection in producing lighter and more reliable structures and, thus, in conserving chromium. While these examples relate mainly to aircraft structure in which the payoff in chromium conservation is slight, the design philosophies exemplified have been extended beyond aircraft, and many nuclear power components currently are being designed using similar practices. Among the advantages of fracture control design are opportunities for developing lighter, more reliable components. If such components are developed, substantial amounts of chromium will be conserved since many nuclear power components currently contain steel alloys with a high chromium content.

Further interdisciplinary interaction among design, materials, processing, maintenance, quality assurance, and

Class I
Single Load Path

Class I (monolithic, inspectable)-structure which is classified as single load path, the failure of which could cause loss of aircraft and which is accessible and easily inspectable in service shall be designed so that initial flaws of size a_1 will not grow to critical size (at limit design stress) during one inspection interval. To qualify as inspectable, however, it shall be demonstrated that the critical crack size at design limit stress shall be a through the thickness crack of dimension large enough to insure positive detection without major disassembly.

Safe Crack Growth Life Requirements
Class I Structure

Class I (monolithic, non-inspectable)-structure which is classified as single load path, the failure of which would cause loss of aircraft, and which is neither accessible nor easily inspectable in service or which will not receive periodic inspection, shall be designed so that initial flaws of size a_2 will not grow to critical size (at limit design stress) in one lifetime.

Class II
Single Load Path
Damage Arrest Capability

Class II-shall have sufficient residual strength and life to complete mission following the incurrence of damage.

FIGURE 21   Summary of Design and Inspection
Requirements (Wood 1974)

NOTE: From Fracture Prevention and Control,
© 1974 by American Society for Metals;
reproduced by permission.

Class III
Multiple Load Path
Redundant Load Path
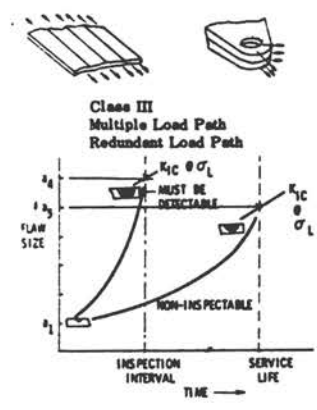
Safe Crack Growth Life Requirement
Class III Structure (Any Member)
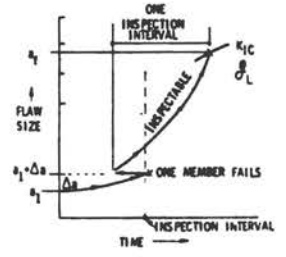
Safe Life Requirement For Remaining
Structure After Failure Of Single
Principal Element Requirement
Class III-Inspectable
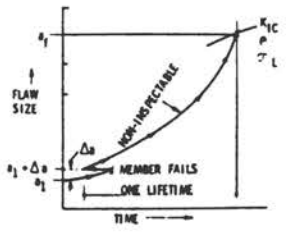
Safe Life Requirement For Remaining
Structure After Failure Of Single
Principal Element Requirement
Class III-Non-Inspectable

Class III (inspectable)-structure which consists of multiple load paths, which is easily accessible for inspection and for which periodic in service inspections are planned shall be designed so that initial flaws of size a_1 in any member will not grow to critical size (at design limit stress) in one inspection period and cause failure of the element. In addition, one principal member shall be assumed to fail at any time during the service life. The remaining structure (assumed to be flawed initially) shall be capable of carrying design limit stress at the end of one inspection interval. The safe crack growth analysis for the remaining structure shall be performed by assuming that each member is flawed initially and that growth in each member has continued at the assumed time of failure of the principal element. The most critical time of member failure shall be determined and safe crack growth allowable stress based on this criteria.

Class III (non-inspectable)-structure which consists of multiple load paths and fulfills the residual strength requirements of C, but is neither easily accessible or inspectable in service shall be designed so that initial flaws in any member of size a_1 shall not grow to critical size (at limit design stress) in one lifetime. One principal element failure shall be assumed to occur at any point in the design life. The remaining structure (assumed flawed initially) shall be capable of carrying design limit stress at the end of one lifetime. The safe crack growth analysis for the remaining structure shall be performed by assuming that each member is flawed initially and that growth on each member has continued at the assumed time of failure of the principal element. The most critical time of member failure shall be determined and the safe crack growth allowable stress based on this criteria.

NDE engineers is essential to the successful propagation of this potentially powerful structural analysis concept. In view of the opportunities to conserve chromium and other strategically significant materials, all practicable resources should be focused on developing the engineering aspects of fracture control designs.

4.3.5.2 Requirements for Specifications and Standards that Minimize Waste and Over-Design

In manufacturing products, industry operates in accordance with technical contract documents (e.g., drawings, specifications, or codes) that are international, national, industry, or proprietary standards. These standards should be kept current; however, the state of the art is so fluid that national or industry standards generally do not reflect the latest technology. Since standards represent specific agreements on quality between buyer and seller, standards that are useful to large segments of industry and government normally are developed.

The U.S. government differs from most nations in that no single agency is empowered to set standards. Several specific government agencies have statutory responsibilities for standards where health and safety are involved, but other U.S. standards generally are set through a voluntary consensus process. Although the nation's materials standards and specifications system operates reasonably well, some serious problems such as the following remain:

1. A proliferation of standards exists in a number of material and product areas due to overlapping interests and has resulted in a large number of different identification systems and formats.

2. Product specifications and standards generally have not kept pace with rapidly advancing materials technology although some code-writing organizations in various product areas are beginning to revise their procedures.

3. Standards and specifications traditionally are based on material compositions rather than end performance and, therefore, tend to restrict the use of new or improved materials.

4. The nation's participation in the activities of the International Standards Organization (ISO) has not kept pace with its mounting interests in international trade (Federation of Materials Societies 1973).

The cry against proliferation has been heard and most standard-, specification-, and code-generating bodies are attempting to consolidate and reduce the number of standards. However, the consensus system under which U.S. industry operates inherently reacts slowly to rapid changes in the state of the art. It is believed that most existing documents were developed without regard for conservation of chromium and other strategic materials. Recommendations for increasing awareness of the need for conservation are presented elsewhere in this chapter.

Another effective means of stretching available material supplies is to simplify and reduce the many grades, and during World War II, sizable savings in materials were realized in this way. By reducing the excessive number of sizes, types, grades and models of products available, fewer items could be manufactured and stocked and those items making the most economical use of scarce materials could be retained. For example, the domestic steel industry currently produces about 13.5 million tons per year of about 330 different grades of structural steel valued at about $4.2 billion. This multiplicity of grades severely impairs structural steel productivity because of such problems as small heat-lot sizes, more home scrap, and off-specification material. In addition, the proliferation of steel grades complicates material selection and fosters conservatism in design and overgrading of material for many applications (Federation of Materials Societies 1973).

At a chromium workshop, one participant stated that users must determine more accurately the metal requirements for a given application before specifying or overspecifying particular grades. Overspecification for stainless steel applications, which use two-thirds of domestic chromium, increases chromium consumption appreciably (Air Force Materials Laboratory 1975). Cited examples were:

Stainless Steel Type	Specification Change	Approximate Chromium Savings (%)
AISI 400 Series	Lowering carbon from 0.05 to 0.02 percent reduces chromium about 1/2 percent	8 to 10
AISI 430 Series	Change to AISI 429 Series with 2 percent less chromium or to AISI 405 Series with 5 percent less chromium and aluminum	12
AISI 304 Series	Change to AISI 200 Series with 2 percent less chromium or to AISI 301 and 302 Series with 1 to 2 percent less chromium	10

4.3.5.3 The Role of In-Process Inspection in Achieving Conservation

In section 4.3.4, the roles of quality assurance and NDE in design and in-service phases of the product life cycle were emphasized. Those roles are relatively modern extensions of the traditional inspection used in the manufacturing or processing phases. A natural outcome of in-process inspection, NDE, and feedback is materials conservation. Today's trends in automated inspection and NDE could yield further opportunities for conservation since automated NDE is only in its infancy (Federation of Materials Societies 1973).

4.3.5.4 Relationship of Quality Assurance and Design in Conservation

Given the complexities of design, the multitude of available materials and the need to prolong the availability of materials that are being sought by the industrialized countries, a more rational approach to design is the design team. This team should be composed of individuals from the involved technologies with the expertise needed to develop a viable product and should be convened when an idea originally is conceived. By careful analysis of a product's function and total life cycle (i.e., design, materials selection, initial manufacture, quality control and evaluation, service life, and recycle), a fine looking, efficiently operating, durable, easily maintained product can be made that conserves materials and energy, is recyclable, and is produced at the lowest total (procurement, maintenance, and operating energy) cost (NATO 1976).

4.3.5.5   Potential of Technical Societies in Conservation Strategies

The basic purpose of most professional and technical societies in the design, materials, quality assurance and NDE disciplines is the advancement of their respective technologies through education and dissemination of information. Without exception, these organizations willingly cooperate with government and industry on projects in the national interest. Individually and collectively (e.g., Federation of Materials Societies), these societies stage forums, workshops, symposia, conferences, etc., that focus on such topics as conservation. Their publications also are media for information dissemination (e.g., summaries of reports such as this are sought by technical society editors for inclusion in their publications).

4.3.6 Design for Recycling

As noted above, the designer should be alert to and, when possible, should provide for the recycling of chromium-containing components from obsolescent products into usable alloys. With proper incentives and motivation, industry and government could establish computerized part numbering and location systems for major chromium-containing hardware so that rapid and systematic recall could be made.

In a system of this type, the design should permit ready retrieval and replacement of the components involved. At present, this approach has sufficient economic value only in those cases where (e.g., the food industry) the bulk of the involved hardware is stainless steel and the entire unit is considered recyclable and replaceable with an equivalent material.

Present procedure for scrapping of a car exemplifies the economic and technical factors working together.

4.4 PRODUCT TRENDS

4.4.1 Energy and Process Equipment

During and following the Arab oil embargo, it became apparent that the United States depended significantly on foreign oil and would become increasingly dependent as energy demand increased and domestic production of oil and natural gas decreased. Accordingly, Project Independence (PI), a massive interagency effort involving over 500 professionals, was initiated in March 1974 to evaluate the nation's energy problems. The study team did not assess the chromium needs of alternate energy programs; however, it did assemble and publish sufficient information (Federal Energy

Administration 1974) to indicate that chromium requirements for several segments of the energy industry could be estimated with a small additional input.

In general, each task force that worked on the Project Independence Blueprint (PIB) chose several alternatives for study in assessing the potential for energy production. Two of these, Business as Usual (BAU) and Accelerated Development (AD), were selected for assessing chromium needs in this section. Where possible, the level of activity or energy production will be identified for these cases. For identifying the chromium needs of the energy industries, no allowance was made for lead time to deliver the materials required for plant construction which could be two to three years prior to the needed operating date.

4.4.1.1 Oil and Gas Exploration and Production

The PI Oil Resource Task Force estimated drilling activity for two cases. The BAU alternative assumed that only price changes would have an impact on potential production levels and that no new government policies would be promulgated to affect the development of energy resources. The AD alternative assumed that certain policy constraints on increasing production would be relaxed and that positive steps would be taken to encourage domestic oil production.

The estimated number of drilling rigs and platforms operating for production of oil in certain target years (Federal Energy Administration 1974, Exhibit VI-2) is shown in Table 16. The chromium needed for oil was assumed to be 500 pounds per rig and platform per year, and the chromium needed for gas was assumed to be 79 percent of that for oil (Albers and Bawiec 1975). The total annual chromium requirement by this segment of the energy industry was indicated to be 1,700 or 3,330 tons per year for the BAU and AD alternatives, respectively.

4.4.1.2 Oil Refineries

The PI Task Force on Facilities developed materials and equipment breakdowns for two typical 200,000-barrel-per-calendar-day (BPCD) oil refineries -- a gasoline refinery and a fuel oil refinery. To estimate chromium needs, the low-alloy steel and the stainless steel requirements reported by the Task Force (Federal Energy Administration 1974, Table III-5), were assumed to contain 2 percent and 18 percent chromium, respectively. The calculated totals were 616 tons of contained chromium for the gasoline refinery and 547 tons of contained chromium for the fuel oil refinery. In this study, 600 tons of contained chromium were used for

TABLE 16 Chromium Needs for Oil and Gas Exploration and
Production (tons)

Alternative	1977	1980	1985	1988	Annual Average
Business as usual					
Chromium needs [a]					
For oil [b]	560	710	1,120	1,500	950
For gas [b]	440	560	890	1,180	750
Total for oil and gas	1,000	1,270	2,010	2,680	1,700
Rigs for oil	1,941	2,314	3,831	5,189	--
Platforms for oil	288	535	656	801	--
Accelerated development					
Chromium needs [a]					
For oil [b]	690	1,070	2,460	3,390	1,860
For gas [b]	550	850	1,950	2,680	1,470
Total for oil and gas	1,240	1,920	4,410	6,070	3,330
Rigs for oil	2,194	3,360	8,569	12,068	--
Platforms for oil	573	923	1,284	1,508	--

[a] Based on 500 pounds of chromium per rig and platform per year
(Albers and Bawiec 1975).

[b] Ratio to oil is about 0.79 (Albers and Bawiec 1975).

a typical 200,000-BPCD refinery. The Facilities Task Force also estimated the additional crude capacity and number of new refineries required for the BAU and AD alternatives to be as shown in Table 17. The total annual chromium requirement for this segment of the energy industry was indicated to be only 1,150 and 1,880 tons per year for the BAU and AD alternatives, respectively.

4.4.1.3 Gas Processing

The number and type of gas processing plants was reported (Federal Energy Administration 1974, Table 7.6) for the BAU and AD conditions, and this information is summarized in Table 18. Alloy and stainless steel plant processing requirements -- 150 million standard cubic feet (scf) of gas per day -- also were published earlier (Federal Energy Administration 1974, Table 4.1). Assuming 5 percent chromium in the alloy steel and 18 percent in the stainless steel, total chromium needs for construction were calculated as 5 and 62 tons for refrigerated absorption and cryogenic plants, respectively. The total annual chromium requirement was indicated to be only 1,170 and 1,300 tons per year for the BAU and AD alternatives, respectively.

4.4.1.4 Shale Oil

Shale oil production rates of 450,000 barrels per day (BPD) and 1,600,000 BPD by the end of 1990 were projected for the BAU and AD alternatives, respectively (Federal Energy Administration 1974, Table II-2). Three types of plants were foreseen: in the first (underground), oil shale will be recovered from underground mines with retorting and processing above ground; in the second (strip), surface mining procedures will be used when the overburden is sufficiently thin with retorting and processing above ground; and in the third (in-situ processing), the oil shale is retorted in its original location below ground after suitable preparations with processing above ground. While in-situ processing has not yet been performed on a production scale, it is of interest because it could eliminate many materials handling and spent-shale disposal problems. These plants may be of different sizes, and capacities of from 50,000 BPD to 200,000 BPD were specified in the PI study.

Chromium usage was estimated from the total steel requirement reported by the PI Facilities Task Force (Federal Energy Administration 1974, Table G-1) that quoted a U.S. Bureau of Mines' estimate of 15 percent of the steel being either alloy or stainless. In high-hydrogen pressure processing (e.g., hydrocracking), the ratio of chromium-containing steels was estimated at 80 percent of 2 percent

TABLE 17 Chromium Needs for Oil Refineries

Alternative	1977-1980	1980-1985	1985-1990	Annual Average
Business as usual				
New crude capacity (1,000 BPD[a])	1,251	2,335	1,564	--
Number of new refineries	6.2	11.2	7.5	1.9
Chromium needs (tons/year)	1,240	1,350	900	1,150
Accelerated Development				
New crude capacity (1,000 BPD[a])	1,468	2,966	3,982	--
Number of new refineries	7.3	14.3	19.1	3.1
Chromium needs (tons/year)	1,460	1,710	2,300	1,880

[a] Barrels per day.

[b] At 600 tons of chromium per 200,000 BPD refinery.

TABLE 18 Chromium Needs for Gas Processing Plants

Alternative	1977-1980	1980-1985	1985-1990	Annual Average
Business as usual				
Number of new plants [a]				
Refrigerated absorption	14	0	0	--
Cryogenic	154	35	56	--
Chromium needs (tons/year) [b]	3,210	430	690	1,170
Accelerated development				
Number of new plants [a]				
Refrigerated absorption	14	2	23	--
Cryogenic	114	52	104	--
Chromium needs (tons/year) [b]	2,380	650	1,310	1,300

[a] Based on a 150 million standard cubic feet (scf) per day average plant.

[b] Based on 5 and 62 tons of chromium for one refrigerated absoprtion or one cryogenic plant, respectively.

chromium steels for thick-walled vessels and 20 percent of 18 percent chromium stainless steels; the chromium usage then calculated to the 0.78 percent basis for the total steel. The chromium needs for shale oil production are summarized in Table 19 at 680 and 2,310 tons per year for the BAU and AD alternatives respectively.

4.4.1.5 Synthetic Fuels from Coal

Conversion of coal to synthetic fuels does not provide a new supply of energy but merely converts the energy in coal into a more convenient gaseous or liquid form that is less likely to pollute. Several processes have been commercialized over the years and many more are under development by the Department of Energy, the U.S. Bureau of Mines, and private industry. The PI Synthetic Fuels Task Force (Federal Energy Administration 1974, pp. 9-13, 19, 101) selected five processes: the liquid fuel Fischer-Tropsch and the Lurgi high-Btu pipeline gas processes (which are representative of current technology) and three others that are representative of developing or advanced technology.

Table 20 provides a summary of estimated materials requirements, the number of plants projected under the BAU and AD construction programs, and chromium requirements. The latter was estimated on the basis of 2 percent chromium in the heavy plate plus 5 percent in pipe. As is shown, potential chromium demand varied from 1,900 to nearly 13,000 tons per year of contained chromium depending upon the time period and the rate at which synthetic fuel plants were to be developed.

4.4.1.6 Nuclear Power

Nuclear power is projected to expand at a rapid rate between 1977 and 1990, when expected nuclear generating capacities for the BAU and AD alternatives are estimated to be 500,000 and 730,000 megawatts (MW), respectively (Federal Energy Administration 1974, p. 3.1-5). The 500,000 MW of installed capacity projected for the BAU case is equivalent to 7 million BPD (of plant operation) on a heat equivalent basis. Alternatively, when allowance is made for a 37 percent heat efficiency in an oil-fired steam boiler-generator, the oil replaced by this power is about 19 million BPD, approximately the expected total U.S. oil consumption (domestic plus imports) in 1977.

Chromium requirements for various kinds of nuclear power plants have been reported (presentation to the Committee by K. E. Horton, Department of Energy, September 1975). When these numbers are reduced to tons of chromium

TABLE 19 Chromium Needs for Shale Oil Production

Type of Plant	Tons of Chromium Per Plant [b]	Number of Plants	
		Business As Usual 1980-1991	Accelerated Development 1978-1991
50,000 BPD [a] underground	554	6	10
100,000 BPD underground	1,014	--	2
100,000 BPD surface	1,030	1	3
150,000 BPD surface	1,500	--	1
200,000 BPD surface	2,000	--	1
50,000 BPD in-situ	3,175	1	5
Average chromium (tons/year)		680	2,310

[a] Barrels per day.

[b] Chromium estimated at 0.78 percent of total steel.

TABLE 20 Chromium Needs for Synthetic Fuels from Coal

| | Advanced U.S. Technology | | | Current Technology | | Average Annual Chromium Needs [a] |
	Low-Btu Utility Gas	Pipeline Gas (Synthane)	Liquid Fuel Plus Gas	Pipeline Gas (Lurgi)	Gasoline Plus Gas Fischer-Tropsch)	(tons/year)
Gas						
Flow (million scf/day)	1,570	250	224	250	325	
Heat value (Btu/scf)	130	930	930	930	930	
Liquid						
Flow (barrels/day)	--	--	38,600	--	19,550	
Heat value (MM Btu/Bbl) [b]	--	--	6.4	--	5.4	
Sulfur (weigh percent)	--	--	0.4	--	10^{-16}	
Steel (tons/plant)						
Reinforcing	400	1,570	6,170	2,400	21,690	
Structural	1,700	11,200	19,290	7,200	21,160	
Heavy Plate	11,100	16,000	77,160	24,000	84,640	
Pipe	3,400	10,100	9,645	12,000	10,580	
Total	16,600	38,870	112,265	45,600	138,070	
Chromium						
Tons/plant	390	825	2,025	1,080	3,290	
% of total steel	2.4	2.1	1.8	2.4	2.4	
Number of new plants completed during time period						
Business as usual						
1984-1990	-	6	-	6	-	1,900
1990-1995	5	3	2	3	2	3,660
1995-2003	7	1	7	-	2	3,040
Total	12	10	9	9	4	2,840
Accelerated development						
1984-1990	3	3	3	3	3	3,800
1990-1994	14	14	14	14	14	26,640
Total	17	17	17	17	17	12,940

[a] Basis: 2 percent chromium in heavy plate plus 5 percent in pipe.

[b] Million Btu/barrel.

per gigawatt (1 Gwe = 1000 MW) of generating capacity and an allowance is made for the chromium requirements of the turbine system, the values shown in Table 21 are obtained. It is worth noting that the liquid metal fast breeder reactor (LMFBR) requires five to seven times as much chromium as the other types. This reactor is not expected to be widely used prior to 1990; however, it may be necessary to develop and use it sooner if the fission reactor is to be a long-term viable option for energy production. All other reactors consume uranium at a rapid rate and will deplete the supply shortly.

The LMFBR, as currently conceived in its prototypes (fast flux test reactor and the Clinch River demonstration breeder reactor), is highly dependent upon the availability of certain raw materials (e.g., chromium, manganese, nickel, and aluminum), and shortages of any of these raw materials can affect commercialization of the LMFBR more seriously than competitive energy sources because: early impacts of any shortages most likely will occur in the mid-1980s, coinciding with the introduction of the LMFBR; the LMFBR is higher in capital cost per megawatt of capacity and, therefore, more sensitive to increases in material prices than competitive energy sources; and the time required to qualify a substitute material exceeds the time needed for most other types of power generating equipment, because of current licensing requirements.

While the LMFBR is expected to use more than twice the chromium per megawatt generated than the light water reactor, the amount actually involved is only 1 to 2 percent of current annual U.S. chromium consumption. A true assessment of the impact of potential chromium shortages depends on factors such as clarification of the development schedule for the demonstration plants, the social and political environment regarding acceptance of nuclear power, the growth rate of electrical energy demand, and the development of alternate energy-producing methods and their associated total life costs.

In any event, chromium for the LMFBR, has a high-priority rating that is applicable to all the candidate energy systems. The discussion below therefore pertains to the design aspects of all candidate high-technology energy systems.

The first question is how to ensure a chromium supply to serve the needs of our energy-producing industries. As indicated above (see also Table 24), the entire chromium consumption for all energy industries is 3 to 5 percent of the total chromium consumed with nuclear reactors using about one-half of this amount. Introduction of LMFBR will

TABLE 21 Chromium Requirements of Different Nuclear Power
Reactors (tons/1,000 MW)

Reactor Type	Chromium Requirements [a]
Boiling water reactor (BWR)	275
High-temperature gas-cooled reactor (HTGR)	350
Liquid metal fast breeder reactor (LMFBR)	2,030
Pressurized water reactor (PWR)	455

[a] Including turbine system.

increase chromium usage slightly, but the amount of chromium involved, although vital to the process, is relatively insignificant. Thus, availability of chromium for the LMFBR should not be a problem.

The nuclear industry has initiated design and substitutability efforts aimed at reducing the industry's dependence on chromium. The high visibility of this industry to the government regulatory agencies, code certification groups, public pressure groups, and public itself has resulted in extreme design conservatism. Chromium design and substitution considerations thus far have focused principally on nonsafety-sensitive systems (e.g., the feedwater supply, auxiliary liquid metal, cover gas, electrical, and plant services) because their qualification and coding time period is relatively short in relation to that of those primary systems that are exposed to irradiation, stress, and sodium.

Looking beyond the year 1990 and assuming successful development and construction of large-scale TOKAMAK (toroidal confinement device) fusion power plants, more severe demands on chromium will be incurred (private communication from G. L. Kulcinski, Department of Nuclear Engineering, University of Wisconsin, 1976). This assumption stems from the basic features of TOKAMAK fusion power plants (e.g., the low power density of 1 MW/m² vs 10 to 100 MW/m² for fission reactors). A 1,475-MW TOKAMAK nuclear island is estimated to require 9,363 tons of chromium with an additional 6,200 for the remaining plant for a total of 15,563 tons or 10.5 tons per megawatt, a demand five times higher than that of breeder reactors (Table 22).

The chromium requirements for the BAU and AD alternatives are tabulated in Table 23. Chromium demands vary from 4,875 tons to 24,000 tons per year depending on the time period and the growth rate of nuclear power.

4.4.1.7 Coal-Fired Electric Utilities

No oil- or gas-fired electric utilities are planned during the period under study (1977-1990). Coal-fired electric utilities, however, are expected to expand as shown in Table 24 for the BAU and AD schedules (Federal Energy Administration 1974, p. III-14). The chromium requirement for the new construction is based on using 135 tons of chromium per 1,000 MW (Federal Energy Administration 1974, Table VIA-XI). Total needs are estimated at 1,600 and 3,840 tons per year for the BAU and AD alternatives, respectively.

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TABLE 22   Chromium Content of 1,475-MW TOKAMAK Nuclear
           Island

Component	Chromium Demand (%)
Nuclear island	
Initial structure	9
First wall replacement	8
Blanket replacement	17
Shield	3
Magnets	23
Subtotal	60
TOKAMAK componants	
Energy storage unit	3
Thermal fly wheel	10
Liner	3
Subtotal	16
Balance of plant	24
Total	100

NOTE: Based on data from Kulcinski 1976.

TABLE 23 Chromium Needs for Nuclear Power

	1977-1980[a]	1980-1985[a]	1985-1990[a]	Annual Average
Business as usual				
New generating capacity (1,000 MW)[b]	39	147	205	--
Chromium needs (tons/year)[c]	4,875	11,025	15,375	11,280
Accelerated development				
New generating capacity (1,000 MW)[b]	53	225	320	--
Chromium needs (tons/year)[c]	6,625	16,875	24,000	17,250

[a] January 1 of each year.

[b] Completed in the time period.

[c] At 375 tons of chromium per 1,000 MW. This is based on a mix of 45 percent boiling water reactor and 55 percent pressurized water reactor with chromium requirements of 275 tons and 455 tons per 1,000 MW, respectively, including 210 tons for the turbine system.

TABLE 24   Chromium Needs for Coal-Fired Electric Utilities

Alternatives	1977-1980 [a]	1980-1985 [a]	1985-1990 [a]	Annual Average
Business as usual				
New generating capacity (1,000 MW) [b]	48	71	35	--
Chromium needs (tons/year) [c]	2,160	1,920	945	1,600
Accelerated development				
New generating capacity (1,000 MW) [b]	93	171	105	--
Chromium needs (tons/year) [c]	4,185	4,620	2,835	3,840

[a] January 1 of each year.

[b] Completed in the time period.

[c] At 135 tons chromium per 1,000 MW.

4.4.1.8 Energy Industries Excluded

Some sections of the energy industry are not included in this report because chromium usage is expected to be trivial, available data are not sufficient to permit a reasonable estimate of chromium needs to be made, the technology is not advanced sufficiently to permit a reasonable estimate of chromium requirements to be made, or the probable application time is beyond the time frame used in this study. The segments not covered in this report include: coal mining, hydroelectric power, oil and gas pipelines, railroad equipment, deep water ports, geothermal, solar, wind, ocean thermal, bioconversion, new oil tankers, and new liquefied natural gas terminals, and vessels.

4.4.1.9 Summary of Chromium Needs in the Energy Industry

A summary of the chromium needs of the energy industry for new construction to be completed between approximately January 1, 1977, and January 1, 1990, is displayed in Table 25. The annual variation within this 13-year time period indicates a difference less than that between the requirements for the BAU and the AD expansion cases.

The average annual consumption of chromium for new construction by the energy industry is shown as 19,480 and 33,710 tons per year for the BAU and AD alternatives, respectively. These requirements are substantially less than the average of 650,000 tons of chromium expected to be consumed annually in the United States during this same time period. The energy sector's usage, therefore, corresponds to about 3 to 5 percent of total U.S. demand.

The summary table also highlights the fact that the chromium needs of the oil and gas segments are a small part of the chromium requirements of the entire energy industry. Even shale oil production is not expected to be a major consumer of chromium because the economically recoverable reserves are fairly modest and the rate of exploitation probably will be restricted by the supply of water and environmental considerations.

The conversion of coal to gas and clean liquids is not expected to be large during the selected time frame. As noted, the figures shown for the "range of annual chromium needs" are for time periods extending to 1994 and 2003. If the average chromium demand for the time period 1984-1994 (12,940 tons per year) had been employed in the AD "average annual value" column, the synthetic fuel program would have required not 11 percent but about 30 percent of the total chromium required by the energy industry. Thus, the synthetic fuels program could become a major chromium

TABLE 25   Summary of Chromium Needs of the Process and Energy Industry [a]

Industry Segment	Business As Usual			Accelerated Development		
	Range of Annual Needs (tons/year)	Average Annual Value (tons/year)	(%)	Range of Annual Needs (tons/year)	Average Annual Value (tons/year)	(%)
Oil and gas exploration and production [b]	1,000-2,680	1,700	9	1,240-6,070	3,330	10
Oil refineries	900-1,240	1,150	6	1,460-2,300	1,880	6
Gas processing	430-3,210	1,170	6	650-2,380	1,300	4
Shale oil	680 [c]	680 [c]	3	2,310 [d]	2,310 [d]	7
Synthetic fuels from coal	1,900-3,660 [e]	1,900 [f]	10	3,800-26,640 [g]	3,800 [h]	11
Nuclear power	4,875-15,375	11,280	58	6,625-24,000	17,250	51
Coal-fired electric utilities	945-2,160	1,600	8	2,835-4,620	3,840	11
Total	10,730-29,005	19,480	100	18,920-68,320	33,710	100

[a] January 1, 1977 to January 1, 1990, except as noted.

[b] January 1, 1977 to January 1, 1989.

[c] January 1, 1980 to January 1, 1991. Approximately uniform through the whole period.

[d] January 1, 1978 to January 1, 1991. Approximately uniform through the whole period.

[e] January 1, 1984 to January 1, 2003. Average for the whole period is 2,840 tons/year.

[f] January 1, 1984 to January 1, 1990.

[g] January 1, 1984 to January 1, 1994. Average for the whole period is 12,940 tons/year. At this rate, the usage is about 30 percent of the energy industry total.

[h] January 1, 1984 to January 1, 1990.

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consumer if the new construction expands as projected for the AD case in the 1990s.

At this time, electric power generation appears to be the industrial segment that will consume the largest share of the industry's chromium, with nuclear power projected to consume the most. Furthermore, if the breeder reactor is developed and commercialized, the chromium need per megawatt of generating capacity could increase by a factor of five or more. Owing to the overriding importance of nuclear energy in the demand for chromium, this subject will be explored in greater detail in the next section of this report.

4.4.2 Automotive Industry

The total amount of chromium used by the automotive industry includes that in cars, trucks, buses, and the after-market service parts as well as production scrap if its chromium content is not used beneficially in the recycled form. To arrive at the industry net usage figure, chromium recovered from junk cars, trucks, and buses and used beneficially after recycling must be subtracted from total usage. A forecast of normal and emergency chromium requirements to the year 2000 is shown in Figure 22. Details regarding the chromium content in cars, trucks, buses and truck trailers are presented in appendix B.

4.4.3 Aircraft Industry

Chromium utilization trends in the aircraft industry have been surveyed using two different approaches. First, actual and estimated total chromium consumption figures were requested from major U.S. aircraft companies. Second, chromium usage was studied for a large commercial transport aircraft. Accurate and complete data in both cases are lacking because of the greater time and effort needed for the data retrieval method used and because many of the data provided by the contributors were identified as proprietary. However, the details for these approaches are presented in appendix C.

Annual chromium consumption by the aircraft industry is minor compared to the national total and represents approximately 6 percent based on U.S. Census statistics for 1972 consumption of chrome products. An estimated 90 percent of the aircraft industry consumption is considered essential. Elimination or even reduction of the chromium content in the alloys used would severely degrade aircraft performance unless a technological breakthrough is achieved in materials development programs.

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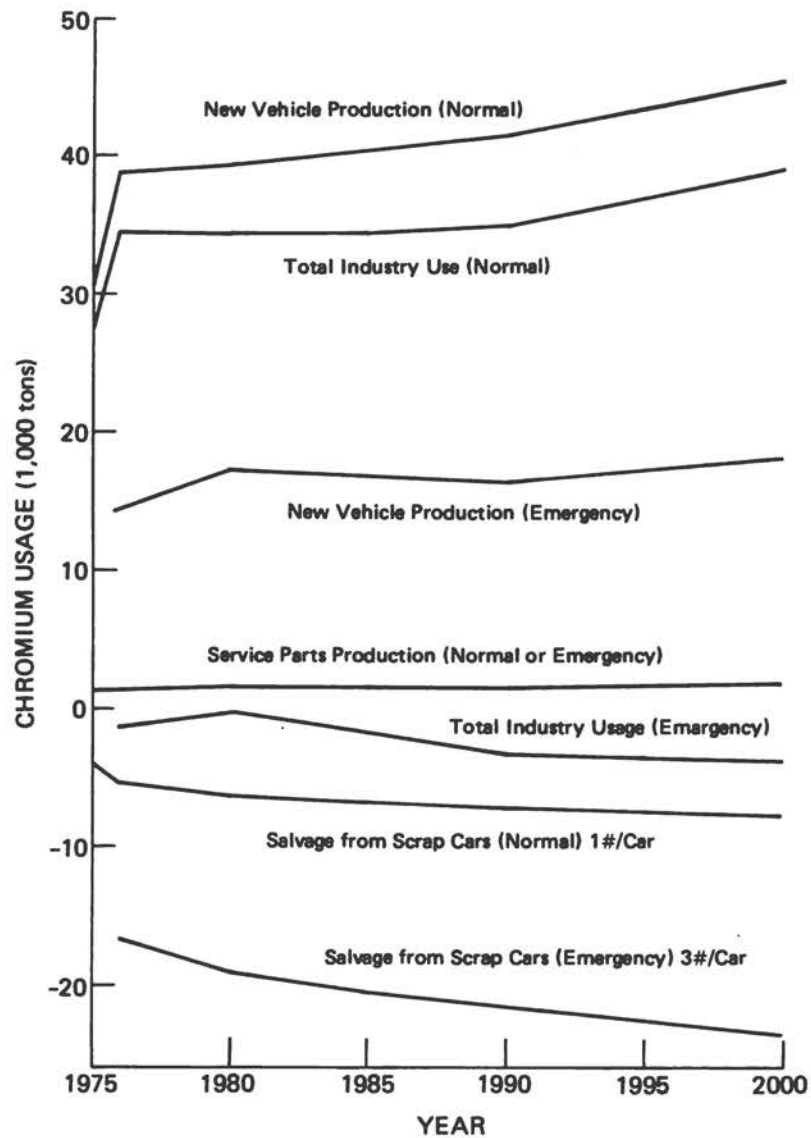
FIGURE 22   Forecast of Automotive Industry Usage of
            Chromium in Cars, Trucks, and Buses, 1975-2000
            (based on data from Jet Propulsion Laboratory
            1975, and 1976 presentation to the Committee by
            J. E. LaBelle, Detroit Diesel Allison, General
            Motors, Detroit)

4.4.4 The Marine Industry

Chromium usage in the marine industry was surveyed by
(a) personal correspondence with 22 shipbuilders and ship
equipment companies requesting information on annual
chromium consumption and (b) a search for data on the
quantity of chromium consumed to fabricate a typical vessel.
Seven of the 22 companies contacted responded and 4 of these
provided chromium consumption data. Data on chromium
consumed for a typical vessel was not available in a form
usable for this survey, although it was determined that the
U.S. Navy is in the process of collecting data which will
permit computation of chromium weight for specific craft.
Results of this Committee's survey (presented in appendix D)
reveal the need for a comprehensive study, if accurate
chromium utilization data are to be developed for the marine
industry.

Chromium consumption by the marine industry is a very
small portion of the national total. U.S. Census statistics
for 1972 consumption of chrome products indicate a
calculated value of less than 1 percent based on data
compiled for ferrochrome, ferrochrome silicon, and chromium
metal. Consequently, conservation of chromium in the marine
industry would not be too fruitful. Chromium savings are
possible in the galley area where its usage is considered
nonessential. In other areas of the ship, chromium is more
closely tied to the performance of the vessel and could be
considered essential.

4.5 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

4.5.1 Summary

Analysis of the chromium consumption trends of the
major heavy industries over the next 20 to 30 years, (e.g.,
energy, process, automotive, aviation, and railroad) does
not indicate any significant upward perturbations except for
the manufacture of synthetic fuels, the introduction of
nuclear breeder reactors (and the eventual fusion reactor),
and the possible introduction of advanced electric batteries
for automotive and central station power plants.

The chromium needs of selected segments of the energy
industry have been assessed. Between January 1, 1977, and
January 1, 1990, chromium demand is projected at 20,000 to
34,000 tons per year for business-as-usual and accelerated
development programs, respectively, and is about 3 to 5
percent of the probable U.S. average demand of 650,000 tons
per year. About 20 percent of the energy industry demand
will be required by oil exploration, production, and
refining and gas processing. Nuclear power, is projected to

consume 50 to 60 percent of the industry total. If the fission reactor is to contribute significantly to the supply of energy after 1990, the breeder reactor must be developed since the currently used boiling water and pressurized water reactors should consume the potential supply of uranium in a short time. The breeder reactor will increase chromium demand by about a factor of five.

Automotive industry usage is currently about 8.3 pounds of contained chromium per car, with the catalytic converter and wheel covers using approximately one-half of this amount. The latter nonfunctional use can be eliminated immediately and design of engines to meet EPA requirements could eliminate the former chromium use.

Most other reviewed cases indicate a critical but rather low-level constant demand for chromium-containing metals. Numerous examples were identified where reduction in chromium requirements is achievable through conservation, processing changes, and substitution. Consideration should be given to initiating such actions now.

The role of chromium in steel is to provide properties such as corrosion resistance, hardenability, and strength. Efficient design with chromium makes suitable allowance for degradation mechanisms while minimizing usage of chromium. The ultimate design goal should be to match component life with desired product life. Conservative design factors of safety, selected arbitrarily and imposed by design specification, can cause excessive weight in a product and inefficient design; both lead to increased chromium consumption.

To provide a basis for minimum chromium use in the tonnage alloy steels without sacrificing properties, a system such as International Harvester's CHAT should be advanced on a national basis and incorporated into design handbooks and specifications. This system requires considerable data to be developed on the effect of carbide formers other than chromium -- tungsten, vanadium, titanium, and columbium -- upon properties such as hardenability, resistance to intergranular cracking, and resistance to hydrogen environments.

At this time, there is no satisfactory chromium substitute as an alloying addition to resist high temperature oxidation and sulfidic corrosion. However, if the sulfidic environment is present without a high pressure hydrogen environment, the corrosion mechanism is a surface phenomenon and a corrosion-resisting material can be applied as a thin lining. In such cases, the liner is usually a high-chromium steel.

Nondestructive testing and evaluation can play an important role in chromium conservation by using materials at higher stress levels, screening materials for flaws before commitment to final processing, sorting mixed or salvageable materials, evaluating repairs, and determining when useful life is ended or safety compromised. Fracture control design permits opportunities for lighter weight and higher reliability components.

Each of these approaches requires changes in curricula in engineering colleges aimed at creating an awareness of the sensitive role of alloying elements in steel, conditioning people from using stainless steel purely for aesthetic reasons, motivating engineers to work as a team using all disciplines to develop an optimized efficient design, and developing more precise handbook data that are oriented to use of optimum chromium-containing materials to perform a given function.

4.5.2 Conclusions

1. The design team (consisting of a designer, materials engineer, processing engineer, nondestructive evaluation engineer and a maintenance entineer) is the most effective technical approach for using and conserving materials.

2. In the design process, consideration must be given to the following factors:

    - Bias -- Select material based on requirements and not on past practice.

    - Available Resources -- Be aware of chromium criticality and recyclability.

    - Reliability and Life Expectancy -- Design with inspectability in mind; select life cycle (short or long); initial and total cost.

    - Weight -- Conscious decision to reduce or increase weight can be a powerful chromium conservation tool.

    - Ease of Recycling -- Design high-chromium-containing products so that they can be identified, disassembled, and recycled readily.

- **Aesthetics** -- Create a demand for nonchromium externals, an immediate conservation area.

- **Corrosion** -- A nonfruitful or limited area for conservation by design.

- **Stress** -- Key factors include life, design handbook data, coatings and claddings.

- **Alternative Materials** -- Highlighted is the International Harvester's Computer CHAT procedure for minimizing use of critical elements without sacrificing desired design properties.

3. An analysis of selected industries -- process, energy, automotive, aircraft, and marine -- indicated current and future requirements, and opportunities, or lack thereof, for chromium conservation. Chromium requirements are forecast in Table 23 for the next several decades. The nuclear and fossil power and synthetic fuel industries are the key users of chromium. Sociopolitical factors such as environment, growth, demand for power, regulations, and geographical impact these demand figures.

4. No satisfactory alternative exists, at present, for chromium as an alloying addition for resisting high-temperature oxidation and sulfidic corrosion.

5. The ultimate design goal should be matching component life with desired product life. Conservative design factors of safety, selected arbitrarily and imposed by design specification, can result in excessive product weight and inefficient design, and lead to increased chromium consumption.

6. Nondestructive testing and evaluation can play an important role in chromium conservation by permitting less conservative design factors of safety. Utilizing nondestructive testing and fracture control in design provides opportunities for lighter weight and more reliable components.

7. Universities and technical societies have a major role to play in creating an awareness of the need for chromium in products through curricula changes, handbook revisions, seminars, and publications.

4.5.3 Recommendations

In the interest of better chromium usage and design, it is recommended that:

1. The team design approach be implemented by top management. To promote chromium conservation, design teams should be encouraged to ensure that:

    - Materials of desired composition and properties are used

    - Combinations of materials are used that are compatible with current recycle systems

    - Materials have consistently high quality and reliability

    - Processing variations can be adjusted by nondestructive testing, evaluation, and feedback during processing

    - Finished products have the highest quality and reliability possible through in-process control and reduced reliance on final inspection

    - Products in service can be inspected in use to determine their remaining useful life and safety and can be disassembled and repaired easily and at relatively low cost

2. Incentives and penalties be considered to stimulate designers to design products with a high chromium content in a manner that will permit them to be identified readily, disassembled, and recycled.

3. Research be accelerated to develop surface coatings with better high-temperature corrosion and oxidation resistance.

4. Programs for nondestructive evaluation be specified and funds allocated specifically for NDE implementation in order to improve material and product reliability, to reduce in-process waste and labor, and to permit designing to higher limits.

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Chapter 5

PROCESSING

5.1 INTRODUCTION

The following discussion focuses only on the actual
processing and fabrication of stainless and alloy steels,
alloys, and metal products containing chromium. The
principal products of interest are chromium-containing
stainless steels, alloy steels, nonferrous alloys
(especially nickel-base) and welding materials. Limited
consideration is given to cast irons and tool steels since
these materials contain relatively little chromium.

Melting and refining, casting, mill product
fabrication, manufacturing processing, joining, surface
coatings, and recycling are considered in terms of: present
status; key problems; probable future processing trends; and
special opportunities, needs, and requirements for chromium
conservation. For each chromium conservation opportunity
identified, an attempt is made to: (1) assess its technical
and economic status and identify potential problems; (2)
determine how much chromium would be saved, what
implementing actions must be taken, and how much time would
be required for implementation; and (3) identify any
peripheral effects, as well as the probability for success.

5.2 MELTING AND REFINING

The selection of a particular melting and refining
process from today's array of technologies depends upon the
type of alloy desired and its final application, economics,
and specific customer specifications. Because of the widely
varying requirements and the extensive technology in
melting, this discussion will focus on major conservation
potentials in key production uses of chromium. Important
metallurgical applications of chromium, the average chromium
content of the principal material groups, and the
distribution of the chromium consumption are listed in
Table 26.

Among the stainless steels, the austenitic stainless
types (primarily Type 304) with their relatively high
chromium content are dominant. The alloy constructional
steels with an average chromium content of about 1 percent
are the second largest users of chromium because of the
large tonnages produced. Other chromium alloying uses cover
a wide range of products, the major portion of which are
used in high-temperature and corrosion-resisting
applications, but comprise only 14 percent of the total
consumption.

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TABLE 26 Key Uses of Chromium in Alloys (1974)

Material Group	Average Chromium Content (%)	Use of Metallurgical Chromium (%)
Stainless steels [a]	16.4	72
Alloy steels	1	14
High-temperature special alloys and Ni-Co-base alloys	18	7
Tool steels	6	2
Alloy cast irons	< 1	2
Miscellaneous (wear resisting alloys, welding, hard facing alloy, others)	--	3

NOTE: Data from American Iron and Steel Institute 1975.

[a] Austenitic stainless steels contain an average of 17.9 percent chromium; ferritic stainless steels, 15.2 percent; and martensitic stainless steels, 12 percent.

Emphasis in this discussion is placed on stainless steels, alloy constructional steels, and the high-temperature speciality alloy group. These three groups offer real potential for saving and conserving chromium, especially through continuing implementation of recent technological developments on a large scale. Greater use of lower grade chromium ferroalloys would permit the use of more readily available lower grade chromium ores. More extensive recycling of mill wastes could reduce chromium consumption significantly in future years.

5.2.1 Primary Melting and Refining Methods

The basic methods used today for making iron and steel are expected to be used in the foreseeable future to meet the growing demand; however, they do not lend themselves easily to effective processing of a combination of chromium-bearing ores, pig iron, and scrap. An investigation to determine the feasibility of using lower grade chromium ores (e.g., chemical grade chromium ore with a chromium-to-iron ratio of about 1.5:1.0) for the production of chromium-iron in the blast furnace was carried out some time ago (Dulis 1974). The results indicated that the process was technically feasible but that the economics were questionable. Further work in this area may be advisable since chromium-bearing, blast-furnace iron could be pigged for use in alloy cast irons that would retain the full value of the contained chromium. However, chromium consumption for alloy cast iron is only 3 percent of total consumption; hence, the savings would be small. The use of chromium-bearing iron for steelmaking would not permit the retention of chromium from alloyed pig iron and simultaneous removal of phosphorus to acceptable levels.

A more promising approach to utilizing low-grade chromium ores might be the development of a production process for chromium-bearing prereduced pellets. The blending of chromite ore with iron ore for combined reduction to a deoxidized product with 2 to 10 percent chromium or the mixing of reduced iron with ferrochrome pellets might be feasible for alloy steelmaking in electric furnaces. Research in this area should be encouraged since alloy steels currently consume about 16 percent of total metallurgical chromium; however, the cost of iron units in such materials must be competitive with alternative iron unit sources such as scrap. (The practice of using prereduced iron pellets is growing rapidly in electric furnace shops.)

