CHAPTER 7

Substitution Alternatives for Strategic Materials

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Roles of Substitution in Materials Use

Designers choose materials that they think offer the most attractive combination of service performance and reliability, ease in processing and manufacturing, cost, and availability. However, these factors constantly change as new materials with better properties are developed, better information about existing materials becomes available, new processing techniques are developed, and relative costs and availability of materials fluctuate. Substitution, the process of revising the match between materials and applications, is the material users' technical response to this shifting environment. In some cases, substitution involves finding or developing the best material for the application (replacement); in others, it involves designing or redesigning the application to make the best use of available materials.

Substitutions can be very costly and therefore are undertaken only when there is a high degree of certainty that the benefits will be substantial. To be adopted, a substitute material or design must demonstrate both technical and economic feasibility and must overcome a variety of institutional hurdles. More important, it must gain the acceptance of the designers and end users who will ultimately use it.

Even though substitution includes both replacement and redesign, current strategic materials-motivated substitution research is, for the most part, oriented toward development of alternative materials that have less strategic material content.[1] At present, considerable research—most of it government sponsored—is focused on development of replacement materials that could reduce strategic material requirements in several critical applications. These include, among others, several lower chromium alternatives for existing stainless steels now used in powerplants, chemical processing facilities, and other applications where corrosion resistance in a range of environments is needed; low- or no-chromium alloy steels for bearings, gears, shafts and other high-stress, long-service life applications; and low- or no-cobalt superalloy for gas turbine applications. Some examples of substitutions that have been or could be important to strategic materials use are shown in table 7-1.

Table 7-1.—Examples of Substitution Relevant to Strategic Materials

Direct material substitution:
- Ceramic magnets for aluminum-nickel-cobalt magnets
- Dolomite for magnesia-chromite refractories
- Interchangeability of platinum-group metals and gold in electronic components
- Modified 9% chromium-1% molybdenum steel for 18% chromium-8% nickel stainless steel in reactor vessels, heat exchangers, and tubing in powerplants
- Polymeric materials for decorative chrome in automobiles
- Cobalt-free superalloy for 56% cobalt superalloy in JT-9 jet engine

Process design substitution:
- AOD vessel for double-slag in stainless steel making
- Precision casting and forging for machining in parts manufacture
- Continuous casting for ingot casting in steelmaking

Product *design substitution:*
- Ceramics in experimental automotive gas turbine engines
- Downsizing of turbine engines made possible through the use of lighter materials in aircraft components

SOURCE: Office of Technology Assessment

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[1] Though product design and redesign can be used to reduce strategic materials requirements, this strategy is less amenable to a centralized research effort because of the vast number of products [and the case-by-case nature of this technique). New manufacturing process designs can also reduce strategic materials needs in some applications, However, these savings are rarely the primary motivation for process development or implementation and are not realized if greater cost or performance advantages lie with other processes. As a national strategy to reduce U.S. dependency on imported materials, product or process design modification can only be successful if design engineers can be convinced to include strategic materials savings as an important objective in design decisions.

Substitution as an Emergency Response to a Supply Problem

To a certain extent, already developed, on-the-shelf substitute materials and technologies can be relied upon in an emergency to conserve materials that are in short supply. As discussed in chapter 3, substitutes for strategic materials in many applications are often available, though not necessarily readily recognizable as such. Alternative materials could be used in these applications with low (or at least tolerable) penalties in performance and cost. The material saved through these measures would then be available for use in critical applications where higher or unacceptable penalties are associated with substitution.

The existence of technically and economically viable substitutes is not the only requirement for a timely response to a supply emergency. For many critical applications, a new material must be tested and its use in a particular component must be qualified (accepted by the consumer) and certified (shown by the producer to meet the consumer's requirements). Thus, immediate response is limited to those materials that are already in (or very close to) commercial use, and to applications that do not have stringent materials requirements or for which the material has been certified and qualified. The substitution response by U.S. industry to prior supply problems involving strategic materials is discussed in chapter 4.

The current ability of U.S. industry to respond to a supply problem with substitution is not known with any degree of certainty. Although a large backlog of alternative materials and technologies is generally conceded to exist, information about many of these potential substitutes has not been assembled in a systematic way which would be accessible to designers, material users, and decisionmakers in an emergency. Development of a substitution data bank or a materials information system that would bring available substitutes to the attention of engineers and designers is one frequently proposed means for reducing U.S. vulnerability to an import curtailment. This concept is discussed further in chapter 8.

Substitution as a Continuing Strategy for Reducing Import Vulnerability

Besides being an emergency response, substitution can also play a key role in long-term strategies to reduce dependency on imported materials. During the last decade, there has been much research focused on development of substitute materials that could reduce strategic material requirements for many alloys currently used in key applications. Other research has been aimed at development and commercialization of advanced materials (e.g., ceramics and composites) which may displace use of strategic materials in some applications.

Although many technically promising substitutes are under development, the extent to which they will be adopted by U.S. industry is difficult to foresee, In the absence of an immediate availability problem, industry's adoption of new materials, designs, and manufacturing technologies is usually not motivated by concerns about strategic materials availability. Generally, the new technologies will be used only if they offer some more immediate benefit such as reduced costs, increased outputs, improved product performance, or potential new products.

A successful long-term strategy for reducing U.S. vulnerability to imported materials through substitution depends not only on the technical feasibility of alternative materials but on acceptance of them as practical alternatives by industry. Acceptance comes only when the technical and/or economic benefits have been clearly demonstrated, various institutional barriers have been surmounted, and a high degree of designer and end-user confidence has been established.

Factors Affecting the Viability of Substitution

Technical Factors

Over time, a backlog of proven, on-the-shelf materials and technologies have been developed that for one reason or another have not been adopted by industry, Research and development (R&D) efforts by public and private agencies throughout the world are adding to this store of potential substitutes almost daily. Only a few of these are likely to be adopted by industry at any given time.

Technological barriers to strategic materials substitution can be time-consuming and formidable, especially for applications in which little or no compromise in performance is acceptable, Even when a promising substitute is developed in the laboratory, new and significant technical problems may be encountered when large-scale tests are undertaken to verify laboratory findings, Often, a return to basic research is required to overcome these scale-up problems. Additional technical problems may be encountered when full-scale industrial production is begun.

Economic Factors

The technical potential of substitution to reduce strategic materials requirements is far greater than what is economically feasible. Industry will not adopt technically promising alternative materials unless they are cost-effective compared with current materials. Often, the cost effectiveness of using the current material is not greatly affected by price increases in strategic raw materials. In fact, the prices of raw materials can be such a small part of the cost picture that they are relatively unimportant in a substitution decision. For example, raw materials account for only about 1 percent of the cost of a jet engine, Even platinum group metals (PGMs), which cost between $100 and $400 per troy ounce, account for less than 5 percent of the cost of products manufactured with PGM catalysts. Therefore, all else being equal, a change in the cost of raw materials often has to be dramatic to warrant the expense of shifting to a substitute material. Adoption of a new material may require costly new equipment or changes in operations. There are also costs associated with change itself—for training workers in the use of a new material or process, for changing the design of products, and for adjusting manufacturing practices.

Institutional Factors

An alternative material may take a decade or more to bring to commercial fruition, even after the technical and economic feasibility of the substitute has been demonstrated. Government, industry, academia, professional societies, and standard-setting organizations may all play roles in this process, depending on the material and its application.

Substitution R&D relevant to strategic materials is conducted in government, industrial, and academic laboratories. Since most of the support for this work has come from the government, funding of the projects is subject to shifting governmental budgetary priorities and may not be sustained for the protracted period needed to adequately demonstrate the technical potential of a material or its application. Also, government conducted or sponsored R&D can suffer from insufficient industrial interest in commercializing a material,

Industry, the group which ultimately decides whether or not substitutes are adopted, usually does not commit the funds, time, and effort necessary to develop and qualify substitutes for strategic materials unless such activities also provide cost or performance advantages. Private firms often do not perceive national materials availability and vulnerability as problems that they have a major role in remedying, Availability concerns are usually not immediate enough to cause much corporate concern. Table 7-2 illustrates the representative R&D priorities by government and industry.