Electric furnace arc melting is the predominant alloy steelmaking process for low- and high-alloy steels as compared to induction melting that is used at relatively low

volumes by the foundry industry. In 1975, electric furnace output accounted for 21 percent of domestic steel production, approximately 70 percent of which was carbon steel. Electric furnace capacity should continue to increase steadily because of the advantages of electric melting. The electric furnace provides excellent flexibility in the selection of raw materials and in operational and metallurgical practices that can be tailored readily to specific needs and requirements. Recent developments in furnace equipment and technology have made the electric arc furnace a prime melting unit for steels of all types. The introduction of ultra-high-power (UHP) furnaces and the development of improved refractories and electrodes have made the electric arc furnace an attractive melting unit even for low-cost tonnage carbon steels. Approximately 40 percent of U.S. electric furnace capacity is UHP and the largest single furnace has a capacity of 400 tons.

UHP melting has relegated the electric furnace to a pure "melting machine" that requires the separation of the melting and refining phases for most economical practice. Starting in 1968, the trend toward separation of the melt-down phase from the refining stage led to development of a number of duplex melting systems that are used predominently in stainless steel manufacture. The electric furnace melts the charge and metallurgical treatments are performed subsequently in the ladle (ladle refining) or in separate refining units that rely on chemical heat input or auxiliary electric heating. A general overview of the various refining systems in operation today for high-alloy chromium steels is presented in Figure 23.

Decarburization of high-chromium-containing melts is somewhat different from that of unalloyed steels. The high affinity of chromium for oxygen retards decarburization, and the chromium-carbon equilibrium for a specific chromium content can be shifted to lower carbon levels only by significant temperature increases. However, by utilizing the pressure dependence of the carbon oxidation reaction, lower carbon contents can be achieved at reasonable temperatures under vacuum without significant chromium losses. The available processes are ladle refining carried out under vacuum and converter refining carried out at atmospheric pressure with inert gases.

The vacuum processes achieve somewhat lower carbon levels with lower chromium losses than converter processes that are based on lowering the carbon monoxide partial pressure by blowing with inert gas and oxygen in varying proportions. The best known processes are argon-oxygen decarburization (AOD) and the more recently developed
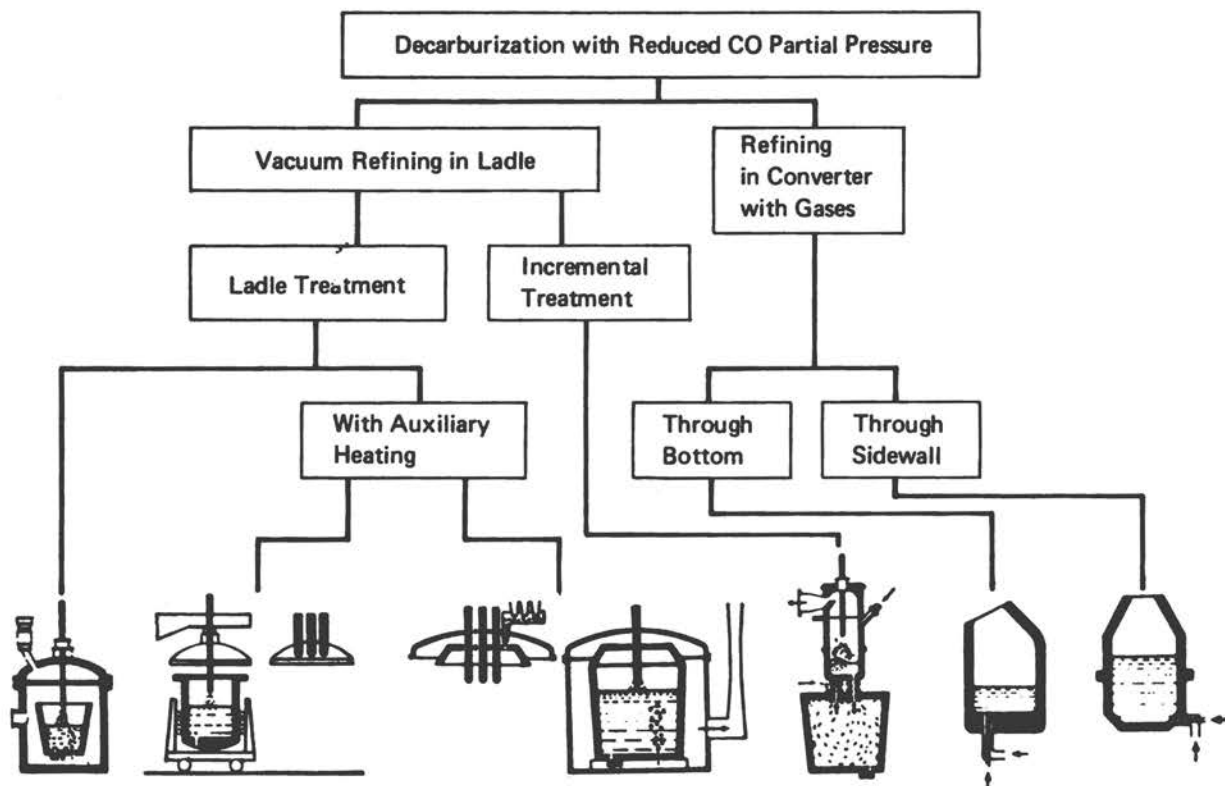
FIGURE 23   Overview of Principal Decarburization Processes
Used in Stainless Steelmaking (Baum et al. 1975)

Creusot-Loire-Uddeholm (CLU) process. The latter uses steam as the oxygen diluent and argon only for final refining and purging. The CLU converter can be charged with chrome pig iron produced directly in a reducing arc furnace from chrome ore, pellets, low-phosphorus iron ore, and nonalloyed scrap.

The development of duplexing processes has had a profound impact on stainless steelmaking. Significant economic benefits result because of the use of lower cost raw materials and the much improved chromium recovery. In conventional electric furnace melting and oxygen blowing, the irreversible chromium losses amounted to 10 to 15 percent (an average of 12 percent); with pneumatic decarburization processes, these losses are reduced to less than 6 percent using electric arc melting followed by vacuum decarburization processes. A typical sequence for stainless slab production is illustrated in Figure 24. The charge is melted in the electric arc furnace or basic oxygen furnace and is refined by AOD or vacuum-oxygen decarburization (VOD). The processing of stainless steel heats of 100 to 150 tons is common today. In addition to greatly increased productivity and chromium recovery from lower cost high-carbon ferrochromium, duplex processing improves product quality due to lower gas and impurity contents.

The rapid acceptance of duplex techniques is causing a major shift in raw material requirements. Scrap, the primary chromium source in stainless steelmaking, supplies about 50 to 70 percent of the needed chromium, and the balance is supplied by ferrochromium. Low-carbon ferrochromium and ferrochromium silicon are being displaced by high-carbon ferrochromium (charge chrome) that is less expensive to produce and can be made from lower grade ores. To make stainless steel using low-cost charge materials, charge chrome can be combined with high-carbon ferronickel. The higher sulfur contents of such lower cost raw materials can be reduced in the converter processes. Future use of low-carbon ferrochromium will be limited to trim additions and special alloy production. Present duplex process capacity amounts to more than 30 percent of the present production in the western world and is increasing rapidly.

The application of the basic oxygen furnace (BOF) for stainless steel production -- primarily for the 400 Series -- provides some unique advantages along with a satisfactory chromium recovery rate of approximately 90 percent. This process uses hot metal from a basic water-cooled hot-blast cupola, a cold charge of stainless steel scrap, and high-carbon ferrochromium that is blown with oxygen in a BOF converter. After adding cooling scrap, a reducing agent is added to recover chromium and manganese from the slag.

Electric arc furnace

AOD Vessel

Continuous casting machine

Slab grinding
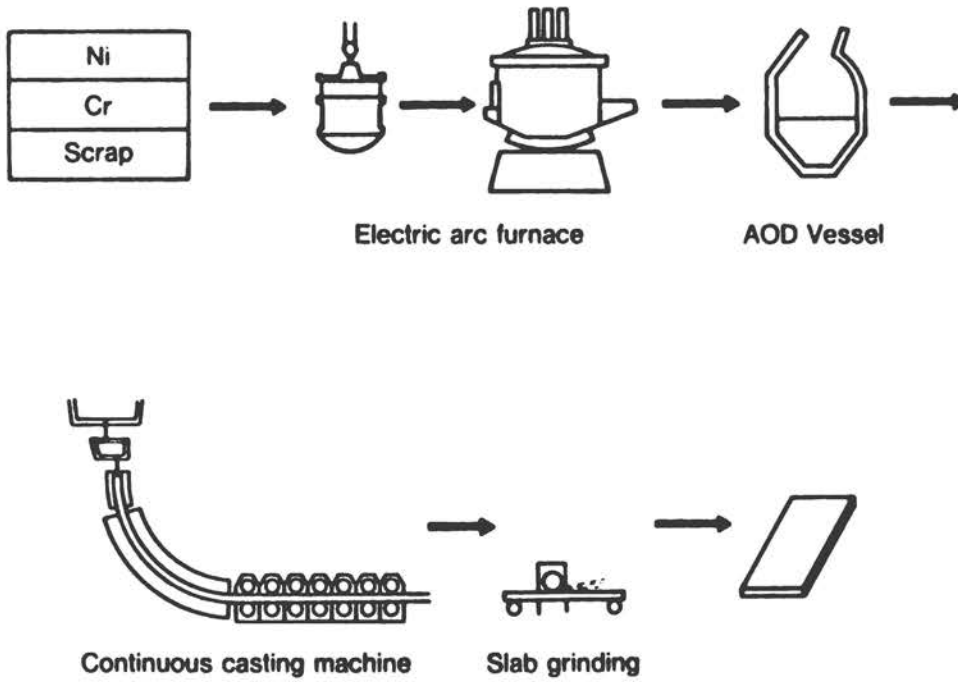
FIGURE 24   Typical Manufacturing Sequence for High Rate
            Production of Alloy and Stainless Steel or
            Billets

In the manufacture of low-alloy constructional steels containing chromium, the application of UHP arc furnaces is growing steadily and the adoption of vacuum treatment after melting is almost universal. The trend is toward truly duplex vacuum refining systems and extended ladle treatments for premium-quality constructional grades. Low-alloy high-strength steels and tool steels also are produced by the BOF process using conventional oxygen-blowing practices.

Technological advances are being made in alloy steel production to improve alloy element recovery and to maintain narrower chemical tolerances at the lower end of specification ranges and thereby conserve alloy additions. Physical specifications are met with lower total alloy contents due to improved chemical and cleanliness control with advanced melting practices. The previously irrecoverable chromium losses of 7 to 10 percent in conventional melting of low-alloy steels are estimated to be reducible to less than 4 percent with improved processing. Careful raw material selection, proper slag control, refined analytical techniques, and duplexing result in maximum chromium recovery.

Utilization of improved and more consistent properties in high-strength and special-purpose low-alloy steels obtained through secondary remelting and refining processes must be mentioned. Vacuum arc remelting (VAR) and, more recently, electroslag remelting (ESR) have upgraded the quality and performance of many alloy steels employed in critical applications, especially in the aerospace industry. Wider use of remelted materials for their improved properties, consistency, and reliability could result in appreciable chromium conservation.

A third materials group -- high-temperature alloys and nickel-cobalt-base superalloys -- consumes about 8 percent of all metallurgical chromium and requires little attention from the viewpoint of conserving chromium through improved melting technology because these costly alloys are handled carefully to minimize losses and waste. Vacuum induction melting and secondary remelting operations (VAR and ESR) are employed extensively to ensure optimum properties in these high-performance materials. Different combinations of processes are used to meet highest industry standards for various alloy types and permit maximum alloy conservation. Chemical compositions of such alloys are optimized, restricted, and maintained carefully within narrow tolerance ranges for maximum property response, processability, and performance. This degree of processing and control is generally not economical for lower cost materials. No significant chromium savings are expected from further

process developments for these types of chromium-rich alloys.

The remaining materials in Table 26 -- tool steels, alloy cast irons, and miscellaneous alloys -- represent a relatively small group of chromium users. Tool steels and wear-resisting, welding, and hard-facing alloys are produced in relatively small electric furnace heats using considerable care to conserve and recover alloying ingredients in these highly alloyed compositions. Careful scrap segregation and internal recycling are practiced, and attempts are made to recycle customer scrap and waste effectively.

Important chromium savings could be achieved in stainless steels by avoiding over-specification and by partially substituting aluminum and silicon for chromium. Reduction of carbon from 0.05 percent to 0.02 percent in the 400 Series stainless would permit a reduction of chromium content of 0.5 percent. Such alloys, with the addition of reactive elements, require that modified melting procedures be developed and that duplexing and advanced casting techniques be adopted more widely to protect the reactive elements from excessive oxidation. Vacuum melting, refining, and casting also might be mandatory in such cases. While this technology is available, economics will limit its use in large tonnage applications.

5.2.2 Environmental Considerations

The newer duplexing and refining processes for alloy and stainless steelmaking do not add burdens to proper fume and dust collection systems. Vacuum treatments are performed in completely enclosed systems and, hence, their environmental effects are insignificant; however, special problems are encountered in melting certain types of scrap, especially oily swarf. Of some concern in recycling melt shop dust is the impurity content of the dust, which contains considerable amounts of arsenic, antimony, lead, and cadmium in addition to chromium and nickel.

Chromium losses in stainless steel slags are significant. For 1.5 million tons of stainless steel produced, approximately 30,000 tons of chromium are lost annually based on an average chromium yield of 85 percent. The wider application of modern melting systems and improved refining and deoxidation practices will reduce this chromium loss to approximately 10,000 to 15,000 tons per year.

5.2.3 Energy Considerations

The energy efficiency and power consumption of electric arc furnaces is not expected to change significantly in the future; however, power consumption may increase somewhat if prereduced pellets are substituted for scrap. Duplex melting systems, which use chemical energy for refining, tend to decrease the energy content of the material produced, but refining methods, which use auxiliary electric heating, increase energy requirements. The most energy-intensive processes are combinations consisting of primary and secondary melting and refining operations (e.g., electric or vacuum induction furnace melting plus VAR or ESR remelting). However, even a considerable expansion in use of such multiple processing would not affect significantly the total energy consumption of the metals industry.

5.2.4 Ferrochromium in the Stockpile

In mid-1976, the U.S. stockpile contained and considered the following quantities of ferrochromium alloys as "excess": 320,000 short tons of low-carbon ferrochromium, 390,000 short tons of high-carbon ferrochromium, and 60,000 short tons of ferrochromium-silicon. These three grades of ferrochromium do not have the same specifications as those produced for commercial use today. The stockpiled low-carbon ferrochromium has a maximum allowed sulfur content of 0.10 percent versus present commercial specifications that call for 0.025 percent maximum. In addition, the maximum carbon content of the stockpiled low-carbon ferrochromium is 0.10 percent compared with present specifications that, depending upon grade, specify a maximum carbon content of 0.025 to 0.05 percent. In the case of stockpiled high-carbon ferrochromium, the maximum allowed sulfur is 0.10 percent versus present commercial grades that have maximum sulfur contents of 0.04 percent, 0.05 percent, and 0.07 percent. The maximum allowable sulfur content of stockpiled ferrochromium-silicon is 0.05 percent versus present commercial specification of 0.03 percent.

Thus, all the stockpiled ferrochromium has a higher sulfur content than the current commercial grades and accordingly might have a reduced value. Since duplex melting and refining can produce stainless steels with lower sulfur contents than conventional melting, producers with duplexing facilities could use stockpiled ferrochromium while other producers of stainless steels and chromium-containing alloy steels must limit their use of ferrochromium to commercial grades.

5.3 CASTING PROCESSES

Since most metals and alloys go through a melting and casting phase at some time, opportunities to conserve chromium exist in processing innovations that improve materials utilization through advanced ingot casting, precision casting, near-net-shape forging, powder metallurgy, and reduced material removal during part and component manufacture.

5.3.1 Casting Processes for Wrought Products

To manufacture low- and high-alloy steel wrought products, molten steel generally is poured into static ingot molds. Technological advancements in this process are concerned primarily with ingot design, ingot surface quality, and exothermic and insulated hot tops to obtain higher yields of rolled products by minimizing internal defects, piping, and cropping. Efforts to improve ingot surface quality further led to limited applications of casting under a molten flux blanket and to inert gas protection of the ingot pouring stream. Most static ingot casting in the United States is by top pouring. Overseas, bottom pouring is used more extensively. Only limited improvement is foreseen through conventional ingot casting practice.

Continuous casting of alloy and stainless steels in billet and slab sections (Figure 24) and pressure casting of slabs are recent technological developments of technical and economic significance. With the trend toward increasing melt shop output, continuous casters are being developed that permit high rates of casting and result in improved yields, reduced scrap and waste, lower energy consumption in further processing, and lower costs. Future development efforts will be directed toward automated-computerized process control.

5.3.2 Casting Processes for Shape Castings

Sand casting has become a versatile, well-engineered, and reliable manufacturing process. New molding and coremaking techniques and innovations in cast materials have improved dimensional control and surface quality that reduce machining and are particularly important for stainless and high-alloy steel castings (corrosion- and heat-resisting cast steels). The use of chromite sand in steel foundries is increasing as it replaces more expensive zircon sand in the facing mixture and, in some instances, is used as a substitute for silica sand, which is unsatisfactory in certain applications. The advantages of chromite with at least 44 percent Cr_2O_3 are its greater chilling effect (heat

transfer) and inertness at high temperature and, hence, reduced metal penetration at high ferrostatic pressure. In 1975, an estimated 80,000 tons of chromite were consumed for facing sand.

The AOD process is another development in stainless and high-alloy steel casting aiding chromium conservation. While the tonnages of cast products are small compared to wrought-stainless and high-alloy steel, potential chromium savings are significant.

Ceramic investment precision casting provides products that require a minimum of machining and therefore are cost- and material-effective. A limitation to further expansion of shape casting technology is that the size and weight of such castings currently are limited to a maximum of 30 to 40 inches in diameter and about 600 pounds. Controlled inert atmospheres or a vacuum frequently are used to aid mold filling and enhance material soundness and properties. The recent introduction of hot isostatic pressing (HIP) to densify castings provides better properties in critical cross sections of investment-cast superalloys and may encourage designers to specify more castings in critical applications. HIP post-treatment improves fatigue, stress-rupture, and tensile properties and may become standard practice for many high-performance castings. However, savings in chromium resulting from technological advances in this field will be small since material utilization in investment casting is already high.

Other precision casting processes, such as permanent mold and pressure die casting, are designed and engineered to meet demanding product requirements with high material utilization. Pressure die casting of stainless and alloy steels has been under development for many years but, despite economic incentives, has received only very limited acceptance due primarily to inadequate die life. Recently, the Ferro-Di process was reported to be operating in the United Kingdom at the Guest, Keen & Nettlefolds, Ltd. (GKN) Group Technology Centre where nickel and cobalt alloys, and stainless, alloy, and carbon steels are die cast to parts ranging from 0.9 to 5.6 pounds (Metals and Materials 1976). Composite dies with inserts of TZM alloy are used and have a die life of about 10,000 cycles. (The TZM alloy contains 0.5 percent titanium and 0.1 percent zirconium, and the balance is molybdenum). However, the impact of this development on chromium conservation is small.

5.4 MILL-PRODUCT FABRICATION

Wrought mill products are produced from cropped and prepared ingot or continuous cast product; they are either

semi-finished (e.g., plate, rod, bar, sheet, strip and forgings) and receive subsequent processing or are finished (e.g., large-volume structural shapes and hollows) and used essentially as produced or after heat treatment or surface conditioning. Chromium conservation in this area is related closely to the shape and surface quality of the feed materials; the efficiency and sophistication of the heating, handling, and working equipment; and the particular material used. Mill-product fabrication is integrated with a melting facility to provide nearly complete recycle of in-house scrap because the scrap is valuable and is generated near the melting facility. This scrap, in addition to ingot top crops, consists of cropped front and rear product ends that may be defective or improperly formed, cobbles, rejects, scale, and conditioning swarf.

5.4.1 Processes and Design Developments

Selecting the metalworking process for a particular mill product from the available metalworking technology is relatively straightforward. Rolling mills for a specific product shape (e.g., sheet, rod, plate, tube, and structural) are rated by maximum and minimum product sizes for a particular alloy class and involve a considerable capital investment. The selection of a particular rolling mill therefore is based on product shape, production required, and the alloy that is sufficiently workable to obtain the necessary minimum economical throughput. A few large mills account for most of the production of alloy and stainless steels and generate a consistent product at consistent yields unless some major changes are made to a particular facility.

The major factors affecting the consumption of chromium in mill-product fabrication are:

1. Large tonnage requirements that may encourage substitutability or cladding

2. Dimensional control and surface quality (e.g., excess stock shipped to meet minimal dimensional and surface requirements)

3. Atmospheric contamination and required conditioning

4. Croppings, flash, and rejects

5. Cobbles

Ingot effects on bloom, billet, and slab quality as well as losses during melting of recycled material also must be considered.

In recent years, stainless steels have accounted for about two-thirds of the annual consumption of chromium and chromium ferroalloys and a large volume of stainless steel scrap. Second in the consumption of chromium and chromium ferroalloys is alloy steel which, although produced in the largest tonnage quantities, contains an average of only about 1 percent chromium.

The production of alloy and tool steels sometimes is combined for discussion but the mill-product fabrication of the two differs significantly. The tool steels typically are made by specialty mills that use less automation and produce greater percentages of reclaimable and nonreclaimable mill scrap.

The high-temperature nickel- and cobalt-base alloys (superalloys) are used principally in aircraft gas turbine engines as cast blades, vanes, guides, and nozzles; forged discs and blades; and formed sheet products. To achieve high-temperature oxidation, corrosion and sulfidation resistance and ductility, the chromium percentage in these alloys is high. (Moore and Athey 1976). Advanced developments in these alloys were as follows:

- Alloys were made to improve corrosion resistance and elevated-stress rupture properties (cast alloys) for blades (Vazquez and Hayes 1974); to reduce density; and to improve toughness and intermediate temperature (1200 to 1500 °F) strength (wrought alloys) for disc applications.

- Processes were developed to improve toughness and intermediate temperature strength of cast alloy or non-castable alloy compositions and conventional wrought alloy compositions by thermal-mechanical processing (TMP) (Proffitt and Thomas 1962) and powder metallurgy (PM) processing (Redlinger and Timura 1964).

- Processes were improved by fabricating more precise products using isothermal forging (Couts and Sjoblad 1975), and shape rolling (Wick 1960) including heated roll sheet and shape rolling (private communication with L. Liuzzi, Watervliet Arsenal); by hot isostatic pressing of casting defects for process improvements (private

communication with W. D. Manly, Cabot
Corporation); and by rejuvenating original
properties after accumulated damage in service
(Barth and Hoffmanner 1974).

Standard practices in the aerospace industry are the
testing of design requirements, new processes, and new
materials to meet the demanding performance specifications.
The critical requirements of the aircraft industry are being
achieved with techniques that have been, or could be,
applied by other industries to products other than finished
or semi-finished mill products. Performance requirements,
the poor workability of the aerospace alloys, and limited
production quantities have resulted in practices that
generate considerable scrap. For this reason, recent
developments have coupled processing for improved
performance with precision fabrication, and these
developments have been applied successfully to other than
aircraft structures.

5.4.2 Consumption of Chromium

To analyze chromium consumption, a material balance
must be established between: input material of chromium and
ferrochromium alloys; scrap (including home and purchased);
and output material consisting of mill products shipped,
home scrap generated, and inventory. This analysis is
presented in appendix E.

5.5 MANUFACTURING PROCESSING

The major processing considerations involved in
converting a rough piece to a preassembly component are
described below as are actions that, if taken, would improve
the total utilization of alloying elements, particularly
chromium. Each major processing step is covered, and the
major problems and needs involved in developing a process
that more closely maximizes raw material utilization and
minimizes raw material losses are identified. The basic
process systems considered are machining and grinding,
forming and deep drawing, part forging, powder metallurgy,
chipless machining, and isothermal working.

The involved processes are not material-sensitive and
apply to most chromium-containing alloy systems to some
degree. Revising processing objectives and priorities to
conserve or extend the chromium supply may require that more
expensive alternates be used, and components may tend to
become more expensive as alloy shortages impact on the total
cost of raw products.

5.5.1 Machining and Grinding

In general, machining and grinding operations, particularly in high-production industries, are designed to produce a finished part in the most economical manner by reaching an effective compromise between labor, material, and capital costs. A major new priority, such as improving the utilization of the alloying elements, requires chip recovery as a key factor in the selection of a particular metal removal technique. Thus, the form of the chip and its suitability for reprocessing are major considerations. At the same time, processes that reduce the total amount of stock removal in the finishing operations will become increasingly important. Processing methods such as precision forging and casting and cold extrusion could be useful, particularly in improving raw material utilization.

Grinding should be considered to be a specialty operation for use only when it can provide a preferred finish obtainable in no other way. Electrochemical machining and electrical discharge machining should be limited to true specialty applications.

Thus, if chromium is to be utilized in the most effective manner, the processing must minimize chip generation. In doing so, the key problem for the processor is to minimize chip generation which depends on the near-net shape of the blank or preform available for processing.

Much of the development effort in processing has focused on providing higher rates of stock removal by higher speeds and feeds, improved coolants, and improved tools including ceramics. Modification of these objectives to concentrate on the recovery of machining chips may help to improve chromium utilization and recovery.

Future needs for the machining and grinding process are more effective machining and a reduction in machining allowances. Advances in closed-loop feedback metal removal processes and a reduction in finishing stock allowances will serve to conserve alloying elements and reduce costs. Additional opportunities for more effective use of raw material may be achieved by developing imaginative new processes that integrate metal forming, metal removal, and metal joining into totally new engineering production systems.

5.5.2 Forming and Deep Drawing

The cost of raw material has stimulated a major effort to reduce the blank requirements and is an important factor in the design of forming and deep draw processes. However,

in an alloy conservation program, it may be necessary for additional operations to improve the total yield while removing excess metal in a most easily and effectively recycled form (i.e., dense, relatively small pieces). An opportunity exists for suppliers to provide improved and more formable raw material for forming and deep drawing operations that should reduce scrap rates and the consequent scrap to be processed.

The main deterrents to improving alloy utilization in forming and deep drawing are the need for lubricants to assist in the forming process for all grades of materials and the development of forming die alloys that require less chromium than currently used alloys. Forming and drawing processes needed to improve the utilization of chromium alloys include: higher formability dies with lower total alloy content, more effective lubrication systems, and total manufacturing systems that join with other processes to maximize alloy effectiveness.

5.5.3 Part Forging

Forging processes have been developed to balance the costs of material, labor, and equipment; however, more precise parts with more closely controlled alloy content require that forgings be more precise and that the basic process be reexamined to identify opportunities for reducing the amount of scrap generated in processing the blank to the finished part. More closed die forgings and equipment are suggested to exert higher pressures on dies, configured so as to withstand the increased pressures. These particular needs require new specialized equipment; therefore, modification of forging operation is a relatively long-range program.

A total system organization and approach is required if the forging industry is to meet alloy conservation goals by developing process combinations that provide finished parts specifically designed to meet engineering requirements at lower cost per pound installed. It is recognized that different processes may be required for various parts of the same component (i.e., partially machined parts of simple configuration squash-formed into a complex nonmachined assembly). Most significant is the need for generalized forging equipment that will increase the flexibility of the forging operation, including better interaction with powder metallurgy, to make a finished part to precise tolerances with high physical properties but requiring little material removal.

5.5.4 Chipless Machining

Chipless machining is the generic phrase describing metalworking processes, usually performed at ambient temperature, that provide a precision product requiring little or no machining. In many cases, conventional equipment can be used with special alignment and tooling. Typical practices include rifle barrel forging or swaging, railroad axle forging, thread rolling, precision cold forging of heading, and wrenched-socket manufacture. Typical processes include precision rotary swaging, radial forging, fine blanking, form rolling, and part forming. Machines usually are designed for particular parts or component lines required in large volumes.

Gesselschaft fur Fertigungstechnik und Maschinenbau Aktiengesellschaft (GFM) radial forging machines have been developed with advanced machine controls, automated part handling, heating, and quick tool change to provide flexibility and permit application of these machines to a variety of products and materials. These radial forging machines represent the most advanced technique for production fabrication of solid, contoured shafting (e.g., railroad and automobile axles), and outside diameter (O.D.) and inside diameter (I.D.) contoured products (e.g., gun barrels and pressure bottles). Typical tolerances for cold-forged rifle barrels are $\pm$ 0.0002 inch I.D. and $\pm$ 0.002 inch O.D. when O.D. contouring, rifling, and chamfering are accomplished in one complete machine cycle. Other applications include automated ingot forging, stainless and alloy steel shapes (e.g., squares, hexagons, rounds, rectangles) made on a single "continuous" machine in quantities not economically suited for a production rolling mill, precision tube fabrication, gas-turbine engine shafting, and preforming of precision forgings.

This technology has been used widely in Europe, and in the past few years machines have been purchased for use in the United States. Current U.S. process evaluations and machine trials involve using cast preforms for precision tube fabrication of artillery rifle barrels and general precision part fabrication.

Process specifications that are predicted on established reliability data (as in the nuclear power industry) make any process change extremely expensive and favor continuation of established and possibly obsolete methods. The capital cost of modern precision equipment is high and apparently has restricted use of the chipless forming techniques to very large volume production of a narrow class of shapes or single products. Competition will require that the use of chipless machining procedures for

large volume production continue to increase; however, the special technology is proprietary, the cost-effectiveness of these procedures has not been widely reported, and published user information on these technologies is lacking.

The U.S. Army now is scheduling artillery barrel production (Cr-Mo-V steels) at the Watervliet Arsenal and will lease their GFM machine commercially, Army schedules permitting. Tubular mill products will be produced in large quantities by chipless machining pending the development of tube-shell (preform) casting practices. These techniques will improve yield, provide better dimensional control, and reduce scale formation.

The flexibility and quick tooling change capabilities of current automated systems provide an opportunity for a great variety of products and more complex shapes than have been produced previously. However, machine time availability has limited such developments since machine purchases usually are justified for a single product or product line. This trend probably will continue for the next several years unless restrictions are placed on material consumption.

Chipless machining technology should minimize production costs by minimizing material consumption and machining operations; however, more public demonstrations and publicizing of the applicability and production capabilities of chipless machining processes are needed. In addition, tube-shell casting practices that effectively can use chipless machining practices for specialty steel and alloy tube protection must be developed.

5.5.5 Isothermal Working

Isothermal working of titanium alloys and nickel-base superalloys has been developed under U.S. Air Force and Army sponsorship. The major advantage of this processing technique is lower working pressures and improved workability (e.g., many superalloys appear to be superplastic when appropriately prepared). This technique has been used in production to forge near-net shapes for aircraft gas-turbine engine discs starting with alloy powders of conventional wrought superalloys and advanced compositions that normally could not be produced in the wrought form. These advanced alloys (e.g., IN 100) have superior strength- and toughness-to-weight properties when properly fabricated and heat treated. Furthermore, the more advanced alloys, because of other alloying additions, contain reduced chromium contents for competitive hot corrosion performance and have improved mechanical properties. Therefore, this processing technique requires

less material and can provide near-net shapes of materials with improved performance. It also is applicable to sheet and form rolling, airfoil forging, and the fabrication of special alloys (e.g., titanium aluminides) containing little or no chromium that can be substituted for higher-chromium-content alloys.

The major problems with conventional fabrication of nickel-base superalloys are that: (1) the working and machining of these alloys is difficult and costly, (2) up to 90 percent of the mill product is converted into chips in disc manufacture, (3) the use of recycle material in the aircraft industry is restricted, and (4) yield is usually very low. Accordingly, performance and cost are continuing concerns that require advances in alloy development and fabrication procedures. The major problems constraining the use of isothermal working techniques are cost, tooling life and reliability, and dimensional precision of structural shapes.

Capital equipment and operating costs are high and, in some cases, require large vacuum systems to permit the use of molybdenum-alloy dies to achieve die temperatures in excess of about 1600 °F. Tooling costs are high and reliable life data have not been established. Most production tooling has been made from large superalloy castings, and problems have been encountered in the scale-up from small to large castings. The most severe problem has been gross centerline porosity that increases in frequency with die size. Precision casters currently will not provide fixed price quotations on these castings, thereby increasing the uncertainty of the success of the process.

Machining costs generally depend primarily on set-up costs, not on the amount of material to be removed. The cost of a precision working process therefore can be minimized if machining is eliminated completely (although reduced machining reduces material consumption). Current die and preform preparation practices, die heating, lubrication, and product heat-treatment procedures have not eliminated the need for machining in the large product sizes (greater than about 300 square inches in plan area). The basic problem has been the lack of a methodology to accurately predict thermal expansion and contractions of the die, workpiece, and product during heat treatment. Further, nondestructive inspection procedures have not yet been developed sufficiently to permit the use of net forgings for many aircraft-engine products.

Isothermal working to produce aircraft engine and structural shapes is a developing technology that will grow and improve. The investment in equipment, to date, appears

inadequate to handle current aircraft production requirements. The factors currently forcing further developments in isothermal working are the need for improved aircraft performance and reliability, and the potential for elimination of machining costs. Raw material costs, particularly those of nickel and chromium, are also a factor. To advance this technology, improved die materials, new or improved lubricants for very-high-temperature use, improved die heating practices, better die and preform designs, and better preparations are needed.

5.6 JOINING

At present, each joining process is preferred for certain applications and involves some key problems; however, the future seems to favor welding and brazing, especially in the event of a chromium contingency. Certain alternatives for chromium utilization proposed in other chapters of this report, such as the substitution of low-chromium alloys for familiar high-chromium alloys of commercial significance today, may require the development of new welding filler materials. These problems are treated in appendix F. An alternative peculiar to welding is the surfacing of chromium-free base metal with corrosion-resisting or wear-resisting weld metal containing chromium to achieve properties available only in that manner. In applications where chromium is the essential element, the use of clad surfaces effects economies of 80 or 90 percent in chromium usage at minimum added cost. This alternative also is discussed in appendix F.

5.6.1 Welding and Weld Repair

A summary chart of welding processes has been prepared by the American Welding Society (Figure 25). In some of these processes, welds are made autogenously (without filler material), but in most, welds are made with filler metal addition. Almost all metallurgical uses of chromium involve alloys that are weldable by some commercial process, and the major alloys are weldable by many processes. Major users of chromium are the stainless steels, alloy steels, and certain nonferrous alloys, principally heat-resisting nickel-base alloys. Filler materials for welding these alloys are readily available from welding electrode manufacturers and supply houses.

Weld repairs to castings and weldments are made to match the properties of the original casting or weldment. For the most part, these repairs use fillers with matching chemical compositions. The principal exceptions are the low-alloy high-strength steels since the desired strength sometimes can be achieved with a different chemical

ARC WELDING (AW)

atomic hydrogen welding ...AHW
bare metal arc welding ....BMAW
carbon arc welding ....CAW
—gas ....CAW-G
—shielded ....CAW-S
—twin ....CAW-T
flux cored arc welding ....FCAW
—electrogas ....FCAW-EG

gas metal arc welding ....GMAW
—electrogas ....GMAW-EG
—pulsed arc ....GMAW-P
—short circuiting arc ......GMAW-S
gas tungsten arc welding ....GTAW
—pulsed arc ....,.GTAW-P
plasma arc welding ....PAW
shielded metal arc welding ..SMAW
stud arc welding ....SW
submerged arc welding ......SAW
—series ....SAW-S

SOLID STATE WELDING (SSW)

cold welding ....CW
diffusion welding ....DFW
explosion welding ....EXW
forge welding ....FOW
friction welding ....FRW
hot pressure welding ....HPW
roll welding ....ROW
ultrasonic welding ....USW

SOLDERING (S)

dip soldering ....DS
furnace soldering ....FS
induction soldering ....IS
infrared soldering ....IRS
iron soldering ....INS
resistance soldering ....RS
torch soldering ....TS
wave soldering ....WS

BRAZING (B)

arc brazing ....AB
block brazing ....BB
diffusion brazing ....DFB
dip brazing ....DB
flow brazing ....FLB
furnace brazing ....FB
induction brazing ....IB
infrared brazing ....IRB
resistance brazing ....RB
torch brazing ....TB
twin carbon arc brazing ...TCAB

WELDING PROCESSES

OTHER WELDING

RESISTANCE WELDING (RW)

flash welding ....FW
high frequency resistance welding ..HFRW
percussion welding ....PEW
projection welding ....RPW
resistance seam welding ....RSEW
resistance spot welding ....RSW
upset welding ....UW

OXYFUEL GAS WELDING (OFW)

electron beam welding ....EBW
electroslag welding ......ESW
flow welding ....FLOW
induction welding ....IW
laser beam welding ......LBW
thermit welding ....TW

THERMAL SPRAYING* (THSP)

electric arc spraying ......EASP
flame spraying ....FLSP
plasma spraying ....PSP

ALLIED PROCESSES

ADHESIVE BONDING (ABD)

air acetylene welding .....AAW
oxyacetylene welding .....OAW
oxyhydrogen welding .....OHW
pressure gas welding .....PGW

OXYGEN CUTTING (OC)

chemical flux cutting ....FOC
metal powder cutting ......POC
oxyfuel gas cutting ....OFC
—oxyacetylene cutting ...OFC-A
—oxyhydrogen cutting ...OFC-H
—oxynatural gas cutting .OFC-N
—oxypropane cutting ....OFC-P
oxygen arc cutting ....AOC
oxygen lance cutting ......LOC

THERMAL CUTTING (TC)

ARC CUTTING (AC)

air carbon arc cutting .....AAC
carbon arc cutting ....CAC
gas metal arc cutting .....GMAC
gas tungsten arc cutting ..GTAC
metal arc cutting ....MAC
plasma arc cutting ....PAC
shielded metal arc cutting .SMAC

OTHER CUTTING

electron beam cutting ......EBC
laser beam cutting ....LBC

*Sometimes a welding process.

FIGURE 25 Master chart of Welding and Allied Processes (American Welding Society 1976)

composition. In the high-chromium alloys, the properties can be achieved only with welds similarly high in chromium. Filler metals for the major chromium alloys are listed in appendix F.

If chromium were unavailable in a contingency that required remodeling existing stainless steel vessels, pure nickel electrodes probably would be used even though they are admittedly inferior in corrosion resistance and it would probably be better to remelt some vessels to provide matching welding electrodes to remodel the remainder. In a contingency during which chromium supplies were allocated to the production of new stainless steel products, proportionate quantities (about 1 percent) should be allocated to welding electrodes for joining those steels. During the contingency, autogenous welding should be adopted to the maximum extent but thick sections still would require filler materials in most weld designs.

If lean-chromium alloys are introduced, suitable filler metals must be identified or developed unless matching electrodes already exist. At some economic disadvantage, the presently popular high-nickel electrodes used for dissimilar metal joints probably would be selected.

Conservation of energy and materials encourages the use of welding in joints requiring little filler material and minimum joint edge preparation. Narrow-gap welds (made by semiautomatic and automatic processes) are important emerging chromium-conservation techniques that should be used increasingly in the future. New extensions of autogenous (no filler metal) welding techniques (electron beam, electric resistance, friction welding, diffusion bonding, etc.) permit the joining of thicker and larger sections each year and should be utilized when possible to minimize chromium use and waste.

Hard surfacing of wear parts by original equipment manufacturers increases equipment life and can be applied where clad or chromized surfaces are unreliable. Weld overlays of corrosion-resisting surfaces are particularly important on sections over 4 inches thick. Renovation of surfaces by weld overlays restores and extends life.

Matching compositions of filler materials may be needed for readily weldable substitutes for lower-chromium-content alloys proposed in chapter 6. Less weldable substitute alloys will require suitable dissimilar filler materials. Current technology would turn to nickel and nickel-base alloys, as suggested in appendix F; however, during certain chromium contingencies, these nickel alloys themselves might

not be available and alternate substitutes must be identified.

5.6.2 Brazing and Soldering

Brazing requires the presence of a suitable brazing filler metal at the joint interface and, frequently, a brazing flux. Most chromium metals and alloys in the metallurgical list may be brazed with a brazing filler metal and flux, and most brazing alloys do not contain chromium. One advantage of brazing over welding is that lower temperatures are used; hence, parts may be joined in less time and with less metallurgical damage to the base metal.

Because of their corrosion- and heat-resisting properties, the nickel filler metals are used commonly to braze AISI Series 300 and 400 stainless steels. With application of a suitable flux, any brazing method (torch, furnace, induction, resistance heating) may be used.

Commercial solders do not contain chromium. Successful soldering of stainless steels requires the cleaning action of mildly corrosive or highly corrosive fluxes to obtain a sound soldered joint.

The strength of brazed joints depends greatly on joint design. The optimum gap for brazing is about 0.005 inch varying from 0.001 to 0.010 inch depending on the specific brazing filler metal. The cost of joint preparation is a major expense in larger assemblies. The joint gap must be preserved until the joint has reached the brazing temperature to permit spreading of the brazing alloy by capillary action.

More developments are expected in high-temperature brazing alloys, and self-fluxing alloys are advancing in popularity. Applications of furnace brazing, vacuum brazing, induction brazing, and diffusion brazing are increasing.

Filler materials are needed with improved dynamic properties (resistance to fatigue) and corrosion (galvanic attack) resistance. Techniques for nondestructive inspection of brazed joints must be improved to determine 100 percent soundness and to monitor in-service stress distributions within large brazements.

5.6.3 Mechanical Joining

Chromium alloys are joined mechanically by bolts (especially high-strength bolts), rivets, sheet metal screws, pins, folded and locked seams, and retaining rings

and keys. The weight penalty of mechanical fastening vis-a-vis welding restricts such applications to lightly stressed joints and to connections that must be disassembled (e.g., turbine blades, flanges, and access ports). Much material is wasted in a mechanical joint in the bolt holes, overlap of parts, and inefficient doubling plates. Sealing of joints in tanks and containers is a vexing problem. Elaborately machined surfaces fitted with O-rings or caulking are required. Preventing crevice corrosion beneath bolt heads and between lapped plates is difficult, and these are classical points of attack.

The switch from mechanical fastening to welding or brazing is accelerating. More state and city building codes and highway bridge codes now permit more efficiently designed welded or brazed connections.

5.6.4 Adhesive Bonding

Many metal joining applications now are bonded with adhesives but usually not stainless steels, tool and die materials, superalloys, special property alloys, or coated metals. Alumina-based cements have been developed with service temperature around 3,000 °F. Weld-bonded joints are primed with an adhesive, resistance-spot welded through the adhesive layer, and cured by aging or heat treating. The adhesive protects the spot welds against tearing in fatigue loading.

Adhesives lack peel strength and cleavage strength, and thermoplastic adhesives soften when heated. Accordingly, most adhesives can not be used for service above 350 °F. The precleaning and setting time are lengthy. The overlap in a lap joint needed to provide sufficient load-bearing capacity is an inefficient use of materials. Some adhesives are attacked by bacteria, molds, vermin, moisture, and organic solvents. Also, inspection for completeness of bond is nearly impossible at present.

Greater use is predicted for the weld-bond technique to improve the fatigue strength of spot welds and resistance seam welds. New applications of adhesive bonding with dissimilar materials also are expected; however, these improvements require the development of better standard nondestructive inspection methods and stronger adhesives with higher softening temperatures.

5.7 SURFACE COATINGS

All of the principal methods for producing chromium-bearing surfaces are discussed below. These include: roll-clad, chromizing, surface alloying, metal spraying, hard-

facing, weld overlay, cementation, electro-deposition, chemical deposition, vacuum metallizing, vapor-phase deposition, and ion implantation.

5.7.1 Clad Stainless Steel

Clad stainless steel technology is over 40 years old and may be a major option for reducing the consumption of chromium contained in stainless steel. Clad steel is the substitution of a multilayered integrally bonded metal product for solid stainless. Today, over 300,000 tons of clad plate are in service in a wide variety of applications. Clad is manufactured by bonding two metals together with heat and pressure during hot rolling until they are integral over their entire adjoining surfaces. As little as 2 percent or as much as 50 percent of the stainless steel can be used in making the clad sandwich. Stainless clad steel, as one example, can effectively provide the surface corrosion characteristics of solid stainless with some 10 to 20 percent of the chromium requirements of the solid material.

The technology is labor-intensive. It requires electrolytic plating on one side with pure nickel to aid in bonding and preventing carbon migration. The sandwich assembly is built up, sealed by welding along its edges, and heated and rolled to gauge. The hot work produces a metallurgical bond between the stainless insert and the steel backing. One layer of stainless clad to carbon steel is the most common form in use. This material is available in shapes including: rolled sheet, strip and plate, drawn tubing and wire, centrifugally cast tubing and pipe, and extruded tubing. The fabrication of clad plate into various shapes, tanks, pressure vessels, etc., is standard practice with many fabricators and joining techniques that have been developed to meet nuclear pressure vessel codes.

The present usage of clad steel is based on the economics of the cost of solid stainless versus clad. Clad steel is used in many of the major consuming markets requiring the optimum properties of solid stainless such as chemical, petrochemical, petroleum refining, food processing, and automotive applications.

Stainless steel plate is used for tanks and pressure vessels for various processes; thicknesses from 1/8 inch to about 1/2 inch are quite common while stainless clad steel is more common in thicknesses over 1/2 inch. Stainless clad steel is manufactured by roll bonding thicknesses from 3/16 inch to about 10 inches. Explosive bonding generally is used for thicknesses greater than 1-1/2 inch. Weld overlay is used for thicknesses over 4 inches.

The stainless steel plate portion of the market is estimated at 150,000 to 200,000 tons, of which a substantial tonnage could be serviced by clad material. The present clad plate tonnage is estimated at less than 10 percent of the plate market or some 15,000 tons annually.

A wide range of flat-rolled product thicknesses from sheet and strip to heavy-gauge plate should be available in commercial tonnages from a variety of clad producers. Substantial expansion of production capacity could be induced with relatively modest capital requirements should chromium contingency plans dictate immediate implementation.

The substitution of a multilayered integrally bonded metal product for solid stainless is a highly developed technology. The present usage of clad steel could be expanded substantially to conserve chromium without new technology.

The application of stainless clad steel can provide surface corrosion-resisting characteristics of solid stainless plate steel effectively with only 10 to 20 percent of the chrome requirement of the solid material. The process presently is labor-intensive and would require additional space. Conventional rolling mills could produce clad product immediately with a minimum of lead time, requiring only a shifting or adjustment of rolling schedules. Substantial expansion of present production capacity could be effected with relatively modest capital requirement in the event of a chrome availability problem. Because chromium-bearing scrap can be recycled into low-alloy steel, consideration should be given to the amount of chromium in the final product; a 10 percent clad product contains one-tenth the amount of chromium as its solid counterpart and a 20 percent clad product, one-fifth the amount.

5.7.2 Weld Overlay

Weld overlays are applied where clad steel surfaces are unavailable or are unreliable. Typical applications have been the flanges (14 inches thick) for nuclear reactors; dished heads for pressure vessels, nozzles welded into boilers and chemical retorts, and cylindrical vessels with wall thickness greater than 4 inches. These overlays provide a corrosion-resisting surface equivalent to commercially clad product. Weld overlays also are applied for wear resistance. Electrodes are available with special properties of hardness, hot hardness, impact strength, oxidation resistance, corrosion resistance, abrasion resistance, resistance to metal-to-metal wear, mechanical properties in compression, and machinability. Methods used

for overlay welding primarily aim for low dilution (low penetration) but high deposition rate.