Standard-setting and professional organizations play key institutional roles in the development process by testing new materials and developing standards for their use. Often, test-

Table 7-2.—Primary Motivations for Substitution R&D

	Industry	Government
Reduced import dependency		x
Cost advantage	x	
Better performance	x	
New market penetration	x	
Materials conservation		x
Maintenance of national industrial competitiveness		x

SOURCE: Office of Technology Assessment,

ing and standard-setting are done by volunteers from professional societies, with limited resources and time to dedicate to the effort. In other instances, such as the qualification of a new superalloy for jet engine use, testing and qualification is undertaken by an individual firm on a proprietary basis. The effort may have to be duplicated by others if the material is to be used broadly. In many cases, several years of effort—and millions of dollars—may be entailed in testing and qualifying a new material for use in a critical application.

Designer and End-User Acceptance

Acceptance by designers and end users can be the highest hurdle in the adoption of a substitute. These groups sometimes have been indifferent to the need to save strategic materials. A heightened awareness of the importance of design to strategic materials vulnerability may be able to reverse this indifference,

Substitutes are adopted only when component designers and end users have acquired a high degree of confidence in the technical capabilities and economic potential of the new technologies. These materials users will not use any substitute technology with which they are uncomfortable; they are reluctant to make changes, especially if the new designs or replacement materials are relatively untried, Substitution in critical applications often requires a degree of confidence or comfort with the new material or design that can only come from a proven track record. Consequently, promising substitutes are often introduced first into noncritical applications where confidence can be gained without fear of catastrophic failures.

These acceptance hurdles can be especially high for advanced materials. Since many advanced materials are relatively recent developments, they are still fighting to establish a track record, This situation is exacerbated by the fact that most designers receive little formal training in the use of advanced materials,

Summary of Substitution Prospects

On-the-shelf substitutes, which could be adopted by industry relatively quickly, enhance U.S. preparedness to deal with import problems. It has been estimated, for example, that immediately available substitutes could replace one-third of the chromium now used. There are also fully developed substitutes for cobalt and PGM in some applications. Substitution prospects for manganese are less promising, although substantial reductions in the amount of manganese needed per ton of steel produced are likely in the coming years because of the upgrading of steelmaking processes, as discussed in chapter 6.

Industry response time depends in part on the ready availability of information about substitute materials. Technologically sophisticated firms are generally aware of available substitutes, and some are reported to have undertaken contingency planning to address future supply availability problems. Less sophisticated firms may have greater difficulties in obtaining such information in the event of an actual supply disruption, and, as a general rule, would have the greatest difficulty in competing for scarce materials.

Substitution prospects in many critical economic and defense applications depends partly on overcoming significant technical barriers. In these applications, substitutes must equal the performance of the materials already used, which is often technically difficult, Substitutes with low strategic material content have not yet been developed for some of these important applications. The degree of commitment needed to develop direct substitutes is substantial in both money and time. For applications which require that alternative materials be qualified, the development effort may take 10 or more years and several million dollars, even after their technical promise has been identified in the laboratory.

Industry has little incentive to develop substitutes on its own unless clear benefits in cost or performance are anticipated. As a result, the Federal Government has undertaken or sponsored most of the research where strategic materials savings, not cost or performance benefits, are given top priority. Several Federal agencies, including the Department of Energy (DOE), the Interior Department's Bureau of Mines, and NASA have sponsored research programs aimed at developing substitutes for strategic materials. However, the sustained support needed to develop particular materials to the point of commercialization generally has been lacking,

Substitution research programs undertaken by NASA, the Bureau of Mines, and DOE national laboratories have resulted in lower chromium research alloys that are potential substitutes for stainless steel in some applications. (Selected examples of these alloys are discussed in a subsequent section, and summarized in table 7-4,) Even if fully developed, most of these materials would not duplicate the great versatility of the high-volume stainless steels and would be capable of replacing stainless steels in only a limited range of applications.

With some exceptions, these substitutes are only in the initial stages of development. In most instances, a continuing government commitment will be required if these materials are to be fully developed, since private industry is unlikely to undertake this research itself. Issues surrounding possible additional Federal support for such development activities are discussed in chapter 8.

The Federal Government–especially NASA, through its Conservation of Strategic Aerospace Materials Program (COSAM)—has also sponsored initial laboratory work on replacement superalloys that have reduced levels of cobalt, These research materials could potentially reduce the cobalt now used in some nickel-based superalloys by one-half or more. However, full development of these replacement materials would require several more years and millions of dollars in additional funds. As with lower chromium stainless steel, subsequent development steps needed to bring these substitute superalloy to the point of commercial use probably will need to be federally supported if this development is to occur at all.

The changing material requirements of the aerospace industry may make it impractical to develop these direct substitutes for superalloys to the point of commercial use. The development steps required could entail 5 to 10 years of additional effort. Beginning in the mid-1990s, advanced superalloy materials may begin to be commercially used in the next generation of military aircraft. The direct substitutes now under development for currently used materials will not be suitable replacements for new materials used in the next generation of jet engines. (Less near- and medium-term change in materials is expected in the case of stainless steel.) Superalloy substitution research is discussed in greater detail in a subsequent section.

In addition to direct substitutes, advanced materials (including ceramics and composites) are also under development because their properties offer new possibilities in product design and performance. These materials, which contain little or no strategic metals, may have long-term implications for reducing import dependency, although to what extent is not clear. Because the emphasis is on cost and performance benefits, much of the development of advanced materials is carried out by private concerns.

Advanced ceramic materials have the potential to displace metals where exceptional wear-resistance or heat-resistance is required. Current and prospective advanced ceramic applications in which strategic materials are now used are discussed in a subsequent section, and summarized in table 7-II. Aerospace and automotive applications command most of the funds for ceramic R&D efforts.

Composites (including polymer matrix, metal matrix, and carbon/carbon materials) are primarily under development because of their lightness compared to conventional materials. In critical applications, their potential role in reducing strategic material requirements is likely to be indirect and will depend upon design factors. At present, commercial applications for advanced composites are dominated by aerospace applications and high-value sporting goods. Increased use of composites in automotive applications is predicted.

Strategic materials conservation is not a primary motivation in the development of advanced materials, and the potential of these materials for displacing current requirements for strategic materials should not be overemphasized. Nonetheless, in the long term, they may well bring fundamental changes in the overall mix of materials in the domestic and international economy. Major industrial countries including the United States, Japan, Great Britain, and several Western European countries are all vying for prospective markets for these materials. Moreover, because of their key importance in defense applications, the question of the adequacy of domestic processing capabilities with respect to these materials is likely to be an increasingly important issue. Processing capacity is often located in several different countries. The United States, for example, currently imports from Japan most of its high-quality polyacrylonitrile (PAN) used as a precursor in carbon-carbon composites. The international nature of these markets could create a new type of materials import dependency.

Prospects for Direct Substitution in Key Applications

Adequate substitutes exist for many applications in which strategic materials are now used. For example, aluminum alloys, plastics, and plated carbon steels already compete with stainless steels for many construction and consumer markets. In the event of a chromium supply disruption, these alternative materials would be readily available as substitutes for stainless steel in many nonessential applications where exceptional corrosion resistance is not needed. Similarly, if the supplies of PGM were to tighten, electronic components manufacturers could quickly substitute gold for much of the platinum and palladium now used for contacts. This is a case where raw materials prices are a significant part of the total product cost and can be counted on to drive substitution. Fifteen years ago, gold was the preferred material for contacts, but current prices favor platinum and palladium.

Materials substitution in many essential economic and defense uses is more difficult, however. Performance compromises are very costly in these cases, so the replacement must match or better the properties of the current material, There are very few, if any, immediately available replacement materials capable of meeting the demanding performance standards required for these applications. In some cases, adequate substitutes for the current materials have yet to be developed. In other cases, technically acceptable substitutes may be known, but are too expensive to be used. In still other cases, potential substitutes have been developed in the laboratory but have yet to be taken through the time-consuming and expensive testing processes necessary to make them acceptable for commercial use. Depending on the extent of the laboratory research and the promise shown by the results, some of these substitutes could be brought to the point of commercialization in the next 5 to 10 years, while others are unlikely to be developed fully.