Oxyfuel gas welding is excellent for depositing thin, undiluted overlays of the chromium-cobalt Stellite compositions on wear surfaces and overlays of tungsten carbide granules. The low-temperature deposition achieved with an oxyacetylene flame leaves undissolved tungsten carbide grains dispersed in the weld deposit, whereas arc welding tends to dissolve most of the granules in the matrix. Shielded metal arc welding (manual deposition) is used in difficult welding positions. Submerged arc welding with series-arc (two wire) deposition achieves rapid coverage of the surface being overlaid with about 12 percent dilution. Submerged arc welding with strip electrodes achieves about the same dilution at faster deposition speeds. Gas tungsten or plasma arc welding with hot wire feed achieve dilutions as low as 5 percent.

Weld cracking is a common difficulty, especially with the harder alloys. With some electrodes, peening of each bead after deposition reduces stresses, and preheating and post-heating schedules often are recommended. The copper-base alloys used for bearing surfaces are deposited with braze-welding techniques. Uniform coverage of the base metal is required. Penetration variations dilute the weld composition. Multiple layers often are deposited to guarantee the required alloy content of the surface layer. Inspection techniques are available to evaluate the soundness and adequacy of overlay welds, but research is needed on the selection and application of barrier layers to combat dilution effects.

Conservation of chromium should encourage extensive use of clad steels. Welding sequences and electrode recommendations are ready now for all popular alloys. Most weldments require only the butt-welding of clad plates but many constructions will have nozzles and flanges that preferably will be surfaced by weld overlay techniques. Use of hot-wire gas tungsten arc (GTA) welding and the hot-wire plasma arc process are expected to increase because they achieve extremely low dilution at high deposition rates.

Substitute coatings without chromium are proposed in chapter 6, and while their development may not be possible, studies to identify equivalent weld deposits should be initiated. It also should be noted that low-chromium alloys will lack the corrosion resistance of higher chromium compositions.

5.7.3 Chromized Sheet Steel

Chromized steel is essentially a stainless-coated sheet steel that is produced by mechanically bonding an iron-chromium alloy powder on the surface of a low-carbon sheet steel, and diffusing the chromium into the surface at elevated temperatures. The stainless surface that is formed is approximately 0.002 inch thick with a chromium content of 25 percent at the outer surface and of 12 to 13 percent at the base steel-coating interface for an average coating chromium content of 18 percent.

The Bethlehem Steel Company uses a higher grade, low-carbon ferrochrome powder in its chromizing process than is used in melting stainless where high-carbon ferrochrome can be used. With more stainless producers changing to the less expensive high-carbon ferrochrome, suppliers are not having problems in delivering the higher priced, low-carbon ferrochrome powder.

Chromized steel has been used basically for ferritic (AISI 400 Series, particularly AISI 409) stainless applications. It is limited to applications (e.g., automotive exhaust and heat exchangers) where cut edges and appearance are not a factor. It is not a substitute for AISI 300 Series (Ni-Cr) applications.

Present chromized sheet applications include furnace heat exchangers and silo components. Chromized steel has replaced AISI 409 stainless steel in roof top installations of commercial heating and air conditioning units. The 30 percent lower cost of chromized steel versus AISI 409 stainless and its better forming and welding characteristics are reasons cited for the changes. The heat exchanger application is limited and should not have a major impact on chromium requirements.

Silo applications of chromized steel include conveyor troughs and wall panels. Chromized steel is used in sheet-type applications but not in rods or tubing. Chromized steel exhaust cylinders are rolled from sheet and resistance welded.

The introduction of catalytic converters for automotive exhaust systems created a strong demand for AISI 409 stainless steel. Reportedly, the General Motors Corporation (GMC) alone was using 75,000 tons of it for converters, and when the Y-pipes off the manifold were added, total consumption was 110,000 tons (Metal Progress 1974). (Note: This summary does not include the chromium required in AISI 300 Series Ni-Cr stainless steel for which chromized steel is not a substitute.)

Bethlehem Steel estimated that the total AISI 409 stainless steel demand in the 1978-1982 period for U.S. automotive exhaust systems may reach 250,000 tons annually. The amount of chromium in 250,000 tons of AISI 409 stainless (11 to 12 percent chromium) is estimated at 28,750 tons. If the recovery rate of the chromium in processing is 90 percent, it will require approximately 32,000 tons of chromium to make the 250,000 tons of AISI 409 stainless.

The stainless sheet steels used in the GMC catalytic converters are all 0.050-inch-thick. To produce a 0.050-inch-thick chromized sheet requires only 15 to 20 percent of the chromium required for a 0.050-inch-thick AISI 409 stainless sheet. Therefore, 250,000 tons of 0.050-inch chromized sheet will require only 5,100 to 6,800 tons of chromium, compared to 32,000 tons for AISI 409 stainless. The recovery rate of chromium in chromized steel is slightly lower at 85 percent, partially because chromized steel scrap is not recycled specifically for chromizing while AISI 409 scrap can be remelted for stainless products.

Chromized sheet is not used now for the catalytic converter systems by automotive manufacturers because of the difficulties in meeting emission requirements with new systems. The manufacturers were conservative and chose a solid stainless material. However, chromized steel use is under review by industry since the cost of stainless has risen, the availability of chromium has become questionable, and many unknowns in the catalytic converter systems have been resolved.

The present technology can produce chromized steel sheet in sufficient volume to effect significant chromium metal conservation in automotive emission applications. Bethlehem Steel's current chromized steel capacity is 12,000 tons per year. An expansion program to increase the present facility capacity to 20,000 tons and then to 40,000 to 50,000 tons is under study. Long-range plans include increasing capacity to 100,000 tons per year.

Conservatively, the cost of a 100,000-ton-per-year mill is estimated at $50 million including chromizing bases, furnaces, washer-brushers, compactor to apply powder, a skin mill, and a building to house the unit. Expansion of the existing 12,000-ton-per-year facility to 40,000 to 50,000 tons is estimated at $15 million because the skin mill and building are available. Conversion of additional bases and furnaces and improvement of washer-brusher and compacting equipment is not as expensive as the installation of all new equipment.

A minimum of 2 additional 100-ton facilities is estimated as necessary to supplement Bethlehem Steel's present and intermediate chromizing capacity to meet the projected annual automotive requirement of 250,000 tons. Total estimated cost is $100 to $150 million.

5.7.4 The Dilex Chromizing Process

The Dilex process (formerly called Surfalloy) for surface alloying of ferrous materials in molten lead alloys is at an early stage of commercialization. The first of several patents was issued in 1971 (Rausch and Van Thyne 1971), but some details had been reported previously (Van Thyne and Rausch 1974). Although complex surface alloys may be produced, the early effort has been directed primarily to the formation of a simple chromized ferritic stainless steel surface case that has a composition of about 30Cr-70 Fe and grades inwardly with lessening chromium content.

In the principal step of the process, the ferrous product is immersed in a lead bath within some retort form; alloying additions (e.g., ferrochromium) are included; and motion or agitation is provided. Lead melts at 620 °F and typical processing temperatures are 1750 to 1950 °F. Conventional materials are used for equipment. The surface alloying occurs by simple metallic diffusion; no chemical or electrochemical processes are involved. Molten lead is an ideal medium and exhibits the following useful characteristics for this application:

1. Lead is inexpensive and readily available.

2. Lead is reusable and simply refined by skimming off impurities that float to the surface.

3. Leads heats and cools rapidly because of its high heat transfer and relatively low energy consumption (the specific heat of lead is about one-third that of steel).

4. Chromium transfer through the molten lead is rapid even though the solubility is only 0.04 percent at 1900 °F.

5. An excess of chromium may be used with the chromium dissolving into the bath as required.

6. Multiple alloyed products are produced readily.

The elements used in surface alloying having the greatest commercial significance are chromium and aluminum that can be diffused individually to produce solid solution

alloy layers. Also, chromium and aluminum can be co-diffused to provide a variety of compositions having a good combination of oxidation resistance and fabricability. The surface composition and composition gradient can be controlled.

In typical small machined parts, a 0.003-inch chromized surface layer accounts for 6 percent of the total volume of the part. The diffusion alloying process described herein offers opportunities for further savings in chromium by multiple alloying (i.e., use of an Fe-Cr-Al surface alloy with lower chromium content for oxidation resistance).

The substitution of surface diffusion alloy products for solid stainless steel has been very limited to date. Further expansion of this market will depend upon the investment in capital equipment to make certain products and the marketing effort to convince potential users of the economic advantages. Field tests required before such substitutions are made, often take six months or longer.

Initially, the molten lead diffusion alloying process was directed to small screw machined parts because the economic advantages could be demonstrated at relatively low cost. Although material savings result, the principal advantage is the substantial reduction in machining costs because free machining steels may be used and machined at much greater speeds than stainless steels. A commercial facility to process such parts is being constructed now by Materials Sciences Corporation, which is licensed by the Surfalloy Corporation to apply the process to machined and fabricated parts and mill products.

This process has been tried on various product forms (such as sheet, tubing, and wire) and on test commercial components using batch or continuous processing. The mechanical and corrosion test results have been reported to be very acceptable.

5.7.5 Electroplating

Electroplating of chromium is one of several commercial methods for increasing the chromium level of the surface of a substrate such as carbon steel. The main difference between "hard" and "decorative" chromium plates is thickness, hard being thick (up to 0.1 inch) and decorative being thin (0.00001 to 0.00003 inch). The thin decorative plates tend to be porous and the thicker coatings often are cracked. The primary purpose of chromium plating is to confer a hard, abrasion- and tarnish-resisting surface to a substrate material. Since chapter 6 presents detailed information on the physical and mechanical properties of

chromium plates, an indication of where chromium plates are
and could be used in commercial application, and statistics
on the savings in chromium consumption that might be
realized in the electroplating area, such material will not
be discussed here. Rather, an attempt will be made to
identify and discuss only those aspects that relate to
processing. These include chromium in the effluent, the
status of the plating technology for substitute materials,
and scale-up possibilities of existing facilities.

Decreasing the chromium in the effluent is of major
importance since more chromium is lost than is plated in
commercial plating operations. An estimated 2,000 tons of
chromium per year are lost in the waste of commercial
electroplating processes. Two reasonable approaches are to
recycle the waste material and to use trivalent rather than
hexavalent chromium. Recycling is becoming commercially
feasible and probably will solve this problem. A strong
impetus for developing recovery techniques is based on
current Environmental Protection Agency regulations calling
for zero discharge of chromium (and other materials) by
1983.

Of the several substitute materials considered in
chapter 6, plating stainless steel is attractive on the
basis of its physical and mechanical properties and tarnish
resistance. Electroless nickel-phosphorus (or nickel-boron)
alloy, although unsuitable for decorative applications, is
suitable for wear or functional applications.

Much effort has been expended in researching and
developing the technology for plating stainless steel
(rather than chromium) with marginal success and little
indication that a development beyond the beaker stage is in
the offing. In the case of electroless nickel-phosphorus,
on the other hand, the processing technology appears to be
developed sufficiently. In particular, the much better
throwing power of electrolessly deposited metals is a big
plus. Additional research and development are needed,
however, to put these processes on a competitive cost basis.

Plating from fused salts, other high-temperature
processes, and vacuum deposition may be viable alternatives
since they allow additional metals to be considered as
substitutes. Tungsten electrodeposited from molten salt
baths and boride diffusion coatings from molten salts are
two possible substitutes for applications where wear and
hardness are prerequisites. Titanium alloy coatings can be
deposited by high-temperature methods, offer the advantage
of excellent tarnish resistance and good color, and are in
the early stages of commercialization. Further development
is needed on scale-up techniques, handling and container

materials, and reducing costs that, for the high temperature process generally, are an order of magnitude (or more) more costly than their counterparts at ambient temperature.

Two factors, expansion capability and lag time, are important in evaluating the scale-up possibility for existing facilities. Expanding existing "hard" chromium shops is possible. The time required for conversion would depend mainly on the procurement of additional tanks, floor space, and electrical power. Converting decorative plating shops probably is not feasible since their conversion takes different and much more demanding expertise.

5.7.6 Ion Implantation

Ion implantation is a method of producing changes in the composition and physical properties of the surface of a solid by bombarding the surface with a beam of energetic ions. In the context of producing a corrosion-resisting surface alloy, it involves bombarding a metal having poor corrosion resistance with ions of the desired alloying addition (e.g., chromium). The depth of implantation can be varied in the range 10^{-6} to 10^{-5} inch by control of the incident energy.

Although only preliminary results are available, the corrosion resistance of chromium-implanted steel seems comparable to steels where chromium layers were applied by other techniques. Since the total amount of chromium involved in ion plating usually will be much less (order of magnitude or more) than the coating method it replaces (e.g., electroplates and clads), the projected savings in chromium are considerable.

The U.S. Bureau of Mines is exploring actively the commercialization of the chromium ion plating process as well as continuing to evaluate the properties of chromium-rich surfaces produced by ion implantation. Several years probably will be needed to develop a commercial process, even for small limited applications.

5.8 ECONOMIC AND TECHNICAL DIMENSIONS OF CHROMIUM RECYCLING

Recycling provides an alternative to the supply of virgin materials. With the possible exception of easily recoverable ferrous and nonferrous metal scrap, only small fractions of the U.S. waste stream are recovered and reused. Recycling is not profitable under current economic conditions in the United States since the cost of collection, separation, shipment, and reprocessing is excessive in relation to the cost of competitive virgin materials. However, environmental controls increase the

disposal cost and thereby encourage reuse. (Recycling conditions differ abroad, and in Japan, Italy, Austria, Germany, etc., more wastes are recycled than in the United States.)

5.8.1 Economics and the Materials Cycle

There are two types of basic materials -- nonrenewable and renewable. Nonrenewable materials (mineral fuels, ferrous and nonferrous metals, and nonmetallic minerals) represent a fixed stock of resources with variable proportions being economically recoverable. For renewable materials (forest and agriculture-based products), a substantial flow of primary materials can be maintained by appropriate management and conservation techniques without impairing regeneration.

The national materials cycle is presented in schematic form in Figure 26. Virgin materials, together with secondary materials that can be utilized economically, are fed into productive processes or into the generation of energy. Both the energy and production sectors generate primary waste (e.g., slag and ash, metal shavings, and plastic trimmings), some of which is not recovered and enters the environment as solid, liquid, or gaseous emissions and effluents. The remainder is recovered and used directly or is collected and enters the secondary materials sector.

Part of the output of the production sector is used for capital equipment and part is funneled to the consumption sector. Worn-out capital equipment and goods that have reached the end of their useful lives become secondary or obsolescent waste. Part of this flow is not recovered and enters the environment, largely as solid waste. The principal functions of the secondary materials sector involve collection and transport of wastes, separation of waste into categories sufficiently homogeneous for reuse, and reprocessing of waste to quality levels reasonably competitive with virgin materials.

The materials-flow network depicted in Figure 26 is a dynamic system. The volume of material throughput depends on the level of economic activity that determines the overall volume of generated waste. Lags of varying duration exist in the network. Most primary waste is associated closely with current output levels and quickly becomes available for recovery (e.g., home and prompt industrial scrap) or injection into the environment. Secondary waste lags are product-specific. For some materials (e.g., newsprint and most packaging materials), the lags are short. For others (e.g., textiles, automobiles, and many consumer
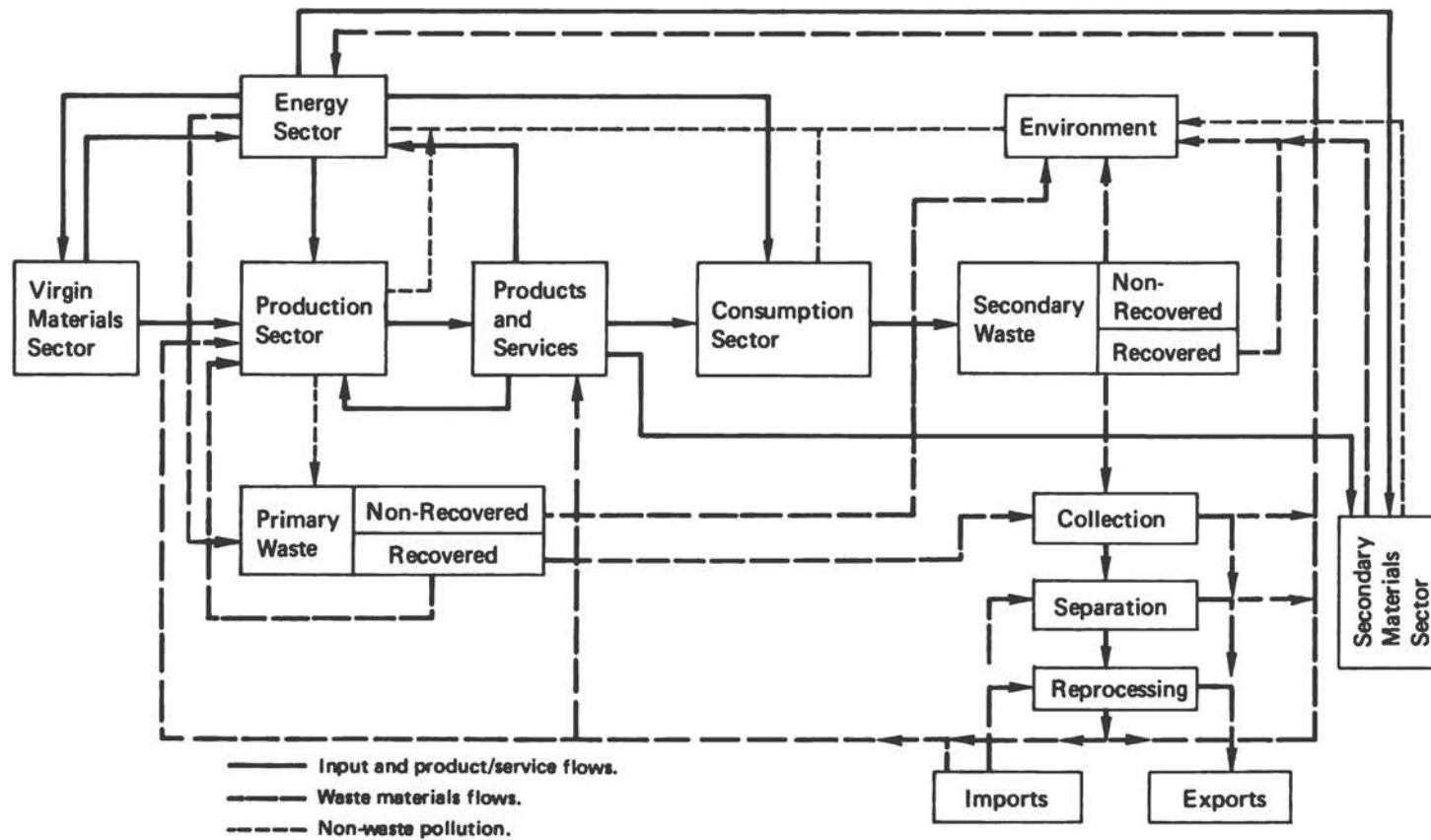
FIGURE 26   Network of Materials Flows and Recovery (Walter 1975)

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durables), the lag is of intermediate duration, perhaps 1 to 10 years. For still others (e.g., capital equipment), the lag may be even longer before scrappage occurs. These lags are important in defining the general characteristics and economic dimensions of waste management.

Finally, what is technically feasible in recycling is not necessarily economically viable. Moreover, the economic incentives influencing the behavior of industry encourage the minimization of the private cost of production incurred. From a social viewpoint, these private costs fail to account for certain externalities, such as pollution and the risk of interruptions in the supply of virgin materials. Thus, the optimal social rate of recycling is probably greater than the rate acceptable to the private sector.

If society applies the "polluter pays" principle via a system of taxes, pollution charges or prohibitions, the effective cost of disposal and consumer products should rise, as should the likelihood of recycling. Society benefits from a cleaner environment, extended life of virgin resources, reduced pollution, and reduced susceptibility to foreign supply constraints. However, recycling itself may be pollutive and uses energy and other resources, and these costs must be accounted for before the net social benefit of recycling can be determined.

Government policies can promote recycling when subsidies favor recovered materials and may retard recycling if labeling requirements make recycled materials appear to be of inferior quality. They also may retard recycling by providing tax benefits to extractive industries, thereby reducing the cost of virgin materials. Reprocessing costs can be excessive; technological constraints can make it impossible to attain competitive quality levels; and certain wastes can be dissipated so highly that effective collection is prohibitively costly. With some notable exceptions, the secondary materials industry is poorly capitalized, highly fragmented, and localized. The result is inefficiency, uneconomic levels of operation, and high costs.

Recycling serves two functions -- conservation of resources and materials, and reduction of waste. The quantity of materials that enters the primary and secondary waste streams creates both economic and social benefits. Reductions in the quantity of waste generated can be reduced by promoting product durability, repairability, and maintainability.

The lowest life-cycle cost (i.e., initial purchase price plus maintenance and repair costs plus longevity) should become the prime motivating force in product

selection if maximum material conservation is to be achieved. Recycling from design through collection, sorting, and remelting must become a way of life that is encouraged by all possible means.

The technical and economic dimensions of secondary materials recovery represent a highly complex problem, one that is sensitive to a large number of variables and policy measures and one wherein cost-benefit analyses are subject to many uncertainties. Yet, the volume of waste materials together with nonfunctioning, obsolete, and discarded products available for recycle and recovery is substantial, as is the gap between what actually is recovered and what technically could be recovered.

5.8.2 Chromium Recovery and Reuse

To promote chromium conservation, designers and manufacturers should be sure that:

1. Materials of the desired composition and properties are used

2. Materials have consistently high quality and reliability

3. Combinations of materials are used that are compatible with current recycle systems

4. Process variations can be adjusted by nondestructive testing, evaluation, and feedback during processing (for more detail, see chapter 4)

5. The finished product has the highest quality and reliability possible through in-process control and reduced reliance on final inspection

6. Products in service can be inspected to determine their remaining usefulness and safety, and can be dissassembled and repaired easily and at relatively low cost

During the actual processing of chromium-containing materials, conservation of chromium can be achieved by:

1. Minimizing material removal in blanking, shearing, machining, cutting, grinding, etc.

2. Using hot and cold deformation

3. Using powder metallurgy to produce parts or preforms

4. Casting to shape or to preform

5. Using surface coatings and treatment

6. Using proper joining

7. Using heat treatment

While there appears to be significant technical recovery potential, the economics of chromium recycling have yet to be tested on a large scale. However, recycling technology is beginning to develop in a variety of products and sectors. Of the approximately 600,000 tons of chromium consumed in the United States in 1974, only a small percentage (about 10 percent) was recycled chromium.

5.8.3 Stainless Steel and Heat-Resisting Alloy Scrap

Almost half of the chromium consumed is used in the production of stainless steel and heat-resisting alloys. Every steel mill generates a certain amount of "revert" scrap in the production process. This scrap is retained by the mill and is reused.

The steel mills ship their products to manufacturers who convert them into consumer durables, capital goods, and intermediates. At this stage of the manufacturing process, additional scrap is generated, usually called "prompt industrial" scrap. This scrap usually is segregated and reshipped to a steel mill either directly or through a secondary metal processor or broker. If properly segregated, most of the chromium in this scrap can be recycled effectively without degradation of the alloy.

Products are sold directly, or after further manufacturing, to a consumer who uses the product until it becomes obsolete or no longer serviceable, at which point it is scrapped. Unless it is dumped in open or landfill sites, much of this material ultimately finds its way to a secondary metal processor who attempts to segregate and prepare it for sale in a form usable to a steel mill.

The chromium in AISI 300 Series stainless steels and high-temperature alloys tends to be recovered since these materials are high-value steels and alloys due to their nickel, molybdenum, and cobalt contents. In the case of AISI 400 Series stainless steels, the contained chromium is mostly lost since the value of the 400 Series steels is less and they do not contain other high-value alloying elements. (To date, chromium itself has been relatively inexpensive and not worth recovering.) Most steel mills buy 400 Series scrap only when business is good and they are melting large

quantities of these particular alloys. In slack periods, steel mills buy ferrochromium because of a price advantage rather than 400 Series scrap, which then is lost or mingled with low-value scrap.

Even when steel mills purchase AISI 400 Series scrap, they buy at a cost under that of equivalent primary metals because of the manufacturing risk incurred as opposed to using virgin material. The lower the price, the more uneconomical it becomes to properly segregate these grades. This relationship discourages recycling and is particularly important when ferrochromium is readily available at today's reasonable cost. The steel mill's evaluation of scrap depends on the price of ferrochromium, not on resource conservation goals, and the price of scrap, particularly AISI 400 Series, rises only when ferrochromium is very expensive or in short supply. Only if steel mills have consistent and realistic buying policies regarding chromium-bearing scrap, such as long-term contracts with reliable processors at prices that cover recycling costs, can reasonable supply be assured them on a consistent basis and at stable prices. (Such conditions also contribute to increased recycling of chromium.)

Because of the lags mentioned earlier, it is not possible to estimate accurately the potential chromium recovery from stainless steel scrap, especially obsolete scrap. However, based on sources associated with production processes in a variety of industries, potential chromium recovery has been estimated, as noted in Table 27. More than 60,000 tons annually are recoverable potentially from these sources and each is discussed below.

5.8.4 Metallurgical Industry Wastes

The principal chromium-bearing process wastes in the metallurgical industry are: (1) ferroalloy flue dusts, fumes, and slags; (2) stainless steel steel furnace flue dust, centerless grinding swarfs, mill scale, pickle liquor, and slag; and (3) Electrochemical machining and electrical discharge machining sludges.

Experimental processes have been developed by the U.S. Bureau of Mines to convert in-plant waste generated during stainless steel production to a recyclable alloy containing iron, nickel, molybdenum, and some lead and zinc as well as chromium. The alloy has been produced from three kinds of wastes: flue dust from metallurgical furnaces making stainless steels, mill scale, and grinding swarf made up of fine metal chips mixed with abrasive particles and cutting oils. The chromium currently wasted that could be recycled

TABLE 27 Estimates of Potential Chromium Recoverable from
Industrial Process Wastes

Source	Recoverable Chromium (tons/year)
Ferroalloy flue dusts	3,500
Ferroalloy slags	1,000
Stainless steel furnace dusts	2,500
Stainless steel centerless grinding swarfs	2,000
Stainless steel mill scale	3,600
Stainless steel pickel liquor	800
Stainless steel slags	1,000
ECM and EDM sludges	1,300
Foundry sand	21,000
Chrome-bearing refractories	19,000
Etching wastes	1,000
Plating wastes	2,000
Catalysts	1,000 [a]
Chromate and dichromate	60 [a]
Leather tanning	270
Paint pigments	75
Textiles	1
Approximate total	60,106 [b]

NOTE: Data from Dressel et al. 1976.

[a] Recoverable chromium from catalysts is 700 to 1,000 tons
per year; from chromate and dichromate, 50 to 60 tons per
year.

[b] Total recoverable chromium is 59,796 to 60,106 tons per
year.

in a commercial application of this experimental process amounts to several million pounds per year.

In this process, the wastes are blended, moistened, pelletized, and smelted in 10- to 25-pound batches in an electric induction furnace at 2,550 to 2,910 °F with the addition of carbon. Virtually all the iron and nickel and about one-third of the chromium are recovered. While the economies of commercial-scale recovery systems of this type remain to be proven, hopefully, they could be commercially attractive.

In stainless steel production, the slags contain sizable amounts of chromium. About 30,000 tons of chromium are lost annually in slag generated with stainless steel produced by conventional methods. However, general adoptions of modern duplexing systems should reduce this chromium loss to 10,000 to 15,000 tons per year. An additional 1,000 tons of chromium are lost in slags generated in ferrochromium production. No efforts to recover chromium from such slags appear to be under way in the United States today.

International Nickel Company, Inc., has announced plans to construct a facility in western Pennsylvania to process some 40,000 tons per year of specialty steel mill wastes and to convert them into a nickel-chromium stainless steel remelt alloy. The facility reportedly will have a positive ecological impact while reclaiming metals vital to industry.

On the effluent side, mixed-acid pickling wastes generated annually contain an additional 800 tons of chromium. Acid currently is recovered from pickling wastes, but the chromium content of the sludge -- averaging 1.6 percent chromium -- is not. A solvent extraction process precipitates chromium hydroxides that could be recycled to metal.

Wastes produced by the electrical discharge machining (EDM) and electrochemical machining (ECM) of chromium-bearing alloys contain 1,300 tons of chromium annually. While EDM wastes are nonpolluting and can be used in landfills, ECM wastes cause serious pollution problems and now are subject to strict EPA guidelines. A drain-filter technique increases the solids content of ECM wastes, with the resultant filter cake being dried and reprocessed to remove the metal content including chromium. Other metalliferous sludges can be treated to recover the metals content although commercial application still seems some years in the future.

5.8.5 Refractory Industry Wastes

Another recycling possibility is chromite sand recovery
from the foundry industry. Over 80,000 tons of chromite
were consumed in molding and coremaking in the United States
during 1975, primarily due to the widespread use of
specialty sands. About 90 foundries currently use chromite
and little recycling has been undertaken. The sand can be
separated and chromite reclaimed by magnetic, air,
hydraulic, or electrodynamic techniques with over 75 percent
of the original chromite recoverable. However, only 6 to 10
foundries are estimated to have sufficient sand volume and
chromite content to make such separation economically viable
and the recovery process itself may be pollutive.

Refractory brick is another possible source of
recoverable chromite although destructive consumption in
steelmaking is increasing because of the use of electric
furnaces and the AOD process. Very little recycling of
refractory brick is undertaken in the United States, but
some recycling seems to be under way in the United Kingdom.

While recycling of chromite in spent foundry sands and
refractory brick is an obvious recommendation to conserve
important quantities of chromite, substitution of other
materials (zircon in foundry sand and magnesite-chromite in
refractories) for chromite in these applications would
result in larger total savings and would be less expensive
and technically easier to accomplish (see chapter 6).

5.8.6 Chemical Industry Wastes

Chromium wastes in the chemical industry are generated
from a number of sources; the most important appear to be
etching wastes, plating waste, catalyst, dichromate-
photosensitive material, chromate, paint pigment, water-
treatment chemicals, and leather tanning chemicals.
Chemical uses amount to about 130,000 tons of chromium
annually with 20,000 to 30,000 tons being used in the
plating industry; 23,000 tons, in the paint and pigment
industry; and 10,000 tons, in the leather tanning industry.

It is estimated that: (1) sludges from the paint and
pigment industry contain about 75 tons of chromium annually;
(2) 35 pounds of waste sodium chromate are produced for
every 1,000 tons of ammonium sulfate produced; (3) several
tons of ammonium chromate are wasted each year in the
graphic arts industry; (4) 39 pounds of sodium chromate are
wasted for every 1,000 tons of nitric acid produced; (5) dye
manufacturing wastes contain 100 ppm of chromium; (6)
lubricating oil production waste contains 16 ppm of
chromium; and (7) 1 pound of chromium is lost for every ton

of sodium dichromate produced. Chromium chemicals also are used as mordants and dyes in the textile industry; however, with waste water containing approximately 2 to 8 ppm of chromium, and in view of the large volume of water used, the chances for economic recycling are slim.

A major potential source of recycled chromium is electroplating waste sludge, most of which is piped into water systems or dumped in landfills which creates substantial environmental hazards. As environmental restrictions mandate increasing levels of effluent treatment, correspondingly larger amounts of electroplating sludge, typically containing 30 to 39 percent zinc, 11 to 17 percent iron, up to 6 percent cadmium and up to 2 percent chromium, will be created. The technically recoverable wastes from this source in the Chicago area alone are estimated at 1.2 million pounds of zinc, 120,000 pounds of cadmium, and 40,000 pounds of chromium per year. Catalytic uses of chromium in the production of formaldehyde and methanol also may provide a recycling feedstock from sludge, and additional chromium-bearing sludge arise in the photochemical and leather-tanning industries.

In one recent series of experiments, chromium, copper, zinc, and nickel were recovered from waste solutions used to etch and brighten brass fittings. One sample plant was estimated to discard 100 tons of chromium, 100 tons of copper, and 70 tons of zinc annually in such solutions.

Low-cost reagents (e.g., shredded paper) have been used by the U.S. Bureau of Mines to reduce hexavalent to trivalent chromium. Copper is recovered by cementation with zinc or electrolysis, and the zinc and chromium are precipitated as hydroxides from which either chromic oxide or sodium chromate can be derived. These experiments indicate that semi-pilot plants might verify the technically feasible recovery, and economic factors seem likely to bring forth commercially viable development. However, at present the chemical industry seems to make little effort to recover chromium.

5.9 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.9.1 Summary

Major opportunities for chromium conservation exist in melting and refining, in which almost 20,000 tons per year of chromium can be saved, and in surface coating, in which some 80,000 tons per year of chromium can be saved. Recycling also offers an opportunity to recover up to 20,000 tons per year of chromium that is now lost. A single processing step, joining, is a problem that relates

specifically to edge and joint protection for surface-coated materials. Table 28 summarizes the Panel's findings and quantifies the potential chromium savings.

5.9.2 Conclusions

1. The most fruitful area for achieving substantial chromium conservation in melting and refining is through the wider application of duplex melting and refining systems for stainless, alloy, and low-alloy constructional steels. The separation of the melting and refining steps results in the most economical, efficient, and alloy-conserving practice. Duplex melting and refining systems minimize the loss of chromium in slags during melting and refining. In conventional electric furnace melting followed by oxygen blowing, the irreversible chromium losses are 10 to 15 percent; these losses are reduced to under 6 percent with combined electric furnace and argon oxygen decarburization (AOD) or vacuum oxygen decarburization (VOD).

2. The U.S. stockpile contains over 750,000 tons of various grades of ferrochromium, all of which has sulfur limits exceeding those of current commercial grades. With duplex melting and refining processes, the steel industry can produce stainless steels with a lower sulfur content than is possible with conventional electric furnace practice; therefore, steel producers with duplexing facilities could utilize, with some cost penalty, much of the ferrochromium in the stockpile. Without duplexing, most of the ferrochromium in the stockpile would be expensive to use for stainless steels and might not be usable at all for chromium-containing alloy steels, tool steels, and high-performance alloys.

3. Continuous-strand casting of slabs and billets for subsequent working into mill product forms of chromium-bearing stainless and alloy steels results in significantly higher yields from molten steel to slab or billet (about 95 percent as contrasted to 85 percent via conventional ingot pouring practice and breakdown rolling). Continuous casting reduces material losses, inventory requirements, energy consumption in further processing, and costs. Particular opportunities exist for chromium conservation in technically proven casting processes such as near-net-shape preforms, hollow cast forms for pipe and

TABLE 28 Potential Chromium Savings through Processing Modifications

Material	Process	Alternatives From	Alternatives To	Baseline Quantities Consumed in Current Process, 1970-1974 (short tons/year) Total Material	Contained Chromium	Chromium Saved (short tons/year)	Remarks	Implementation Requirements
Stainless and alloy steel	Melting and refining	Electric furnace practice	Duplex melting and refining	1,600,000	270,000	19,000	Rapidly becoming standard practice	Modest investment
Stainless and alloy steel		Ingot breakdown practice	Continuous-strand casting	1,600,000	270,000	3,000	Most producers have adequate capacity for ingot practice	
Stainless steel and superalloys	Casting	Conventional casting	Near-net-shape preform	40,000	10,000	1,000	No current incentive	Cost reduction
Superalloy	Casting	Conventional casting	Investment casting	20,000	5,000	500	No current incentive	Cost reduction
Cast super-alloys	Casting	Conventional casting	Post casting hot isostatic pressing treatment	30,000	6,000	800	Reduced chromium consumption through improved product life and performance	Cost reduction and established specifications
Superalloys and stainless steel	Casting	Conventional casting	Slush, squeeze and rheocasting	30,000	6,000	100	Opportunity for chromium conservation appears low	Cost reduction
Alloy steel castings				150,000	1,500	200		
Alloy steel, stainless steel Nickel and cobalt alloys	Casting	Conventional casting	Tube shell preforms; Castings plus radial forging	300,000 50,000 4,000	6,000 9,500 1,000	1,300 2,000 150	Improved casting yield - 2% alloy savings	Large capital investment or rental of Watervliet machine
Nickel and cobalt alloys	Mill product fabrication	Forging and rolling	Isothermal forging	20,000	5,000	500	Minimal machining and improved properties	Reduced processing costs for near-net-shapes

Stainless and alloy steel	Manufacturing processing	Conventional metal removal processing	Precision formed parts	2,000,000 to 4,000,000	40,000	2,500	No current incentive	Reduced product cost
Stainless and alloy steel and superalloy	Manufacturing processing	Conventional metal removal processing	Non-metal removal processing—rolling, coining and chipless machining	1,000,000 to 2,000,000	20,000	2,000	No current incentive	Needs process development and capital investment
Stainless and alloy steels and superalloys	Manufacturing processing	Grinding ECM and EDM processing	Trimming, drilling and milling	500,000	60,000	4,000	No current incentive	Reduced product cost
Stainless and alloy steels	Joining	Welding	Brazing	Small	500	50	Little opportunity to save chromium	–
Stainless and alloy steels	Joining	Mechanical joints	Welding and brazing	25,000 to 40,000	5,000	100	Better properties saves material	Feasible except for components that need to be disassembled
Stainless and alloy steels	Joining	Conventional welding	Narrow gap welding	25,000 to 40,000	5,000	200	Less waste in preparation for welding	Capital investment required
Stainless and alloy steels	Joining	Conventional welding	Autogeneous welding	100,000	10,000	1,000	Reduces wastage	Capital investment required
Stainless clad plate	Surface coating	Solid stainless steel plate	Clad plate	150,000	35,000	29,000	Established product; heavy plate much more economical	Economic incentive needed
Chromized steel sheet	Surface coating	Solid stainless steel sheet	Chromizing sheet	250,000	32,000	29,000	Established product use for 409 stainless steel primarily for automotive exhaust systems	Large capital investment required
Carbon, alloy and stainless steel	Surface coating	Solid steel (stainless and alloy)	Weld overlays	25,000	5,000	4,000	Established process, especially applicable for heavy sections over 4" thick	Incentive to expand its use needed

TABLE 28 Potential Chromium Savings through Processing Modifications (continued)

Material	Process	Alternatives		Baseline Quantities Consumed in Current Process, 1970-1974 (short tons/year)		Chromium Saved (short tons/year)	Remarks	Implementation Requirements
		From	To	Total Material	Contained Chromium			
Chromium-bearing effluent	Surface coating	Chromium plating	Chromium plating with effluent recycle	2,000	2,000	2,000	Affects small shops, of which there are many; some may be forced out of business	EPA regulations will force recycling
Chromium-plated steel for functional applications	Surface coating	Chromium plating	Electroless plating	3,500	3,500	3,500	A substitute for "hard" chromium, but poor tarnish resistance and color	Needs an incentive
Chromium-plated steel for decorative applications	Surface coating	Chromium plating	Stainless steel and zinc plating	7,000	7,000	7,000	Stainless steel is a substitute with comparable tarnish resistance and good color. Zinc would protect but is not decorative	Needs research effort
Chromium-plated steel	Surface coating	Chromium plating	Ion implantation				Laboratory process today	Needs extensive research effort
Stainless steel	Surface coating	Solid stainless steel	Dilex (surfalloy) processing	150,000	23,000	20,000	Established process	Capital investment and product evaluation
Waste	Recycle	Waste	Chromium recovery		30,000	20,000	Little economic incentive to recover	International Nickel Co. has announded a facility that will process some specialty steel mill wastes containing chromium

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tube production, and investment and other
precision casting techniques. Today, economics is
the primary restraint to more widespread use of
these processes.

4. More than 95 percent of the raw stainless steel
   melted and converted into steel mill products is
   either shipped to customers or recycled (as home
   scrap) indicating that, within the stainless steel
   mills themselves, little opportunity exists for
   further chromium conservation during processing.
   In the case of chromium-bearing alloy and low-
   alloy steel, improved chromium conservation may be
   possible.

5. To maximize chromium utilization in chromium-
   containing steels and alloys, established
   manufacturing practices that currently are the
   most economical processing operations must be
   reassessed. First, and most important, is the
   ability to provide precision-formed intermediate
   stock that is created by processes such as
   forging, powder metal processing or casting that
   requires minimum metal removal. Second is to use
   finishing processes such as rolling, coining, and
   chipless machining that do not involve
   conventional metal removal. A third, but less
   attractive, option is to supply a work piece that
   closely approximates the finished-form
   configuration and is finished by a conventional
   machining or trimming operation so that the little
   excess metal removed is in the most convenient and
   recoverable form.

6. With more public demonstrations and publication of
   information and data on its applicability and
   production capabilities, chipless machining (e.g.,
   GFM machines) could be developed and applied to
   certain operations such as specialty steel and
   alloy tube production using tube shell castings as
   the starting material.

7. Isothermal forging, especially for chromium-
   containing nickel-base superalloys, is well suited
   to the production of aircraft engine and
   structural shapes. Particular needs for advancing
   this processing technology are improved die
   materials, new or improved lubricants for high
   temperature use, improved die heating practices,
   and better preform design and die preparation
   methods.

8. Current methods of joining alloys containing chromium include welding, brazing, soldering, mechanical fastening, and adhesive bonding. Welding is the most efficient method. Brazing and soldering are of commercial significance but few brazed joints match the strength of the chromium-containing alloys being joined. Mechanical fastening using high-strength bolts, rivets, lock-seams, sheet-metal screws, and keys is still done but only with weight and strength penalties. Nevertheless, items that must be unfastened later are usually keyed or bolted. Adhesive bonding is far behind other joining techniques in strength.

9. Stainless steel clad plate offers an important chromium-conservation opportunity. The application of clad plate can provide effectively the surface-corrosion-resisting characteristics of solid stainless steel plate with only 10 to 20 percent of the chromium requirement of a solid plate. The process is labor-intensive. The technology of production and of joining by welding is proven, and currently over 300,000 tons of clad plate are in service in a wide variety of applications. Conventional rolling mills could produce clad product with a minimum of lead time, and substantial expansion of present productive capacity could be effected with modest capital requirements in a short time frame.

10. Present chromized sheet applications are typical replacements of AISI 409 stainless steel. Potentially the most important uses of several applications are the automotive emission exhaust components and catalytic containers. Present technology is adequate. Substantial investment in additional production facilities is needed to meet projected automotive exhaust requirements of 250,000 tons per year since present capacity is only 12,000 tons per year. The capital requirements for 250,000 tons of new capacity exceed $100 million and cannot be justified on economic grounds today.

11. Dilex processing involves surface alloying of steel products at high temperatures for improved corrosion or wear resistance. The process employs a liquid metal medium (molten lead) at a temperature in the range of 1950 °F to transport the alloying elements to the steel surface where alloying occurs by diffusion. Principal application to date has involved the use of

chromium to produce small parts with high-chromium surfaces, although aluminum and other elements may be employed effectively either singly or in combination. The molten lead offers many technological and economic advantages. Effective procedures have been developed to remove the lead from the surface after processing. Parts coated by the Dilex process are used because of lower cost, improved properties, or ability to produce unique properties. Greater use of Dilex treated parts requires extensive evaluation by manufacturers of stainless steel components.

12. Weld overlays can be applied where clad or chromized surfaces are unreliable. Weld overlays of corrosion-resisting materials are particularly important on sections over 4 inches thick. Weld overlays also are applied for wear resistance and to extend product and component life. Welding electrodes are available to impart special hardness, hot hardness, impact strength, abrasion resistance, metal-to-metal wear, and oxidation and corrosion resistance. Efforts to conserve chromium will encourage the extensive use of weld overlays. Welding sequences and electrode recommendations are available today for most popular electrodes.

13. Of the various substitutes for chromium plating, electroless nickel-phosphorus or nickel-boron alloy plating, although unsuitable for decorative applications, is suitable for wear and functional applications. The processing technology is developed sufficiently but additional research and development are needed to make these processes competitive on a cost basis with hard-chromium plating.

14. Converting decorative chromium-plating shops to hard-chromium shops is probably not feasible since they require different and more demanding expertise. Expansion of hard-chromium shops is possible but the lag time would be significant.

15. Environmental Protection Agency regulations calling for zero discharge of chromium and plating wastes will result in the recovery of 2,000 tons per year of chromium now lost in plating effluent.

16. Ion implantation may have the potential of producing a corrosion-resisting chromium layer on steels. Since the total chromium involved in ion

plating probably will be an order of magnitude less than the coating method it replaces, the projected chromium savings are considerable. However, the process is several years away from becoming commercial even in a small way.

17. Recycling conserves materials resources by reducing waste. Reducing the quantities of materials that enter the waste stream creates economic and social benefits. The key problem in recycling chromium is that the recovery of secondary chromium is not cost-effective because primary or virgin chromium is relatively inexpensive at present.

18. The maximum technical recovery of chromium from process wastes in the ferroalloy, stainless steel, refractory, and chemical industries in the United States currently is estimated at 60,000 tons per year. Very little of this waste is recovered now for economic reasons, although some stainless steel and specialty alloy producers are recovering some scrap values from such wastes. Reductions in generated waste can be made by promoting product durability, repairability, and maintainability.

19. Increased recycling of mill materials used by part or product manufacturers is possible through better segregation of scrap (offal) that is returned to steel and alloy producers either directly or by scrap dealers. A similar opportunity exists for obsolescent scrap if product design provides for ready part disassembly and identification of relatively valuable alloys. Normally, the cost of collecting, separating, and shipping obsolete scrap is high and recovery is low.

5.9.3 Recommendations

1. The use of duplex melting and refining processes for alloy steels, especially for tool steels and high-chrome-content alloy steels, should be increased. The resultant savings could amount to 20,000 tons of chromium annually.

2. Steel producers should upgrade and modernize their facilities to include continuous casting so that up to 3,000 tons of chromium can be saved annually.

3. New processes (such as hot isostatic pressing [HIP] to heal casting defects and improve the mechanical properties of castings, and rheocasting, slush and squeeze casting) should be evaluated fully to establish their technical and economic feasibility and their potential chromium conservation possibilities.

4. Better separation and segregation of potentially recyclable home scrap in steel mills that produce chromium-containing alloy and low alloy is recommended to conserve the chromium now lost when home scrap is remelted.

5. Near-net-shape semi-finished forms should be supplied for finishing to reduce metal loss, energy, and the cost per pound of the part in place in the product.

6. To maximize chromium utilization, manufacturing operations should be used that minimize scrap generation but produce scrap in a readily-recyclable form (i.e., discrete, relatively large chips free of foreign material) through turning, drilling, or milling rather than through grinding, ECM, or EDM, which produce sludges, require more energy, and result in high chromium losses during recycling if such sludges are recycled.

7. Welding and brazing should be used as replacements for bolted, riveted, and mechanically joined surfaces.

8. Where possible, brazing should be used rather than welding since most brazing alloys contain little or no chromium.

9. Autogenous (no filler metal) welding techniques -- electron beam, electric resistance, friction welding, diffusion bonding, etc. -- should be used where possible to minimize chromium use and wastage.

10. Narrow-gap welds, made by several semi-automatic and automatic processes, are important emerging chromium-conservation techniques that should be used increasingly in the future.

11. The new lower-chromium-content alloys proposed in chapter 6 may require welding in certain applications. Existing technology may require such alloys to be welded with available high-

chromium-content welding electrodes. Advanced planning and research should be encouraged to develop lower-chromium-content or matching filler material electrodes for the new alloys proposed.