Chromium Substitution in Stainless Steel

Stainless steel accounts for almost half of the total U.S. chromium demand, and about 70 percent of the chromium consumption in metallurgical uses. Table 7-3 shows the contribution of the highest volume stainless steel grades to chromium use. The most common grade, AISI **304,** alone accounts for over 40 percent of domestic stainless steel production and over 20 percent of total domestic chromium consumption. Although the chromium content of stainless steels varies from 10 to over 30 percent, on the average stainless steels contain about 17 percent chromium.

The primary function of chromium in stainless steel is to provide corrosion and oxidation resistance.[2] Chromium makes stainless steel highly resistant to damage in a large variety of environments. This characteristic, along with good fabricability and mechanical properties, is what makes stainless steel so attractive for a wide variety of applications, ranging from decorative trim, kitchen utensils, and other consumer products to industrial applications such as tubing and reaction vessels in powerplants and chemical processing facilities.

There is little chance that a universal substitute for stainless steel can be found for use in all of these applications. However, some opportunities exist for piecemeal substitution. The potential for reduced use of stainless steel (and thus chromium) in an emergency is very great in the decorative and consumer uses and low-temperature (room temperature to 900°F) industrial applications. Materials such as aluminum, titanium, plastics, and low-chromium stainless steels (9 to 12 percent chromium) can often substitute without serious performance compromises for stainless steels in these relatively undemanding uses. The possibilities for replacement in the industrial applications operating at higher than 900° F (500° C) is somewhat smaller. In some of the moderately severe (referring to both temperature and corrosiveness) industrial environments, steels with 12 to 15 percent chromium would suffice where high-chromium stainless grades (18 percent or more) are now used. This substitution opportunity exists because engineers often specify the common grades, which have better properties (and more chromium) than needed, in order to expedite the design process. In addition, there are low-chromium (e.g., 9 percent) or chromium-free steels now under development for use in these moderately harsh environments. Even considering these new alloys, re-

Table 7-3.—High-Volume Stainless Steels

AISI stainless steel grade	Percent of domestic stainless steel production	Typical chromium compositions	Percent of chromium consumed in stainless steel	Percent of total domestic chromium consumption
301	9.60/o	17.0%	9.4%	4.60/o
304	42.3	19.0	46.5	22.6
304N & 304L	4.0	19.0	4.4	2.1
316	3.6	17.0	3.5	1.7
316L	3.1	17.0	3.1	1.5
409	10.1	11.1	6.5	3.2
430	3.5	17.0	3.4	1.6
Other grades	23.9	NA	23.1	11.2
Total stainless	100.0 "/0	17,3"/0	100.0 "/0	48.50/o

[a] Includes chromium in metal, ferroalloys, and chromite

Columns may not add to totals because of rounding

NA = Not applicable, chromium compositions vary greatly among these stainless steels

SOURCE American Iron and Steel Institute, *Quarterly Production of Stainless and Heat Resisting Raw Steel*, publication AIS-I04(1983) and U S Bureau of Mines, *Minerals Yearbook,* Chromium Preprint (1982)

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[2] The protection from corrosion and oxidation damage comes from the chromium oxide skin that forms at the surfaces of stainless steels. Chromium concentrations of 12 percent or higher are required for the formation of the protective skin, but since corrosion and oxidation resistance increases with chromium content, much greater concentrations are often used. AISI 304 stainless steel contains 18 to 20 percent chromium, and some superstainless grades have chromium contents of 30 percent or more.

In addition to conferring corrosion and oxidation resistance, chromium improves the hardenability and stabilizes the austenite, the highly workable, ductile, and weldable microstructure found in the majority of stainless steel grades.

placement of the high-chromium stainless steels in extremely severe industrial applications, especially those at temperatures above 1,300° or 1,400° F (700° to 800° C) appears infeasible. Much of this currently irreplaceable demand for stainless steel is in critical defense applications, the chemical processing industry, and energy facilities such as powerplants and petroleum and natural gas refineries. These applications make full use of stainless steel's impressive high-temperature corrosion and oxidation resistance and strength.

According to a 1978 report by the National Materials Advisory Board (NMAB), in a supply emergency 60 percent of the chromium used in stainless steel could be saved through the use of low-or no-chromium substitutes that are either already available or could be developed within 10 years.[3] The other 40 percent of the chromium consumed in stainless steel was found to be irreplaceable unless compensated for by design or process improvements. This amount represents approximately 20 percent of the current total domestic chromium use.