12. When the availability or cost of chromium dictate, the following surface coating techniques are recommended, where appropriate, to reduce chromium usage: stainless steel cladding of steel plate, chromizing or other forms of diffusing chromium into steel sheet and products, weld overlays for very thick plates or shapes, and electroless nickel-phosphorus or nickel-boron plating.

13. Further research and development is recommended for ion implantation since the required chromium is an order of magnitude less than the chromium coatings that it might replace.

14. Scrap recycling, particularly by part and product manufacturers and by product designs that promote ready disassembly and identification of obsolete scrap, should be encouraged.

15. To promote chromium conservation, designers and manufacturers should promote greater usage of the following elements:

- Materials of desired composition and properties

- Combinations of materials that are compatible with current or more effective recycle systems

- Materials of consistently high quality and reliability

- In-process control that is monitored effectively by nondestructive testing and evaluation, and can be adjusted by feedback during processing

- Reduced reliance on final inspection of finished products consistent with maintenance of the highest quality and reliability

- Design products so that they can be monitored in use to determine their safety and remaining useful life, and be inspected readily and repaired easily for increased durability

16. The lowest life-cycle cost (initial purchase price plus maintenance and repair costs plus longevity) should be the prime factor in product selection to achieve maximum material and energy conservation.

17. To improve the recovery of secondary chromium material, efforts should be made to stabilize the secondary market that currently is subject to extreme price fluctuations.

18. Laboratory research should be undertaken to solve specific technical problems in recycling such as removing harmful impurities, improving and developing new recycling processes, and developing recycling technology for currently nonrecyclable chromium-containing materials.

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Chapter 6

SUBSTITUTION

6.1 INTRODUCTION

Substitution, a possible action to anticipate and prevent scarcity, may be defined as the use of alternative materials that are able to provide relatively equivalent benefits to the user. It can reduce the demand for critical materials by replacing them with noncritical materials having equivalent effectiveness in specific end uses and may be cost-effective except when the replacement material is inferior or requires paying additional costs in terms of materials, design, or processing. Unfortunately, the technology of substitution is not well developed and long lead times are required for implementation (Bittner 1974, Gold 1976), and the economy is not helped in an emergency scarcity situation.

In considering substitution, each commodity must be examined separately since each has a well-established supply, demand, and price history based on import dependence, available alternative material, productive capacity, and other factors (Radcliffe 1974). Chromium is an especially unusual commodity in that it confers unique properties on a wide variety of alloys and compounds and historically has been a relatively low-cost and plentiful material. Thus, current research efforts are devoted more to finding new uses for chromium than to searching for chromium-free substitutes. Previous investigations mainly serve to confirm the unique and superior properties of chromium in applications requiring properties such as hardenability, creep strength, hot strength, impact resistance, wear resistance, and corrosion and oxidation resistance (U.S. Air Force Materials Laboratory 1975, Brown 1976, Department of Commerce 1962, Committee on International Economic Policy 1974, Guy 1960, National Materials Advisory Board 1970).

This situation creates a special challenge to any study of the substitutability of chromium-free materials for the chromium-containing materials used almost exclusively in the applications listed in Table 29. For some of these applications, the present state of the art offers no substitute for chromium and, for others, suggested alternatives are not supported by the technology development and service experience that would permit confident predictions. The best current step is to identify the directions that research, development, and testing should take and to assign probabilities for research success.

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TABLE 29 Typical Applications of Chromium-Containing Materials

Material Designation	End Use
Metals	
High-strength, multiple-alloy	Building and construction Bridges
Low-alloy engineering steels	Gears and work rolls Ball and roller bearings Shafting
Cast iron and steel	Industrial machinery Engines Transportation equipment
Tool and die steels	High-speed cutting tools High-temperature forging, die casting, and extrusion dies Aircraft and missile components
Hard-facing alloys	Rolls and crushers Exhaust valve seats Pump parts
Hardenable chromium stainless steels	Turbine blades Cutlery Mining machinery Sports equipment
Non-hardenable chromium stainless steels	Auto trim Catalytic converters Small parts and fasteners

Non-hardenable chromium- nickel stainless steels	Food and chemical processing equipment Home appliances Complex welded structures
High-temperature alloys	Engine exhaust valves Gas turbine and jet engines Electric heating elements Chemical and metallurgical process equipment

Refractories

Chrome-magnesite	Furnace bricks and linings
Chrome-alumina	Mortars and cements
Chromia	Electrocast refractories

Coatings

Chromium compounds	Electroplated components Plasma spraying and welding Clad sheet and plate

Chemicals

Chromium compounds	Mordants and dyes Catalysts Drilling muds Leather tanning Pigments and paints

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By assuming a complete cessation of supplies to the United States, attention can be focused on the specific, serious consequences of the sudden unavailability of chromium. In most applications, the substitutability of candidate alternate materials has three aspects:

1. The elimination of chromium has little effect on properties but substitute materials carry a significant cost penalty. Examples might be low-alloy, heat-treatable steels and some alloy cast irons.

2. The elimination of chromium causes a significant degradation of properties that can be compensated through short-term research in areas such as design restraints and improved processing. Direct or indirect cost penalties are involved. An example might be the replacement of oil-hardening steels with water-hardening varieties.

3. The elimination of chromium causes major degradation of properties without fruitful research being evident. Either the product must be discontinued or new technology that might include designing for new classes of materials, such as ceramic or composite materials, is required. Examples might be heat-resisting engine exhaust valves, gas turbine components, and electrical heating elements.

In this discussion, the possibilities for substitution are separated into eight major areas of chromium usage: stainless steels, tool steels, wrought alloy steels, cast iron and steels, coatings and claddings, refractories, nonferrous alloys, and chromium chemicals. Because the complexities involved in material selection and substitutability vary from one type of chromium usage to another, a uniform tabular format is used to present the findings related to each usage area in a manner that will help the reader grasp the substitutability situation for each chromium-containing material considered. Information is presented in terms of current material, typical material application, contained chromium, chromium demand, role of chromium (i.e., special properties are endowed or enhanced by chromium), substitute material, chromium content of proposed substitute material, chromium savings if substitute material is used, property deficiencies resulting if substitute material is used, remarks (i.e., urgency of research, guidelines, restraints, amplifying statements), research needed to conserve and preserve chromium, and probability of research success (i.e., qualitative assessment of near-term success if research is begun now).

This chapter, therefore, should permit estimation of the amount of chromium needed for essential applications and indicates where and how substitutions might be effected for other applications. It is intended to provide policymakers with suggested alternatives upon which they may base future decisions. It also should be helpful to designers, materials engineers, and industry procurement managers who use chromium-containing materials. Areas where research and new technology are needed to provide chromium-free materials with required properties are identified to serve as a guide to those planning future research programs in both the public and private sectors. The implications of chromium curtailment on industry, technology, economy, and environment also are evaluated.

6.2 SUBSTITUTABILITY

6.2.1 Ferrous Materials

6.2.1.1 Chromium Demand and Substitutability in Stainless and Heat Resisting Steels

The largest single use of chromium in the United States is for the production of stainless steels. In 1968, 70 percent of total U.S. chromium consumption was used for metallurgical purposes and 51 percent of that total was used for stainless steels (National Materials Advisory Board 1970). The amount currently used for stainless steel is probably greater since stainless steel has a higher growth rate than other chromium-bearing products.

The chromium used in the production of stainless steels comes from three sources: ferrochromium, purchased stainless steel scrap, and internal recirculating scrap. Included under ferrochromium are low-carbon ferrochromium, high-carbon ferrochromium, and ferrochromium silicon. Metallic chromium has been omitted since it is negligible. AISI ingot production data (Form 104) have been used to calculate the chromium used for stainless steel production. The details of the calculations and assumptions made are shown in appendix G. The average annual production for 1965 to 1975 amounted to 1.52 million ingot tons and has been used, first, to calculate the current use of chromium and, second, as the basis for growth to 1980 and 1990. The projected estimates are listed in Table 30.

To select proper substitutes for stainless steel, it is advisable to remember that:

1. Chromium provides passivation in iron-base alloys. A minimum of about 12 percent chromium is required for this purpose. At the present state of

TABLE 30 Stainless Steel Production (ingot tons)

	1965-1975 Average	1980 Estimate	1990 Estimate
Annual production	1,520,000	1,850,000	3,015,000
Total contained chromium	249,300	303,400	494,460
Total chromium used	282,700	325,600	530,640
Chromium from ferrochrome	113,300	131,350	214,060
Chromium from purchased scrap	69,000	79,890	118,810
Chromium from recirculated scrap	99,800	121,360	197,770

NOTE: Data from American Iron and Steel Institute 1975.

technology, passivation cannot be achieved with less chromium or without chromium. Replacement of 12 percent chromium in stainless steels therefore is not feasible.

2. The addition of from 12 to 30 percent chromium to iron-base alloys increases their resistance to corrosion or oxidation to various degrees as needed to meet industrial or environmental requirements. Replacement by other elements of the chromium present in excess of 12 percent is feasible to a certain extent. Molybdenum, copper, and silicon can be used for corrosion resistance and aluminum, silicon, and yttrium, for oxidation resistance.

3. The function of chromium in austenitic stainless steels is to impart corrosion resistance and to stabilize the austenitic structure by depressing the martensitic transformation temperature below the ambient temperature. Replacement of chromium by other elements to perform this function is feasible.

Chromium savings in stainless steels can be accomplished into two ways: by partially replacing the chromium in excess of 12 percent with other alloying elements, and by completely replacing stainless steel with a different material containing very little or no chromium. A detailed listing of these savings follows:

1. Replacement of higher chromium steels with existing lower chromium stainless steels. It is known that the stainless steels used in a large number of applications are over-designed for corrosion resistance. This has occurred because chromium has been a readily available, relatively low cost element and because some higher chromium steels (especially the austenitic 18-8 CrNi stainless steels) offer outstanding fabricating characteristics. Accordingly, stainless steels are used in places where their corrosion resistance is not absolutely necessary and where lower chromium steels would have adequate corrosion resistance. For example, considerable chromium could be saved by replacing AISI 302 and 304 stainless steels (containing 18 percent chromium) with AISI 429 (containing 15 percent chromium) or 405 (containing 13 percent chromium).

2. Development of new 12-14 chromium austenitic stainless steels. About 25 to 30 percent of the

chromium in AISI 301, 302, and 304 stainless steels, by far the largest tonnage group, could be saved by developing a new family of stainless steels with 12 to 14 percent chromium. The chromium must be replaced by nickel, copper, manganese, or molybdenum in order to duplicate the stability of austenite in the AISI 300 series. Corrosion resistance can be enhanced by molybdenum and copper addition, and oxidation resistance, by aluminum and silicon addition. While this new series of austenitic stainless steels could not substitute for the AISI 300 series in all applications, its development is technically feasible.

3. Clad Products. In principle, stainless steel metallurgically bonded to a carbon steel, low-alloy steel, or other metal substrate could replace most monolithic metals. Application of this existing technology is restricted, however, to a limited combination of alloys and especially to certain thicknesses. To become a viable substitute that maximizes chromium savings, the clad material must be expanded to all thicknesses, particularly to products where the stainless steel layer would be very thin. Fabrication, joining, and edge protection technology also would require further development if clad products were to be usable on a large scale.

4. Coated Products. Many coating methods are available; some are in production and others are in the developmental stage. Chromium plating, stainless steel cladding, chromizing, and weld overlay are well-established production processes; ion implantation, Dilex coatings, and organic coatings are still under development. Although some chromium is used in these methods, the amount is so small that considerable chromium would be saved if coated products were used in lieu of stainless steels. Coatings have great potential for replacing stainless steels, but more research and development are needed to improve processing technology and to identify those applications for which they are especially suited.

5. Alternate Materials. Metals such as titanium, aluminum, tantalum, and zinc and thermoplastic and thermosetting plastics can replace stainless steels in many functional and decorative applications. Each of these materials could replace stainless steels only in specific areas.

For instance, titanium could be used in chemical apparatus and in gas turbines at the lower end of the temperature range; aluminum could replace stainless steels in decorative and some structural applications; tantalum and lead, in chemical apparatus. The plastics could replace stainless steels in both functional and decorative applications. The role of these materials is discussed in more detail in section 6.2.6.

The principles outlined above have been used to formulate the detailed master list of substitute materials for current standard steels presented in appendix H and summarized in Table 31. The current steels have been grouped according to structure, chromium level, product form, and application. A total of 47 substitute materials are listed. The substitute materials are either chromium-free or have a much lower chromium content than their standard counterparts. The technical or economical limitations of the substitutes have been included. The research needed and the probability of success conclude the list. This approach has been used during previous material shortages. During the early 1950s, a shortage of nickel resulted in the development of the AISI 200 series stainless steels that use about half as much nickel as the AISI 300 series. The balance of the nickel was replaced by manganese. Development of lower chromium stainless steels requires additional research.

A calculation of potential chromium savings by resorting to the alternate materials shown in Table 32 requires quantitative market data such as that contained in the Department of Commerce 1972 U.S. Standard Industrial Classification (SIC) of chromium-containing products. Using the SIC data, the chromium content was calculated from the ferrochromium, silicon chromium, and metallic chromium quantities on the assumption that the chromium content was 65 percent, 40 percent, and 100 percent, respectively. This was done only for the two-digit code and is shown in Table 32. The SIC data do not provide any information regarding the type of stainless steel used or any details concerning application; therefore, they are not suitable for a quantitative treatment of chromium savings. However, the SIC market categories do provide an indication of potential chromium savings possibility based on what is considered their industrial importance. For instance, for SIC No. 25, Furniture and Fixture, 95 percent of chromium presumably could be saved if practically all the stainless steel were replaced by other materials. On the other hand, for SIC No. 19, Ordnance and Accessories, the assumption was that all stainless steel is essential and irreplaceable. Similar assumptions were made for the other market categories. The

TABLE 31 Alternate Materials for Stainless Steels

Current Material	Material Application	Contained Cr, %	Chromium Demand tons/year 1972	Role of Chromium	Substitute Material	Chromium Content, %	Potential Chromium Savings tons/year	Property Deficiencies	Remarks	Research Needed	Probability of Success
18/8 Cr-Ni type austenitic stainless steels: Types 301, 302,304, 304L,303, 347,321, 201,202, 204,203, 305	Functional and decorative application requiring corrosion and oxidation resistance throughout industry.	18			1. Clad stainless steel on carbon steel substrate	approx. 3%	Major	Loss of corrosion resistance at all exposed edges and welds. Limited high temp. and cryogenic properties.	Restricted to sheet and plate. See Section 3.4.6 and also Processing section on Surface Coatings.		
	SIC Nos. 25,30,33,34, 35,36,37,38, 39,19,11-14, 13,15-17		91,000 (based on 1972 AISI ingot production 60% yield)	—Corrosion resistance —Oxidation resistance —Formation of austenitic structure	2. Cr coatings on carbon steel (electrolytic, vapor deposition or solid state diffusion).	Negligible	Minor	Damaged surface causes loss of corrosion resistance. Limited high temp. and cryogenic properties.	Size and shape limitations. Limited fabricability. See Sections 3.4.1, 3.4.3, 3.4.4 and also Processing section on Surface Coatings	New and improved coatings and methods	High
All wrought product forms					3. 9% Ni steel		Minor	Adequate substitute only in cryogenic end use.			
					4. Aluminum alloys		Major	Not adequate for high temperature application. Some corrosion and structural property limitations.	See Section 3.2.4		
					5. Plastics		Major	Limited fabricability. Not suitable above about 400°F. Lower strength.	See Section 3.6.3, 3.6.4	Develop improved plastics	High

Material	Applications	~%	Production	Resistance	Substitute	Major/Minor	Limitation	Feasibility	R&D Needed	Priority
					6. New ferritic Cr-free steel with Al, Ti, Si addition for high temp. oxidation resistance	Major	Low-high temp. strength	Low-high temp. strength inherent to ferritic stainless steels	Develop new ferritic steel and dispersion hardened ferritic steels	Medium
Total substitutes for above categories						54,600				
High alloy Cr-Ni austenitic stainless steels and valve steels 308,309, 310,314, Inconel 800, valve steels (21-4N, 21-2N) All wrought product forms	Applications involving high temperature oxidation, carburization and sulfidation. Overlay welding. SIC Nos. 13,15,16,17, 33,34,35,38	~22	8,800 (based on 1972 ingot production 60% yield)	—Oxidation resistance —Corrosion resistance	6. New Ferritic Cr-free steel with Al, Ti, Si addition for high temperature oxidation resistance	Minor	Ferritic steels have low strength at high temperatures.	Oxidation resistance of Cr-Ni steels probably attainable. Dispersion strengthening system probably needed for high temperature strength.	Develop new ferritic Cr-free steel. Develop dispersion strengthening system.	Medium
Total substitutes for above categories						3,500				
Mo-bearing austenitic stainless steels: 316, 316L,317 All wrought product forms	Applications involving several corrosion conditions. Primarily in the chemical industry. SIC Nos. 33,34,35,39, 13,15-17	17	9,500 (based on 1972 ingot production 60% yield)	—Corrosion resistance —Oxidation resistance	7. Titanium	Major	Not acceptable in some sulfuric acid environments, hydrofluoric acid and some organic acids.	Cannot substitute for 316 at high temperature. See Sections 3.2.5 and 3.6.7.		
					8. Tantalum	Minor		Very expensive. Limited supply. See Section 3.6.8		

TABLE 31 Alternate Materials for Stainless Steels (continued)

Current Material	Material Application	Con-Tained Cr, %	Chromium Demand tons/year 1972	Role of Chromium	Substitute Material	Chromium Content, %	Potential Chromium Savings tons/year	Property Deficiencies	Remarks	Research Needed	Probability of Success
					10. Lead		Minor	Limited to environments such as sea water, buried pipes			
					5. Plastics (see plastics above)		Major	Not suitable above about 400°F.	See Sections 3.6.3 and 3.6.4	Develop improved plastics	High
					11. Impervious graphite		Minor	Limited to 335°F and stresses not over 50 psi. Very brittle.	Limited productive capacity		
					12. Glass (piping, glass-lined vessels, distillation columns)		Minor	Very brittle.	Limited productive capacity		
Total substitutes for above categories							1,000				
Martensitic stainless steels including PH and semiaustenitic steels: 403,400, 414,422, 416,420, 431,440, 17-4PH, 17-7PH, 15-7 Mo, AM-350, AM-355	Functional applications requiring corrosion or oxidation resistance and high strength SIC Nos. 33,34,35,36, 37,38,39,19, 11-14,13,15, 16,17	Average 13	15,800	—Corrosion resistance —Oxidation resistance —Hardenability	13. Hardenable lower alloy steels.		Minor	No corrosion resistance.	Substitute acceptable only for low temperatures.		
					7. Titanium (see titanium above)		Major	Not acceptable in some acid environments	Higher cost		
All wrought product forms											
Total substitutes for above categories							9,500				

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Material	Applications	No.	Quantity	Requirements	Substitute		Importance	Disadvantages	Reference	R&D	Priority
Ferritic stainless steels: 430,430 Ti, 434,405, 436,439, 26-1,18-2, 446.	Decorative and functional application requiring corrosion resistance. SIC Nos. 25,33,34,35, 36,37,38,39, 13,15,16,17	Average 18	16,200	—Corrosion resistance —Oxidation resistance	1. Clad stainless steel on carbon steel substrate (see above)		Major	See above	See above		
					2. Chromium coatings on carbon steel (electrolytic, vapor deposition or solid state diffusion) (see above)		Minor	See above	See above	New and improved coatings	High
					4. Aluminum alloys (see above)		Major	See above	See Section 3.2.4		
					5. Plastics (see above)		Minor	See above	See Sections 3.6.3 and 3.6.4	Develop improved plastics	High
					6. New ferritic Cr-free steel with Al, Ti, Si addition for high temp. oxidation resistance (see above)		Major	See above	See above	Develop new ferritic steel and dispersion hardened ferritic steels	
Total substitutes for above categories			12,100								
Type 409 stainless: All wrought product forms	Applications in mild corrosion and oxidation condition. SIC Nos. 15,16,17,37	11	8,600 (based on 1975 estimate)	—Oxidation and corrosion resistance.	14. Aluminized carbon steel or low alloy steel.		Major	Lower corrosion resistance. Shorter service life.	See Section 3.6.1		
					15. Chromizing carbon steel.	Negligible	Major	Loss of corrosion resistance at edges and welds.	See Section 3.4.4 and also Processing section on Surface Coatings.	New and improved coatings and method	High
Total substitutes for above categories			6,300								
TOTAL, all substitute materials			87,000								

NOTE: See also Table H-1, Appendix H.

TABLE 32   Example of Possible Chromium Savings in Stainless Steel (tons)

SIC Number	SIC Code	U.S. Chromium Demand in 1972	Possible Chromium Savings	Chromium Use After Savings
25	Furniture and fixtures	2,400	2,280 (95%) [a]	120
33	Primary metal industries	13,000	11,700 (90%)	1,300
34	Fabricated metal products	61,000	30,500 (50%)	30,500
35	Machinery, except electrical	40,000	20,000 (50%)	20,000
36	Electrical machinery, equipment and supply	10,000	4,000 (40%)	6,000
37	Transportation equipment	19,500	18,100 (93%)	1,400
38	Instruments and related products	2,800	560 (20%)	2,240
39	Misc. manufacturing industry	8,000	7,600 (95%)	400
19	Ordnance and accessories	1,250	0 (0%)	1,250
11, 12, 13, 14	Mining, petroleum, natural gas	170	0 (0%)	170
15, 16, 17	Building construction, contractors	9,400	4,700 (50%)	4,700
13	Crude petroleum, natural gas	330	0 (0%)	330
	Total	167,850	99,440	68,530

NOTE: Data from U.S. Department of Commerce, Standard Industrial Classifications, 1972.

[a] The figures in parentheses indicate the percentage of possible chromium savings in that category.

only well-founded assumption is for SIC No. 37,
Transportation Equipment, since the automotive industry is a
well-defined market for which a detailed stainless
substitution calculation could be made and is presented in
appendix I. The total potential chromium savings, based on
the assumption for SIC 37 and chromium supply cut-off, is
approximately 93 percent.

The total chromium usage implied by Table 32 is much
lower than that given in the summary table (see
section 6.4.2, Table 50) which presents a summary of
potential savings. Because the available data on stainless
steel in specific end uses are so incomplete, the larger
figure appears more realistic and is used in Table 50 with
the assumption that its end use category distribution is the
same as that in Table 32.

The most important substitutes, as a group, are
existing materials, such as aluminum, titanium and plastics,
that require no developmental work. Many of these materials
currently compete with stainless steels and therefore have a
proven record as alternatives. They are chromium-free and
provide the optimum chromium-saving solution.

The second group consists of clad products in which the
amount of stainless steel used in a particular application
may be reduced by as much as 90 percent. The advantage of
these products is that the corrosion and oxidation
properties of the original material are maintained. Coated
(or other than clad) products can be included in this group
when the coatings are thin chromium-bearing layers that
permit substantial savings of chromium. Coatings have many
technical limitations and probably are the substitutes
requiring the most research and development, particularly in
the area of fabricating and joining composite materials.

The last group of substitutes, modified stainless
steels possessing lower chromium content, provides the least
chromium savings but their mechanical and fabricating
characteristics could duplicate those of the standard
steels. The loss in corrosion and oxidation resistance
caused by the lower chromium content can be partly or
completely compensated by the addition of other alloying
elements.

6.2.1.2 Substitutability of Chromium in Tool Steels

Table 33 presents information on chromium in the
following classes of tool steels: high-speed steels, hot-
work tool steels, cold-work tool steels, shock-resisting
steels, special-purpose steels, and water-hardening steels.
The production figures used were the 1974 AISI shipped tons

TABLE 33 Chromium Demand and Substitutability in Tool Steels

Current Material	Materials Applications	Contained Chromium, %	Chromium Demand, pounds	Role of Chromium	Substitute Material	Contained Chromium pounds	Chromium Savings	Property Deficiencies	Remarks	Research Needed	Probability of Success
High speed steels	Cutting tools, hot work dies	4	3,000,000	Harden-ability, hardness, wear re-sistance	Sintered carbides	None	3,000,000		High cost, de-sign limita-tions	New design concepts	High
Hot work tool steels	Dies-forging, molding and extrusion tooling	5	1,500,000	Same as above	No replace-ment	–	–		No replace-ments in sight	None	–
Cold work tool steels	Blanking, forming, draw-ing, and slit-ting tools	12	2,300,000	Same as above	Sintered carbides	None	2,300,000		High cost, design limitations	New design concepts needed	High
		5	900,000	Same as above	1% Cr cold work steel	1%	720,000		Substantial chromium re-duction likely	Optimize composi-tion	High
Special purpose steels	Bearings, rolls, gages	1	300,000	Same as above	Cold work, oil harden-ing steels	Low	250,000		Substitution should not cause difficulty	None	–

data. The total amount of contained chromium is 4,167 tons or less than 1 percent of total U.S. consumption. The largest use is in high-speed steels in which chromium plays an important role in the hardening mechanism and is considered irreplaceable. In any case, the relatively small chromium tonnage for this case hardly would justify such research. The second largest use is in the high-carbon, high-chromium cold-work steels in which chromium is essential for hardness and wear resistance, and again is irreplaceable. Sintered carbides make adequate substitute materials for high-speed and high-carbon high-chromium steels if serious cost penalties are accepted. Replacement of chromium hot-work tool steels is not feasible and present technology does not indicate the development of chromium-free substitutes. In view of the relatively small amount of chromium involved, no research is recommended. Some of the other tool steels can be replaced by lower chromium steels or chromium-free materials but, again, the quantity of chromium used or saved is negligible.

The replacements for tool steels are assumed to conserve 3,135 tons, or 78 percent, of the chromium used in this application. Most of these savings would be the result of replacement by sintered carbides. In view of the small amount of chromium used in tool steels, the importance of tool steels for the industry, and the high cost of the replacing materials, it might be advisable to consider the chromium in tool steels irreplaceable.

6.2.1.3 Substitutability of Chromium in Wrought Alloy Steels and Iron and Steel Castings

Although the major metallurgical use of chromium is in stainless and heat-resisting steels, a significant amount also is used to produce wrought alloy steels and alloy iron and steel castings. Historically, these latter categories account for 20 to 25 percent of all new chromium consumed within a given year.

Chromium is used in wrought and cast steel primarily for its influence on hardenability. Many opportunities exist to eliminate or reduce the chromium content of these steels by using other alloying elements that also have a strong influence on hardenability. In most cases, the addition of these substitute elements carries an economic penalty given current chromium prices (i.e., the chromium contribution to hardenability on a dollar basis is relatively high compared to most other alloying elements).

In this section, an attempt has been made to quantify the present use of chromium in wrought alloy steels and castings of irons and steel, and to identify the chromium-

containing grades that are the most likely candidates for
alternative lower chrome grades. Substitution for chromium
in iron and steels by nonferrous materials has not been
considered because the fundamental premise is the necessity
for ferrous base materials. However, materials other than
iron and steel (e.g., aluminum, titanium, and reinforced
plastics) could be considered for applications where
chromium-containing alloys are used presently at a
substantial increase in cost by current economics.

Alternatives for present chromium usage in wrought and
cast alloy steel and alloy irons are discussed by major
alloy categories (e.g., Ni-Cr, Ni-Cr-Mo steels). While it
is very difficult to discuss this subject in terms of the
major SIC categories, Table 34 presents the best estimate of
chromium consumption in alloy steels attributable to the
major SIC markets. These 1972 data originally were in the
form of chromium products consumed but, for this discussion,
the data were converted into tons of actual chromium
consumed.

6.2.1.3.1 Wrought Alloy Steels

The amount of chromium used in 1974 in wrought alloy
steels was determined from the production figures reported
in AISI Form 7A. Assumptions were made concerning the
average chromium content contained in the reported grades
and the amount of chromium contained in the scrap charge.
The reported tonnage for each grade was assumed to represent
90 percent of the actual tonnage produced. The latter
assumption was made because a few alloy steel companies do
not report their production figures to AISI. Table 35 shows
1974 chromium consumption in wrought alloy steels by alloy
grade classification. As can be seen, the majority of
chromium consumed by wrought alloy steels is associated with
straight chromium, the Cr-Mo, and the Ni-Cr-Mo composition.

Table 36 presents a forecast of chromium usage in
wrought alloy steels through 1985. This consumption
estimate is based on historic data that relate the specific
chromium content from the scrap and additions used in making
these steels as a percentage of total alloy steels, and that
relate total alloy steels as a percentage of total raw steel
production.

Unfortunately, available statistics do not permit the
broad alloy categories shown in Table 35 to be classified
into quantities of a specific grade produced; however, by
using past experience as a guide, the major grades that
contribute to the tonnages shown can be identified even
though the specific tonnages are unknown. The material
below identifies these grades and suggests alternate steels.

TABLE 34 Consumption of Chromium in Alloy Wrought and Cast Steel by Market Category, 1972

SIC Number	SIC Code	Chromium Consumed (short tons)	Percent of Total Market
25	Furniture and fixtures	500	0.9
33	Primary metal industries	13,730	24.8
34	Fabricated metal products	7,390	13.3
35	Machinery, except electrical	9,130	16.5
36	Electrical machinery	3,150	5.7
37	Transportation equipment	6,110	11.0
38	Instruments	70	0.1
39	Misc. manufacturing industry	320	0.6
19	Ordnance	1,970	3.6
11, 12, 14	Mining and quarrying	1,680	3.0
13	Crude petroleum and natural gas	4,040	7.3
15, 16, 17	Construction	7,380	13.2
	Total	55,470	100.0

NOTE: Data from U.S. Department of Commerce 1972.

TABLE 35 Chromium Consumption in Wrought Alloy Steels in 1974 (1,000 tons)

Alloy	Steel Produced[a]	Average Chromium Content (%)	Chromium Consumption		
			From Scrap	New	Total
Chromium[b]	1,250	0.85	1.59	9.04	10.63
Chromium[c]	330	1.45	0.72	4.07	4.79
NiCr	120	0.65	0.12	0.66	0.78
CrV	55	0.90	0.07	0.43	0.50
NiCrMoV	160	0.50	0.12	0.68	0.80
CrMo	2,750	1.05	4.30	24.58	28.88
5-9%CrMo	44	6.00	0.66	1.98	2.64
CrMoV	210	1.05	0.33	1.87	2.20
NiCrMo	2,470	0.50	1.84	10.51	12.35
Total	7,389		9.75	53.82	63.57

NOTE: Data from American Iron and Steel Institute 1975.

[a] Production figures from AISI Form 7A adjusted (increased 10 percent) to compensate for nonreporting companies.

[b] AISI 5100 series of steels.

[c] AISI 52100.

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TABLE 36   Chromium Consumption Forecast for Wrought
            Alloy Steel

| | Chromium Consumption (1,000 short tons) | | |
Year	From Scrap	From Additions	Total
1974 [a]	10	54	64
1975	9	50	59
1976	10	55	65
1980	12	62	74
1985	14	78	92

[a] Production figures from AISI Form 7A adjusted (increased 10 percent) to compensate for nonreporting companies.

The nominal chemical analysis of the reference AISI and EX-steels are given in Table 37.

The broad group of chromium-molybdenum grades accounts for approximately 50 percent of all new chromium attributed to wrought alloy steels. The most widely produced grades under this general category are AISI 4118, AISI 4130, AISI 4140, AISI 4142, AISI 4150, and the ASTM elevated-temperature steels (e.g., 2-1/4Cr-1Mo, 1-1/4Cr-1/2Mo, 1/2Cr-1/2Mo, and the 5 to 9 Cr heat-resisting alloys). The following alternates are available:

1. AISI 4118. For most products, the use of other carburizing grades such as AISI 4023, AISI 4027, and AISI 4419 or one of the AISI 1500 grades could be adapted with little or no change in present heat-treating practice.

2. AISI 4130 through 4150. Adjustments in the levels of manganese and molybdenum and the use of boron should permit, with minimal problems, chromium-free replacement steels in constructional applications.

3. 4100 Types Used in Oil Country Tubular. Increases in manganese, molybdenum, and possibly silicon plus consideration of boron-containing steels should allow the use of chromium-free steels at most strength levels. Where resistance to H_2S corrosion is necessary, more basic data are needed to determine the feasibility.

4. Elevated Temperature and Heat Resisting Chromium-Molybdenum Steels. Although chromium could be replaced in these steels if hardenability were the sole consideration, the environments in which these steels normally operate necessitate using from 5 to 9 percent chromium to provide the required corrosion-resisting and heat-resisting characteristics. The elimination or reduction of chromium in these steel would require extensive research and is not considered a likely area for chromium substitutability.

The Ni-Cr-Mo grades account for approximately 20 percent of all new chromium used in the production of wrought alloy steels. The larger tonnage grades in this category are the carburizing grades (i.e., AISI 8615-25, AISI 8822, AISI 4320, AISI 8115-17, AISI 8720 and AISI 9310) and the through-hardening grades (i.e., AISI 4340 and its various aircraft steel modifications, AISI 8630-60, and

TABLE 37 Nominal Chemical Analysis of Standard and EX Steels Referenced in Report

AISI Grades	C	Mn	Ni	Cr	Mo	Other
1527	0.24	1.35	--	--	--	--
15B62	0.60	1.25	--	--	--	0.50Si-0.005B min.
3310	0.10	0.55	3.50	1.50	--	--
4023-27	0.23/0.27	0.80	--	--	0.25	--
4118	0.20	0.80	--	0.50	0.12	--
4130	0.30	0.50	--	0.95	0.20	--
4140-50	0.40/0.50	0.90	--	0.95	0.20	--
4320	0.20	0.55	1.80	0.50	0.25	--
4340	0.40	0.70	1.80	0.80	0.25	--
4419	0.20	0.55	--	--	0.50	--
5120-60	0.20/0.60	0.80	--	0.80	--	--
52100	1.00	0.35	--	1.45	--	--
8115	0.15	0.80	0.30	0.40	0.12	--
8615-60	0.15/0.60	0.80	0.55	0.50	0.20	--
8720	0.20	0.80	0.55	0.50	0.25	--
8822	0.22	0.90	0.55	0.50	0.35	--
9260	0.60	0.90	--	--	--	2.00Si
9310	0.10	0.55	3.25	1.20	0.10	--
EX Grades						
55-56	0.10/0.17	0.85	1.80	0.55	0.70	--

armor steels such as HY-80, STS, and high-hardness armor compositions). The following alternates are available:

1. Carburizing Grades. The majority of the chromium-containing carburizing steels is produced to a 0.35 to 0.65 percent chromium specification. The case and core hardenability provided by this amount of chromium could be attained by substituting increased amounts of manganese and molybdenum and, possibly, the combination of molybdenum and silicon that exhibits a strong synergism at high carbon levels. At least two-thirds of the chromium used in the carburizing grade AISI 9310 can be replaced with no loss in case or core hardenability by increased additions of manganese and molybdenum. The SAE EX-55 and 56 steel compositions exemplify this approach.

2. Through-Hardening Grades. Chromium-free alternates for the AISI 4300 and 8600 compositions, when used for construction applications, could be developed by adjusting manganese and molybdenum levels and by additions of boron. The aircraft and armor compositions, however, have combinations of toughness, strength, weldability, and ballistic characteristics that would entail considerable testing of newly developed chromium-free replacement steels before their suitability would be accepted. Although alternate steels could be developed for the present materials, the total chromium used in these materials probably would not justify the time and money necessary to gain acceptance of the new alloys.

3. Chromium Grades. The straight chromium grades account for approximately 25 percent of the chromium used in wrought alloy steels. The major uses of these steels are in springs (AISI 5150-60), bearings (AISI 52100), through-hardening construction applications (AISI 5140), grinding mill balls, and some carburized applications (AISI 5120). The following alternates are available:

   a. Spring Steels. The most extensively produced single alloy grade in the United States is AISI 5160, whose greatest usage is in springs. Presently, two chromium-free standard grades of steel, AISI 15B62 and 9260, can be used in lieu of AISI 5160. Considerable effort also is under way to

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develop spring steels that are chromium-free or possess less chromium than AISI 5160. These steels (under development) have a hardenability equivalent to that of AISI 5160, and include MnCrMo, SiCr, SiCrMo, and SiMo combinations. Economics permitting, these low-chromium steels appear to be acceptable substitutes for AISI 5160.

b. Bearing Steels. Substitutes for AISI 52100 with lower chrome levels and increased amounts of manganese, silicon, and molybdenum have been, and could be, developed further. Their lack of acceptance primarily is associated with higher cost and requirements for extensive qualifiation testing. Also, the ease of machinability might be less than that of AISI 52100.

c. Medium Carbon AISI 5100 Steels. These steels could be replaced without any problems by increasing manganese contents and making small additions of molybdenum.

d. Grinding Mill Balls (Wrought) Steels. These balls normally are produced from high-carbon manganese-chromium steel (1.15Mn-0.45Cr). At least one steel producer successfully substituted a 1.3Mn-0.2Mo chemistry for this application.

e. Carburizing Steels. AISI 5120 could be replaced by chromium-free steels such as the ones previously mentioned for chromium-molybdenum grades as possible alternates for AISI 4118.

4. Other Alloys. The remaining alloy combinations account for only 8 percent of the total chromium used in wrought alloy steels. The most notable grades include the Cr-Mo-V and Ni-Cr-Mo-V rotor steels, the T-1 type plate steels and the carburizing grade, AISI 3310. The following alternates are available:

a. Rotor Steels. Extensive research and development is required to alter the composition of these long established rotor steel chemistries.

b. T-1 Type Chemistries Identified as ASTM A-517 Grades A to P. Depending on the gauge and

the steel producer, these 100,000 minimum yield strength quenched and tempered steels vary widely in chromium content and include four grades that do not specify any chrome. Thus, chromium-free substitutes that meet the ASTM A-517 specification are available, but they have thickness limitations.

    c.   <u>AISI 3310</u>. At least two-thirds of the chromium used in this carburizing steel can be replaced with no loss in case or core hardenability by increased additions of molybdenum. The SAE EX-55 and EX-56 steel compositions are examples of this approach.

The chromium demand and substitutability in wrought alloy steels are summarized in Table 38.

6.2.1.3.2 Alloy Steel Castings

The present and anticipated future consumption of chromium in alloy steel castings is shown in Table 39. This category accounts for about 4 percent of new chromium used in the production of metallurgical products. For market analysis purposes, alloy steel castings generally are divided into the following groups:

1.   Low-alloy constructional cast steels including modified AISI grades such as 8600, 8700, 4100, 4300, 4700, 5000, and 5100 along with nonclassified proprietary grades. The average chromium content of this group is estimated at 0.7 percent. The present trend, unless reversed by economic or metallurgical factors, is toward increasing chromium content.

2.   High-alloy cast steels including the 4 to 6 percent chromium steels, the austenitic AISI 300 series stainless, the martensitic or ferritic AISI 400 series, and heat-resisting alloys containing between 18 and 30 percent chromium and 0 to 65 percent nickel.

3.   Abrasion-resisting steels comprised of the high-manganese austenitic steels (between 6 and 12 percent manganese), the pearlitic Cr-Mo steels with carbon contents in the 0.5 to 1.0 percent range, and the air-hardening or quenched and tempered multiple alloy martensitic steels with nominal carbon ranging between 0.25 and 0.45 percent.

The major market for low-alloy chromium-containing cast steels is in railroad equipment; Cr-Mo castings are used extensively in the truck body components and the couplers. Sufficient data exist to permit the development of chromium-free grades by increasing one or more of the following elements: manganese, nickel, molybdenum, and boron. This probably could be accomplished without hardship in a short period of time.

The high-alloy cast steel group accounts for over 60 percent of the new chromium used in cast alloy steels and would be the most difficult group of materials in which to decrease chromium consumption. Since the majority of materials in this group are stainless steels and heat-resisting materials, the recommendations for chromium substitutions made in section 6.2 also are applicable to the cast materials.

In the majority of applications of abrasion-resisting cast alloys, chromium could be replaced by combinations of manganese, nickel, molybdenum, and boron.

6.2.1.3.3 Alloy Cast Irons

The primary chromium consumption of this group accounts for approximately 5 percent of the total primary metallurgical chromium consumption. Present and forecast use of chromium is shown in Table 40. For purposes of estimating chromium consumption and possible substitutability, this group of irons has been subdivided into rolling mill rolls, abrasion-resisting castings, and engineering castings.

Indefinite chill rolls with chromium contents of 1.5 to 2 percent are interchangeable with cast steel rolls with less than 1.0 percent chromium or with spheroidal graphitic rolls containing 0.4 percent molybdenum and no chromium. These substitutions, if made, probably would reduce roll performance in the mills.

Recent experience has demonstrated that shortages of chromium cause a reduction in the production of cast irons, containing 28, 20, and 15 percent chromium. For applications requiring higher impact resistance than can be obtained with Ni-Hard® Type 2 irons, Ni-Hard® Type 4 with a chromium content of between 6 and 8 percent could be used. For most other applications, Ni-Hard® Type 2 with a chromium content of between 1.5 and 2 percent could be used. Other possible suitable alternatives include wrought low-alloy steels or Cr-Mo pearlitic or oil quenched and tempered steels containing less than 2 percent chromium. Such changes would not be difficult for the major foundries

TABLE 38 Chromium Demand and Substitutability in Wrought Alloy Steel

Current Material	Material Application	Contained Chromium, %	Chromium Demand (million pounds)	Role of Chromium	Available Alternative Materials			Property Deficiencies	Required New Technology—Remarks		
					Substitute Materials	Contained Chromium, %	Chromium Saved (million pounds)		Research Needed	Priority of Research	Probability of Research Success
Cr-Mo		0.5/9.00									
Carburizing steels, e.g., 4118	Gears and bearings	0.5	8	Case and core hard-enability	Mn-Mo and Mo steels	0	8	Cost	None	None	High
Thru harden-ing e.g., 4130, 4140 and oil country tubu-lar goods	Construction and machinery equipment	0.5/1.00	33	Harden-ability and toughness	Mn-Mo-B and Mn-Mo steels	0	33	Cost and cor-rosion in oil country tubu-lar applications	Improved cor-rosion resis-tance to certain environments	Low	High
Elevated temperature steels, e.g., ASTM A387	Electrical machinery and power equip-ment	0.5/2.00	15	Corrosion resistance	No exist-ing steels	0.5/2.0	0	Corrosion resistance	Long range basic research	High	Low
Heat resist. steel 5-9% Cr-Mo	Chemical pro-cess and petro-leum reference	5.0/9.0	5	Oxidation resistance	No exist-ing steels	5.0/9.0	0	Oxidation resistance	Long range basic research	Low	Low
Subtotal			61				41				
Ni-Cr-Mo		0.5/1.50									
Carburizing steels, e.g., 8620, 8822, 4320,9310	Gears and bearings	0.5/1.00	12	Case and core hard-enability and toughness	Mn-Mo and Mn-Ni-Mo steels	0	12	Cost	None	None	High
Thru hard-ening steels, e.g., 4340, 8640 and HY steels	Construction and trans-portation equipment	0.5/1.50	13	Harden-ability and toughness	Mn-Mo-B and Mn-Ni-Mo-B	0	13	Cost and im-pact resistance	Verify com-parable tough-ness, weld-ability and ballistic char-acteristics	Low	High
Subtotal			25				25				

Cr		1.00									
5160, 52100, and Mn-Cr grinding balls	Springs, bearings, and thru-hardening constructional steel applications	1.00	31	Hardenability, fatigue resistance, abrasion-resistance and sag resistance	Si-Mo and Mn-Mo	0	31	Cost	Qualification testing for bearing steels	Medium	High
Subtotal			31				31				
Cr-Mo-V and Ni-Cr-Mo-V		0.50/1.50									
T-1 types	Constructional	0.50	1	Hardenability and impact strength	Mn-Mo-B (listed in ASTM A517)	0	1	None	None	None	High
Rotor forgings	Electrical machinery	0.50/1.00	4	Creep and stress rupture strength and impact strength	No existent steels	0	4	None	Long range basic research	Low	Medium
AISI 3310	Heavy duty gears and bearings	1.50	1	Hardenability and toughness	EX-55 and 56	0.3	0.7	None	None	None	High
Subtotal			6				5.7				
TOTAL			123				102.7				

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TABLE 39 Chromium Consumption in Alloy Steel Castings (1,000 short tons)

| Year | Alloy | Production | Chromium Consumption [a] | | |
			From Scrap	From Additions	Total Consumption [b]
1974	High alloy	70	7.0	7.0	14.0
	Low alloy	369	0.4	2.2	2.6
	Abrasion resisting	257	1.3	1.3	2.6
	Total	696	8.7	10.5	19.2
1975	High alloy	70	7.0	7.0	14.0
	Low alloy	338	0.4	2.0	2.4
	Abrasion resisting	255	1.3	1.3	2.6
	Total [c]	663	8.7	10.3	19.0
1976	High alloy	75	7.5	7.5	15.0
	Low alloy	365	0.4	2.2	2.6
	Abrasion resisting	276	1.4	1.4	2.8
	Total [d]	716	9.3	11.1	20.4
1980	High alloy	84	8.4	8.4	16.8
	Low alloy	410	0.4	2.5	2.9
	Abrasion resisting	337	1.7	1.7	3.4
	Total	831	10.5	12.6	23.1

NOTE: Chromium content of alloy groups is as follows:

Alloy	Average % Chromium Content	% Chromium Contributed from Scrap	% Chromium Additions
High alloy	20.0	10.0	10.0
Low alloy	0.7	0.1	0.6
Abrasion resisting	1.0	0.5	0.5

[a] Specific chromium contents are assumed to remain constant.

[b] Estimates of total chromium consumption do not include estimated 10-15 percent loss occurring during melting. This estimated loss would normally be compensated for under the chromium addition column.

[c] Modest decline of 4.7 percent is projected for 1975 production of alloy castings.

[d] Growth projections for total alloy steel assume 4.0 percent increase in 1976, followed by 3.6 percent through 1980.

TABLE 40 Chromium Consumption in Alloy Cast Irons (1,000 tons)

Year	Product	Chromium Consumption		
		From Scrap	New	Total
1974	Rolls	1.4	0.5	1.9
	Abrasion resisting	1.0	8.8	9.8
	Engineering castings	4.8	4.8	9.6
	Total	7.2	14.1	21.3
1975	Rolls	1.5	0.5	2.0
	Abrasion resisting	1.0	9.1	10.1
	Engineering castings	3.9	3.9	7.8
	Total	6.4	13.5	19.9
1976	Rolls	2.0	0.7	2.7
	Abrasion resisting	1.0	9.4	10.4
	Engineering castings	4.7	4.7	9.4
	Total	7.7	14.8	22.5
1977	Rolls	2.9	1.0	3.9
	Abrasion resisting	1.1	9.8	10.9
	Engineering castings	5.4	5.4	10.8
	Total	9.4	16.2	25.6
1978	Rolls	3.8	1.3	5.1
	Abrasion resisting	1.1	10.1	11.2
	Engineering castings	6.0	6.0	12.0
	Total	10.9	17.4	28.3
1979	Rolls	4.6	1.5	6.1
	Abrasion resisting	1.2	10.6	11.8
	Engineering castings	6.1	6.1	12.2
	Total	11.9	18.2	30.1

supplying the mining industry since they have both iron and steel casting facilities. Alloy combinations of manganese, boron, tellurium, molybdenum, and tungsten could be considered as replacements for chromium; however, no prior technology has been developed for such a change.

In the production of cylinder heads or blocks, alloys containing tin, copper, and molybdenum have been acceptable substitutes for chromium. The present trend is toward irons with less or no chromium for use in many engineering castings in section sizes of 2 inches or less. This trend should continue as the advantages of Cu-Mo or Sn-Mo irons become more widely known.

The chromium demand and substitutability in cast alloy iron and steel are summarized in Table 41.

6.2.1.3.4 Substitute Materials

From this analysis it is apparent that numerous opportunities exist for substituting other alloying elements for chromium in wrought and cast alloy steels and cast irons. For the most part, this substitution can be accomplished with little research and would cause no detrimental effects on properties or processing. Tables 40 and 41 present tabular summaries of the chromium demand, suggested alternate materials, and estimates of the chromium that can be saved using these alternates.

6.2.2 Substitutability of Chromium in Nonferrous Alloys

Chromium is an important and widely used alloying element in nonferrous alloys, and chromium-containing compositions are found in virtually all major families of nonferrous alloys. Six alloy families are considered in this report -- i.e., those based on nickel, iron-nickel, cobalt, aluminum, titanium, and copper. Although the metallurgical role of chromium is somewhat different in each family, one important distinction can be used to separate the alloys into two groups. In alloys of nickel, iron-nickel and cobalt, chromium is used primarily to confer corrosion and oxidation resistance and, as a rule, no adequate substitutes are available for chromium in these alloys. In alloys of aluminum, titanium and copper, chromium is used primarily to control microstructure and improve physical and mechanical properties, and substitutes are readily available for chromium in these alloys.

Current Material	Material Application	Contained Chromium, %	Chromium Demand (million pounds)	Role of Chromium	Available Alternate Materials			Property Deficiencies	Required New Technology		Probability of Research Success
					Substitute Materials	Contained Chromium, %	Chromium Saved (million pounds)		Research Needed	Priority of Research	
Low alloy steel e.g., 8600, 4100, 5100	Shafts, bearings	0.5/1.00	5	Harden-ability	Same as shown for wrought alloy steels	0	5	Cost	None	None	High
High alloy steels, e.g., stainless and heat resistant	Industrial machinery and equipment and engines	0.5/30	28	Corrosion resistance	Refer to recommendations made by wrought stainless committee		?*		Much basic research	High	Low
Abrasion resistant steels	Transportation and machinery	0.5/1.0	5	Abrasion resistance, hardness and toughness	Mn, Ni, Mo and B compositions	0	5	Cost	Alloy development	Low	High
Engineering cast irons	Transportation equipment	0.5/2.0	20	Wear resistance, strength, and dimensional stability	Ni-Hard 4 or Ni-Hard 2	0	20	Wear resistance, machinability and cost	Improve process technology, wear resistance and machinability	Low	High
Abrasion resistant cast iron	Machinery equipment	15/28	20	Abrasion and impact resistance	Ni-Hard alloy	2 to 8	7 to 26	Impact resistance, abrasion resistance and cost	Improve process technology and impact resistance	Low	High
Rolls	Steel mill equipment	1.5/2.0	4		Spheroidal graphitic irons	0	4	Roll performance		Medium	Medium
TOTAL			82				41 to 60				

*No estimate made for high alloy steels.

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6.2.2.1 Iron-Nickel-Base Alloys Including Nickel-Base Alloys other than Superalloys

This alloy category spans a broad class of materials ranging from iron-rich to nickel-rich compositions and includes both solid-solution and age-hardening alloy types. These alloys typically contain 15 to 25 percent chromium and are used in a wide variety of applications requiring corrosion or oxidation resistance at temperatures ranging from ambient up to 2000 °F. Chromium is essential for adequate corrosion resistance.

Present annual consumption of chromium (in the form of ferrochromium) in the Fe-Ni-base alloys is estimated at 18 million pounds, which is by far the largest of the nonferrous alloy classes considered in this study. No reliable estimates of growth in the U.S. demand for the Fe-Ni-base alloys were found but, considering the anticipated increase in use of high-nickel alloys by the nuclear power industry, the demand for chromium in this class of alloys probably will increase.

For some applications, titanium or titanium-base alloys probably could replace the iron-nickel alloys although the cost penalties might be inhibiting. Coatings or claddings also might be suitable alternates in some cases and ceramic materials (e.g., SiC) might be used successfully for heating element applications. New alloys (with increased amounts of aluminum, titanium, molybdenum, silicon, etc.,) that do not rely on the formation of a protective chromium-rich oxide film for their corrosion and oxidation resistance possibly could be developed; however, in a number of applications (e.g., nuclear reactor components), extensive and lengthy test programs would be required before a substitute material could be accepted. Furthermore, the broad spectrum of service conditions to which these alloys are exposed requires substitute alloys or coatings that perform adequately in many different environments. Thus, many different alternative materials probably must be employed, greatly complicating materials selection. In the near future, only limited substitution apparently could be accomplished and, for most applications, it would be very difficult to effect any significant reduction in chromium consumption.

6.2.2.2 Nickel-Base Superalloys

Nickel-base superalloys are used principally in gas turbine engines. Many commercial alloys contain, and rely on, chromium to provide at least part of the necessary hot corrosion resistance. At present, the trend in nickel-base superalloy development is towards alloys with higher

chromium contents so as to better withstand hot corrosion. This trend is dictated by the desire to burn lower grade fuels that increase corrosive attack and to prolong the operating times between engine overhauls. Consequently, current chromium consumption of about 7 million pounds per year (as chromium metal) may increase at a rate more rapid than the 8 percent annual growth rate projected for nickel-base superalloys during the next decade (Stanford Research Institute 1972).

Two potential routes for reducing chromium consumption in nickel-base superalloys are substitution by coated superalloys with lower chromium contents and by ceramics. At the present state of development, both of these substitution routes involve unacceptable performance penalties.

Considerable coating development work has been done in the past, and aluminum-rich coatings now are applied commonly to turbine blades to improve resistance to oxidation and sulfidation attack. However, coatings tend to deteriorate during service and the underlying alloy must resist the corrosive attack or be replaced quickly. Thus, while available coatings can prolong the service lives of alloys having adequate intrinsic resistance to degradation in the service environment, coatings cannot be used safely to remedy a major basic deficiency of the substrate material. To satisfactorily protect materials that lack adequate intrinsic oxidation or corrosion resistance, the coatings must possess self-healing characteristics. Unfortunately, to date, no completely satisfactory coating has emerged. In view of the extensive research and development effort already expended in this area, the probability of success is considered low. If presently available coatings were used on alloys with very low chromium contents, the service lives of the various engine components would be impaired significantly. Frequent replacement of the corroded parts to keep the engines in service is a theoretical possibility but is an impractical or uneconomical solution to the problem.

Ceramic materials, particularly SiC and Si_3N_4, have been promoted widely as potential substitutes for superalloys in gas turbines capable of operating at substantially higher inlet temperatures. Hot-pressed Si_3N_4 is probably the most advanced material in terms of overall properties. Current grades of this material (e.g., HS130 and NC132) combine exceptional resistance to oxidation and hot corrosion with good thermal shock resistance and adequate high-temperature creep strength. However, these and other ceramics exhibit very low fracture resistance in comparison to superalloys (e.g., the plane strain fracture

toughness of HS130 is more than an order of magnitude less than that of the cast superalloy IN738LC). At present, the problems of using brittle materials in tensile load-bearing components are far from solved. Moreover, the methods used to fabricate SiC and Si_3N_4 components are slow and expensive. Although ceramics eventually may compete with nickel-base superalloys in gas turbine applications, significant substitution is certainly not possible at present.

6.2.2.3 Cobalt-Base Alloys

Cobalt-base alloys are used in gas turbines and in a number of industrial applications. Current consumption of chromium (predominantly in the form of chromium metal) in these alloys is estimated at 2 million pounds per year, and chromium consumption is expected to grow at an 8 percent annual rate during the next 10 years (Stanford Research Institute 1972).

The situation with respect to the jet engine uses of cobalt-base alloys is much the same as for the nickel-base superalloys. Here again, chromium is essential for hot corrosion resistance, and the potential substitutes are ceramics or coated products, but no fully satisfactory substitutes are available. The performance deficiencies of ceramics and coatings described above are equally important here, and the near-term reduction of chromium consumption would involve unacceptable performance penalties. If adequate coatings become available, low-chromium or chromium-free alloys must be developed. Although such a development appears feasible, achieving improvements in properties is less certain than in the case of the nickel-base alloys. In some industrial applications, cobalt-base alloys might be replaced by titanium or titanium-base alloys but, for most applications, no adequate substitute presently exists for this use of chromium.

6.2.2.4 Aluminum-Base Alloys

Chromium is used as a minor alloying addition (typically 0.1 to 0.3 percent) in many of the 5000, 6000, and 7000 series alloys. These high-performance wrought alloys are used in space vehicles, aircraft, marine craft, and surface vehicles in a variety of load-bearing applications. U.S. consumption of chromium as metal in aluminum alloys for 1975 is estimated at 1.5 million pounds. Industry sources project a chromium demand of 2 million pounds for 1980, which represents an annual growth rate of approximately 6 percent.

The chromium alloying additions in aluminum alloys control recrystallization behavior and help achieve consistent product performance. In the 7000 series, chromium also improves resistance to stress corrosion cracking. Zirconium and manganese produce effects that are similar to those produced by chromium, and replacement of the alloys containing chromium with chromium-free grades is possible in many applications; however the slight performance penalties involved could be important in some critical structural uses. Some research and development work therefore would be desirable to optimize the chromium-free alloys. Also of some concern are the lead time and expense involved in materials substitution in applications, such as aircraft structures, for which the replacement material must be qualified before it would be acceptable. However, in the event of a cessation of chromium supply, the use of chromium in aluminum alloys could be reduced substantially or possibly eliminated without incurring major penalties.

6.2.2.5 Titanium-Base Alloys

Chromium is used as an alloying addition in several commercially available titanium alloys including the venerable 13-11-3 beta-alloy (11 percent chromium), the 6-2-2-2-2 alpha-beta alloy (2 percent chromium) and 3-8-6-4-4-(β-C) beta-alloy (6 percent chromium). In addition, General Electric recently announced a new alloy called Ti-17 that contains 4 percent chromium. As yet, none of the chromium-containing titanium alloys has captured a major application successfully. Consequently, the 1975 U.S. consumption of chromium as metal in titanium alloys was very small, perhaps even less than the Committee estimate of 50,000 pounds. Demand for chromium could increase significantly if the Ti-17 alloy captures a significant fraction of the market for aircraft gas turbine engine compressor and fan disks, as seems possible at present. However, even with the most optimistic assumptions, the consumption of chromium in titanium alloys is unlikely to reach 100,000 pounds by 1980.

Chromium alloying additions stabilize the beta (high temperature) allotrope of titanium. Several other alloying elements, notably molybdenum and vanadium, produce similar effects and frequently are used instead of, or in combination with, chromium. Therefore, chromium-free alloys are available that have similar, although not identical, characteristics to those of the chromium-containing grades. Accordingly, in most instances, chromium demand could be reduced by alloy substitution combined with a slight redesign. The Ti-17 alloy is a possible exception to this general conclusion, and a considerable lead time would be

required to replace it, if it finds widespread use in jet engines, because of the necessity for qualifying the substitute material.

6.2.2.6 Copper-Base Alloys

A very minor amount of chromium metal, about 10,000 pounds per year, is consumed in copper-base alloys. Chromium additions of about 1 percent produce useful strengthening effects in copper alloys, but chromium-containing alloys do not exhibit particularly unique property combinations. Apparently, chromium-free grades could be substituted in most applications without significant penalties in either cost or performance.

6.2.2.7 Substitute Materials

Table 42 presents a summary of current U.S. demand of chromium in nonferrous alloys, outlines the major substitution possibilities, and identifies research and development needs. Since the quantity of chromium used in nonferrous alloys is relatively small, only a moderate priority should be assigned to research and development of potentially promising substitutes. Areas of major emphasis should include the development of superior coatings, the further development of engineering ceramics and high-temperature composite materials, and additional work on the refractory metals.

6.2.3   Ceramic Products

6.2.3.1   Chromite Uses (Brick, Gunning, and Ramming Mixes, and Chromite Sands)

Chromite in the mineral spinel form is used mostly in basic refractories. Such chromite-bearing refractories essentially range from all chromite to various mixtures of chromite and magnesia. They are designated as chrome (essentially all chromite), chrome magnesite (with chromite equal to or greater than weight percent magnesite), and magnesite chrome (with greater than 50 weight percent magnesite) to distinguish them from chrome-free basic refractories (American Society for Testing and Materials 1975).

Refractories are supplied as granular material or shaped brick. The former consists essentially of chromite granules with minor additives and is supplied in formulations for mortars, ramming, or gunning mixes. Chromite in large amounts is used in formulations for gunning maintenance of in-use basic refractories structures

(e.g., open hearth roofs and sidewalls, and electric furnace sidewalls).

The brick may be bonded chemically (unburned), burned, or fusion cast. Currently, the average content of such brick is about 55 percent magnesia and 45 percent chromite (about 15 to 18 percent Cr_2O_3 dependent on chrome ore source) (Mikami 1975). Chromite imparts thermal shock and slag resistance, volume stability, and structural strength. For chemically bonded and conventionally burned brick, only massive (nonfriable) refractory grade chromite ores (Philippine and Cuban) are used to provide the requisite coarse sizing of the chromite content of the brick. For chemically bonded brick, such ore is still preferred. With the advent of high-temperature firing to effect bonding of MgO to MgO and chromite to produce "direct bonded" brick, the use of chromite ore concentrates or fines, formerly used in granular refractory products, has increased. Concurrently, the use of chemical grade ores (Transvaal, Turkish, etc.) and, in isolated instances, chromia has increased in preference to refractory grade (Philippine) chromite ores for the most technically advanced brick compositions.

To gain insight on the production and usage trends of chrome-bearing refractories, a questionnaire was sent to the 10 major domestic basic refractories producers. This survey was conducted with the cooperation, and under the auspices, of The Refractories Institute and is summarized below in a manner that does not identify the replies of individual producers. Of the 10 suppliers, 9 responded and account for over 94 percent of American production and shipment of chrome-bearing refractories.

The survey revealed that the steel industry is the predominant consumer of chrome-bearing refractories (over 85 percent). The major usage is in the open hearth (OH) furnace, the electric furnace (EF), and the new vacuum oxygen decarburizing (VOD) and argon oxygen decarburizing (AOD) processes. Minor amounts are used in the slag line area of soaking pit bottoms and reheating furnace bottoms. Virtually no chrome-bearing refractories are used in the basic oxygen furnace (BOF) process.

In 1960, a pronounced shift from the OH to the BOF process for steelmaking began. By 1969, equal tonnages of steel were made by both processes and, by 1974, the BOF process produced 2.3 times more steel than the OH process. Because of this swing to the BOF process, projections in 1968 (Miska) and in 1970 (National Materials Advisory Board) indicated a 4 percent per year reduction in steel plant usage of chrome-bearing refractories. Obviously, what was

TABLE 42 Chromium Demand and Substitutability in Nonferrous Alloys

Current Material	Material Application	Contained Chromium (%)	Chromium Demand (millions of pounds)	Role of Chromium	Available Alternative Materials				Required New Technology		Remarks
					Substitute Materials	Contained Chromium	Chromium Savings	Property Deficiencies	Research Needed	Probability of Research Success	
Fe-Ni and Ni-base alloys except super-alloys	Nuclear reactors, chemical plants, heat treating hardware	15 to 25	18	Oxidation and corrosion resistance	None in most cases	—	80 to 100% of contained Cr in applications where substitution is possible	—	Coating development Low Cr alloys	Medium High	Coated and clad materials, ceramics and Ti-alloys can be used in a few applications (probably <20% of total). Use of alternates in other applications would involve unacceptable performance and/or cost penalties. Ferrochromium is the required melt stock with present trend towards high-C ferrochromium.
Ni-base superalloys	Gas turbines	15	7	Oxidation and corrosion resistance	None	—	None	—	Coating development Low-Cr superalloys Ceramics	Low High Medium/Low	Strategically essential application with no immediate substitution possibilities. Electrolytic grade chromium metal is required melt stock.

Material	Application			Function	Substitute				R&D		Comments
Co-base alloys	Gas turbines, chemical plants	17	2	Oxidation and corrosion resistance	None	–	None	–	Coating development Low Cr alloys Ceramics	Low High Medium/Low	Strategically essential application with no immediate substitution possibilities. Electrolytic grade chromium metal melt stock is required for most alloys.
Al-base alloys	Aerospace and land vehicle structures	0.1 to 0.5	1.5	Micro-structure control, corrosion resistance	Other Al-base alloys	None	100% of Cr now used	Slightly less consistent properties	Optimization of Cr free alloys	High	Zr and Mn are alternate alloying elements. Use of substitute materials for some applications could require qualification testing involving long lead times (years) and high costs (millions of dollars).
Ti-base alloys	Aerospace structures, gas turbines	2 to 11	0.05	Micro-structure control strength	Other Ti-base alloys	None	100% of Cr now used	Probably none	Probably none	–	Mo and V are alternate alloying elements. Use of substitute materials for some applications could require qualification testing involving long lead times (years) and high costs (millions of dollars).
Cu-base alloys	Heat resistant alloys	1	0.01	Strength-ener	Other Cu-base alloys	None	100% of Cr now used	Probably none	Effects of other hardeners	Very high	No significant problems are foreseen in using alternative materials but Cr consumption is insignificant.

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not foreseen when the projections were made was the
increased steel production by the EF and the new VOD and AOD
processes that consume significantly larger amounts of
chrome-bearing refractories (up to six times more) than the
OH process.

As noted in Table 43 , between 1969 and 1974, steel
production increased by 3.16 percent from 141.2 to 145.7
million tons, OH production decreased 25.4 million tons, and
EF production increased by 8.53 million tons (American Iron
and Steel Institute 1975). Combining these statistics with
those derived from replies to the refractories industry
survey (Table 44), it appears that the steel industry
increased its consumption of Cr_2O_3 in refractories by 4,923
tons, an increase of 3.2 percent approximately matching the
3.16 percent increase in steel production. More
significantly, however, by converting the statistics to
pounds of Cr_2O_3 consumed per ton of steel produced by the
processes using chrome-bearing refractories, an actual
increase of 30.3 percent (i.e., 3.786 pounds/ton in 1969 to
4.935 pounds/ton of OH and EF steel processed in 1974) is
noted. This increase reflects not only the higher
consumption by the EF process but also the increased
production from such processing. Virtually all of the steel
processed in AOD and VOD units is melted first in electric
furnaces and is reported as EF steel in the AISI statistics.
Most industry projections indicate continued growth for EF
steelmaking, which presages an even higher demand for
chrome-bearing refractories in the future (unpublished data
from Data Resources, Inc. 1976) unless substitute materials
are found.

Glass, nonferrous, rotary kilns and all other
industries increased their consumption of Cr_2O_3 in
refractories by 7,925 tons between 1969 and 1974. Aside
from increased business activity, this increase (120 percent
for rotary kilns, 49 percent for nonferrous, and 27 percent
for glass) represents a growing preference for chrome-
bearing refractories over other refractories.

Respondents' estimates of the use of chrome-bearing
refractories in the future ranged from the same consumption,
to less than a 10 percent decrease, to an increase of 15 to
25 percent, and related consumption to the level of steel
production (see above). Granular material producers predict
a marked decrease in consumption in the future. Both
production statistics and replies show a trend toward use of
chromite ores with higher Cr_2O_3 and lower SiO_2, iron oxide,
and Al_2O_3 contents. All respondents emphasized lower silica
and iron oxide ores as most desirable, and beneficiation of
Philippine ores to remove the silica would meet this
requirement. . The use of chromia (Cr_2O_3) as an additive to

TABLE 43   Iron and Steel Industry Consumption of Chromium-Bearing Refractories, 1969 and 1974.

	1969	1974	Net Change
Steel produced (1,000 tons)			
Basic oxygen furnace	60,236	81,552	+21,316 (+35.4%)
Open hearth furnace	60,894	35,499	-25,395 (-41.7%)
Electric furnace	20,132	28,669	+ 8,531 (+42.4%)
Total	141,262	145,720	+ 4,458 (+ 3.16%)
Cr_2O_3 contained in refractories delivered to steel industry (tons)			
Brick	60,994	73,472	
Granular	92,420	84,865	
Total	153,414	158,337	+ 4,923 (+ 3.2%)
Open hearth and electric furnace steel produced (1,000 tons)	81,026	64,168	-16,858 (-20.8%)
Cr_2O_3 containing refractories per ton of open hearth and electric furnace steel (pounds)			
Brick	1.505	2.29	
Granular	2.281	2.64	
Total	3.786	4.935	+1.149 (+30.3%)

NOTE: Data based on American Iron and Steel Institute 1975 and the replies to the questionnaire distributed by The Refractories Institute in 1976.

TABLE 44   Summary of Replies to The Refractories Institute Questionnaire on Chrome-Bearing Refractories, April 1976

Industry Delivered To	1969 — Cr_2O_3 Contained in Refractories						1974 — Cr_2O_3 Contained in Refractories						1969-1974 Increase in Total Cr_2O_3 (%)
	Shaped Brick (tons)	(%)	Granular [a] (tons)	(%)	Total (tons)	(%)	Shaped Brick (tons)	(%)	Granular [a] (tons)	(%)	Total (tons)	(%)	
Iron and Steel	60,994	81.9	92,420	97.20	153,414	90.5	73,472	78.2	84,865	96.0	158,337	86.8	3.2
Glass	3,866	5.2	505	0.53	4,371	2.6	5,112	5.4	438	0.5	5,550	3.0	27.0
Nonferrous	4,171	5.6	586	0.62	4,757	2.8	6,283	6.7	803	0.9	7,086	3.9	48.9
Rotary kilns	2,240	3.0	34	0.03	2,274	1.3	4,921	5.2	102	0.1	5,023	2.8	120.9
Other	3,167	4.3	1,561	1.62	4.728	2.8	3,617	4.4	2,224	2.5	6,396	3.5	35.3
Total reported	74,438	43.9	95,106	56.1	169,594	100.0	93,960	51.5	88,432	48.5	182,392	100.0	

NOTE: Data based on replies from 9 companies producing over 94 percent of American chrome-bearing refractories. Survey sponsored by The Refractories Institute, 1976.

[a] Gunning, ramming, mortars, etc.

refractories to enhance slag resistance has increased from 150 tons in 1969 to over 400 tons in 1974. Interest is growing in its use in both basic and high alumina refractories.

Historically, chromite ore was priced significantly lower than refractory magnesia (periclase). This fixed the price of basic refractories in direct proportion to the magnesia content and, consequently, lower cost, higher chromium content brick was favored where it would give equal performance. In recent years, the price of chromite ore has been rising to close the gap. For copper convertors and the new AOD and VOD processes, higher chromium compositions reportedly give better performance. In most other applications, substitution of magnesite chromite (70 percent or more MgO) for chromite and chromite magnesite can be made at no penalty in performance and minimal increase in initial cost. The extent of such substitution could yield a savings in Cr_2O_3 consumption for brick well in excess of 50 percent.

The new AOD and VOD processes consume up to six times more refractories per ton of processed steel than conventional EF processing. Recent experience indicates a growing interest in the use of dolomite refractories for these applications.

Six of the nine respondents to the refractories survey practice some measure of in-house salvage and reuse of chromite. Two respondents stated that they are negotiating for salvage from consumer plants. With favorable cost incentives and a scarcity of chromite, considerable potential exists for salvage and reuse of chromium-bearing brick in all consuming industries. Chromium-bearing bricks in many units are distinctly different and recognizable from chromium-free refractories even after use, and the bricks can be separated by hand and stacked separately for salvage, reprocessing, and reuse. The experience of several steel companies shows that up to 33 percent of the bricks in an original structure can be salvaged by such practice. Wasted OH roofs and endwalls, EF sidewalls, and AOD and VOD linings fall into this category.

6.2.3.2 Chromium Carbides and Borides

Chromium carbides, and to a lesser extent chromium borides, have been developed and marketed as unique refractory materials. The chromium carbide grades are highly resistant to both acids and alkalies -- more so than the more conventional tungsten carbide grades -- and possess good oxidation resistance. These qualities lead to applications such as extrusion dies, valve parts, and seals for food and chemical process equipment, and high-

temperature bearing races. Excellent wear resistance, coupled with an expansion coefficient close to that of mild steel, makes chromium carbide attractive for dimensional gauges. Chromium borides are used principally as a hard-facing material applied by gas torch fusion of a paste. The amount of chromium used for these refractory compounds is insignificant and, with very few exceptions, nearly comparable performance can be obtained with other hard, corrosion-resisting materials.

6.2.3.3 Chromite and Chromium Oxide Grains and Powders

The two major uses of chromite in granular form are as maintenace gunning mixtures for steelmaking furnaces and as facing sands in steel foundries. Chromium-bearing gunning materials are used mostly for OH roof and wall and EF wall maintenance. With the swing away from OH to BOF steel processing, the use of such material is decreasing (8.2 percent between 1969 and 1974) (Table 44). Substitutes for such material include magnesite, dolomite, and salvaged and reprocessed chromite, and chromium-free basic materials.

The steel foundry industry is using in excess of 20,000 tons of chromium as chromite for facing sand. This usage is expanding (Dressel et al. 1976) and became the preferred material when the price and availability of zircon made the use of chromite economical. The preferred chromite must have a low content of low fusing gangue. The high-iron, high-chromite Transvaal ore is used mostly. Such ore responds to gravity or magnetic separation, recovery, and reuse, although recycling is not practiced generally. Substitute materials include zircon, olivine, and silicon sands. Olivine (magnesium ortho-silicate) sands are popular and preferred only for high-manganese steel castings. Silica sands still are used primarily as back-up, not as facing sands.

Minimal amounts of chromite and chromium oxide powders are used as colorants in glass and structural clay products. Chromia, green Cr_2O_3, is being used increasingly as an additive to enhance the slag resistance of high alumina refractories.

6.2.3.4 Material Substitutes

The largest use of chromium in ceramic products is as chromite in basic steel plant refractories and as facing sands in steel foundries. The onus of reducing the usage of chromite in ceramics by finding suitable substitutes, by salvage, and by reuse falls on the major industrial consumers (i.e., the steelmaking and steel foundry industries). The data in Table 45 indicate that these

TABLE 45   World Total Chromium Production Cumulated through
           1974 (million tons)

Chromium End Usage	Now in Use	Losses	Total
Metallurgical	13	13	26
Chemical	1.5	6.5	8
Refractories	0.5	5.5	6

materials are a fruitful source of chromium conservation.
Table 46 presents a tabular summary of chromium demand for
ceramic products, suggested alternate materials, and
estimates of how much chromium could be saved if these
alternates were to be used.

6.2.4 Plated Coatings

Although chromium plating is an important and highly
visible industry, it uses only about 4 percent of the
chromium consumed in the United States. Chromium savings in
this market would have little impact on the overall
availability of chromium (National Materials Advisory Board
1970). Chromium chemicals, used in all chromium plating and
other metal finishing operations, are made from chemical
grade rather than metallurgical grade ore. Chemical grade
ore is only marginally competitive at present, but this is
beginning to change (Smith 1976).

Perhaps 60 percent of the chromium consumed in
electroplating is used in decorative end uses, 30 percent is
used in engineering (hard) chromium plating, and a smaller
amount is used in other forms of metal finishing such as
chromate conversion coatings and chromic acid anodizing of
aluminum. In an emergency, decorative chromium plating
could be discontinued with some sacrifices. In automotive
bumpers, the chromium plate is, to some extent, functional
since it helps to prevent premature rusting. Anodized
aluminum or organic-coated bumpers could be used but the
chromium savings would be minor since decorative chromium on
autos only uses about 600,000 pounds (0.05 percent) of the
total U.S. consumption. Except for the bumpers, decorative
chromium plating on automobiles is not functional and could
be discontinued.

Hard chromium plating is used mainly for its excellent
physical properties, hardness, wear resistance, and low
coefficient of friction. The only apparent substitute is
electroless nickel-phosphorus alloy that is better than hard
chromium for wear resistance in certain applications (Tope
1975, Johnson 1976). In addition, its "throwing power" is
far superior and it does not degrade the fatigue properties
as hard chromium plating sometimes does. This substitution
could be considered in appropriate applications if the
chromium saving appeared worthwhile. Costs probably would
be higher although overall (life cycle) costs might be
comparable (Safranek 1974).

Another use for chromium plating is in the manufacture
of "tin-free steel" (chromium type) that can replace
tinplate in some canning uses and is now in production.
According to the AISI, total shipments of tin-free steel in

1975 were 28.5 million base boxes with a contained chromium content of 164,000 pounds, a relatively insignificant amount (Lamantia 1975). These figures for chromium plating, however, do not accurately represent the demand situation since the total amount of chromic acid sold for this application contains at least 500,000 pounds of chromium (personal communication from A. J. Lowenheim, Consultant, Plainfield, N.J., 1976). Only 15 to 20 percent of the chromic acid used actually ends up on the plate, and a marginally useful saving of chromium could be made by recycling the wasted material. Active research is under way in this area, supported by the existing stiff pollution control regulations.

There is some hope for chromium conservation in the development of plating baths using trivalent chromium compounds in place of chromic acid. The savings would result from the use of less chromic acid spray and effluent rather than from any direct reduction in actual chromium metal on the parts plated. Intensive research has been performed but the outlook seems questionable (Bride 1972, Carter and Christie 1973, Ward and Christie 1971, Ward et al. 1971).

Many alloy deposits have been investigated on a laboratory "beaker" scale with some promise for corrosion resistance, hardness, and other properties that approach those of stainless steel. None of these investigations has been carried far enough to indicate their practical possibilities or whether intensive research in this area should be supported. Such research must be undertaken with government funds since the profit motive is minimal (Krohn 1974).

Another use for chromic acid and chromium chemicals in metal treatment is the anodizing of aluminum. Since most aluminum anodizing uses sulfuric acid, chromic acid anodizing is important only to the aircraft industry. Chromium savings in this application would be small, as it would be for other metal treatments and uses of chromic acid and chromates in conversion coatings.

There seems to be little economic incentive to save chromium by eliminating the use of chromic acid or chromates in metal plating, anodizing, and other treatments. Zinc plate could be substituted for decorative chromium in a few cases but not, on the whole, satisfactorily. Chromates are used in post-dip processes for brightening zinc. Aluminum coatings can be produced by hot dipping and not by electroplating but they are no more decorative than zinc. Anodized aluminum is used in some automotive hardware as a substitute for chromium-plated parts. Table 47 presents a

TABLE 46   Alternatives for Ceramic Products

Material	Application	Contained Cr_2O_3	Cr_2O_3 Demand, tons	Role of Cr_2O_3	Available Alternate Materials				Required New Technology		
					Substitute Materials	Contained Cr_2O_3	Cr_2O_3 Savings, tons	Property Deficiencies	Research Needed	Priority of Research	Probability of Research Success
Chrome and chrome magnesite brick	Furnace and kiln linings	18 to 23%	Ca 30,000	Improved slag resistance and thermophysical properties	Magnesite chrome brick	6 to 12%	20,000 to 24,000	Most applications significantly none, in copper converters less slag resistance	None	None	–
					Magnesite brick	0	30,000	Cost, lower slag resistance and volume stability	None	None	–
					Spinel	0	30,000	As above	Improved physicals	Low	Good
					Forsterite	0	30,000	As above	Improved physicals	Low	Good
					Dolomite	0	30,000	As above and hydration	Improved purity and physicals	Low	Good
Magnesite chrome brick	Furnace and kiln linings	5 to 16%	Ca 45,000	Slag resistance and thermophysical properties	Magnesite	0	45,000	Cost, slag resistance and volume stability	Establish minimum amount of Cr_2O_3 needed	Medium	Good

					Spinel	0	45,000	As above			
					Forsterite	0	45,000	As above			
					Dolomite	0	45,000	As above plus hydration			
Granular chrome-bearing materials	Furnace and kiln maintenance	18 to 44%	Ca 86,500	Thermal stability and slag resistance	Magnesite	0	86,500	Cost, volume stability	None	None	–
					Dolomite	0	86,500	Volume stability and hydration	None	None	–
					High Al_2O_3	0	40,000	Cost, availability, chemical compatibility	None	None	–
Granular chromite	Foundry facing sands	44+%	Ca 30,000	Chill, chemical and thermal stability	Zircon	0	30,000	Cost, availability, heat capacity and chemical resistance	None	None	–
					Olivine	0	30,000	Heat capacity and chemical resistance	None	None	–
					Quartz	0	30,000	Heat capacity, chemical resistance and thermal stability	None	None	–

TABLE 47 Chromium in Electroplating Applications

Current Material	Material Application	Contained Chromium	Chromium Demand (million pounds)	Role of Chromium	Available Alternate Materials				Required New Technology		Probability of Research Success
					Substitute Material	Contained Chromium	Chromium Savings (million pounds)	Property Deficiencies	Research Needed	Remarks	
Cr Electroplate 10 to 30 micro-in.	Decorative trim, automotive, appliances	<0.1%	14	Reflectivity, hardness, corrosion resistance	Zn Electroplate	None	14	Low hardness, low reflectivity, high coeff. friction, low service temp.	None	Poor surface texture, not decorative, low priority	
					Cd Electroplate	None	14	Low hardness, low reflectivity, high coeff. friction, low service temp., toxic	None	Poor surface texture, not decorative, high cost	
Cr Electroplate 10^{-2} to 10^{-4} in.	"Hard" chromium machine parts	<1%	7	Hardness wear resistance, low coeff. friction	Electroless nickel	None	7	Higher cost, slower	Lower cost chemicals, faster processing	May be better in wear resistance and other properties	High

summary of the current demand for chromium in electroplating, lists some possible substitutes, and indicates possible chromium savings that might result from the use of substitutes.

6.2.5 Chemicals Containing Chromium

Historically and today, practically 100 percent of the chemical grade chromite ore is imported from South Africa and shipped through the port of Maputo in Mozambique. Chemical grade chromite ore is roasted with soda ash and lime to convert the Cr_2O_3 to Na_2CrO_4. The resultant roast is leached with water to extract the water soluble sodium chromate. Sodium chromate then is converted to the principal chromium chemical, sodium dichromate, by acidifying with the sulfuric acid or carbon dioxide. Most chromium chemicals, such as chromic acid, basic chromium sulfate, tanning compounds and chromium pigments, are made from sodium dichromate (Table 48).

6.2.5.1 Pigments and Paints

Chromium pigments represent the largest outlet for sodium dichromate, and this market has been increasing about 3 percent per year. The main chrome pigments are chrome yellow, molybdenum orange, zinc chromate, chrome green, and chrome oxide green. The primary uses for chromium pigments are for coloring plastics and printing inks. The other large use is in paints for yellow lines on roads, and industrial finishes for automobiles, school buses, appliances, tractors, and heavy equipment. Zinc chromate is used mainly as a corrosion inhibitor primer for metals. Chromium pigments are inexpensive in comparison to other proven colored pigments, and in most cases their replacement with proven nonchromium pigments to obtain the same color would involve a price penalty of 300 to 2,000 percent. However, recent very strict recommendations by the National Institute for Occupational Safety and Health Administration (NIOSHA) regarding chromium in air could result in no growth in the future and possibly could result in some decrease in their use.

In a chrome shortage, chrome pigments could be eliminated, along with the colors of yellow, orange and red, in over 50 percent of their uses. The chrome pigments could be replaced with pigments such as carbon black, iron oxide, and titanium oxide pigments, but these substitutes would limit the number of colors.

TABLE 48   U.S. Consumption of Chromium Chemicals

Use Segment	1973 Tons	1973 %	1974 Tons	1974 %	1975 Tons	1975 %	Estimated Availability 1976 Tons	1976 %	1980 Tons	1980 %	In an Emergency (tons)
Pigments	37,000	25.0	46,000	25.0	30,000	22.7	35,000	22.2	35,000	21.7	15,000
Metal finishing and treatments	34,000	23.0	40,000	23.0	28,000	21.0	38,000	24.0	30,000	18.6	15,000
Leather tanning	25,000	17.0	30,000	17.0	30,500	23.0	35,500	22.5	35,000	21.7	30,000
Drilling muds	6,500	4.5	8,000	4.5	5,000	4.0	8,500	5.3	10,000	6.2	6,000
Wood treatment	7,500	5.0	10,000	5.7	8,000	6.0	9,000	5.7	15,000	9.3	3,000
Water treatment	10,500	7.0	12,000	7.0	5,000	3.0	6,000	3.8	8,000	5.0	5,000
Chemical manufacture	11,000	7.5	13,000	7.5	10,000	7.5	12,000	7.6	14,000	9.0	5,000
Textile	6,000	4.0	6,000	3.5	3,000	2.5	3,000	2.0	–	–	–
Catalysts	1,500	1.0	1,500	1.0	1,000	1.0	1,500	1.0	1,700	1.0	1,500
Export and other	9,000	6.0	10,000	5.7	11,000	8.0	9,000	5.7	12,000	7.5	3,000
TOTAL Sodium Dichromate Dihydrate ($Na_2Cr_2O_7 \cdot 2H_2O$)	148,000		176,000		132,000		157,500		160,700		83,500
TOTAL Contained Chromium	51,600		61,600		46,000		55,000		56,000		29,100

NOTE: Section 6.2.5 is based on information gathered internally by members of the Diamond Shamrock Corporation and from their contacts with knowledgeable individuals in related industries.

6.2.5.2 Leather Tanning

Sodium dichromate is used to make chromium compounds that tan the bulk of the leather produced in the United States. No practical substitute exists for chromium in tanning the majority of this leather without a definite price and performance penalty. The most practical substitutes, vegetable tanning compounds, also are imported completely, and the majority of U.S. tanners do not have the proper equipment to use vegetable tanning compounds in place of chromium. Government regulations will force most tanners to recycle 15 to 20 percent of their present chromium consumption, probably making this area a no-growth market for chromium in the foreseeable future.

In an emergency, it would be very difficult to reduce the use of chromium for tanning leather. Although substitutes, such as plastics, could replace leather in most uses, the problem would be the millions of cattle hides whose only practical use is for leather.

6.2.5.3 Metal Finishing and Treatment

Chromium is used for chromium plating (decorative and engineering) and the treatment of copper, brass, zinc, and cadmium alloys and galvanized steel. This market has grown about 2 percent per year. About 80 percent of the chromium in metal treatment is for chromium plating, of which over 50 percent is for decorative purposes. No known substitutes exist for chromium chemicals in metal treatments and plating that would not result in a severe performance and cost penalty. Environmental Protection Agency (EPA) regulations will result in the recycling of considerable chromium that is used now in decorative chromium plating and lost as drag-out. This chromium recycling should result in reduced chromium demand in the metal treatment field.

In an emergency, considerable chromium could be saved by eliminating most decorative chromium plating. Materials now being plated for decorative purposes either could be painted or made from plastics or other chromium-free materials.

6.2.5.4 Drilling Mud Additives

Sodium dichromate is used to produce chromium ligno-sulfonates, an additive to drilling muds. This market is growing about 3 percent per year, and no known satisfactory substitutes exist (especially for drilling deep wells over 10,000 feet). Chromium compounds also are used as a corrosion inhibitor in additives to drilling mud to greatly extend the life of the drilling equipment. In an emergency,

reducing the use of chromium in this area would not be in the national interest since less exploration for oil and gas could result.

6.2.5.5   Water Treatment Compounds

Sodium dichromate is used to make water treatment compounds, such as corrosion inhibitors for cooling towers and air conditioners. This market is growing about 10 percent a year and is projected to continue at that rate in the foreseeable future. The largest users are petrochemical and chemical plants and oil refineries. No substitutes have been satisfactory as corrosion inhibitors for use in waters at temperatures of 150 °F or higher, the temperatures usually found in petrochemical and oil refinery operations. Substitutes are available for less critical applications, such as air conditioners and cooling towers operating at temperatures of 120 °F or less, but they result in a performance and price penalty. In an emergency, it is questioned whether much chromium could be saved in the national interest due to its essential role in petrochemical plants and oil refineries.

6.2.5.6   Wood Treatment Compounds

Sodium dichromate is used to make copper-chromium-arsenic compounds to treat wood as a protection against termites, fungus, etc. This market is growing in excess of 10 percent a year and is expected to continue do so unless government regulations restrict use. Other preservatives, such as creosote and pentachlorophenol, can be used to treat wood; however, the substitution for chromium-containing compounds in some cases would result in a performance penalty, primarily in paintability. In an emergency, copper-chromium-arsenic compounds for wood treating could be eliminated, and most woods could be treated with other known compounds.

6.2.5.7   Chemical Manufacture and Other Uses

Sodium dichromate is used to manufacture other chemicals such as potassium dichromate; chromium organic complexes for treating textiles, papers, and leathers; chromium dioxide for magnetic tapes; and chromium-containing catalysts. Chromium catalysts are used to synthesize ammonia and methanol and for many hydrogenation and polymerization reactions. Growth in these areas has been about 4 percent a year and is expected to continue at this rate. In most cases, no substitute is known for these specific chromium uses, and the elimination of chromium would result in a performance penalty in practically all cases. In an emergency, restricting chromium for use in

catalysts could create a serious problem. The chemical manufacturing and other uses probably could be cut 50 percent or more.

6.2.5.8   Material Substitution Considerations

Using chromium chemicals for the above applications essentially provides a substantial price advantage over any known proven substitute materials; therefore, substitutes are not expected to replace chromium naturally. Government regulations (EPA and NIOSHA) will result in the recycling of much of the chromium that presently is wasted, particularly in the metal finishing and leather tanning areas. Recycling the chromium in pigments, leather tanning, wood treatment compounds and the chromium deposited in metal treatments is impractical because of the very thin layers involved or the difficulty of obtaining the chromium in a recyclable form. In the case of pigments, proposed regulations regarding their toxicity to humans exposed during their manufacture could result in some contraction of this market. However, the economic advantage of chromium pigments over proven substitutes to obtain the same color could initiate the development of methods to meet the proposed regulations.

In an emergency, certain uses could be eliminated. This happened in World War II when chromium plating on automobiles and other appliances was replaced by painting or plastics. Also, colored pigments could be replaced for many uses. The projected possible savings are shown in Table 49.

6.2.6   Chromium-Free Coatings

6.2.6.1   Aluminum, Zinc and Aluminum-Zinc Alloy Coatings

Steel may be zinc coated by hot dipping or electroplating on one or both sides. The zinc coating protects the steel from corrosion due to exposure to humidity or outdoor elements. The ability to withstand such exposure is directly proportional to the thickness of the sacrificial zinc coating and the painted surface applied for appearance. Phosphate or chromate coatings usually are applied before painting to improve paint adhesion and improve corrosion resistance. While zinc is excellent for protecting steel from atmospheric corrosion, it cannot be used in the presence of strong acids or strong alkalies where stainless sometimes is used. The zinc sacrificially protects the iron and steel from corroding for some distance beyond the zinc coating, especially at minor discontinuities such as sheared edges or scratches extending to the substrate.

TABLE 49 Chromium Demand and Substitutability in Chemicals Containing Chromium

Current Material	Material Application	Contained Chromium	Chromium Demand (millions of pounds)	Role of Chromium	Available Alternative Materials				Required New Technology		Remarks	
					Substitute Materials	Contained Chromium	Chromium Savings (%)	Property Deficiencies	Research Needed	Priority of Research	Probability of Research Success	Type of Research
Chrome pigments	Paints, plastics, and inks	10-15%	24	Color and corrosion inhibitor	Organic pigments	0	100	3 to 20 times more expensive	Low cost substitute	Low	Medium	
Chrome tanning compounds	Tan leather	15-17%	24	Tanning agent	Vegetable tannins	0	100	7 to 14 times longer tanning time	Tanning compound containing domestic produced materials	Low	Low	Long term
Metal finishing and chrome plating	Corrosion protection	Decorative 10-30 microinches Engineering 1-10 mils	26	Protective coating	Nickel, cobalt	0	100	High costs and short supply	More economical methods of recycling unused chromium	Low	Medium	Medium
Drilling muds	Drilling muds	5-10%	5.6	Corrosion control and fluidity of mud	Bentonite, lime, tannins	0	100	Not suitable for well 10,000 ft or more	Non-chrome containing additive to drilling muds	Low	Medium	Long term
Water treatment	Corrosion control in cooling towers	5-20 parts per million	4.2	Corrosion inhibitor	Phosphates, silicates	0	100	Not suitable for higher temperatures, higher cost	Effective corrosion inhibitor for water 150°F or higher	Low	Medium	Medium
Wood treatment	Wood preservation		6.0	Bond copper and arsenic to wood	Creosote, pentachlorophenol	0	100	Appearance and paintability	None			
Chrome catalysts	Chemical reactions	3-10%	1.0	Promote reactions	Other metal		100	Cost and performance	Catalyst not containing chrome	Low	Medium	Long term

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For hot dipping and electro-galvanizing, the steel must
be cleansed of oil and lubricants, and surface oxide must be
removed. In hot dip coating, a molten flux covers the
liquid zinc bath for its protection and to ensure a clean
surface after oxide removal. The coating produced by hot
dip galvanizing consists of several layers; those closest to
the base metal are composed of various zinc-iron compounds
while the outer layer is almost pure zinc.

Galvanized steel can be welded easily and the
galvanized sheet is as readily formable as uncoated steel
but not with the same tooling. Since the melting point of
zinc is 787 °F, it limits the temperature to which
galvanized steel may be used.

In 1976, the United States produced about 7 million
tons of galvanized sheet and 140,000 tons of galvanized
fixtures. Although the galvanizing capacity is somewhat
higher than this, it has not been determined accurately.
Since the areas in which galvanized steel could be
substituted for stainless are limited by temperature and
lack of resistance to acids and alkalies or oxidizing
materials, the additional galvanized material that would be
used for this purpose probably could be absorbed at this
time. With a full economy, this capacity would not be
available, and the lead time to increase capacity is about
two to three years.

An alternative to galvanizing is a proprietary system
called Zincrometal®, registered to the Diamond Shamrock
Company. This is a two-coat system in which the first layer
contains, in part, zinc dust and hexavalent chromium while
the second layer is a formable and weldable zinc-rich
primer. Each of the layers is applied to steel on a coil
roller-coating machine at speeds up to 500 feet per minute
and the coatings are baked after each application.

The Zincrometal® has excellent corrosion resistance,
formability, and weldability. It can be formed to the
rupture strength of the steel, can be deep drawn, and meets
the automotive standards for spot welding. However, it
cannot be used in acid or strong organic solvent atmospheres
and is limited to applications where ambient temperatures do
not exceed 500 °F (Smith 1976). The protection of cut edges
would not be as good as galvanized steel. It is supplied as
a precoated coil or sheet steel and usually is painted after
forming.

Present U.S. capacity is about 1 million tons per year.
Lead time on additional coil coating machines to increase
capacity by about 400,000 tons per year would be 18 months.

Aluminum coatings on steel can be applied in many ways, the most common of which are hot dipping (both continuous and batch) spray coating, and pack diffusion. To some extent, their uses depend on the method of application.