Most research on reducing the use of chromium in stainless steels is sponsored by Federal agencies. The focus is on developing alternative alloys with lower chromium contents than those stainless steels in greatest demand (e.g., AISI 304,409, and 301) for use in moderately harsh industrial environments. In addition, R&D related to advanced surface treatment processes and ceramic and composite materials, though not motivated by chromium conservation, may uncover ways to reduce the use of stainless steel in some applications,

Low-Chromium or Chromium-Free Substitutes for Stainless Steels

Current commercial low-chromium steels are unsuitable as substitutes for stainless steel in critical applications. However, several low- or no-chromium alternatives for some grades of stainless steel are under development (table 7-4.) These new steels show promise for various moderately harsh environments but do not perform as well as high-chromium grades in extremely severe applications. Most are still at the laboratory stage of development, although some are now undergoing certification, The bulk of the research is being sponsored by Federal agencies, since private firms have little incentive at current chromium prices to develop low-chromium substitutes. (See ch. 3 for chromium price information.)

Low-chromium or chromium-free substitute alloys for the AISI 300 (austenitic) series stainless steels have received the greatest attention from researchers. Austenitic grades, most of which contain between 16 and 26 percent chromium, account for nearly 70 percent of domestic stainless steel production and for about 36 percent of all domestic chromium demand. Among this group is the very popular and versatile type 304. Excellent fabricability and mechanical properties, combined with corrosion and oxidation resistance in a wide range of environments, makes the 300 series stainless steels attractive for many applications, Unfortunately, the remarkable combination of properties that enables this great versatility is currently impossible to replicate, Consequently, a universal substitute for the entire 300 series (or even one of the particularly popular grades) is not a likely development, The promise of each of the substitutes tends to be very application- or environment-specific.

Examples of promising research on substitutes for 300 series stainless steels in moderately severe applications include:

- DOE's Oak Ridge National Laboratory development and promotion of a modified 9 percent chromium (Cr), 1 percent molybdenum (Me) steel [modified 9Cr-lMo alloy).[4] The initial objective of the laboratory was to develop a single reference material for intermediate sections of liquid metal fast breeder reactors, Currently, these reactors contain 18 percent chromium-8 percent

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[3] National Materials Advisory Board, Contingency Plans for Chromium Utilization, National Research Council, Commission on Sociotechnical Systems, Publication NMAB-335 [Washington D. C.: National Academy Press, 1978).

[4] Basically a standard 9Cr-1Mo alloy with additions of columbium and vanadium.

Table 7“4.—Oevelopment Status of Potential Substitutes That Could Reduce Chromium Requirements in Stainless Steel

Substitute material	Key objective	Technical status	Institutional sponsors	Economic factors and commercial status
1. Modified 9 % c hromium-1 % molybdenum steel.	Develop single material system to replace ferritic (2.25°/0 Cr) and austenitic (18°/0 Cr) steels used in pressure vessels and connecting tubing in liquid metal fast breeder reactors.	Fully developed; may also find use in fossil, solar thermal, and fusion energy systems,	Oak Ridge National Laboratory.	In process of certification by ASME boiler and pressure code committee. Cheaper than 18%Cr-8% Ni stainless for indicated uses; lack of industry sponsorship may slow commercialization.
2. 12°/0 chromium alternative to 18°/0 chromium 304 stainless steel.	Determine feasibility of reducing Cr use in type 304 stainless.	Mechanical properties and corrosion and oxidation resistance compare favorably with type 304 stainless.	NASA-Lewis Research Center.	Laboratory stage; initial work completed in 1979.
3. Iron aluminum molybdenum (Fe-8 °/O Al- 6°/o Mo) alloy strengthened by zirconium carbide (ZrC).	Develop chromium-free material for midtemperature oxidation-resistant application.	Early tests show excellent workability and oxidation resistance, ZrC strengthening mechanism could not be controlled reliably and needs additional work.	U.S. Bureau of Mines Albany Research Center.	Laboratory stage.
4. 9°/0 chromium austenitic alloys.	Determine if other alloying elements could replace part of the chromium in stainless steels.	Tests show corrosion resistance (in less severe environments), fabricability, weldability, and mechanical properties comparable to conventional stainless grades.	INCO under U.S. Bureau of Mines sponsorship.	Laboratory stage.
5. Theoretical method to develop low-chromium austenitic stainless steel compositions.	Develop a technical tool for devising low-chromium alloys with mechanical properties equivalent to those of type 304 stainless steel.	Modeling of alternative compositions has been undertaken. No test heats have been made.	Allegheny Ludlum Steel Corp.	Could add to the stockpile of information about substitutes, but work has yet to progress to the experimental stage.
6. Manganese-aluminum steel (Fe-M n-Al).	Develop general use alternative to chromium-nickel stainless steel.	Laboratory work shows that these alloys may be useful at cryogenic and moderate temperatures and various corrosive environments.	Studies are being conducted in many different laboratories.	Most work is still at the laboratory stage. Limited prototype testing is being done in other countries. May be cheaper than current stainless steels.
7. 6-12°/0 chromium ferritic steels.	Develop low-chromium oxidation-resistant ferritic stainless steels.	Oxidation and creep resistance are superior to type 409 stainless.	ARMCO (producer company).	Laboratory stage.