Hot dipped aluminum coated steel can be divided into two general categories. The first type, without special diffusion of the iron-aluminum interface, resists atmospheric corrosion very well and has good formability. The second type, with diffused interface, withstands high temperatures. Both of these coatings are bright and have the appearance and properties of pure aluminum. The high-temperature coating shows no discoloration at temperatures up to 900 °F and provides resistance to heat scaling up to 1,250 °F. Formability gets progressively poorer as the diffusion layer thickens. The heat required for aluminizing is much higher than that for galvanizing.

The pack diffusion process usually employs an aluminum powder, a ceramic phase, and a volatile halide. These materials are packed into a retort and held at temperatures of 1,500 to 1,800 °F for 6 to 24 hours. In this process, the entire coating is a diffusion alloy and no pure aluminum layer forms. These coatings depend on the diffusion alloy for resistance to oxidation, scale formation and abrasion, and for high hardness.

Sprayed aluminum coatings are obtained by melting aluminum wire, atomizing the droplets, and propelling them against the surface to be coated. The spray of droplets is cooled during transfer and the partially oxidized particles flatten on impact to make a coating with a density of 85 to 90 percent of theoretical and an oxide content of 0.5 to 3 percent. Thicker coatings are required to eliminate pores. The work then is heat treated to form a good bond with the base metal. Various sealers may be used to improve heat resistance. For protection from atmospheric corrosion, the aluminum thickness should be 5 to 12 mils. This type of coating has been used, for example, on automobile exhaust poppet valves because of its resistance to high temperature and sulfur dioxide fumes. Welding of aluminized steel causes a loss of ductility and corrosion resistance in the weld due to the formation of iron-aluminum alloys.

In March 1976, aluminum coated sheet steel was quoted at \$17.15 to \$17.20 per 100 pounds as compared to galvanized steel quoted at \$15.40 to \$16.20 per 100 pounds (Mock 1976). It is estimated that steel tubing and pipe coated by pack cementation will cost between two to three times as much as uncoated.

The U.S. capacity for aluminum coated sheet steel is estimated as 455,000 tons in 1972, 624,000 tons in 1973, and 657,000 tons in 1974. About 100,000 tons of excess capacity are believed to exist, but requirements appreciably above this amount would necessitate a new plant and two to three years lead time. Data on the capacity for pack diffusion and spray coatings were not obtained, but the estimated lead time to increase pack diffusion capacity markedly would be two to three years. The substitution of aluminum coated products for stainless steel could increase aluminum usage appreciably and cause an aluminum shortage.

6.2.6.2 Plated Coatings as Substitutes for Chromium-Containing Alloys

The wide range of stainless steel end uses and the different properties that each end use requires discourage quantifying the extent to which candidate coating systems may be substituted. Where chromium alloys are used for their mass properties, plated coatings offer no prospect for satisfactory substitution since a coating alters only the surface properties of a material and not its massive properties.

Where stainless steels and other chromium alloys are used for their corrosion-, heat- or wear-resisting properties, plated coatings may be considered for many applications. Substitutability depends on the criticality of the end use, the ability to inspect, and the type of exposure to which the component will be subjected. The limitation of plated coatings must be recognized in attempting to substitute them for solid stainless steel or other corrosion-resisting alloys.

Unless plated coatings are essentially nonporous, corrosion can be initiated through the pores. In such cases, the following electrochemical relationships between the coating and the substrate must be considered:

1. If the coating is less noble (more active electrochemically) than the substrate, protection will continue in spite of pores until the coating is corroded away. Such coatings on steel are limited practically to zinc and cadmium. Zinc is cheap, easily plated, and widely used. Its properties are so well known that zinc-coated steel (galvanized, either hot or electrolytic) would be used already if it were a satisfactory substitute for stainless steel. Cadmium is expensive and poisonous, and its supply is relatively inelastic since it is a by-product of the mining of other metals, particularly zinc. It

is used extensively by the aircraft industry and, if it were a satisfactory substitute for a specific stainless steel application, it already would be used.

2. If the coating is more noble (less active electrochemically) than the substrate, corrosion would be aggravated by a porous coating. Nickel, copper, and chromium are in this category. These coatings can be produced in a nonporous condition if they are relatively thick, cost is no object, and various precautions can be taken. Plated coatings can be inspected for porosity if the application is critical.

Another limitation of plated coatings also must be considered: Without special anode configurations, plated coatings do not "throw" (deposit) well into recesses, blind holes, small internal angles, and similar configurations. The design of the article itself may determine whether electroplated coatings can substitute for stainless steel in applications requiring corrosion resistance.

"Electroless" or autocatalytic plating does not suffer from this last defect. Its "throwing power" is essentially unlimited so that heavy, nonporous coatings may be produced. Currently, the only relevant metal is nickel and its alloy with phosphorus and boron. These coatings could be considered in corrosion and wear applications, and their corrosion resistance is good in many environments. The limitation is mainly cost. Nickel is more costly than chromium and the plating process itself uses very expensive chemicals (Safranek 1974).

Many attempts have been made to plate various chromium-nickel alloys. None has proceeded beyond the laboratory "beaker" stage and no breakthrough is in sight (Chisholm 1968, Bazzard 1972). On the whole, the substitution of plated coatings for solid stainless steel does not promise chromium savings. Each end use should be considered on a case-by-case basis because few generalizations seem possible.

6.2.6.3 Coated Plastics and Polymer-Coated Steel

Coated plastics may be used as replacements for either chromium-plated parts or stainless steel in many decorative applications. The coating, in this case, serves mainly as an aesthetic function. A number of processes (vacuum metallizing, electroplating, painting with argent paint, chemical vapor deposition, adhesive bonding of thin metal films) can be used to obtain a bright, metallic appearance

(see appendix J). These coatings differ from one another in factors such as durability, corrosion resistance, appearance, and cost. They all share one characteristic -- relatively poor scratch and abrasion resistance -- and coated plastics intrinsically are not as strong as metals.

In some specific applications where stainless steel is used because of its corrosion resistance, coated plastics or polymer-coated mild steel may be acceptable substitutes. Neither coated plastics nor polymer-coated steel are suitable for high-temperature applications since current high-temperature plastics and other polymers are expensive, unavailable, or too difficult to use to be of general practical applicability. Another limitation of polymer-coated steel is that, in general, its corrosion resistance is inferior to that of stainless steel; moreover, the polymer coating may be degraded by exposure to solvents or to sunlight. Because of these and similar considerations, the substitutability of chromium plating and stainless steel by coated plastics and polymer-coated steel must be examined in terms of the specific conditions of each application.

The use of chromium in applications such as automotive trim and household hardware is based mainly on appearance without any stringent functional requirements. In this case, many substitutes are available. Appendix K examines these uses in detail in the case of automotive trim. The conclusion is that substitutes are available for all automotive applications in which chromium is used for appearance.

Similar substitutions are possible for many household items such as chromium plated door knobs, bright mirror frames and light fixtures, but the problems are more complex for many other household appliances. For instance, most kitchen utensils must resist frequent scrubbing, the use of aggressive cleaning agents, and, in some cases, heating. Most polymeric materials are not suitable for these uses. Either enameled steel or corrosion-resisting metals such as silver, copper, and brass may be used in many of these cases. If the bright appearance is not needed and the temperature of use is moderate, it may be possible to use rubber- or vinyl-coated steel. These coatings are relatively abrasion resisting and have found acceptance in uses such as dish drainers, trays for dishwashers, and refrigerator components.

Stainless steel products are used generally in applications involving the corrosive environments of chemical equipment such as stainless steel pipes, valves, and pumps. If the temperature of use is sufficiently low, polymer-coated steel may be used in most of these cases even

though its durability usually is greatly inferior to that of stainless steel. The types of coatings that may be used depend on conditions. For instance, most thermoplastics soften above 200 °F and are not satisfactory above this temperature. Moreover, most thermoplastics are attacked to some extent by solvents. Thermosets have greater resistance both to temperature and solvents, but thermoset-coated steel cannot be deformed appreciably without cracking the coating. Thermosets are suitable only when they can be applied to the finished part. Cleanliness is more difficult to achieve with coated steel since the coating often absorbs contaminants and vigorous cleaning procedures may be unacceptable because of the limited resistance of the coating to scouring, heating, and chemical cleansing (e.g., polymer-coated steel would be greatly inferior to stainless steel in such applications as milk tanker trucks).

6.2.6.4   Ceramic Coatings as Replacement for Stainless Steel

The stainless steel used for domestic appliances and plumbing fixtures often can be replaced by porcelain-enamel-coated steel or cast iron. Enamel coatings containing little or no chromium are quite attractive to the consumer because of their wide color spectrum, corrosion and abrasion resistance, ready cleansability, and modest cost. Their principal disadvantage is their susceptibility to chipping. Except for highly stressed parts or those subject to impact loads, enameled steels could substitute for stainless in most applications in the above classes.

6.2.6.5   Titanium and Titanium-Clad Metals

Titanium is really two separate products -- titanium metal and titanium oxide. The metal is used widely by the aerospace industry (Brooks 1965, U.S. Bureau of Mines 1970, Aviation Week 1976). The oxide is used as a pigment by the paint and plastic industries and as a paper coating. About 5 percent of the titanium is used as metal while 95 percent of U.S. consumption is used as pigment (Committee on International Economic Policy 1974).

Titanium and its alloys are noted primarily for outstanding strength-to-weight and stiffness-to-weight ratios, good fatigue strength, toughness, and good cryogenic properties. It is more inert than aluminum and has better corrosion resistance to sea water and marine atmospheres than stainless steel. It is highly resistant to chloride ion attack (Materials Engineering 1974). Commercially pure titanium is available in wrought mill forms, castings, and powder (Modern Metals 1975). It is used for aircraft skins and components, commercial heat exchangers, marine

components, and chemical processing equipment. Titanium alloys are produced by melting in vacuum or inert gas and are used primarily in aerospace applications where a high strength-to-weight ratio is essential (Aviation Week 1976).

Titanium is produced from titanium oxide (rutile) by the Kroll process (National Materials Advisory Board 1974). A lower grade but more plentiful ore, ilmenite, is usable for pigment production but requires costly beneficiation for metal production (Committee on International Economic Policy 1974, U.S. Bureau of Mines 1970).

U.S. demand for titanium in 1975 was 35 million pounds of which 25 percent was imported. Total productive capacity of U.S. titanium producers is estimated at 35 million pounds annually (Modern Metals 1975). Demand by 1980 is expected to rise to 50 million pounds, including 20 million pounds in nonaerospace applications. With the abortion of the B-1 bomber program, total demand will be much lower (Aviation Week 1976).

Titanium is an expensive metal compared to stainless steel. Ingot prices are about $6 per pound with sheet and strip running up to $15 per pound. Serious consideration of titanium as an emergency substitute for stainless steel must await resolution of several negative factors:

1. High cost relative to stainless steel

2. Limited domestic productive capacity

3. High cost and long lead times of new productive capacity

4. Limited world reserves of titanium ore, particularly rutile

5. No domestic reserves of rutile although ilmenite is available in the United States.

Titanium probably could be most effective when used as a thin overlay or cladding on a base material such as aluminum or carbon steel. Such clad materials have been made by roll-bonding and explosion bonding. Using as little as 10 percent of titanium in the composite is feasible (Smith 1976). With satisfactory edge protection, such composites might find application in chemical processing equipment where longer service life and freedom from maintenance and downtime would justify a premium price. Typical end uses might be in acid recovery, copper refining, paper and pulp processing, petroleum refining, chemical heat

exchangers, desalination, and sewage treatment (Modern Metals September 1975).

Many of the problems associated with titanium technology must be solved if titanium-clad materials are to be accepted. These composites are difficult to fabricate and to provide with adequate edge protection. Titanium is highly reactive and has a low tolerance for contamination (Sayre and Chang 1975). Commercially pure titanium can be considered as several distinct alloys with selected ranges of tramp or residual elements. Control of the identity and concentration of these residuals is difficult and costly but essential for the titanium producer (Smith 1976). Temperatures above 700 °F must be avoided because of possible creep and stress-corrosion problems. Titanium sheet and strip also exhibit variance in texture and microstructure that can affect fatigue strength and corrosion resistance adversely.

6.2.6.6   Tantalum and Tantalum-Clad Metals

Tantalum has long been an attractive material because it is less active chemically than any other metal, has the corrosion-resisting properties of glass, and is particularly resistant to most acids. It is ductile but tends to gall, seize, and tear unless care is taken in fabrication. Because it does not work-harden rapidly, it can be deep-drawn readily (Emerson 1975).

Tantalum retains its strength and undiminished corrosion resistance up to about 400 °F. Above that temperature, surface coatings are required in strongly oxidizing environments. Tantalum must be cold-worked since it absorbs gases (particularly oxygen) when hot, resulting in embrittlement (U.S. Bureau of Mines 1970).

Up to the present, the United States has been almost entirely dependent on foreign sources for raw tantalum. Unless new sources materialize, tantalum shortages beyond 1977 could lead to explosive price increases (Emerson 1976). Much of the primary tantalum production comes from developing countries so that political considerations are important.

U.S. consumption of tantalum in 1974 was as follows (Emerson 1976):

Use	Consumption (pounds)
Electronics	1,000,000
Structural	300,000
Cutting Tools	240,000
Alloys	6,000

Tantalum is an expensive metal (Brooks 1965). The price of tantalite in 1974 was $12 to $15 per pound and that of tantalum metal was $48 to $115 per pound depending on product form.

The major uses of tantalum are in applications where its unique properties provide a distinct cost and performance or cost and service-life-cycle advantage. By far, the largest use is in tantalum capacitors for the electronics industry.

The excellent welding and fabricating characteristics of tantalum make it an economical liner material for chemical process towers, large acid-handling valves, nuclear reactor tubing, and other applications where long service life and freedom from downtime and maintenance are vitally important. Recent improvements in process technology have been vitally important and have led to tantalum sheet flat enough for bonding to carbon steel by an explosive-bonding process (Jenstrom and Schussler 1974). Such tantalum-clad materials should provide a higher quality, lower cost alternative to solid tantalum or tantalum liners in the applications listed above. In an emergency, the tantalum-clad material could replace stainless steel in critical applications at a severe cost penalty but with no degradation in performance.

6.3 EVALUATION

The unique properties, low cost, and plentiful supply of chromium-containing materials have, over the years, made important segments of U.S. industry virtually dependent on the continued availability of these materials. These same factors almost inhibited both research on possible substitutes for chromium and serious efforts to conserve, reclaim, or recycle chromium-containing materials. Apparently, a drastic curtailment of this availability would have serious consequences -- some short-term but others more far reaching. It is instructive to consider the implications of such an event for the United States. Assuming that all of the conclusions of this report are valid and that all the alternative actions proposed are

accepted and implemented, what would be the foreseeable impacts on the United States?

6.3.1 Effects on Industry and Technology

Some industries will be affected slightly by drastically reduced availability of chromium and strong efforts to conserve it. Examples are:

Industry	Use
Tool steels	Metal cutting and forming
Superalloys	Jet engines, gas turbines
Chromium chemicals	Water treatment and leather tanning

This result is expected since chromium is essentially irreplaceable for these applications and the total amounts are small compared to all U.S. consumption. Hence, the available chromium will be allocated preferentially to these end uses.

Some industries will benefit by the drastically reduced availability of chromium and strong efforts to conserve it. Examples are manufacturers of alternative substitute materials such as titanium, tantalum, aluminum, zinc, plastics, porcelain enamel coatings, and metal paints. A lack of chromium because of high prices or government taxes to restrain the use of the material and to enforce its recycling will encourage strongly the use of substitute materials whenever possible. The industries listed above are examples of those that might benefit by recapture of old markets previously lost to chromium-containing materials or by the creation of new ones. Since no one alternative material possibly could substitute across-the-board, the impact of any given alternative would be modest but always positive.

Other industries likely to benefit are those associated with recycling efforts. Examples are:

Industry	Application
Scrap sorting	Metals
Crushing and grinding	Refractories and foundry sands
Chemical processing	Chemical wastes and effluents
Beneficiation	Stock-piled material and low-grade ore

An immediate demand to use state-of-the-art equipment and technology in the above applications can be predicted as

well as incentives to develop more efficient and less costly new processes.

Other industries likely to benefit are associated with the production of clad and coated materials and their subsequent testing and processing. In the event of a requirement to reduce chromium demand substantially, the use of stainless clads and coatings applied to less corrosion- and oxidation-resisting materials will increase. Widespread adoption of this approach would require both new technology and increased productive capacity. More importantly, demand would arise for equipment capable of forming, joining and edge-sealing such composite materials. New nondestructive testing equipment would be required to assure the integrity of the protective surface layer after initial production and after subsequent in-plant processing.

A number of industries will be affected unfavorably by drastically reduced availability of chromium and strong efforts to conserve it. Examples are:

Industry	Use
Refractories	Steel producers and foundries
Nonferrous alloys	Broad spectrum of users
Stainless steels	Fabricated metals, machinery other than electrical, transportation
Alloy steels	Primary metals, machinery other than electrical, fabricated metals

Refractory manufacturers and nonferrous alloy producers would not be affected over the long term because little or no loss of markets would be anticipated. A period of intensive research and development is required to achieve the products and processing technology for chromium-free or low-chromium materials. The same is true to a somewhat lesser extent with the alloy steel producers and users who would have new and possibly more costly alloys to reduce their chromium demand. The greatest impact would be on stainless steel producers and users because the opportunity to apply or develop low-chromium stainless alloys is limited. In a truly drastic supply situation, it will be necessary to live with less stainless steel. While the consequences for some user industries would be modest or only economic in nature, the effects would be devastating for others, such as the nuclear power industry. Long-range

(greater than 15 years) research would be required with no
identifiable substitutes in sight.

6.3.2   Effects on the Economy

It seems certain that all innovations to reduce
chromium consumption will involve substantial costs and some
sacrifice in service performance. These added costs can
arise in several ways -- from more complex designs, from
additional processing steps, from additional testing, or
from more expensive substitute materials that do not contain
chromium. For example, painted steel has been proposed as a
substitute for stainless steel in some applications. For
many paints, however, chromium chemicals are essential
ingredients so that increasing their use to combat corrosion
and extend product life will cause an increase in chromium
demand, at least partially offsetting the savings generated
by using less stainless steel.

Another example of the almost mandatory use of
stainless steel is the manufacture of the myriad small
miscellaneous parts and fasteners used universally in the
assembly of various durable goods. The important properties
required are the outstanding corrosion resistance,
formability, high elastic modulus, and good strength
possessed almost exclusively by stainless steel. Stainless
steel is one of the most widely used materials for
combatting corrosion, the major cause of short product life
and early replacement. Assembling is a logical place to
reduce chromium demand by going to more welds, brazed
joints, locking tabs, rivets, etc., in joining operations.
Such a move, however, would frustrate the drive for chromium
conservation, which calls for a greater use of threaded
fasteners in order to improve maintainability,
repairability, and recyclability. Apparently, compromises
and trade-offs must be made everywhere to identify those end
uses where chromium-containing materials are absolutely
necessary for acceptable product life.

This report suggests many fruitful areas where research
and development could alleviate demand for chromium,
increase primary supply, or improve industry capability for
recycling. However, much of the necessary investigative
work is inappropriate to university or government
laboratories; rather, the expertise, the facilities, and the
environment of industry are required. Because much of the
work is high risk in nature or provides national insurance
against international political blackmail, substantial
government financial support may be required in the form of
direct subsidy, tax privileges, guaranteed markets, or
relaxation of regulations.

If adoption of new chromium-free or low-chromium
materials is enforced rather quickly by circumstances,
incentives will be created to settle promptly on some new
standard materials to replace older, well-known and reliable
ones. In turn, this will force much testing of new or less-
well-known materials. Although it will be urgently needed,
this type of research generally is not favored by academic
institutions.

Once the new engineering information is available for
the new materials, intensive effort will be needed to make
the potential users aware of the existence of the materials
as well as their advantages and disadvantages. Handbooks,
data banks, and other information services will be needed to
make the engineering data quickly accessible.

The maintenance of a strategic stockpile of chromium-
containing materials generally is accepted as a necessary
and effective strategy. On the other hand, the desirability
of a separate economic stockpile is a controversial subject
both in and out of Congress. It does seem, however, that an
economic stockpile could take advantage of the cyclical
nature of world industry by accumulating excess stocks of
minerals and metals when times are slack. Stockpiling would
provide some insulation for emergency conditions and allow
valuable time for the research and development necessary to
prepare for coming minerals shortages.

6.3.3   Effects on the Environment

One of the alternative actions is to press exploration
in the United States, Canada, and other friendly countries
to discover new deposits of chromium-containing materials.
Unfortunately, public opinion is largely negative to such
proposals at present. Ever-expanding production and use of
minerals in the past have been a cause of environmental
deterioration. Environmental regulations and economics have
increased the shift to foreign sources for chromite and
ferrochromium. These include:

1. Depletion of deposits mineable at low cost

2. Diminishing availability of land for exploration

3. Costly measures to protect air and water quality
    and to reclaim the land surface after mining

If pollution is regarded as waste of the polluting materials
then, over the long term, their recovery as useful material
and land may more than pay for the cost of pollution
control. If the environmental impacts of all activities in
a system (mining, processing, fabrication, manufacturing and

disposal, along with interspersed transportation steps) are measured, a system using secondary materials causes less air and water pollution, generates less solid waste, and uses less energy than a system using virgin materials. Up to now, these costs have not been identified, evaluated, and assessed against those responsible elements. At present and over the short term, the private sector has no real incentive to conserve chromium-containing materials, to recycle wastes in place of waste disposal, or to gather and recycle obsolescent scrap for reuse. Government support will be needed to reverse this trend by long-term projects aimed at:

1. Exploration for yet undiscovered resources

2. Improvement of the economics of utilizing poorer quality ores

3. Less wasteful mining, extraction, and ore cleaning

4. Efficient recycling of discarded products and materials

6.4 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.4.1 Summary

Table 50 summarizes the findings concerning substitutability. It should be noted that the assigned development times predicted assume a reasonably well-funded and well-staffed investigation. Clearly, a crash program fully supported by government and industry might achieve the desired results in much less time. On the other hand, a poorly funded and understaffed program might run indefinitely with no tangible results. In addition, only the time required to arrive at a viable technological solution to the substitution problem is estimated. Determining the time required to implement the technology is beyond the scope of this Committee and depends on economic, social, and political factors that are too complex to evaluate quantitatively.

6.4.2 Conclusions

1. Substituting other materials for chromium-containing stainless steel, tool steel, wrought alloy steel, cast iron and steel, nonferrous alloys, electroplate, refractories, and chemicals can result in a total chromium savings of 744 million pounds.

TABLE 50 Potential Savings of Chromium-Containing Materials by Substitution (million pounds)

Material Designation	Total Chromium Used	Total Chromium Saved	Time Required for Substitution				Irreplaceable Chromium[e]
			Immediately[a]	Within 5 Years[b]	5 to 10 Years[c]	At Least 10 Years[d]	
Stainless steel	569	332	203	--	129	--	237
Tool steel	7	--	--	--	--	--	7
Wrought alloy steel	123	103	22	35	46	--	20
Cast iron and steel	82	54	5	10	35	4	28
Nonferrous alloys	29	2	--	--	2	--	27
Chromium electroplate	21	17	14	3	--	--	4
Refractories	249[f]	225	110	--	115	--	24
Chromium chemicals	68	11	6	--	5	--	57
Total	1,148	744	360	48	332	4	404

NOTE: The assigned development times imply a reasonably well-funded and well-staffed investigation -- a crash program supported by government and industry might achieve desired results in much less time, while a poorly funded and under-staffed program might drag indefinitely with no tangible results. The development times estimate only the time required to arrive at a viable technological solution to the substitutability problem involved. The time required to implement the technology depends on economic, political and social factors that are too complex to evaluate in any quantitative way and are beyond the scope of this study.

[a] Amount saved by functionally acceptable chromium-free substitutes currently available. Direct or indirect cost penalties are incurred.

[b] Amount saved by functionally acceptable chromium-free substitutes provided after short development (less than 5 years) with a high probability of success. Direct or indirect cost penalties are incurred.

[c] Amount saved by functionally acceptable chromium-free substitutes provided after intermediate-term (5 to 10 years) research with a high probability of success. Direct or indirect cost penalties are incurred.

[d] Amount saved by functionally acceptable chromium-free substitutes provided after long-term (more than 10 years) research with a high probability of success. Direct or indirect cost penalties are incurred.

[e] Amount considered irreplaceable. No functionally acceptable chromium-free substitutes are identifiable. Basic research and new technology are needed.

[f] Includes refractory types not reported by the U.S. Bureau of Mines.

2. An assessment of the end-use requirements of major stainless steel categories indicates that:

    -   10 percent (about 32 million pounds of chromium) could be replaced by existing chromium-free materials without serious degradation of service performance

    -   50 percent (about 160 million pounds of chromium) might be replaced with a high probability of success after a short-term research and development effort

    -   40 percent (about 125 million pounds of chromium) are in end uses where severe service requirements prevent a major reduction in chromium content unless compensated by design or process improvements because it would result in unacceptable degradation of service performance

    Economical chromium-free substitutes are unavailable for chemical processing where corrosion or elevated temperature resistance are required. In a chromium cut-off, these applications must be supplied by allocation or abandoned until new technology is developed.

    Alternative copper- and nickel-base alloys also are subject to serious scarcities and are produced in limited quantities. Titanium and titanium-clad steels might be suitable substitutes for chemical tanks and piping where their service temperatures are relatively low. Coatings, clad materials, aluminum alloys, and plastics need more research and evaluation before qualifying as substitutes in many applications.

3. The primary contribution of chromium to wrought and cast steel is its influence on hardenability. Several other elements that influence hardenability can eliminate or reduce chromium usage but at a significant economic penalty. An assessment of the end-use requirements of wrought alloy steels indicates that:

    -   50 percent (about 64 million pounds of chromium) of the chromium now used probably could be replaced with little difficulty

- 30 percent (about 39 million pounds of chromium) more might be replaced after a short-term research and development effort

- 20 percent (about 20 million pounds of chromium) is considered irreplaceable

Opportunities for substitution are substantial in iron and steel castings where an estimated 50 million pounds of chromium could be saved. In high-alloy steel castings where chromium is essential, 32 million pounds of chromium are considered irreplaceable.

4. Chromium in tool steels is considered irreplaceable in view of the relatively small amount of chromium used (less than 1 percent of total U.S. consumption), the importance of tool steels to the national economy, and the high cost of replacement materials.

5. Although the number of nonferrous alloy compositions containing chromium is large, the amount of chromium consumed represents only about 2 to 3 percent of total U.S. consumption.

In aluminum-base, titanium-base, and copper-base alloys, chromium primarily alters phase relationships to produce specific and preferred microstructures. Although lead times of several years might be required to qualify a substitute alloy for a critical application, reducing or eliminating chromium consumption in aluminum, titanium, and copper-base alloys would not cause major difficulties.

The chromium content of nickel-base, iron-nickel-base, and cobalt-base alloys ranges from 10 to 25 percent and no other alloying elements approach conferring the same degree of oxidation and corrosion resistance. Although further research and development, especially in the areas of coatings and engineering ceramics, eventually may decrease chromium dependence, it is impossible at present to reduce chromium consumption significantly in these alloys by material substitution. For the foreseeable future, it will be necessary to ensure the availability of chromium for these alloys.

6. The largest use of chromium in ceramic products is as chromite refractories in basic steel plants and

as facing sands in steel foundries, and, to a great extent, non-critical materials may be substituted at some cost or performance penalty. About 50 percent of the chromite could be replaced with little trouble if magnesite chrome refractories were used instead of chrome or chrome magnesite refractories. The refractory industry currently is not geared to producing promising chromium-free substitutes such as spinel, fosterite, and dolomite in suitable form and quantity, and considerable research, development, and evaluation of these materials is warranted. With favorable cost incentive and chrome scarcity, the potential for salvage and reuse of chrome-bearing refractories is considerable in all consuming industries.

7. Electroplating uses about 4 percent of total U.S. chromium consumption, and the chromium chemicals used are made from chemical-grade chromite ore that generally has been unacceptable for metallurgical processing. About 60 percent of the chromium used in electroplating is for decorative applications, about 30 percent is for engineering (hard) chromium plate, and the remainder is for other metal finishing. Painted steel, aluminum, or plastic could be used to replace decorative chromium plate, resulting in an annual savings of about 14 million pounds of chromium.

A promising available substitute for hard chromium plate is electroless nickel deposition, and about 3 million pounds of chromium could be saved annually by substituting this process; however, considerable development would be necessary to provide the needed productive capacity.

More chromic acid is lost or wasted in processing than actually is deposited as chromium metal on the plated parts, and total consumption of chromium could be reduced substantially by successful recycling.

8. U.S. consumption of chromium chemicals amounts to about 100 million pounds of contained chromium annually. The primary chemical, sodium dichromate, is made from chemical grade chromite ore.

Considerable research has been done in all areas of chemical application (pigments and

paints, leather tanning, drilling muds, water treatment, and wood treatment) to find acceptable substitutes. Their substitutability status is as follows:

- **Pigments and Paints** -- In an emergency, chrome pigments could be eliminated in about half their uses, drastically reducing the producible colors and saving about 14 million pounds of chromium annually.

- **Leather Tanning** -- No practical substitute exists for chromium in tanning leather. The alternate tanning compounds are imported and require new U.S. technology to be used, besides imposing a severe cost and performance penalty. Furthermore, any wide use of leather substitutes would cause serious dislocations because of the vast number of animal hides whose only practical use is to make leather.

- **Drilling Muds** -- No known satisfactory substitutes exist for chromium lignosulfates used as mud additives for the drilling of deep oil and gas wells. Since this is a critical and strategic industry, it would not be in the national interest to attempt chromium savings in this application.

- **Water Treatment** -- Corrosion-inhibiting chromium compounds are used widely for water treatment by petrochemical plants and oil refineries. No satisfactory substitutes are known for water treatments over 150 °F. The relatively low chromium usage and the economic importance of this end use make it inadvisable to attempt chromium savings.

- **Wood Treatment** -- A relatively small amount of chromium chemicals is used for wood treatment and preservation. While the use of known substitutes would result in a loss of paintability, chromium savings of about 6 million pounds annually could be made without serious trouble.

6.4.3 Recommendations

1. Incentives and penalties should be considered to stimulate the design of high-chromium-content

products in a manner that makes them readily identifiable for disassembly and recycling.

2. Research should be accelerated to develop surface coatings with better high-temperature corrosion and oxidation resistance, including very thin coatings high in chromium.

3. Programs should be expedited for the development of stainless steels of lower chromium content (alloyed with aluminum, titanium, and silicon) that might be substituted for many current stainless steel applications.

4. Low-alloy, chromium-free steel compositions should be developed and tested to replace steels where chromium is used mainly for its hardenability characteristics.

5. Economic incentives should be created to spur the development and use of lower chromium or chromium-free refractories.

6. Further research should be undertaken to develop economic chromium-free water treatment compounds.

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Appendix A

STEEL SELECTION
BY HARDENABILITY AND ALLOY ELEMENTS

Computer harmonized (CH) steels are designed to meet one of three objectives: (1) to provide a special steel that meets a component's application tailored (AT) requirements -- quantitative metallurgical requirements, (2) to aid in the selection of the most economical standard steel that meets a component's AT requirements, or (3) to develop replacements for standard AISI H steels. The use of computer harmonizing to achieve the first or second objective depends on whether the tonnage or other requirements of the component justify a special steel (e.g., if the component under consideration is a low-tonnage item, the engineer may lean toward a standard steel that will be readily available from a steel mill or warehouse). Using computer harmonizing to achieve the third objective provides a systematic method for devising chemical compositions for replacement steels that match the base and case hardenability and other characteristics of the original steel.

In each instance, the resulting CH steel has a chemical composition that is optimized with respect to the cost of alloying elements and, generally, the steel has an optimum price in terms of its "chemistry grade extra," as covered in the steel product price book. The difference between cost and price in this context must be understood; there is not always a one-to-one correspondence between the two although a close correlation does exist.

The need for using a computer approach to develop a least-cost steel is apparent when the various aspects of the problem are considered. A least-cost steel that must meet only a specified D_{Ib} (base composition) value could be designed fairly easily by a manual method with tables (or nomographs) containing alloy costs and hardenability multiplying factors. When a carburizing grade is designed, however, at least one additional restriction, a minimum D_{Ib} value, is added to the problem. Because hardenability factors for the individual alloying elements are different for the case and the base composition, a steel designed to have a least-cost base composition most likely would not satisfy the D_{Ic} (case composition) requirement. If further restrictions such as the martensite start temperature (M_S) of the case and base analyses are added, the least-cost combination of alloying elements to satisfy the multiple requirements becomes impossible to find manually. Because

of the multiple restrictions discussed below, the problem of cost optimization requires separate programming techniques.

The CH procedure is designed to optimize one property while simultaneously satisfying multiple restriction. Described here is the Computer Harmonized Application Tailored (CHAT) system which determines the least costly alloy combination that will satisfy specified values for D_{Ib}, D_{Ic}, and M_S (martensite starting). Other properties can be optimized and other restrictions added, provided all features can be expressed as quantitative functions of the chemical element. Working with hardenability and M_S temperatures as a basis, the CH process solves the least-cost alloy problem by using a modified linear programming technique known as separable programming.

Shortcomings of the CHAT system (e.g., using a multiplier for boron, residual stress effects, and grain size) do not detract from its utility but simply indicate that it is not a panacea. As is the situation for many useful tools, the system should be manipulated and applied with discretion, utilizing all available technology as a base.

In addition to these prime engineering and cost aspects, definition of the CHAT system creates an awareness of the explicit definition of a steel. A steel cannot be defined using a simple single analysis as might be implied by the standard numbering system and as is assumed by many design engineers. Instead, a large, finite number of analyses having quantifiable statistical characteristics, in terms of items such as base and case hardenability, is required. This comprehension by designers as to what comprises a steel is an important link in a viable, flexible materials engineering activity.

The principle of optimum steel usage has never been ignored completely by the maker of machine parts and assemblies although it has been relegated at times to a subordinate role when profits are good and the climate for change is unfavorable. This climate is complex and is influenced by the personality of the final decision maker.

As shown in Figure A-1, many metallurgical developments of alloy steels stem from national or international crises (Breen et al. 1973) and are not necessarily favorable to the metallurgical community. With the knowledge that history repeats itself, an acceptable system for changing from one alloy system to another certainly would be useful in the future. Perhaps heat-treatable steels will be defined in the future essentially in terms of their response to heat treating rather than composition, and then periodic
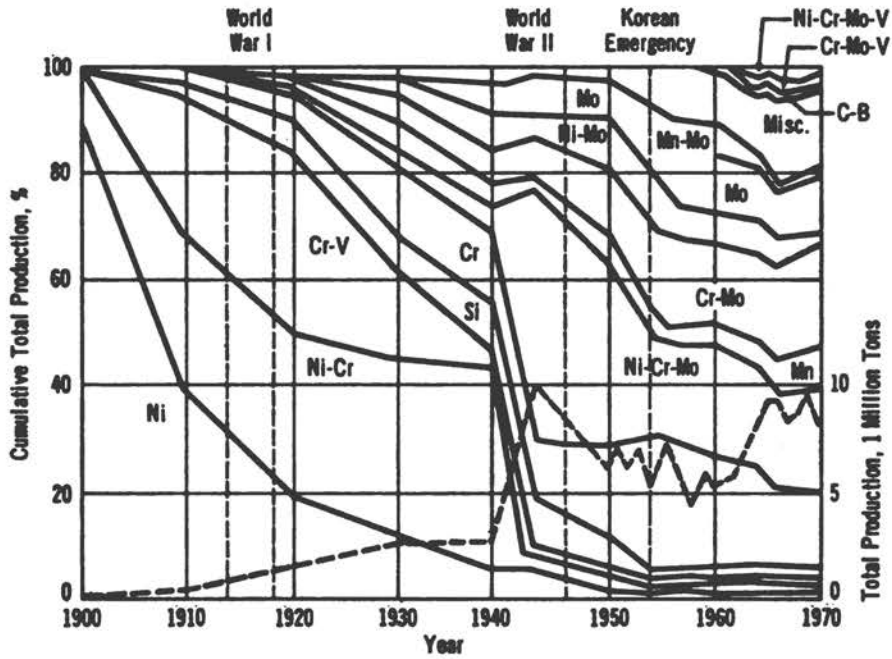
FIGURE A-1 History of Alloy Steel Usage (Smith 1963)

NOTE: Since 1900, the pattern of alloy steel usage
has changed greatly. The dotted line indicates
alloy steel production.

adjustments in alloy content could be made unhesitatingly, taking immediate advantage of changing alloy costs or availability.

The strategic alloy problem has become the subject of much discussion given the fact that the nation's dependence on foreign ores could be an important factor in future international relationships. A weak link principle has been described in which an advantage could be gained by a potential enemy who subtly promoted dependence on a strategic alloy import that would require alternate approaches during a war (Sutton 1969). Having well known, established principles could influence reaction time considerably if the need for change arose.

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Appendix B

CHROMIUM CONTENT
IN CARS, TRUCKS, BUSES, AND TRUCK TRAILERS

The traditional chromium uses in cars include decorative and functional stainless steel, alloy in steel and cast iron, and chromium plate. The average 1976 car, weighing 3,750 pounds, contains approximately 6.75 pounds of chromium in the above categories as shown in Table B-1 (presentation to the Committee by J. LaBelle, General Motors Corporation, July 1976). This 6.75 pounds includes 2.59 pounds of chromium in the catalytic converter and its accessories.

From 1972 to 1975, total truck and bus production was about 1/3 of that for passenger cars. Fifty-two percent of these trucks and buses weighed under 6,000 pounds (gross) and therefore would require a catalytic converter similar to that in passenger cars (see Table B-2). None of the remainder had the catalytic converter. Without the catalytic converter the average truck would contain significantly less chromium than the average passenger car. In some exceptional cases, the chromium content of buses and truck trailers greatly exceeds that of passenger cars.[1] Also, a significant number of heavy-duty trucks, which constitute only 4 percent of the total truck population, have large quantities of external decorative and functional stainless steel, much of which is optional equipment. In considering the large assortment of ways in which chromium is used in the total truck, bus, and trailer industries, the passenger car figure of 6.75 pounds per vehicle could be used as a reasonable estimate of the chromium content in heavy trucks and buses if the chromium used in truck trailers also is included. In this appendix, the total population of cars, trucks, and buses, as well as the annual production, will be considered to have 6.75 pounds per vehicle for the year 1976 and to be subject to the same changes as passenger cars in the event of an emergency. After 1980, heavy-duty diesels are expected to average 5.48 pounds of chromium, but all other diesels are expected to average 4.33 pounds.

The automotive industry in its processing generates large volumes of recyclable metal scrap and takes elaborate precautions to properly isolate and collect this useful chromium-containing scrap. This segregation of chromium-containing material includes the offal from stainless steel stamping operations (sold to stainless steel mills), forging offal, and iron and steel turnings as well as scrap parts (sold to the foundries producing automotive castings). In

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TABLE B-1 Chromium Usage in U.S.-Built Passenger Cars Powered by Conventional Otto Cycle Piston Engines (pounds)

	Actual Typical 1975 Full-Size Car (4,450 lb)	Estimated Average U.S. 1976 Car (3,750 lb)	Projected Average U.S. 1980 Car (3,000 lb)
Propulsion System			
Cylinder block, head, camshaft, valves	1.277	1.077	0.860
Cooling system	0.017	0.014	0.011
Electrical system	0.007	0.006	0.005
Carburetor, air intake, exhaust	0.118	0.099	0.079
Catalytic converter	3.335	2.587	2.070
Transmission (automatic)	0.169	0.142	0.114
Propulsion shaft, rear axle, differential	0.061	0.051	0.041
Subtotal	4.984	3.976	3.180
Chassis			
Deluxe wheel covers	1.440	1.214	0.971
Front suspension	0.250	0.211	0.169
Brakes	0.047	0.040	0.032
Steering gear	0.019	0.016	0.013
Steering wheel	0.028	0.024	0.019
Rear suspension	0.136	0.115	0.092
Lights	0.071	0.060	0.048
Miscellaneous	0.067	0.056	0.045
Subtotal	2.058	1.736	1,389
Body			
Windshield wipers	0.265	0.265	0.265
Seat belts	0.355	0.355	0.355
Windshield lower molding	0.276	0.069[a]	--
Roof drip moldings	0.203	0.171	0.137
Door window moldings	0.155	0.131	0.105
Chromium plate	0.060	0.051	0.041
Subtotal	1.314	1.042	0.903
Total chromium per car	8.356	6.754	5.472
Total without catalytic converter	5.766	4.764	3.402

[a] Used on an estimated 25 percent of total production.

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TABLE B-2 U.S. Production of Passenger Cars, Buses, and Trucks, 1972-1975

Year	Cars	Total Buses and Trucks	Total Vehicles	Ratio of Total Vehicles to Cars	Light Trucks under 6,000 lb[a]
1972	8,823,938	2,482,503	11,067,095	1.29	1,414,551
1973	9,884,446	3,014,361	12,898,807	1.30	1,735,645
1974	7,324,504	2,746,538	10,071,042	1.37	--
1975	6,717,177	2,266,567	8,983,774	1.34	897,292
Total	32,510,719	10,509,969	43,020,688	1.32	--

NOTE: Derived from data from Jet Propulsion Laboratory 1974 and Automotive Industries 1976.

[a] Ratio of light trucks to total buses and trucks in 1972, 1973, and 1975 is 0.52.

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some cases, such foundries are part of the same company or division. One General Motors' foundry, which casts cylinder heads, blocks and camshafts, obtains about 80 percent of its chromium (typical for the industry) from a combination of chromium-containing steel and iron turnings from its own returns.[1] Therefore, the chromium content of production-generated scrap should not be added to the chromium content of a vehicle as additional usage.

Recycling junk cars has not been extensive until recently. Economic conditions have increased the scrap value, and new salvaging equipment and methods have improved the situation. A shredder of scrap car bodies, for example, can produce 1 ton of metal per minute. However, the amount of chromium-containing alloys that is recovered and used in similar chromium alloys from these operations is questionable. One installation handling large volumes of scrap cars is recovering nonmagnetic stainless steel of enough value to pay for the cost of separation. No other chromium-containing alloy is recovered from scrap cars and identified as such. Magnetic stainless is shredded along with steel sheet and sold only as shredded car body steel. Cylinder blocks are sold without publicizing the chromium content; however, some foundries use the chromium content beneficially. While actual figures are unavailable, an estimated 1 pound of chromium is recovered beneficially from each of the 8 million cars scrapped per year. In an emergency, methods for recovering a total of 3 pounds per car should be possible. Both catalytic converters and deluxe wheel covers are identifiable and recoverable under economic and emergency stimulation.

Service parts used to repair vehicles in the field are supplied by new vehicle manufacturers and many after-market suppliers. Actual chromium consumption has been calculated at 0.023 pounds per year per car in operation (Harvey and Menchen 1974). Since the discarded parts have a high content of exhaust valves, camshafts and cylinder blocks, and head castings, they are not converted as readily into comparable chromium-bearing products as the decorative trim on passenger cars.

The Clean Air Energy Acts have changed automobile design significantly and can have an important effect on future chromium consumption. As a result of the Energy Act, cars will be lighter and engines smaller. The Clean Air Act has an important effect on the specific kind of engine that may be used and may result in substantially more chromium being used. Currently, however, it does not appear that any alternate engine can replace the conventional Otto type. It is estimated that 500,000 urban cars per year will be powered by batteries by the early 1980's. Appraisals of

each of the proposed power plants including the rotary, Rankine, Brayton and Stirling are presented in Lists B-1 through B-7.

Table B-3 forecasts gains in diesel and electric vehicles starting in 1980. The diesel is expected to be used in small trucks and large cars; now uncommon applications for U.S. manufacturers. Their efficiency should allow the 1985 energy standards to be met by larger cars and their better fuel economics favor their use in both light and medium trucks, which constitute the bulk of the truck market. In all likelihood, the passenger car diesel will handle the light trucks while something heavier will take over at about 10,000 pounds gross vehicle weight. By the year 2000, the forecast assumes total production of 18 million vehicles of which 13.3 million will be Otto powered, 4 million will be diesel powered, and 0.7 million will be electric powered.

The forecast of chromium usage by the automotive industry and the action that can be taken in an emergency has two parts. Table B-4 shows vehicle parts requiring chromium until alternates are developed. Table B-5 shows the changes in chromium content per car that are almost immediately possible in an emergency and the means for achieving them. The details of such changes are covered in chapter 6.

From a design standpoint, deluxe stainless steel wheel covers, regular stainless or aluminum hub caps, and chromium-plated acorn-capped nuts all provide equal protection for the wheel stud threads. They are required to prevent thread damage so the wheels can be removed. In some cases, special cast aluminum or magnesium wheels with special nuts are considered more decorative than the deluxe wheel covers. The least expensive system is either the aluminum hub caps or the acorn nuts.

About 80 percent of the 85 million cars in service are believed to have the deluxe wheel covers that have about 8 pounds of stainless steel per car. The stainless is either AISI Type 302 or 434. Assuming 17.5 percent chromium, the total chromium content is 47,600 tons in the deluxe wheel covers of cars presently in service. From a conservation standpoint, the most unique thing about them is their easy retrievability and replaceability in an emergency chromium shortage; if the industry substitutes something else for the deluxe stainless steel covers, this reserve supply of chromium might not exist in an emergency.

Another design change, already effected on some cars, involves the lower windshield molding. In some cars with a

LIST B-1 Characteristics of the Piston Otto Engine

Current Status
  Dominates market.

Advantages
  Least expensive combustion engine; best performance; good durability; good fuel consumption;
  least development required to achieve realistic energy and emission goals.

Disadvantages
  Higher fuel consumption than diesel or Stirling; higher emission levels with converter than
  Brayton, Stirling, battery electric, or Rankine.

Future
  A version of the piston Otto probably will continue as the dominant engine for the foreseeable
  future. Some engine design concepts will improve emissions, fuel economy, or both. Among these
  are: stratified charge -- lean fuel/air ratio, fuel injection, smaller engine -- automatic
  four-speed transmission with positive lockup, wide distillation range fuel capability, and
  electronically controlled spark timing. Actual direction depends on whether or not emission
  standards are frozen at the 1976 level to optimize fuel economy. No version of the Otto
  presently can meet the 0.40 grams/mile NO_x limit mandated for 1978.

Chromium Usage (lb per total car)
  Not expected to be significantly effected by above options. Chromium usage for normal and
  emergency conditions in 1976 and projected for 1980-2000 is:

Condition	1976 (3,750 lb per Average car) With Catalytic Converter	1980-2000 (3,000 lb per Average Car)	
		With Catalytic Converter	Without Catalytic Converter
Normal	6.75	5.48	3.41
Emergency	3.08	2.46	0.39

LIST B-2   Characteristics of the Rotary Otto Engine

Current Status
  Limited usage in some Japanese and European cars. No present or contemplated U.S. production.

Advantages
  Light weight; compact size; good performance.

Disadvantages
  Higher fuel consumption, emissions, and cost than piston Otto engine. Durability still questionable.

Future
  Not expected to reach production stage in United States.

Chromium Usage (lb per total car)
  No usage is predicted for 1980. Chromium usage for 1976 follows:

Condition	1976 3,750 lb per Average Car With Catalytic Converter
Normal	6.45*
Emergency	2.80*

  * Estimate only, based on experimental information.