SOURCE Off Ice of Technology Assessment

nickel (Ni) (18 Cr-8Ni) alloys (e.g., AISI 304, 321, 347) in the reactor vessels and heat exchangers and a 2¼Cr-1Mo alloy in the steam generators. Use of a single material in these applications eliminates, among other problems, an undesirable dissimilar metal weld at the transition joints. The modified 9Cr-1Mo alloy was found to be a promising replacement for both types of materials. The encouraging results of the research suggest that this alloy may find use in conventional power applications, as well. Although it will replace both low- and high-chromium materials, modified 9Cr-1Mo will probably yield a net chromium savings. However, chromium conservation is a byproduct of this development effort, not a primary motivation. If this new material sees widespread use in the power industry, the resultant availability and designer acceptance may encourage its use in other low or moderately hostile applications now dominated by high-chromium materials.

Nearing commercialization, this modified 9Cr-1Mo alloy is being considered by the American Society for Testing of Materials (ASTM) and by the American Society of Mechanical Engineers (ASME) boiler and pressure vessel code committee for final certification. Since use of the material entails fabrication and inspection cost savings, as well as a materials cost reduction, prospects for successful substitution are good if it is approved[5,6] (table 7-4, item 1).

- NASA's comparison of the mechanical properties and oxidation and corrosion resistance of reduced chromium alloys with those of type 304. One steel, containing 12 percent chromium, 10 percent nickel, 1.5 percent silicon, 1 percent aluminum (Al), 2 percent molybdenum, and 2 percent manganese (Mn), demonstrated properties that compare favorably with 304 stainless steel and could be used for most applications (except nitric acid environments) where type 304 is currently used. This alloy conserves one-third of the chromium normally used in type 304 stainless steel[7] (table 7-4, item 2).
- The U.S. Bureau of Mines' investigation of a chromium-free iron-aluminum-molybdenum (Fe-Al-Mo) alloy as a potential substitute for high-chromium, heat-resistant alloys. An optimal composition for the alloy has yet to be developed, but early findings suggest that the chromium-free alloy may resist oxidation at moderate temperatures to an extent comparable to 300 series stainless[8,9] (table 7-4, item 3).
- The Bureau of Mines' work on reduced-chromium substitutes for high-performance stainless steels (e.g., type 310 with 25 percent chromium) used in elevated-temperature, severely corrosive environments, Steels containing chromium (12 to 17 percent), nickel, and aluminum are being studied in this program. The Albany Research Center of the Bureau of Mines has been successful in reducing the chromium content to 12 percent. One 12 percent chromium substitute has about three times the sulfidation-resistance of, and approximately equivalent mechanical properties to type 310 stainless steel.[10]
- The Bureau of Mines' study of low-chromium stainless steels for high-temperature, oxidation-resistant applications. Research has shown that steels having 8 to 12 percent chromium with additions of aluminum and silicon can have excellent oxidation-resistance and mechanical properties (to 800° C), These alloys are potential substitutes for 18Cr-8Ni stainless steels in

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[5] Robert R. Irving, "What's This Steel They're Raving About Down in Tennessee?" *Iron* Age, June 25, 1982,

[6] V. K. Sikka and P. Patriarca, Data Package for *Modified 9Cr-1Mo Alloy* (Oak Ridge, TN: Oak Ridge National Laboratory, December 1983).