LIST B-3 Characteristics of the Piston Diesel Engine

Current Status
  Limited production of foreign cars. Extensive usage in U.S. and foreign trucks. General Motors anticipates U.S. production in about 1978.

Advantages
  Best fuel consumption of any developed and in-production engine; excellent durability; good emission control without converter.

Disadvantages
  Heavier, more costly, and noisier than Otto engine.

Future
  A diesel designed for maximum efficiency may achieve 50 percent more miles per gallon of fuel than an Otto engine. This would mean saving about $10 per 1,000 miles if the fuel cost is $0.60 per gallon and the car achieves 20 miles per gallon with the Otto engine. If the diesel costs $500 more than the Otto, the payback on a straight cost basis would require 50,000 miles. For $1.00 per gallon fuel, the period is 30,000 miles. The diesel future is obviously dependent on the actual engine cost differential, the cost of fuel, and government-mandated fuel consumption and exhaust emission control requirements. Much greater use in lighter trucks and heavier passenger cars is forecast.

Chromium Usage (lb per total car)
  Chromium usage predicted for 1980 for normal and emergency conditions is:

Condition	1980 3,000 lb Car Without Catalytic Converter
Normal	3.83
Emergency	0.39

Current Status

Some minor use for lightweight, limited-range transportation to combat air pollution and noise. Batteries are lead acid, recharged on off-peak hours.

Advantages

Minimum air and noise pollution at point of use. No power consumption in propulsion unit when vehicle is stopped. Multifuel capability since commercial power generating stations are power source.

Disadvantages

Low energy and power density in lead acid battery type seriously limits performance and range. No viable alternate battery exists at present. Car heating and other similar devices might require added nonelectrical heat source.

Future

The use of lead acid battery powered utility vehicles is expected to increase in short-range urban usage as an alternate to a second conventional family car. No prediction is possible on alternate battery development. Containment of the sodium-sulfur or lithium-sulfur elevated temperature types is unsolved but expected to require at least 15 percent chromium. About 500,000 vehicles per year are possible with either lead acid or more advanced batteries. Battery charging is possible in off-peak hours with no added power generation equipment. Recent Congressional action advocating battery research could have an upward effect on the usage numbers.

Chromium Usage (lb per total car)

Chromium usage for normal and emergency conditions is:

Condition	Lead-Acid Type 2,900 lb Car 30 mile range	Sodium-Sulfur or Lithium-Sulfur Type* 3,500 lb Car 235 mile range
Normal	2.48	8.48 - 22.48
Emergency	0	6 - 20

* Data from presentation to the Committee by S. Gratch, Ford Motor Company, July 1976.

LIST B-5   Characteristics of the Brayton (Gas Turbine) Engine

Current Status
  Under development at Chrysler, General Motors, Ford, and independent engineering organizations.
  None in production.

Advantages
  Good emission control in regenerative version with variable air intake system. Some multifuel
  capability.

Disadvantages
  High cost; questionable durability; high fuel consumption in the lower power output ranges.

Future
  The Brayton is not in production because of the disadvantages listed above. The optimum
  economy is reached at about 2,500 to 3,000 °F gas temperature, which requires that all parts
  exposed to these temperatures be made of ceramics. A reasonably priced combustor made of
  silicon carbide appears possible. The turbine stators of silicon nitride also appear possible.
  The turbine wheel has so far been the stumbling block. It also is made of silicon nitride but
  no feasible method has been found for producing good blades and hub and then bonding them
  together. Costs rise because higher and higher purity silicon is being used in an attempt to
  overcome the problems. Unless an unexpected breakthrough occurs in solving this problem, the
  Brayton engine has no chance of operating at the higher temperature and reaching efficiencies
  comparable to the diesel engine. Its future is questionable (Iron Age 1976).

Chromium Usage (lb per total car)
  Chromium usage for an experimental car in 1976 was:

Condition	1976 Experimental 3,000 lb Car Using Ceramic Regenerator
Normal	6.88
Emergency	4.4

LIST B-6   Characteristics of the Rankine (Steam) Engine

Current Status
  Under development by independent engineering organizations only. None in
  production.

Advantages
  Good emission control and multifuel capability.

Disadvantages
  Adverse weight, cost, and fuel consumption. High usage of heat- and corrosion-
  resisting alloys.

Future
  Poor.

Chromium Usage (lb per total car)
  Chromium usage of an experimental Rankine engine (Jet Propulsion Laboratory 1975)
  was:

Condition	1975 Experimental 3,000 lb Car
Normal	34.48
Emergency	32

LIST B-7   Characteristics of the Stirling Engine

Current Status
  Under development at Ford. None in production.

Advantages
  Good emission control. Good fuel consumption.

Disadvantages
  High cost; questionable durability; design and manufacturing complexity. High
  usage of heat-resisting alloys.

Future
  The engine is a closed cycle piston engine operating with external combustion at
  high internal temperatures. There are significant durability problems. Ceramic
  materials may be helpful.

Chromium Usage (lb per total car)
  Chromium usage of an experimental Stirling engine (Jet Propulsion Laboratory
  1975) was:

Condition	1975 Experimental 3,000 lb Car
Normal	43.48
Emergency	41

TABLE B-3 Chromium Balance for Automotive Vehicles

	1975	1976	1980	1985	1990	2000
Annual production of vehicles						
Otto engine	8,881,266	11,350,000	14,000,000	12,950,000	12,650,000	13,300,000
(lb Cr/vehicle — normal usage)	6.75	6.75	5.48	5.48	5.48	5.48
(lb Cr/vehicle — emergency usage)		3.08	2.46	2.46	2.46	2.46
Diesel engine — trucks	102,508 [a]	150,000 [a]	250,000	500,000	500,000	1,000,000
(lb Cr/vehicle — normal usage)			5.48	5.48	5.48	5.48
(lb Cr/vehicle — emergency usage)			2.46	2.46	2.46	2.46
Diesel engine — automobiles [b]			100,000	1,500,000	2,500,000	3,000,000
(lb Cr/vehicle — normal usage)			3.83	3.83	3.83	3.83
(lb Cr/vehicle — emergency usage)			0.39	0.39	0.39	0.39
Battery electric engine	0	0	50,000	500,000	600,000	700,000
(lb Cr/vehicle — normal usage)			2.48	2.48	2.48	2.48
(lb Cr/vehicle — emergency usage)			0	0	0	0
Total chromium in U.S. vehicle production (tons)[c]						
Normal usage	30,320	38,813	39,299	40,345	41,563	45,795
Emergency usage		14,145	17,547	16,837	16,663	18,174
Total number of scrap cars [d]	8,000,000	10,120,000	12,716,000	13,596,000	14,300,000	15,840,000
Total chromium from scrap cars (tons)						
Normal usage — 1 lb Cr/car	4,000	5,600	6,358	6,798	7,150	7,920
Emergency usage — 3 lb Cr/car		16,800	19,074	20,394	21,450	23,760
Total U.S. produced vehicle population	111,000,000	115,000,000	129,000,000	142,000,000	150,000,000	169,000,000
Total chromium used to produce service parts (tons) [e]	1,265	1,323	1,483	1,633	1,725	1,944
Total chromium used in auto industry (tons) [f]						
Normal usage	27,585	34,536	34,403	34,865	35,612	39,189
Emergency usage		− 1,332	− 44	− 1,924	− 3,062	− 3,642

[a] Includes automobiles.

[b] Includes light trucks.

[c] Usage of Otto, diesel, and battery electric engines.

[d] Equals 88% of total Otto, diesel, and battery electric.

[e] Total U.S. produced vehicle population times 0.023 pounds.

[f] Total chromium in auto industry equals chromium in vehicle production, minus chromium from scrap cars, plus chromium used to produce service parts.

TABLE B-4   Vehicle Parts Requiring Chromium in an Emergency until Alternatives
Are Developed

Vehicle Parts	Pounds of Chromium Required Per Vehicle		
	1976 Car	1980 Car	1976 Diesel
Exhaust valves	0.319	0.255	0.319
Camshafts and tappets	0.087	0.070	0.087
Catalytic converters	2.587	2.070	--
Miscellaneous heat-resisting parts	0.084	0.067	0.084
Total	3.077	2.462	0.490

TABLE B-5 Emergency Chromium Reductions in Vehicles

Vehicle Parts	Methods of Reducing Chromium Usage	Pounds of Chromium Reduction per Vehicle		
		1976 Car (3,750 lb)	1980 Car (3,000 lb)	1976 Diesel
Exterior trim and wheel covers	Elimination, redesign, or substitution	1.585	1.213	1.585
Seat belts and windshield wipers	Using zinc or Cu-Ni-Cr plate on plain steel in place of stainless	0.620	0.620	0.620
Suspension springs	Using a non-chromium spring steel instead of 5160	0.326	0.261	0.326
Cylinder blocks, heads, and other iron castings	Substituting other alloying elements for chromium	0.617	0.537	0.862
Gears, ball and roller bearings, and other chromium alloy steel parts	Substituting another alloy without chromium	0.480	0.384	0.480
Total chromium reduction		3.682	3.015	3.844

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windshield well, this molding has been eliminated completely
and its lack is hardly noticeable. The glass merely extends
down into the well and is sealed on the bottom. The molding
was made of 1.699 pounds. of AISI Type 430 stainless steel
containing 0.272 pounds of chromium. However, it still
might be used on about 3 million cars per year, and 408 tons
of chromium could be saved if it were eliminated.

Another highly interesting part, from a volume
standpoint, is the windshield wiper blade. These blades
presently are marketed with a stainless steel holder
attached to the rubber blade. An optional replacement
design provides only a rubber blade that can be inserted in
the existing holder. Unfortunately, one must buy most of
the wiper assembly to take advantage of this feature, since
it is not available on new cars.

An estimated 41 million replacement wiper blades
containing 0.1 pound of AISI Type 430 stainless steel are
used per year (Harvey and Menchen 1974). This, plus new car
blades, amounts to about 488 tons of chromium per year that
could be saved with another design.

Another existing design option involves the hydraulic
valve lifter -- 16 per typical car with a total weight of
2.336 pounds of cast iron containing 1 percent chromium or
0.0234 pounds of chromium per car. It is estimated that an
additional 15 million are sold in the after-market. About
130 tons of chromium would be needed if all lifters
contained this amount. The optional design is a 5-gram
wafer of 1 percent chromium cast iron that is brazed to an
extruded steel body and would require only 9.69 tons of
chromium per year. Over 50 percent of the hydraulic valve
lifters made have this chromium-saving design.

The catalytic converter of the typical 1975 car
(Table B-1) contained a total of 3.335 pounds of contained
chromium in three parts made of 29 pounds of AISI Type 409
stainless steel. The average for all U.S. cars is
approximately 22.5 pounds of AISI Type 409 steel.
Reductions in chromium usage are possible in this area if
stainless clad steel is substituted for AISI Type 409 steel.
Another approach would be to use a lean-burn electronic
carburetor system without the convertor.

Figure B-1 was calculated by combining the information
in Table B-2 with the various factors previously discussed
in this report. It shows both normal usage and essential
usage in the event of a critical shortage of chromium. The
forecast can be altered in the event any of the alternate
power plants become a reality using the data in Lists B-1
through B-7 for initial production. If any of the Jet

Propulsion Laboratory (JPL) advanced engines ever become
reality, the figures in Table B-6 could be used
(presentation to the Committee by J. LaBelle, General Motors
Corporation, July 1976).
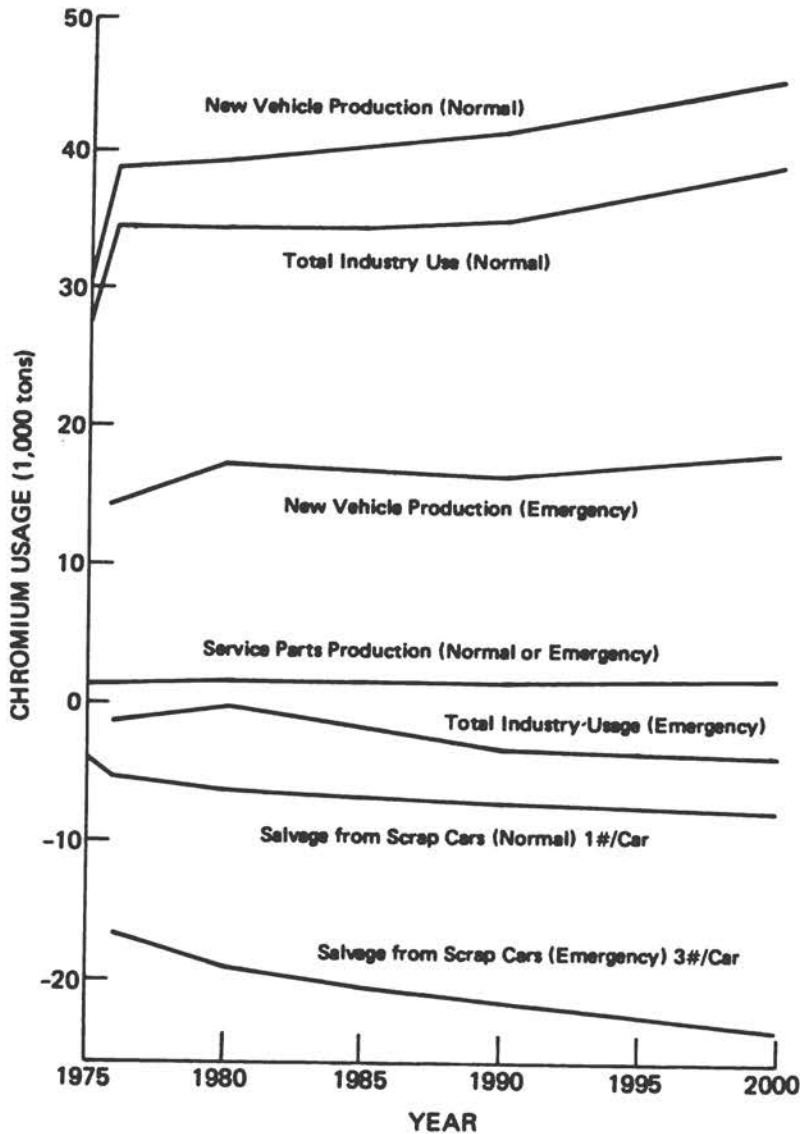
FIGURE B-1   Forecast of Automotive Industry Usage of
Chromium in Cars, Trucks, and Buses, 1975-2000
(based on data from Jet Propulsion Laboratory
1975, and 1976 presentation to the Committee by
J. E. LaBelle, Detroit Diesel Allison, General
Motors, Detroit).

TABLE B-6 Total Chromium Content (pounds) in Various Engines[a]

Materials	Present Piston Otto, 150 hp	Present Diesel, 150 hp	Battery Electric, 50 mph, 4 Passenger	Free Turbine Brayton, 150 hp		Single-Shaft Brayton, 150 hp		Stirling, 170 hp			Rankine, 150 hp	
				Mature	Advanced	Mature	Advanced	Present	Mature	Advanced	Mature	Advanced
Chromium-Containing												
Super alloy				2.33		0.77		12.15	1.50		1.65	
Stainless steel	2.905	0.319	0	5.40	3.25	4.19	1.61	28.8	14.94		30.6	4.14
Alloy steel	0.014	0.014	<.01	0.08	0.06	0.08	0.06	0.22	0.08	0.07	0.12	0.12
Cast iron	0.735	0.949[b]	0	0	0	0	0	0	0	0	0	0
TOTAL Chromium	3.654	1.282	<.01	7.81	3.31	5.04	1.67	41.17	16.52	0.07	32.37	4.26
Other												
Ceramic				20	112	20	106	22	22	110	—	93
Aluminum								51	181	178		
Cobalt				3.9		0.60			2.2		2.2	
Tungsten				0.80		0.75			0.37		0.27	

[a]Engine ready to run less transmission and battery.
[b]The diesel is assumed to have head, block, and bearing caps weighing 1.35 times the Otto. Other castings are the same.

NOTE: Based on data from Jet Propulsion Laboratory, 1975.

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Automotive Industries. "58th Engineering Specifications and Statistics Issue." *Automotive Industries* (April 1, 1976):25, 43.

Harvey, D.G., and Menchen, W.R. *A Technology Assessment of the Transition to Advanced Automotive Propulsion Systems.* Columbia, Maryland: Hittman Associates, Inc., May 1974.

Iron Age. "Ceramic Gas Turbine Has a Promising Future." *Iron Age* 217 (March 1, 1976):37-9.

Jet Propulsion Laboratory. *Should We Have a New Engine?,* Vol. II. Pasadena: California Institute of Technology, Jet Propulsion Laboratory, 1975.

NOTES

1. J.E. LaBelle, General Motors Corporation, reports that in a December 1975 conversation, Robert Nelson, Materials Engineer, General Motors Truck and Coach Division, indicated that:

    > Stainless and chromium usage is similar to that of a passenger car in gasoline-powered trucks, the two principle exceptions are diesel-powered heavy duty trucks and some buses. Since diesel engines are much heavier and the vehicles are larger, the engine, transmission, and drive line components are all larger and employ more alloy iron and steel. (It is probable however that without the catalytic converter, actual chromium content is nearly the same). In the case of coaches, aluminum is used externally; however, two models employ large stainless components. Otherwise they would be similar to trucks in actual stainless and chromium usage. One type of coach employs Type 304 stainless steel bumpers on both front and rear. These weigh 200 pounds each or 400 pounds per vehicle. The 200 units produced per year represent a usage of 80,000 pounds of stainless and 15,200 pounds of chromium. An additional 50 percent of production is used for replacement parts. The total is therefore 120,000 pounds of stainless containing 22,800 pounds of chromium.

The other part is the front step well employed on 375 coaches per year. This part has a finished weight of 80 pounds and a rough weight of 120 pounds. The finished weight usage of stainless Type 304 is 30,000 pounds containing 5,700 pounds of chromium. The above is for GM truck and coach production only.

In a January 1976 conversation with J.E. LaBelle, Art Sewart, Chief Metallurgist, General Motors Central Foundry Division, indicated the following for 350 cubic inch V8 automobile engines:

Cylinder Blocks and Heads

Chromium content is held to 0.28 - 0.32% for heads and blocks.

Approximate charge = 10,000 lbs.

```
20%      - 0.3% Cr steel turnings
28%      - 0.3% Cr foundry returns
45%      - 0.1 - 0.2% Cr gray iron
            casting turnings
Balance - pig iron
```

60% ferrochrome is added to achieve 0.28 to 0.32%; 6 to 10 pounds normally containing 3.6 to 6 pounds of chrome.

Camshafts

```
Olds    - 1.30 - 1.50% Cr
Pontiac - 0.90 - 1.10% Cr
```

Little, if any, chromium was lost in remelting chromium-containing scrap. The principle problem is that cast iron chips are not segregated by chrome content nor are scrap castings. As a result, cast iron chips containing chrome are purchased by foundries that do not require it and vice versa.

In a January 1976 letter to J.E. LaBelle, Carl J. Casza, Research and Development Division, Fruehauf Corporation, reported that:

The volume of stainless steel tankers (which are used to haul milk, acids, and various chemicals) produced by all trailer manufacturers is tabulated below.

1973	1974	1975 (6 months)
1,450	1,410	500

Each unit uses about 5,000 lbs. of stainlss steel making a total stainless steel usage of 3,500 tons (based on 1,400 units/year).

Some bulk hopper trailers which are used to haul fertilizer and other hygroscopic materials are made of stainless steel as are some vans that are used for hauling ammunition; however, there is no industry breakdown on this, but the number of these units would probably not exceed 50 and would consume an estimated 125 tons of stainless.

The industry also uses stainless steel tubes and hangers in "meat-railers" which transport beef carcasses and other meat products. There are about 5,000 of these units produced yearly by the trailer manufacturers with about 350 pounds of stainless steel per unit; this gives an additional usage of 875 tons of stainless steel making a grand total of 4,500 tons per year.

Appendix C

CHROMIUM UTILIZATION IN THE AIRCRAFT INDUSTRY

Eighteen major aircraft engine and airframe manufacturers were contacted by letter requesting actual chromium consumption quantities for 1975 as well as projected quantities for each subsequent year through 1980. Seven of the eight responses contained the information requested in varying detail. Two of the larger airframe and one aircraft engine manufacturers are included among the seven respondents. Generally, the chromium consumption quantities provided included metallurgical and chemical chromium that was purchased by the respective companies for the manufacture of their products, as well as the excess necessary for fabrication operations and projection. Material purchased by subcontractors is not included. Historically, significant portions of large commercial aircraft transports are fabricated by subcontractors.

Table C-1 summarizes the aircraft chromium consumption data provided by the 7 respondents, rounded to the nearest 10 tons. The value for 1975 includes both actual data and estimates, while the values for subsequent years are the estimates made by the various companies. Projections for future chromium consumption for individual companies varied from a constant annual rate to an increased consumption rate 46 percent greater for 1980 than for 1975. The three major consumers shared 95.6 percent of both the 1975 and the 1980 totals. Data received for 1975 represent approximately 20 percent of the 1972 consumption computed for the U.S. aircraft industry.

Chromium consumption in terms of the various mill products and materials is shown in Table C-2. The various forms are listed in the same manner that they were identified by the individual companies, but unfortunately, over 85 percent of the total consumption was not identified as to the forms involved.

Corrosion-resisting steels and superalloys account for the values shown for the mill products in Table C-2. Chromium contained in low-alloy steels and aluminum alloys was not determined for by those supplying data for these forms. Low chromium content, averaging approximately 0.2 percent in the high-strength aircraft-type aluminum alloys, should result in only small changes in the total consumption. Low-alloy steel chromium contents average about 1 percent and may increase the consumption total by a significant amount. Approximately 20 percent of the chromium used in fabricating a large commercial transport

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TABLE C-1   Estimated Aircraft Industry
Chromium Consumption

Year	Chromium Consumption (short tons)
1975	2,890
1976	2,940
1977	3,100
1978	3,250
1979	3,250
1980	3,370

TABLE C-2   Aircraft Industry Chromium Consumption
by Material Form for 1975

Material and Mill Product Form	Chromium Consumption (short tons)
Sheet and plate	96.9
Bar	36.6
Forging	20.0
Wire	0.9
Tubing	35.3
Castings	5.9
Low alloy steels	12.4
Corrosion-resisting steels	98.3
Aluminum alloys	7.1
Paint primers	14.2
Chemicals	62.5
Unidentified	2,503.1
Total	2,893.2

airframe was in low-alloy steels. Airframe, as used here, refers to the structure, controls, and hydraulics of the aircraft and excludes the engines.

Purchased equipment (excluding engines) that is installed in aircraft generally has a very low chromium content and is presumed not counted in the submitted data. The time and effort required to develop data for this equipment would be excessive considering the weights involved.

Yield figures (flying weight versus purchased weight) were furnished by one aircraft manufacturer for each form of metallic raw material and are shown in Table C-3. Overall yield figures, identified for different models of aircraft, also were provided and varied from 48 percent to 61 percent. Yield figures are expected to improve with the maturity of the production line for each model due to less rejections, the use of die forgings, and more efficient operations.

The catastrophic consequences of failure in critical aircraft components while landing or in the air result in a cautious approach to changes in the materials involved. Aerospace use of chromium is only a small percentage of the total chromium production; yet, the effect of chromium on the life and reliability of aerospace alloys is extremely critical, and elimination or even reduction of chromium in these alloys would be particularly devastating to aircraft turbine engines.

TABLE C-3   Ratio of Chromium Contained in Completed Airframe versus that Purchased by Manufacturer

Raw Material Form	Fly/Buy (%)
Sheet and plate	58
Bar	37
Castings	91
Forgings	57
Tubing	70

Chromium contained in the metallic materials that are required to fabricate a large commercial transport aircraft currently can be determined only by review of all drawings released for a particular series of aircraft. The total number of drawings involved for the aircraft airframe used in this survey is estimated at over 80,000, and includes drawings for all the models offered as well as various optional features that are available. An automated data process is being developed to list metallic materials used on the aircraft airframe (private communication with J. H. Adams, Boeing 1976). Drawings reviewed to date include essentially all the larger metallic components and about two-thirds of the estimated total. This list will not cover purchased equipment, thereby excluding the engines.

Data presented herein for the airframe were obtained from 1,280 drawings for superalloy and steel components. Chromium usage was calculated from the average alloy composition and the raw material stock size listed on the drawing or weight in the case of forgings and castings. Less than 5 percent of these drawings, primarily forgings, did not list raw material weight or stock size.

Table C-4 indicates the chromium usage computed from available data in terms of raw material form and the type of alloy. Quantities of part numbers and individual parts also are included. Chromium usage by alloy type totals 4,001 pounds for corrosion-resisting steels, 426 pounds for superalloys, and 1,127 pounds for low-alloy steels.

Table C-5 contains the chromium usage results for different functional areas of the airframe as calculated from available data. A total lower than in Table C-4 results because a functional area was not listed for every item in the data lists. Essentially all of the difference is contained in corrosion-resisting steel castings.

As mentioned above, chromium usage data generally are based on stock sizes listed on the engineering drawing, but for a few sheet metal parts, the stock size was not listed and was estimated. Chromium usage totals, determined from these stock sizes, will be less than the quantity actually purchased since increases for rejections and additional allowances involved in the manufacture or fabrication of parts are not included. The latter allowance would be negligible for forgings or castings and would be the greatest for tubing or sheet where forming is used to produce complex contours.

Airframe components fabricated from each raw material form can be grouped into a limited number of general types. Bar and forgings are used for fittings (e.g., structural,

TABLE C-4 Chromium Usage for a Large Commercial Transport Airframe by Raw Material

Form	Alloy Type	Quantity of Parts	Quantity Part Numbers	Chromium (pounds)
Sheet and plate	Corrosion-resisting steel	20,890	162	356
	Superalloys	415	64	126
	Low-alloy steel	222	26	4
Bar	Corrosion-resisting steel	20,700	352	1,847
	Superalloys	4,995	18	252
	Low-alloy steel	2,946	395	190
Forging	Corrosion-resisting steel	6,959	83	1,185
	Superalloys	18	2	46
	Low-alloy steel	699	158	927
Tubing	Corrosion-resisting steel	227	20	419
	Superalloys	45	8	2
	Low-alloy steel	50	10	6
Casting	Corrosion-resisting steel	1,350	133	194
Total		59,516	1,431	5,554

TABLE C-5 Chromium Usage for a Large Commercial Transport
          Airframe by Functional Area

Functional Area	Alloy Type	Chromium (pounds)
Body	Corrosion-resisting steel	488
	Superalloys	57
	Low-alloy steel	27
Wing	Corrosion-resisting steel	567
	Superalloys	75
	Low-alloy steel	596
Landing gear	Corrosion-resisting steel	456
	Superalloys	--
	Low-alloy steel	405
Propulsion (excluding engines)	Corrosion-resisting steel	1,780
	Superalloys	293
	Low-alloy steel	49
Controls	Corrosion-resisting steel	35
	Superalloys	--
	Low-alloy steel	26
Hydraulics	Corrosion-resisting steel	14
	Superalloys	1
	Low-alloy steel	21
Payloads	Corrosion-resisting steel	456
	Superalloys	--
	Low-alloy steel	--
Total		5,346

hydraulic actuator, and cargo handling). Sheet and plate are used for formed parts (e.g., brackets and duct parts), doublers, and fittings from the thicker gauges of plate. Castings are used for components of hydraulic, control, and pneumatic systems as well as on the landing gear. Tubing transmits hydraulic fluids and air, and is used as structural components on the landing gear as well as in other functional areas. Selection of a chromium-containing alloy for the above components is based on many factors.

Low-alloy steels are selected for such engineering properties as elastic modulus, hardenability, and high strength capability. Strength ranges as high as 275,000 to 300,000 psi are not uncommon since weight is of primary concern in aircraft design. An estimated period of 10 years has been required to develop reliable use of steel at these high strengths. The techniques employed should be useful also on substitute steels; however, the industry would be reluctant to use substitute steels in critical applications without thorough evaluation of their properties as well as some accumulation of service experience in noncritical applications. Substitution of low-alloy steels containing no chromium could result in a significant reduction in the amount of chromium used in an airframe. Data presented in Tables C-3 and C-4 indicate that 20 percent of the metallurgical chromium used is contained in the low alloy steels.

Corrosion-resisting steels are used primarily for their corrosion resistance and the resulting low maintenance. The low maintenance is particularly attractive for parts that are subject to surface damage (e.g., parts involved in cargo handling). For less severe applications, surface corrosion can be controlled by coatings applied to substitute materials. Some coatings, however, have adverse effects on engineering properties of the material. Chromium plating reduces fatigue life of a part by as much as 25 percent (Boeing Company 1975). A coated low-alloy steel part also would not perform as well as a corrosion-resisting alloy where stress-corrosion cracking determines the service life of a component. Stress corrosion tests (private communication with S. E. Wilson, Boeing, 1976) have indicated 17-4 PH at a 180,000 to 200,000 psi strength level had over 4 times the stress-corrosion-cracking resistance of 4340 steel (Erdmann 1973). Penetration of the coating on a low-alloy steel component by the corrosion environment is a potential problem due to damage, coating defects, or inadequate thickness.

Titanium has been used to replace corrosion-resisting steels for some applications (e.g., fasteners) and no doubt would be suitable for other applications. Weight savings

associated with use of titanium alloys make them an attractive substitute even though material costs are higher.

Superalloys are chosen because of their elevated temperature properties. Substitute materials with lower chromium contents could be utilized in those airframe applications where present materials are not subjected to temperatures near their maximum working temperature.

Chromium usage in aircraft turbine engines has been excluded from previously presented data because the engines are equipment purchased by the aircraft producer. Information provided by a major aircraft turbine engine manufacturer reveals that the engines account for the bulk of the chromium used in a jet aircraft. The total weight of chromium used in alloys purchased for a typical large aircraft turbine engine has been reported at 6,066 pounds. Considering 4 such engines as propulsion for the typical large transport aircraft discussed earlier, the engines account for approximately 81 percent of the total chromium purchased for manufacture of the aircraft.

Aircraft turbine engines use chromium principally as a constituent of superalloys in applications involving exposure to elevated temperatures. Modern designs use the high-strength alloys of approximately 10 percent chromium to near their maximum capability while relying on air-cooling systems to minimize exposure temperatures. Improvement in air-cooling efficiency is a continuing effort in engine development. Other cooling systems, such as liquid cooling, also are being investigated and developed to further improve engine performance.

Chromium contents up to 22 percent are utilized in other engine applications where oxidation or corrosion resistance, formability, and weldability are given more consideration than strength at temperature.

Design limitations imposed by the elevated temperature capability of turbine engine alloys severely restrict material substitutions if equal performance and reliability are to be maintained. The potential high loss of human life caused by engine failure dictates that new alloys be incorporated into production only after their capability has been proved through extensive development effort.

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Erdmann, J.C. "Review of Data on Subcritical Crack Growth in 4340 Steel." In <u>Minuteman Materials and Processes</u>, MM-MP-215. Seattle, Washington: Boeing Aerospace Company, November 21, 1973.

Appendix D

CHROMIUM USAGE IN THE MARINE INDUSTRY

Twenty-two large shipbuilders and ship equipment companies from a list of fifty-five were selected and requested to supply chromium consumption data. Actual consumption for 1975 was requested as well as estimates of chromium consumption for each succeeding year through 1980. Included among the four respondents who supplied data were a major company involved in new construction and ship repair, and another that manufactures barges, vessels, and off-shore platforms. In most cases, the data supplied were identified by the sources as proprietary. Two additional shipbuilding companies and one ship equipment company responded to the Committee's inquiry by noting that chromium consumed was contained in purchased equipment and the amount was not readily determined or that no chromium was consumed.

Table D-1 shows annual chromium consumption quantities compiled from the limited data received. The quantities shown are based on raw materials purchased by the respective companies and, consequently, do not include quantities purchased by subcontractors or contained in purchased equipment. The 1975 quantity consists of 35 tons from low-alloy high-strength steel, 132 tons from ferrochrome, 5 tons from paint, and 108 tons from corrosion-resistant steels. Data received for 1975 represent approximately 15 percent of the 1972 consumption calculated from U.S. Census statistics for ship building and repair plus boat building and repair.

TABLE D-1   Estimated Marine Industry
Chromium Consumption

Year	Chromium Consumption (short tons)
1975	280
1976	180
1977	273
1978	345
1979	430
1980	475

Data reported in Table D-1 are believed to exclude quantities of chromium that would be required to construct deep water ports or terminal facilities for crude oil and liquid natural gas (LNG) tankers. Annual consumption for these applications depends on a decision to build and the scheduling of the construction.

Chromium required to construct a deep water port to accommodate large crude oil tankers has been estimated at 2,160 short tons (Albers and Bawiec 1975):

> The deep water port facilities include the berths for the tankers, any necessary booster pumping facilities, the pipelines from berth to tank farm, and the necessary intermediate tankage at the terminal. They do not include the distribution pipelines and pumping facilities from marine terminal to refineries.

An estimated 21.6 short tons (Albers and Bawiec 1975) of chromium are required to construct an LNG terminal facility:

> The typical liquid natural gas (LNG) terminal contains facilities to berth a liquid natural gas (LNG) tanker, receive and store LNG, raise the pressure of the LNG to the gas pipeline pressure, vaporize the LNG, compress the boil-off gases, and deliver a daily average of 500 million cubic feet to a gas pipeline at generally not less than 40 °F and 1200 psig.

A search for detailed data on the quantity of chromium required to fabricate a typical marine vessel revealed that the data are not readily available at this time. Contacts were made with shipbuilders, Navy Offices, the Maritime Administration, the American Bureau of Shipping, and the Society of Naval Architects in addition to reviewing marine industry periodicals.

A number of ship applications were identified as requiring alloys containing chromium. Low-temperature applications such as containers for LNG may utilize stainless steel; however, two sources indicated that current economics favored use of aluminum alloys and that currently only limited use was being made of stainless steel for shipboard LNG containers. Higher strength ship hull steel containing 0.25 percent maximum chromium is used as required by the American Bureau of Shipping rules. An estimate was received that 10 percent of hull steel is this grade. Low-alloy steel pipe conforming to ASTM A335, Grade P11, is used for steam lines. Using an estimated 20,000 pounds of low-

alloy steel per ship results in 250 pounds of contained chromium being consumed for this application. Stainless steel is used for nuclear primary pipe systems, gas turbine exhaust lines, galley areas and equipment, and cladding of tail shafts. In the case of hydrofoil vessels, it is used for strut and foil material. Ship machinery also can be expected to involve use of chromium, the degree of consumption being dependent on the application and its design requirements.

REFERENCE

Albers, J.P., and Bawiec, W.J. Demand and Supply of Non-Fuel Minerals and Materials for the United States Energy Industry, 1975-1990: A Preliminary Report. USGS Professional Paper 1006-A,B 75-583. Washington, D.C.: U.S. Geological Survey, 1976.

Appendix E

CONSUMPTION OF CHROMIUM AND FERROCHROMIUM

Table E-1 lists the annual consumption of chromium and ferrochromium, and the production allocations to stainless and alloy steels for 1968, 1970, 1972, and 1974. Tables E-2 through E-5 present the consumption of chromium additions, the general composition of the input charge, the raw steel produced, the reported home scrap generated, calculated yields, and the distribution of shipments according to mill product for stainless and alloy steels.

Table E-1 provides calculated allocations of ferrochromium and ferrochromium-silicon based on annual production of these ferroalloys and the following distribution: 67.4 percent for stainless steel, 18 percent for chromium-containing steels, and 14.6 percent for other alloys. (The relation between ferrochromium production and chromium-containing steel production is changing because an increasing fraction of ferrochromium has been imported.)

Annual raw steel production and shipments are the measures of the input and output volumes, respectively, for steel-mill-product fabrication. Since a portion of the fabrication may be placed in inventory, a second measure of the mill output is the annual raw steel production minus the generated home scrap. A factor critical to chromium consumption and recovery -- net yield of steel -- is the sum of shipments plus home scrap.

The gross yields, shipments as a percent of raw steel production, for stainless steels (Table E-2) averaged 57 percent and alloy steels (Table E-4) averaged 57 percent with relatively narrow variations. The equivalent yield for the entire steel industry is about 67 percent. The lower yields for chromium-containing steels are associated with their smaller ingot sizes, the workability of the alloys, and the efficiency of the available equipment. The corresponding net yields are 95.3 percent for raw stainless steel processed into mill products (leaving a net loss of 4.7 percent equivalent to 3 percent of total annual consumption) and 67.7 percent for chromium-containing alloy steel, resulting in an apparent loss of 32.3 percent. According to AISI data, 36.6 percent of alloy steels contain chromium, an amount equivalent to a loss of 4 percent of total annual chromium consumption. These losses, which are much greater than the losses with stainless steel, are associated with the greater variety of alloy steel chemistry, large volume of hot-rolled products, greater ingot crop length, larger scale and pickling losses, and

TABLE E-1 Production and Allocations of Ferrochromium Alloys
           for Stainless Steels and Chromium-Containing Steels
           (1,000 tons)

Ferroalloy Type	1968	1970	1972	1974
Annual Production				
Ferrochromium	253	275	295	326
Ferrochromium silicon	129	165	112	133
Total	382	440	407	459
Production Allocations				
Ferrochromium to stainless steel	257.5	296.6	274.3	309.4
Ferrochromium to alloy steel	68.8	79.2	73.3	82.6
Ferrochromium to other alloys	55.7	64.2	59.4	67.0

NOTE: Data from American Iron and Steel Institute 1975, and
       Charles River Associates, Inc. 1970.

TABLE E-2 Stainless Steel Production and Losses

	Chromium Content (1,000 tons)			
	1968	1970	1972	1974
Furnace Charge				
Ferrochromium [a]	156	181	171	188
Stainless steel scrap [b]				
Purchased	62	79	72	100
Home	92	82	97	127
Total	310	342	340	415
Raw stainless steel produced	235	210	257	353
Melt losses	75	132	83	62
Stainless steel shipped	134	116	140	221
Gross yield [c]	(57%)	(55%)	(54%)	(62%)
Home scrap produced	92	82	97	127
Losses unaccounted for	9	12	20	5
Net yield [d]	(96.2%)	(94.3%)	(92.2%)	(98.6%)

NOTE: Data from American Iron and Steel Institute 1975, and U.S. Bureau of Mines 1968, 1970, 1972, and 1974.

[a] Average chromium = 60.9%.   [c] Shipments/raw steel production.

[b] Average chromium = 16.4%.   [d] Shipments plus home scrap/raw steel production.

TABLE E-3 Breakdown of Stainless Steel Shipments, 1968-1974 (1,000 tons)

Product Form	1968		1970		1972		1974	
Ingots and Castings	5.9	(0.7%) [a]	9.6	(1.4%)	17.3	(2.0%)	26.9	(2.0%)
Semifinished mill products	49.0	(6.0%)	48.6	(6.8%)	40.5	(4.7%)	66.6	(5.0%)
Finished mill products (except sheet and strip)								
Shapes and plates	56.6	(6.9%)	54.8	(7.7%)	57.0	(6.7%)	128.4	(9.6%)
Bars								
Hot rolled	44.6	(5.4%)	42.8	(6.0%)	44.8	(5.2%)	61.0	(4.5%)
Cold drawn	91.8	(11.2%)	79.3	(11.2%)	70.5	(8.2%)	107.0	(8.0%)
Pipe and tubes	26.0	(3.2%)	32.1	(4.5%)	28.8	(3.4%)	53.1	(3.9%)
Wire	24.5	(3.0%)	14.7	(2.1%)	29.8	(3.5%)	38.3	(2.8%)
Subtotal	243.5	(29.7%)	223.7	(31.5%)	230.9	(27.0%)	387.8	(28.8%)
Sheet and strip								
Sheet								
Hot rolled	32.9	(4.0%)	34.2	(4.8%)	17.9	(2.1%)	44.7	(3.3%)
Cold rolled	182.9	(22.3%)	157.8	(22.3%)	258.7	(30.3%)	475.5	(35.3%)
Strip								
Hot rolled	22.7	(2.8%)	23.4	(3.3%)	15.9	(1.9%)	17.1	(1.3%)
Cold rolled	282.1	(34.5%)	212.1	(29.9%)	273.5	(32.0%)	326.1	(24.3%)
Subtotal	520.6	(63.6%)	427.5	(60.3%)	566.0	(66.3%)	863.4	(64.2%)
Total shipped	819.0	(100.0%)	709.4	(100.0%)	854.7	(100.0%)	1,344.7	(100.0%)

NOTE: Data from American Iron and Steel Institute, 1975.

[a] Numbers in parentheses indicate the percentage of total stainless steel shipped.

TABLE E-4 Chromium-Containing Alloy Steel Production and Losses

	Chromium Content (1,000 tons)			
	1968	1970	1972	1974
Furnace charge				
Ferrochromium [a]	41.9	48.0	45.6	50.3
Alloy steel scrap [b,c]				
Purchased	2.2	2.2	2.2	2.3
Home	9.2	9.0	7.7	7.7
Total	53.3	59.2	55.5	60.3
Raw steel produced [c]	50.4	48.0	51.2	62.1
Melt losses	2.9	11.2	4.3	(1.8)
Steel shipped	28.6	25.4	28.5	37.3
Gross yield [d]	(57%)	(53%)	(56%)	(60%)
Home scrap produced	9.2	9.0	7.7	7.7
Losses unaccounted for	15.5	24.8	19.3	--
Net yield [e]	(70.9%)	(59.1%)	(66.2%)	(74.7%)

NOTE: Data from American Iron and Steel Institute 1975, and U.S. Bureau of Mines 1968, 1970, 1972, and 1974.

[a] Chromium average = 60.9%.

[b] Chromium average = 1.0%.

[c] See Table E-5 for ratio of chromium alloy to total alloy steel.

[d] Shipments/raw steel production.

[e] Shipments plus home scrap/raw steel production.

TABLE E-5 Breakdown of Chromium-Containing Alloy Steel Shipments, 1968-1974 (1,000 tons)

Product Form	1968		1970		1972		1974	
Ingots and Castings	64.0	(2.2%) [a]	96.2	(3.8%)	84.6	(3.0%)	158.6	(4.3%)
Semifinished mill products	197.5	(7.0%)	240.9	(9.5%)	263.2	(9.2%)	314.0	(8.4%)
Finished mill products								
Shapes and plates	594.6	(20.8%)	612.7	(24.1%)	647.0	(22.7%)	925.5	(24.8%)
Bars — hot rolled	847.8	(29.6%)	727.3	(28.6%)	889.4	(31.2%)	1,148.2	(30.8%)
Tool steel	39.6	(1.4%)	32.7	(1.3%)	33.4	(1.2%)	40.2	(1.1%)
Pipe and tubes	709.0	(24.8%)	438.2	(17.2%)	507.0	(17.8%)	555.3	(14.9%)
Wire	11.0	(0.4%)	7.3	(0.3%)	10.4	(0.4%)	13.4	(0.4%)
Subtotal	2,202.0	(77.0%)	1,818.2	(71.5%)	2,087.2	(73.3%)	2,682.6	(72.0%)
Strip and sheet								
Sheet — hot rolled	139.8	(4.8%)	122.0	(4.8%)	147.6	(5.2%)	254.4	(6.8%)
Coated sheet and strip	228.0	(8.0%)	239.0	(9.4%)	227.4	(8.0%)	263.0	(7.1%)
Strip								
Hot rolled	15.8	(0.6%)	14.3	(0.6%)	22.6	(0.8%)	37.6	(1.0%)
Cold rolled	12.3	(0.4%)	10.8	(0.4%)	13.6	(0.5%)	15.4	(0.4%)
Subtotal	395.9	(13.8%)	386.1	(15.2%)	411.2	(14.5%)	570.4	(15.3%)
Total shipped	2,859.4	(100.0%)	2,541.4	(100.0%)	2,846.2	(100.0%)	3,725.6	(100.0%)

NOTE: Data from American Iron and Steel Institute 1975.

[a] Numbers in parentheses indicate the percentage of total chromium-containing alloys shipped.

lower material cost (and scrap value) and its effects on overall process economics. Most importantly, much alloy scrap loses its identity, which is the probable cause for its low chromium content recovery. A program for more active scrap segregation and reuse of its alloy content would reduce chromium losses. The recovery of stainless steel is excellent in mill-product fabrication and indicates that the major source of chromium consumption is in melting.

Tables E-6 and E-7 show that about 60 percent of stainless steel production is associated with 7 different steel chemistries, whereas 60 percent of alloy steel production is associated with 4 ranges of composition, each of which includes several specific compositions. The greater variety in the stainless steels reduces the order size and therefore increases the processing costs and lowers the efficiency of the mill employed. In general, losses from scale, pickling, and conditioning would be significantly larger for alloy than for stainless steels. These losses are associated with the chemistries of the alloys, the product mix (Tables E-4 and E-5), and the available equipment. Approximately 60 percent of stainless steel shipments are cold-rolled sheet and strip with the production of sheet having increased significantly from 182,900 tons in 1968 to 475,500 tons in 1974. During this same period the alloy steel finished mill products -- hot-rolled shapes, plates, and bar -- accounted for about 52 percent of the total production, an increase from 1.450 million to 2 million tons.

The continuous casting capacity for alloy and stainless steel also increased markedly between 1968 and 1972, and included at least one stainless continuous slab casting facility in the United States. Continuous casting is made economically attractive because of significant improvements in yield (and therefore costs) plus lower capital costs because the ingot and blooming/slabbing mill stages are eliminated. No actual yield figures could be obtained.

TABLE E-6   Major Stainless Steel Grades, 1970 Production

Steel Grade	Percent of Total Production
304	30.0
430	8.8
301	6.4
316	5.3
304L	3.8
201	3.5
410	4.0
All other 300 series grades	10.3
All other 400 series grades	6.1
Other chromium-nickel stainless steels	4.8
501, 502, and all other high-chromium heat-resistant steels	2.9
All other grades	14.1

NOTE: Data from American Iron and Steel Institute Form AIS-7A, 1970. The principal alloy elements in the AISI 200 and 300 series are chromium and nickel, and in the AISI 400 and 500 series, chromium.

TABLE E-7 Major Alloy Steel Grades, 1970 Production

Steel Grade	Percent of Total Production
High-strength, low-alloy steels	26.5
Nickel-chromium-molybdenum (Ni-Cr-Mo)	12.2
Chromium-molybdenum (Cr-Mo)	12.0
Silicon sheet steel	10.4
Chromium	9.5
Molybdenum	6.6
Manganese	5.1
Nickel-molybdenum (Ni-Mo)	1.5
Manganese-molybdenum (Mn-Mo)	1.4
Chromium-molybdenum-vanadium (Cr-Mo-V)	1.3
All other grades	13.5

NOTE: Data from American Iron and Steel Institute Form 104, 1970.

REFERENCES

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Appendix F

JOINING

F.1 WELDING

The American Welding Society (AWS) summary chart of welding processes (see Figure F-1) shows 19 arc welding processes and variations, 8 solid state welding processes, 7 resistance welding processes, 3 oxyfuel gas welding processes, and 6 other welding processes.

The autogenous processes, which use no filler material, are notably resistance welding, solid state welding, electron beam welding, laser beam welding, induction welding, and pressure gas welding. Optimally, no filler is used in gas welding and certain arc processes, especially gas tungsten arc and plasma arc welding. These autogenous applications, except for flash, friction, and electron beam welding generally are limited to thin sections (i.e., 2 mm thick). Welds with filler metal addition are made by shielded metal arc welding (covered electrodes or stick welding), gas metal arc and flux cored arc welding, submerged arc welding, electroslag welding, and thermit welding; welds with hot or cold wire feed are made by gas tungsten arc, plasma arc, and oxyfuel gas welding.

Those few chromium-containing materials that are not thought of as weldable are the metal-ceramics, magnetic alloys, glass-to-metal alloys, and some coatings other than weld overlays. It is possible that even these exotic materials may still be welded by solid state processes.

The nominal compositions of all welding electrode grades containing chromium or used to join chromium-containing materials are listed in Tables F-1 through F-7.

Some chromium alloys are brittle and difficult to weld. The martensitic steels require care in welding since they are air-hardening and produce martensite in the weld heat-affected zone. The martensitic layer is extremely hard and may crack from shrinkage stresses, especially if hydrogen is present. Preheating and postheating are almost always needed.

Distortion from shrinkage stresses is a perennial problem in welding and is expecially acute with stainless steels because of their high coefficients of expansion and their low heat conductivities. Favorable weld designs and welding sequences that minimize this problem have been developed by welding specialists.

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atomic hydrogen welding . . . AHW
bare metal arc welding . . . . BMAW
carbon arc welding . . . . CAW
  —gas . . . . CAW-G
  —shielded . . . . CAW-S
  —twin . . . . CAW-T
flux cored arc welding . . . . FCAW
  —electrogas . . . . FCAW-EG

gas metal arc welding . . . . GMAW
  —electrogas . . . . GMAW-EG
  —pulsed arc . . . . GMAW-P
  —short circuiting arc . . . . . . GMAW-S
gas tungsten arc welding . . . . . GTAW
  —pulsed arc . . . . GTAW-P
plasma arc welding . . . . PAW
shielded metal arc welding . . . SMAW
stud arc welding . . . . SW
submerged arc welding . . . . . . SAW
  —series . . . . SAW-S

cold welding . . . . CW
diffusion welding . . . . DFW
explosion welding . . . . EXW
forge welding . . . . FOW
friction welding . . . . FRW
hot pressure welding . . . . HPW
roll welding . . . . ROW
ultrasonic welding . . . . USW

arc brazing . . . . AB
block brazing . . . . BB
diffusion brazing . . . . DFB
dip brazing . . . . DB
flow brazing . . . . FLB
furnace brazing . . . . FB
induction brazing . . . . IB
infrared brazing . . . . IRB
resistance brazing . . . . RB
torch brazing . . . . TB
twin carbon arc brazing . . . TCAB

dip soldering . . . . DS
furnace soldering . . . . FS
induction soldering . . . . IS
infrared soldering . . . . IRS
iron soldering . . . . INS
resistance soldering . . . . RS
torch soldering . . . . TS
wave soldering . . . . WS

electron beam welding . . . EBW
electroslag welding . . . . . . ESW
flow welding . . . . FLOW
induction welding . . . . IW
laser beam welding . . . . . . LBW
thermit welding . . . . TW

flash welding . . . . FW
high frequency resistance welding . . HFRW
percussion welding . . . . PEW
projection welding . . . . RPW
resistance seam welding . . . . RSEW
resistance spot welding . . . . RSW
upset welding . . . . UW

air acetylene welding . . . . . AAW
oxyacetylene welding . . . . . OAW
oxyhydrogen welding . . . . . OHW
pressure gas welding . . . . . PGW

electric arc spraying . . . . . . EASP
flame spraying . . . . FLSP
plasma spraying . . . . PSP

air carbon arc cutting . . . . . AAC
carbon arc cutting . . . . CAC
gas metal arc cutting . . . . . GMAC
gas tungsten arc cutting . . GTAC
metal arc cutting . . . . MAC
plasma arc cutting . . . . PAC
shielded metal arc cutting . SMAC

chemical flux cutting . . . . . . FOC
metal powder cutting . . . . . . POC
oxyfuel gas cutting . . . . OFC
  —oxyacetylene cutting . . OFC-A
  —oxyhydrogen cutting . . . OFC-H
  —oxynatural gas cutting . OFC-N
  —oxypropane cutting . . . OFC-P
oxygen arc cutting . . . . AOC
oxygen lance cutting . . . . . . LOC

electron beam cutting . . . . . . EBC
laser beam cutting . . . . LBC

Circles:
ARC WELDING (AW)
SOLID STATE WELDING (SSW)
BRAZING (B)
SOLDERING (S)
WELDING PROCESSES
OTHER WELDING
RESISTANCE WELDING (RW)
OXYFUEL GAS WELDING (OFW)
THERMAL SPRAYING* (THSP)
ALLIED PROCESSES
ADHESIVE BONDING (ABD)
OXYGEN CUTTING (OC)
THERMAL CUTTING (TC)
ARC CUTTING (AC)
OTHER CUTTING

*Sometimes a welding process.

FIGURE F-1   Master Chart of Welding and Allied Processes (American Welding Society 1976)

TABLE F-1   Nominal Compositions of Low-Alloy Steel Chromium-Bearing
Welding Electrodes

American Welding Society Classifications		Nominal Compositions				
Covered Electrodes (Spec. A5.5-69)	Bare Electrodes (Spec. A5.23-76)	Cr	Mo	Ni	Mn	Fe
E 80XX-B1	EB1	0.5	0.5	--	0.6	98
--	EB5 (0.5Si)	0.5	1.0	--	0.6	98
--	EF4	0.5	0.2	0.5	0.8	97
--	EF5	0.4	2.5	0.5	2.0	94
E12018M	--	1.0	0.5	2.0	2.0	94
E80XX-B2, E80XX-B2L	EB2, EB2H (0.2 Va)	1.2	0.5	--	0.6	97
E90XX-B3, E90XX-B3L	EB3	2.4	1.0	--	0.6	96
--	EB6, EB6H	5.0	0.5	--	0.6	93

NOTE: Consult specifications for exact ranges and limitations.

TABLE F-2 Nominal Compositions of Stainless Steel Welding Electrodes

American Welding Society Classifications			Nominal Compositions				
Covered Electrodes (Spec. A5.4-69)	Bare Electrodes (Spec. A5.9-69)	Flux-Cored Electrodes (Spec. A5.22-74)	Cr	Ni	Mo	Other	Fe
E308, E308L	ER308, ER308L	E308T-X, E308LT-X	20	10	--	--	68
--	--	E308MoT-X, E308MoLT-X	20	11	2.5	--	66
E309	ER309	E309T-X, E309LT-X	24	13	--	--	61
E309Cb	ER309Cb	--	24	13	--	1Cb	60
E309Mo	ER309Mo	--	24	13	2.5	--	58
E310	ER310	--	26	22	--	--	50
E310Cb	ER310Cb	--	26	22	--	1Cb	49
E310Mo	ER310Mo	--	26	22	2.5	--	48
E312	ER312	--	30	9	--	--	59
E16-8-2	--	--	16	8	1.5	--	72
E316, E316L	ER316, ER316L	E316T-X, E316LT-X	18	12	2.5	--	65
E317	ER317	--	20	13	3.5	--	62
E318	ER318	--	19	13	2.2	0.8Cb	63
E320	ER320	--	20	34	2.5	4CuCb	37
E330	--	--	16	35	--	0.8Cb	47
E347	ER347	E347T-X	20	10	--	0.8Cb	67
--	ER348 (no Ta)	--	20	10	--	0.8Cb	67
E349	ER349	--	20	9	0.5	3CbW	66
E410	ER410, E410T-x	--	12	--	--	--	87
--	ER420	--	13	--	--	--	86
E430	ER430	E430T-X	16	--	--	--	83
E502	ER502	E502T-X	5	--	0.6	--	93
E505	--	E505T-X	10	--	1.0	--	87
E7Cr	--	--	7	--	0.6	--	97

NOTE: Consult specifications for exact ranges and limitations.

TABLE F-3   Nominal Compositions of Nickel Alloy Welding Electrodes
            Containing Chromium

American Welding Society Classifications		Nominal Compositions					
Covered Electrodes	Bare Wires						
(Spec. A5.11-69)	(Spec. A5.14-69)	Cr	Ni	Mo	Cb	Other	Fe
ENiCr-1	--	18	76	--	3	--	2
--	ERNiCr-2	20	77	--	--	--	--
--	ERNiCr-3	20	72	--	2.5	3Mn	--
ENiCrFe-1	--	16	72	--	3	--	8
ENiCr-Fe-2	--	16	67	2	2	3Mn	10
ENiCrFe-3	--	16	66	--	2	8Mn	8
--	RNiCrFe-4	16	75	--	--	--	8
--	ERNiCrFe-5	16	72	--	2	--	8
--	ERNiCrFe-6	16	72	--	--	6MnTi	5
--	ERNiCrFe-7	16	72	--	1	3TiAl	7
ENiMo-3	ERNiMo	5	63	25	--	--	6
ENiMoCr-1	ERNiMo-5	16	57	16	--	4W	6
--	ERNiMo-6	5	63	24	--	--	6

NOTE: Consult specifications for exact ranges and limitations.

TABLE F-4 Nominal Compositions of Surfacing Electrodes Containing Chromium

Classifications and Specifications

Rods and Electrodes (AWS A5.13-70)	Composite Rods and Electrodes (AWS A5.21-70)	Nominal Compositions							
		C	Cr	W	Mo	Va	Si	Mn	Fe
RFe5-A, EFe5-A	RFe5-A, EFe5-A	0.8	4	6	5	2	--	--	82
RFe5-B, EFe5-B	RFe5-B, EFe5-B	0.8	4	2	7	1	--	--	85
-- EFe5-C	-- EFe5-C	0.4	4	2	7	1	--	--	85
RFeCr-Al	RFeCr-Al, EFeCr-Al	4.0	30	--	--	5	2	5	59

(AWS A5.13-70, cont.)	(Military R-17131B)	C	Cr	W	B	Si	Fe	Co	Ni
RCoCr-A, ECoCr-A	MIL-R-CoCr-A-1	1.0	30	4	--	--	2	62	--
--	MIL-R-CoCr-A-3	1.0	30	5	--	1	1	61	--
RCoCr-B, ECoCr-B	--	1.5	30	8	--	--	2	58	--
RCoCr-C, ECoCr-C	MIL-R-CoCr-C-1	2.5	30	12	--	--	2	53	--
RNiCr-A, ENiCr-A	--	0.5	11	--	2.5	2	2	--	81
RNiCr-B, ENiCr-B	RNiCr-B-1	0.6	13	--	3	4	4	--	75
--	RNiCr-B-2	0.6	11	--	2.5	4	4	--	78
RNiCr-C, ENiCr-C	RNiCr-C-1	0.8	15	--	3.5	5	5	--	70
--	RNiCr-C-2	0.8	15	--	3.5	5	--	--	75

NOTE: Consult specifications for exact ranges and limitations.

TABLE F-5 Nominal Compositions of Titanium Alloy
Electrodes [a] Containing Chromium

AWS Classification Bare Rods and Electrodes (Spec. A5.16-70)	Nominal Composition			
	Cr	Ti	Va	Al
ERTi-13V-11Cr-3Al	11	72	13.5	3

NOTE: Consult specification for exact ranges and
limitations.

[a] Welding filler metal ERTi-13V-11Cr-3Al is the only
commercially available all-beta alloy. The welds
respond to heat treatment, but the mechanical
properties in the heat-treated condition are sensi-
tive to variations in microstructure.

In the as-welded state, joints in the beta alloy
are ductile but low in strength compared to the
heat-treated base metal. Heat treatment increases
the strength and decreases the weld ductility.
Exposure to elevated temperatures embrittles the
welds. At present the full strength potential of
alloy Ti-13V-11Cr-3Al cannot be realized in welding
applications.

As suggested by the Panel on Substitutability,
many other alloying elements are available to
strengthen titanium. Deletion of this chromium-
bearing alloy and the corresponding welding
electrodes and rods will save chromium with no loss
in desired properties.

TABLE F-6 Nominal Compositions of Chromium-Free Nickel-Base Welding Electrodes

American Welding Society Classifications		Nominal Compositions					
Covered Electrodes (Spec. A5.11-69)	Bare Rods and Electrodes (Spec. A5.14-69)	Ni	Cu	Mn	Fe	Ti	Others
ENi-1	ERNi-3	97	--	--	--	3	--
--	RNi-2	99	--	--	--	1	--
ENiCu-1, ENiCu-2	--	66	26	3	2	1	2Cb
ENiCu-4	--	66	27	3	2	1	1Al
--	RNiCu-5	66	31	1	2	--	--
--	RNiCu-6	58	41	--	--	--	1Si
--	ERNiCu-7	66	25	3	2	2	1Si,1Al
ENiMo-1	ERNiMo-4(0.5Va)	66	--	--	6	--	28Mo

NOTE: Consult specifications for exact ranges and limitations.

TABLE F-7   Nominal Compositions of Chromium-Free Surfacing Electrodes

American Welding Society Classifications

Rods and Electrodes (Spec. A5.13-70)	Composite Rods and Electrodes (Spec. A5.21-70)	Nominal Compositions					
		C	Mn	Ni	Si	Mo	Fe
EFeMn-A	EFeMn-A	0.7	13	14	--	--	82
EFeMn-B	EFeMn-B	0.7	13	--	1	1	84

		Cu	Zn	Sn	Si	Al	Fe	Pb
RCuZn-E	--	57	39	25	--	--	1	--
RCuSi-A, ECuSi	--	95	1	1	3	--	--	--
RCuAl-A2, ECuAl-A2	--	89	--	--	--	10	1	--
RCuAl-B, ECuAl-B	--	85	--	--	--	11.5	3.5	--
RCuAl-C, ECuAl-C	--	83	--	--	--	12.5	4	--
RCuAl-D, ECuAl-D	--	82	--	--	--	13.5	4	--
RCuAl-E, ECuAl-E	--	81	--	--	--	14.5	4	--
RCuSn-A, ECuSn-A	--	95	--	5	--	--	--	--
-- ECuSn-C	--	92	--	8	--	--	--	--
RCuSn-D	--	90	--	10	--	--	--	--
RCuSn-E, ECuSn-E	--	88	--	6	--	--	--	16

NOTE: Consult specifications for exact ranges and limitations.

A welding technique being encouraged by the present interest in energy and materials conservation is narrow gap welding which is accomplished using several semiautomatic and automatic processes. New extensions of autogenous welding involve the joining of thick sections by electron beam welding and plasma arc welding in the keyhole mode. As power output improves, laser beam welding will join heavier sections. Solid state welding applications are steadily increasing in size.

Welding electrodes that currently would be required in a chromium contingency would be the chromium-free nickel and nickel-base alloys listed in Table F-6.

F.2 BRAZING AND SOLDERING

The AWS summary chart of welding processes (see Figure F-1) identifies 11 brazing processes and 8 soldering processes. Brazing may be used to join practically any of the chromium metals and alloys shown in the metallurgical list. Even a weld-deposited stainless steel overlay or hard surfacing overlay could be brazed to a die or mounting if desired. Normally, however, the overlay would be deposited in its final form and position by welding.

Most brazing alloys do not contain chromium (Table F-8). Those suitable for brazing stainless steels are found in the silver group (classification BAg), the precious metals group (BAu), the copper and zinc group (class BCu/BCuZn), and the nickel classification group (BNi). Brazing alloys in the nickel group retain their heat resistance at service temperatures up to 1800 °F and higher, depending on the specific filler metal.

Brazing filler metals containing chromium are found only in the nickel and cobalt classifications (Table F-9).

The BNi-1, BNi-1a (low carbon), BNi-2, and BNi-5 (nuclear grade, no boron) filler metals are used for joining turbine blades, jet engine parts, highly stressed components (including sheet metal structures), and apparatus for cryogenic service. Alloy BNi-7 (no boron) is used for furnace brazing honeycomb structrures, thin-walled tube assemblies, and high-temperature structures including nuclear applications.

BCo-1 alloy is used for its high-temperature properties and compatibility with cobalt-base metals. Under diffusion brazing conductions, it is used in jet engine applications with service temperatures up to 1900 °F and excursions to 2100 °F.

TABLE F-8 Nominal Compositions of Brazing Filler Metals without Chromium,
Suitable for Brazing Chromium-Bearing Alloys

AWS Classification	Brazing Temperature °F	°C	Nominal Composition Ag	Cu	Zn	Cd	Ni	Sn	Others
BVAgO	1,761-1,900	961-1,038	99.95	0.05	--	--	--	--	--
BAg1	1,145-1,400	618-760	45	15	16	24	--	--	--
BAg1a	1,175-1,400	635-760	50	16	16	18	--	--	--
BAg2	1,295-1,550	702-843	35	26	21	18	--	--	--
BAg3	1,270-1,500	688-816	50	15	16	16	3	--	--
BAg5	1,370-1,550	743-843	45	30	25	--	--	--	--
BAg6	1,425-1,600	774-871	50	34	16	--	--	--	--
BVAg6b	1,600-1,800	871-982	50	50	--	--	--	--	--
BAg7	1,205-1,400	652-760	56	22	17	--	--	5	--
BAg8, BVAg8	1,435-1,650	779-899	72	28	--	--	--	--	--
BAg8a	1,410-1,600	766-871	72	28	--	--	--	--	0.4Li
BVAg8b	1,470-1,650	799-899	71	28	--	--	--	1	--
BVAg8c	1,490-1,700	810-927	68	27	--	--	--	--	5Pd
BAg13	1,575-1,775	857-968	54	40	5	--	1	--	--
BAg13a	1,600-1,800	871-982	56	42	--	--	2	--	--
BAg18	1,325-1,550	718-843	60	30	--	--	--	10	--
BAg19	1,610-1,800	877-982	93	7	--	--	--	--	0.2Li
BAg20	1,410-1,600	766-871	30	38	32	--	--	--	--
BAg21	1,475-1,650	802-899	63	29	--	--	2	6	--
BAu-1	1,860-2,000	1,016-1,093	37	63	--	--	--	--	--
BAu-2	1,635-1,850	891-1,010	80	20	--	--	--	--	--
BAu-3	1,885-1,995	1,029-1,091	35	62	--	--	3	--	--
BAu-4	1,740-1,840	949-1,004	82	--	--	--	18	--	--
BAu-5	2,130-2,250	1,166-1,232	30	--	--	--	36	--	35Pd

			Ag	Cu	Zn	Sn	Fe	Others
BVCu-1x	2,000-2,100	1,093-1,149	0.05	99.95	--	--	--	--
BCu-1	2,000-2,100	1,093-1,149	--	99.9	--	--	--	P,Pb,Al
RBCuZn-A	1,670-1,750	910-954	--	59	40	1	--	--
RBCuZn-C	1,670-1,750	910-954	--	58	40	1	1	Mn

			Ni	Cu	Si	B	Fe	Others
BNi-3	1,850-2,150	1,010-1,177	92	--	5	3	--	--
BNi-4	1,850-2,150	1,010-1,177	94	--	3	2	1	--
BNi-6	1,700-2,000	927-1,093	89	--	--	--	--	11P
BNi-8	1,850-2,000	1,010-1,093	67	4	7	--	--	22Mn

NOTE: Consult specifications for exact ranges and limitations.

TABLE F-9 Nominal Compositions of Brazing Filler Metals Containing Chromium

| AWS Classification | Brazing Temperature | | Nominal Composition | | | | | |
	°F	°C	Ni	Cr	B	Si	Fe	Others
BCo-1	2,100-2,200	1,149-1,232	17	19	1	8	-	4W,51Co
BNi-1	1,950-2,200	1,066-1,204	75	14	3	4	4	0.7C
BNi-1a	1,970-2,200	1,077-1,204	75	14	3	4	4	low C
BNi-2	1,850-2,150	1,010-1,177	83	7	3	4	3	-
BNi-5	2,100-2,200	1,149-1,204	71	19	-	10	-	-
BNi-7	1,700-2,000	927-1,093	76	14	-	-	-	10P

NOTE: Consult specifications for exact ranges and limitations.

Commercial solders also do not contain chromium. The largest portion in use belongs to the tin-lead alloy system but solders containing tin-antimony-lead, tin-zinc, lead-silver, cadmium-silver, cadmium-zinc, zinc-aluminum, fusible alloys (or solders) containing bismuth, and Indium solders are available. Specifications for solders are ASTM B-32, "Solder Metal," ASTM B-284, "Rosin Flux Cored Solder," and Federal Specifications QQ-S-571, "Solders."

Corrosion is a problem with brazed joints. Galvanic attack is invited by the dissimilar metal joint which has been made, and crevice corrosion is always possible if the joint design creates pockets. Brazing filler metal BAg-21 seems immune to crevice corrosion on AISI type 400 series stainless steels because of its high nickel content (2 to 3 percent), which imparts a nickel-rich layer to the fillet edge.

Compatible brazing materials must be selected. Copper-phosphorus fillers (not shown in Tables F-8 and F-9) should not be used on ferrous and nickel-base alloys with a nickel content in excess of 10 percent. Erosion occurs with some alloys and attacks, and dissolves iron- and nickel-base alloys. BAu fillers have a low rate of interaction with base metals.

Brazing filler metal BAg-20 is finding new applications due to its good brazing properties, its freedom from cadmium (otherwise a health hazard from brazing fumes), and its more economical silver content. The self-fluxing brazing alloys in Tables F-8 and F-9 are fillers BAg-8, BAg-8a, BAg-18, BAg-21, and BAu.

F.3 MECHANICAL JOINING

Mechanical fastening is applicable to all tabulated applictions of chromium except coatings.

F.4 ADHESIVE BONDING

With adhesive bonding, thin and thick sections of any shape may readily be joined. Adhesive joints resist fatigue, and the adhesive seals the joint, insulates against electrical and thermal currents, and dampens vibrations. The heat required for aging the thermosetting adhesives usually does not affect the strength of metal parts. Adhesive bonding is a fast and inexpensive process.

F.5 WELD OVERLAY

Weld overlays are applied where clad steel surfaces are not available or are not reliable. Typical applications

have been the flanges (14 inches thick) for nuclear reactors, dished heads for pressure vessels, nozzles welded into boilers and chemical retorts, and cylindrical vessels with wall thickness greater than 4 inches. These overlays provided a corrosion-resistant surface equivalent to commercially clad products.

Weld overlays also are applied for wear resistance. Electrodes are available with special properties of hardness, hot hardness, impact strength, oxidation resistance, corrosion resistance, abrasion resistance, resistance to metal-to-metal wear, mechanical properties in compression, and machinability. Methods used for overlay welding are primarily those with low dilution (low penetration) and high deposition rate.

Oxyfuel gas welding is excellent for depositing thin, undiluted overlays of the chromium-cobalt Stellite compositions on wear surfaces and overlays of tungsten carbide granules. The low-temperature deposition achieved with the oxyacetylene flame leaves undissolved tungsten carbide grains dispersed in the weld deposit while arc welding tends to dissolve most of the granules in the matrix.

Shielded metal arc welding (manual deposition) is used in difficult welding positions. Submerged arc welding with series-arc (two-wire) deposition achieves rapid coverage of the surface being overlaid with about 12 percent dilution. Submerged arc welding with strip electrodes achieves about the same dilution at faster deposition speeds. Gas tungsten arc welding with hot wire feed and plasma arc welding with hot wire feed achieve dilutions as low as 5 percent.

Weld cracking is a common difficulty, especially with the harder alloys. With some electrodes, peening of each bead after deposition is employed to reduce stresses. Preheating and postheating schedules often are recommended. The copper-base alloys used for bearing surfaces are deposited with braze-welding techniques.

Uniform coverage of the base metal is required. Variations in penetration change the weld composition by dilution. Multiple layers often are deposited just to guarantee the required alloy content in the surface layer.

Conservation of chromium will encourage extensive use of clad steels. Welding sequences and electrode recommendations are ready now for all popular alloys. Most weldments will require only the butt-welding of clad plates, but many constructions will have nozzles and flanges that preferably will be surfaced by weld overlay techniques.

Substitute coatings without chromium are proposed in chapter 6. Equivalent weld deposits may not be possible to develop, but studies should be initiated. Low-chromium alloys will lack the corrosion resistance of higher chromium compositions.

Appendix G

CALCULATIONS AND ASSUMPTIONS FOR DETERMINING
THE CHROMIUM USED FOR STAINLESS STEEL PRODUCTION

Table G-1 is based on data from American Iron and Steel
Institute (AISI) Form 104, "Ingot Production of Stainless
and Heat Resisting Steels -- Net Tons," for the years 1965
to 1975. The following factors were used in calculating
data for 1976 and 1980-1990:

Years Used

1965 to 1975. The 1975 production calculated as twice
the first half-year value.

Baseline Production for Growth Calculation

Average of years 1965 to 1975 -- 1.52 million tons.
1976 production assumed 1.52 million tons.

Assumed Yearly Growth

5 percent. 1980, 1985 and 1990 production calculated
from 1.52 million with 5 percent per year growth.
This is growth without conservation or substitution
measures.

Average Chromium Content of Stainless Steels Calculated
from 1974 AISI Production by Grade

16.4 percent. The same chromium content assumed to
hold for all years.

Irreversible Chromium Loss in Melting

1965 to 1976 -- assumed 12 percent
1980 to 1990 -- assumed 7 percent
The reduction in losses is due to widespread
introduction of AOD melting.

Source of Chromium

Assumed 60 percent from scrap (own recirculating scrap
plus purchased scrap); 40 percent from ferrochromium
(high carbon ferrochromium, low carbon ferrochromium
and chrome-silicon). From 1980 on, all ferrochromium
will be mostly high carbon with the low carbon becoming
practically negligible.

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TABLE G-1 Chromium Use in Stainless Steel, Based on AISI Ingot Tons

Source of Chromium	Contained Chromium (tons)	
	Up to 1976	1980-1990
Chromium in ingot	16.4	16.4
Chromium charged	18.6	17.6
Chromium loss in slag	2.2	1.2
Chromium from ferrochromium	7.44	7.1
Chromium from scrap	11.16	10.5
Source of scrap for 100 ton ingot		
Total chromium from recirculating scrap	6.56	6.57
Total chromium from purchased scrap	4.60	3.94
Total chromium from scrap	11.16	10.50
Purchased chromium for 100 ton ingot		
Chromium from ferrochromium	7.44	7.1
Chromium from purchased scrap	4.60	3.94
Total purchased chromium	12.04	3.94
Purchased chromium for 100 ton finished steel (60% yield from ingot)		
Chromium from ferrochromium	12.33	11.84
Chromium from purchased scrap	7.66	6.56
Total purchased chromium	19.99	18.40

NOTE: Data from American Iron and Steel Institute, Form 104, 1965-1975.

Yield from Ingot to Shipped Weight

60 percent. This assumed value was used to calculate the recirculating scrap; 41 percent of total scrap up to 1976 and 40 percent after calculation was as follows: Chromium in 100 ton ingot -- 16.4 tons; chromium in finished steel mill product assuming a 60 percent yield -- 9.84 tons; 16.4 tons minus 9.84 tons equals 6.56 tons of chromium recirculated. This remains constant at a constant rate of production. It is probably invalid for periods of change in production.

Appendix H

SUBSTITUTES FOR STAINLESS STEEL

Substitutes for stainless steel are shown in Table H-1.

TABLE H-1 Substitutes for Stainless Steels

Stainless Steel Type	Contained Chromium	Product Form	Properties Needed	Material	Contained Chromium	Limitations	Research Needed	Probability of Success
201,202, 301,302, 304,304L, 321,347	18	Sheet + strip	Atmospheric and mild aqueous corrosion resistance. Good fabrication including welding. Good structural properties. Broad strength range (∿70-250 ksi)	12-14 Cr austenitic steel Cr, Ni or Cr-Ni-Mn or Cr-Mn-N of equivalent stability of austenite.	13	Slightly lower corrosion resistance which could be compensated, when needed, by Mo addition.	Determine optimum composition and evaluate properties.	High
				Single clad stainless steel on carbon steel (10% average stainless).	1.8	Loss of corrosion resistance at all exposed edges and welds. Corrosion resistant on one side only. Some formability and strength limitations.	Develop processing methods and edge protection methods. Evaluate properties.	High
				Double clad stainless steel-carbon steel core (20% average stainless steel)	3.6	Same as single clad stainless steel on carbon steel except corrosion resistance available on both sides.	Same as single clad stainless steel on carbon steel.	High
				Cr electrolytic plating on carbon steel (0.001″ Cr on average 0.040″ carbon steel).	2.5	Can be applied only on finished components. Size and shape limitations. Surface damage destroys corrosion resistance. Higher cost. Potential ecology problems.	Existing technology.	
				Cr solid state diffusion (chromizing) 0.002″ Cr on 0.050″ (average) carbon steel, both sides	4	Loss of corrosion resistance at all exposed edges and welds. Surface damage impairs corrosion resistance.	Existing technology.	
				Cr vapor deposition, ion implantation, etc.	Negligible	Damage prone surface layer will lose corrosion resistance. Limited fabrication shape and size.	Develop processes and fabrication methods. Evaluate properties.	Medium

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	Aluminum alloys	–	Some limitation in fabrication, especially welding, and in structural properties.	Existing technology. Need to determine capacity of aluminum industry.	
	Plastics	–	Low strength. Limited fabrication.	Develop stronger materials with better fabrication.	High
Cryogenic application	Aluminum alloys	–	Slight fabrication disadvantage.	Existing technology.	
	9% Ni steel	–	Slight fabrication disadvantage. No corrosion resistance.	Existing technology.	
Atomic power	Not replaceable.	–	–	–	
High-temperature application requiring strength and oxidation resistance.	12-14 Cr austenitic steels (Cr-Ni, Cr-Ni-Mn or Cr-Mn-N with Al to obtain sufficient oxidation resistance).	13	Expected to have equivalent properties.	Develop new austenitic steels. Evaluate properties.	High
High-temperature application requiring oxidation resistance but not strength.	New Cr-free Al, Ti, Si-ferritic steel system.	–	Fabrication not as good as that of austenitic steels. Low strength at high temperature.	Develop new ferritic steels. Develop processing and fabrication methods. Evaluate properties.	Medium
Chemical industry.	Titanium	–	Not acceptable in certain sulfuric acid environments, hydrofluoric acid and some organic acids. Higher cost.	Check availability of Ti industry capacity.	
	Tantalum	–	Very expensive.	Check capacity.	
	Lead	–	Limited to some environments like sea water, buried pipes and cables, sulfuric acid, nitric and hydrofluoric acid.	Existing technology. Check capacity. Poor structural properties. High density.	
	Plastics	–	Limited to 400 °F. Strength limitations.		

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TABLE H-1 Substitutes for Stainless Steels (continued)

Stainless Steel Type	Contained Chromium	Product Form	Properties Needed	Material	Contained Chromium	Limitations	Research Needed	Probability of Success
				Impervious graphite.	–	Limited to 335 °F and 50 psi. Brittle.		
				Glass (piping, tubing, glass-lined vessels, distillation columns).	–	Limited to 550 °F. Limited availability.		
201,202, 301,302, 304,304L, 321,347	18	Plate	Atmospheric and mild aqueous corrosion resistance, fabrication including welding structural properties.	12-14 Cr austenitic steel Cr, Ni or Cr-Ni-Mn or Cr-Mn-N of equivalent stability of austenite.	13	Slightly lower corrosion resistance which could be compensated, when needed, by Mo addition.	Determine optimum composition and evaluate properties.	High
				Single clad stainless steel on carbon steel (10% average stainless).	1.8	Loss of corrosion resistance at all exposed edges and welds. Corrosion resistant on one side only. Some formability and strength limitations.	Develop processing methods and edge protection methods. Evaluate properties.	High
				Type 308 or 309 weld overlay on carbon steel (¼" type 308 on average 2" carbon steel).	2.5	Economic limitations at lighter gage. Some shape limitations.	Existing technology.	
201,202, 301,302, 304,304L, 321,347	18	Billet bar forgings wire	Atmospheric and mild aqueous corrosion resistance. Acceptable machinability. Good mechanical and strength properties.	12-14 Cr austenitic steel Cr, Ni or Cr-Ni-Mn or Cr-Mn-N of equivalent stability of austenite.	13	Slightly lower corrosion resistance which could be compensated, when needed, by Mo addition.	Determine optimum composition and evaluate properties.	High
				Cr electrolytic plating on carbon steel (0.001" Cr on average 0.040" carbon steel).	Negligible	Can be applied only on finished components. Size and shape limitations. Surface damage destroys corrosion resistance. Higher cost. Potential ecology problems.	Existing technology.	
				Cr solid state diffusion (chromizing) 0.002" Cr on 0.050" (average) carbon steel, both sides.	Negligible	Loss of corrosion resistance at all exposed edges and welds. Surface damage impairs corrosion resistance.	Existing technology	

Alloy		Form	Application	Substitute	Factor	Limitations	Action	Priority
				Cr vapor deposition, ion implantation, etc.	Negligible	Damage prone surface layer will lose corrosion resistance. Limited fabrication shape and size.	Develop processes and fabrication methods. Evaluate properties.	Medium
316,317, proprietary Cr-Ni-Mn, Mo, Cu, N, highly corrosion resistant alloys	18	Sheet, strip, plate, bar, billet, wire	Corrosion resistance in chemical industry and in sea water application.	Titanium	–	Not acceptable in certain sulfuric acid environments, hydrofluoric acid and some organic acids. Higher cost.	Check availability of Ti industry capacity.	
				Tantalum	–	Very expensive.	Check capacity.	
				Lead	–	Limited to some environments like sea water, buried pipes and cables, sulfuric acid, nitric and hydrofluoric acid.	Existing technology. Check capacity. Poor structural properties. High density.	
				Plastics	–	Limited to 400 °F. Strength limitations.		
				Impervious graphite.		Ltd. to 335°F & 50 psi. Brittle.		
				Glass (piping, tubing, glass-lined vessels, distillation columns).	–	Limited to 550 °F. Limited availability.		
				Clad 316, etc. on carbon steel (average 10% on 2″ carbon steel).	1.8	Requires special welding technique.	Existing technology.	
308,309, 310	22	Sheet, strip, bar, billet, wire	High temperature strength, oxidation and corrosion resistance.	Not replaceable				
			Oxidation resistance at high temperature. No strength or corrosion resistance.	New Cr-free Al, Ti, Si-ferritic steel system.				

TABLE H-1 Substitutes for Stainless Steels (continued)

Stainless Steel Type	Contained Chromium	Product Form	Properties Needed	Material	Contained Chromium	Limitations	Research Needed	Probability of Success
409	11	Sheet, strip, plate, bar, wire	Corrosion and oxidation resistance for auto exhaust.	Aluminized carbon steel or low alloy steel.	–	Shorter life, lower corrosion resistance.	Develop alloy system. Aluminizing technology available.	High
				Cr solid state diffusion (chromizing) 0.002" Cr on 0.050" (average) carbon steel, both sides.	4			
				New 5-6 Cr, Al alloy steel	5	Oxidation resistance of new alloy system should be equivalent to 409 but the corrosion resistance will be lower.	Develop new alloy and fabrication and processing. Evaluate properties.	High
430,434, 436,439	17	Sheet, strip, plate, bar products	Corrosion and oxidation resistance. Decorative.	Ferritic steel with 13-14% Cr	13	The slightly lower corrosion resistance due to lower Cr can be compensated by Mo addition.	Existing technology.	
				Single clad stainless steel on carbon steel (10% average stainless) but using ferritic steel for clad.	1.8	Loss of corrosion resistance at all exposed edges and welds. Corrosion resistant on one side only. Some formability and strength limitations.	Develop processing methods and edge protection methods. Evaluate properties.	High
				Double clad stainless steel-carbon steel core (20% average stainless steel) but using ferritic stainless steel for clad.	3.6	Same as single clad stainless steel on carbon steel except corrosion resistance available on both sides.	Same as single clad stainless steel on carbon steel.	High

				Aluminum alloys	–	Some limitation in fabrication, especially welding, and in structural properties.	Existing technology. Need to determine capacity of aluminum industry.	
446, 26-1	26	Sheet, strip, plate, bar products	Oxidation resistance.	Not replaceable.				
			Corrosion resistance.	Titanium	–	Not acceptable in certain sulfuric acid environments, hydrofluoric acid and some organic acids. Higher cost.	Check availability of Ti industry capacity.	
21-4N, 21-2N	21	Bar	Automotive valves.	Develop new Cr-Mn, Ni-N valve steel with 12-14% Cr content.	13	No major disadvantages anticipated with a lower Cr steel.	Develop new alloy with equivalent strength properties. Evaluate properties.	High
410,422, 418, and other modified 12 Cr martensitic steels	12	Bar products	Strength, corrosion resistance steam turbine.	2-3 Cr-Mo-V steel	3	No major disadvantages expected.	Existing technology.	
			Strength, corrosion resistance gas turbines.	Not replaceable.	–	–	–	
17-7PH, 15-7 Mo, 350,355	15	Sheet, plate, bar products	Strength and corrosion resistance.	Titanium alloys	–	Titanium alloys are currently alternate materials for PH stainless steels. Cost disadvantage.	Existing technology.	

Appendix I

ALTERNATIVES TO STAINLESS STEELS IN AUTOMOBILES

The following data used for the automotive industry were provided by Allegheny Ludlum Steel Corporation and represent average stainless steel use per car in 1976, which includes 22.5 pounds per car of AISI type 409 for the catalytic reactor, that was not used in 1974.

Automotive

1976 Average: 22.5 lb/car   AISI type 409 for catalytic converter, including pipes
       9.5 lb/car   Functional -- various parts
       9.5 lb/car   Decorative -- trim, hub caps, wheelcovers
      _____
      41.5 lb/car

Basis: 10 million cars/year

Stainless Steel Function

  Decorative -- 9.5 lb/car
  Functional -- 32 lb/car

Current Steels

  Decorative -- AISI types 201, 301, 430, 434, 436
  Functional -- AISI types 301, 201, 409, 305, 21-2N, 17-7 PH

Current Use of Stainless Steel Tons/Year for 10 million Cars

  Decorative -- 47,500 tons
  Functional -- 160,000 tons
       207,500 tons

Contained Chromium

It is assumed that:

  Average for Decorative   -- 17 percent
  Average for Type 409   -- 11 percent
  Average for Balance Function -- 18 percent
  Average Irreversible Loss
   in Melting   -- 7 percent

Contained chromium (corrected by 7 percent for melt loss):

Decorative -- 8,640 tons
Functional -- 22,330 tons*
            30,970 tons

* 13,182 tons for T409 and 9,148 tons for balance

Alternative Chromium-free Materials

Assuming a severe shortage (i.e., all chromium imports stopped):

- Replacement for decorative stainless -- aluminum (nil chromium content).

- Replacement for functional stainless: aluminized carbon steel or low-alloy steel (nil chromium content) for AISI type 409 in catalytic reactor; 75 percent replacement by alloys with no chromium for balance of functional stainless.

- Chromium used in decorative and functional replacements: 9,148 x 0.25 = 2,287 tons.

Chromium savings versus current usage: 30,970 - 2,287 = 28,683 tons.

Comments

- Replacement of AISI type 409 by aluminized steel requires research and development.

- Other functional parts such as seat belt anchor plates, seat belt retractors, piston ring expanders, door lock springs, flex fans, bumper guard brackets, and hose clamps to be replaced by existing coated carbon and low-alloy steel. No research and development is needed.

- Radiator tanks (trucks and buses), radiator and tank caps, and manifold gaskets to be replaced by brass. No research and development is needed.

- Valve steels (21-2N) to be replaced by new 12-15 percent chromium austenitic steel. Research for alloy development is needed.

- AISI type 305 for fasteners to be replaced by new 12-14 percent chromium austenitic stainless steel with

equivalent work hardening characteristics. Research is needed.

Chromium usage is much greater after 1975 than that shown in Table 26 (chapter 5).

A substantial amount of chromium can be saved by replacing stainless steel mostly with existing materials. The only new materials are for exhaust valves and fasteners. These should be essentially lower chromium versions of the existing stainless steel grades.

It is believed that the substitutions recommended are feasible without any significant technical degradation. The life cycle of the car would, however, be decreased by the elimination of stainless steel and initial cost will be higher than for conventional vehicles.

Appendix J

COATINGS FOR PLASTICS

J.1 ELECTROPLATING

This process typically involves an oxidizing acid etch, an activation step (e.g., deposition of finely divided palladium), an electroless nickel deposit to make the surface conductive, and conventional electroplating such as duplex nickel covered by microcracked chromium. Approximately 2 grams of chromium is used per square meter of plated area. When properly applied, these electroplated coatings are durable, and they have gained general acceptance even in such demanding applications as exterior automotive trim.

J.2 VACUUM METALLIZING

This process typically includes: a base coat that seals the plastic to prevent gassing in subsequent operations and provides a surface to which the metal film will adhere; a very thin, somewhat porous metal film; and a clear topcoat. Because of the thinness and porosity of the metal film, the adhesion of the topcoat is enhanced by penetration through this film to the base coat. The three principal deposition processes used for the metal film are filament evaporation, electron beam heating, and sputtering.

Filament evaporation generally is used for the vacuum deposition of aluminum; aluminum on tungsten is the source. Filament evaporation of refractory metals results in short filament life and relatively dark films. Alloy composition is difficult to control. There is extensive literature on this process (Holland 1956).

Electron beam heating is similar to filament evaporation except that the energy for the evaporation is delivered by an electron beam incident on the material to be evaporated. It has essentially the same limitations as filament evaporation (Modern Plastics 1974).

In the case of ion sputtering, an ionized sheet of an easily ionizable gas (e.g., argon) is confined near a cathode by a suitably shaped magnetic field. The impact of the ions on the surface of the cathode causes the surface to be eroded, and the removed material then is deposited on the workpiece. The main advantages of ion sputtering are that it is applicable to relatively refractory metals and that the composition of the material deposited on the workpiece

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is essentially the same as that of the surface of the cathode (Penfold and Thorton 1976).

J.3 CHEMICAL VAPOR DEPOSITION

In chemical vapor deposition, the workpiece is introduced in a space containing the vapor of a volatile metal compound such as nickel carbonyl. Decomposition of the compound on the surface of the workpiece is achieved either thermally (by preheating the workpiece) or chemically (by coating the workpiece with a substance capable of causing the decomposition of the volatile metal compound).

J.4 PAINTING

A metallic appearance of a plastic may be produced by painting with a suitably pigmented paint such as the argent paints.

J.5 ADHESIVELY BONDED METALLIC FILMS

In the most common application, a three-part film consisting of a clear polymeric film, a thin aluminum foil, and a layer of pressure sensitive adhesive is prepared. This composite film then is bonded to the part to be coated so that the clear polymeric film is on the outside to provide protection to the aluminum film, which in turn provides the bright, metallic appearance.

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Appendix K

ELIMINATION OF CHROMIUM FROM BRIGHT TRIM

Significant reduction in overall chromium use is achieved most readily by replacement of stainless steel components by anodized aluminum, painted steel, or metallized plastic. Elimination of chromium from bright trim would require substitution of chrome-free alloy plating and metallizing or restyling to allow expanded use of anodized aluminum and painted steel trim. The issues involved are related primarily to styling although design changes would be necessary in some applications.

The chromium layer of standard nickel chromium plating is typically 0.00025 mm in thickness (American Society for Testing and Materials 1974), corresponding to about 2 grams of chromium per square meter of plated surface. Bumpers, bezels, and grilles (the large area chrome plated parts) thus account for only a small fraction of total chromium usage -- perhaps 10 grams of the 3.5 kilograms estimated for the average U.S. car in 1970 (Personal Communication with N. Heller, Ford Motor Company, 1976). Proposed metallizing processes based on chromium sputtering use thinner films than electroplating -- about 0.0001 mm or less (Product Finishing 1975). Stainless steels suitable for bright trim contain about 18 percent chromium by weight (Zapffe 1949); wheel covers alone can account for 400 grams or more chromium per car (Personal Communication with R. Dickie, Ford Motor Company, 1976).

Replacement of stainless steel by plated or painted steel or plastic or by anodized aluminum can result in major reductions in chromium usage. Elimination of chromium would require additional changes, as outlined below, for specific applications.

K.1 BUMPERS

Bumpers currently are nickel-chromium electroplate. Chromium-free alternatives include:

1. Chromium-free alloy plating (e.g., Ni-Sn); however, some sacrifice in performance (brittle and hard-to-remove rust deposits) and appearance (rosy color) would be likely (Brenner 1963)

2. Soft-face painted bumpers, but a major styling change would be involved

3. Anodized aluminum; however, some sacrifice in performance (pitting) and appearance (yellowish color) would be involved (Hoover 1974)

K.2 GRILLES, BEZELS, AND OUTSIDE REAR-VIEW MIRRORS

These parts currently are nickel-chromium electroplate. Alternatives include:

1. Argent paint

2. Anodized aluminum, but a design change would be needed in some cases to accommodate use of extrusions

3. Chromium-free plating or metallizing, but development work would be needed to prove feasibility and assess performance for plastic parts

K.3 WHEELCOVERS

Stainless steel and anodized aluminum are both used currently. Some design modifications might be needed to meet strength requirements, but anodized aluminum or painted steel (currently used for trucks) could be substituted for stainless steel.

K.4 WINDSHIELD WIPER ARMS

Stainless steel is currently used. Redesign might be needed to allow material substitution.

K.5 DOOR HANDLES

Chrome-plated zinc die castings are used for abrasion characteristics as well as corrosion resistance and appearance. Alternatives include:

1. Anodized aluminum; however, design changes might be needed to accommodate use of extrusions

2. Chromium-free alloy plating

K.6 LETTERING AND EMBLEMS

These usually are chrome-plated die-cast zinc, but they could be changed to:

1. Metallized plastic (possibly a second surface process as currently used for some emblems)

2.   Plastic-metal foil composite (in-mold decoration)

3.   Chrome-free alloy plating

K.7 WINDOW SURROUND MOLDINGS, ROCKER PANEL MOLDINGS, BODY SIDE MOLDINGS

Some stainless steel is used, but the primary material is anodized aluminum. Aluminum foil/plastic coextrudate has been proposed for window surround moldings.

K.8 INTERIOR BRIGHT TRIM

Aluminum metallizing and hot stamping are used for much of the interior bright trim; door handles and dome lamp housing are chrome-plated. Alternatives include: metallized plastic, anodized aluminum, and chrome-free plating.

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15. Supplementary Notes

16. Abstracts The United States depends entirely on foreign sources for the critical material, chromium, making it very vulnerable to supply disruptions. This vulnerability results because chromium is essential for the fabrication of corrosion-resisting steels and high-temperature, oxidation-resisting alloys in applications that are vital to the nation's technological well-being; because no substitutes are known for these materials in those applications; and because the known substantial deposits of chromite ore are only in a few geographical locations that could become inaccessible to the United States as a result of political actions. The effectiveness of programs such as stockpiling, conservation, and research and development for substitutes to reduce the impact of disruption of imports of chromite and ferrochromium are discussed. Alternatives for decreasing chromium consumption also are identified for chromium-containing materials in the areas of design, processing, and substitution.

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

Chromite Ore	Ferrochromium	Stainless Steels
Chromite Refractories	High-Temperature Alloys	Steels
Chromium	Metallurgy	Stockpiling
Coatings	Oxidation-Resisting Alloys	Strategic Materials
Corrosion-Resisting Steels	Pigments	Superalloys
Critical Materials	Recycling	Tool Steels
Ferrochrome Silicon		

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