[7] Joseph R. Stephens, Charles A. Barrett, and Charles A. Gyorgak, "Mechanical Properties and Oxidation and Corrosion Resistance of Reduced-Chromium 304 Stainless Steel Alloy s," NASA Technical Paper 1557, November 1979.

[8] J. S. Dunning, An iron-Aluminum-Molybdenum *Alloy* as a Chromium-Free Stainless *Steel* Substitute, U.S. Department of the Interior, Bureau of Mines Report of Investigations 8654 (Washington, DC: U.S. Government Printing Office, 1982).

[9] J. S. Dunning, M. L. Glenn, and H. W. Leavenworth, "Substitutes for Chromium in Stainless Steel s," *Metal* Progress, October 1984, p. 23.

[10] Ibid., p. 23.

some applications. Further long-range research to qualify other important properties such as high-temperature stability, weldability, and age-hardening characteristics is underway.[11]

- Research sponsored by the Bureau of Mines at the Inco Alloy Products Research Center aimed at replacing some of the chromium now needed for stainless steels used in corrosive environments. The findings suggest that it may be feasible, with additions of nickel, molybdenum, copper, and vanadium, to produce 9 percent chromium austenitic stainless steels with corrosion resistance, hot working behavior, weldability, and mechanical properties comparable to those of conventional grades. These low-chromium alloys, while not adequate for more severe environments, could be used in decorative, aqueous, and some industrial applications" (table 7-4 item 3).
- Allegheny Ludlum Steel Corp. Research Center's development of a theoretical model for devising new reduced chromium alloys that would duplicate the excellent mechanical properties of type 304 stainless steel, although not its corrosion resistance. Actual alloys have not been developed from these theoretical compositions, which range from 6 to 16 percent chromium, but some of them could be suitable as substitutes in noncritical applications[13] (table 7-4 item 5).
- Various researchers' work with iron-manganese-aluminum (Fe-Mn-Al) steels. The Fe-Mn-Al steels contain no chromium, but may consist of up to one-third manganese, another strategic material. The high aluminum content of the Fe-Mn-Al steels provides oxidation resistance, Though most of the work is still preliminary, these alloys show promise as replacements for 300 series (chromium-nickel) stainless steels in some moderately corrosive environments. With heat treatment, the Fe-Mn-Al steels demonstrate excellent mechanical properties, in some cases as good as or better than type 304. In addition, they are 10 percent lighter (and have greater strength-to-weight ratios) than nickel-chromium stainless steels, Though the economics depend on the relative costs of manganese, aluminum, chromium, and nickel and the size of the production runs, Fe-Mn-Al alloys are likely to be less costly than 300 series grades[14][15] (table 7-4, item 6).

Photo credit: US. Department of the Interior, Bureau of Mines

An 80-pound heat of an experimental low-chromium stainless steel is poured into a split steel mold at the Bureau of Mines, Albany Research Center

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[11] Ibid., p. 23.

[12] S. Floreen, "An Examination of Chromium Substitution in Stainless Steels, " Metallurgical Transactions A, November 1982.

[13] R. A. Lula, "Potential Areas for Chromium Conservation in Stainless Steels, " in Technical Aspects of Critical Materials Use by the Steel Industry, vol. 11A, NBSIR 83-2679-2 (Washington, DC: U.S. Government Printing Office, June 1983).

[14] Samir K. Banerji, "The 1982 Status Report on Fe-Mn-Al Steels, " as cited in Technical Aspects of Critical Materials Use by the Steel Industry, " vol. IIB, NBSIR 83-2679-2, June 1983.

[15] Rosie Wang, "New Stainless Alloy is Less Costly, " American Metal Market, Sept. 19, 1983,

Information requirements for stainless steel substitutes are under evaluation by the Metal Properties Council, Inc. (MPC), an organization set up by industry and technical societies in 1966 to provide engineering data on materials, MPC established a Task Group on Critical Materials Substitution in 1981. An initial MPC task group report,[16] issued in 1983, noted a gap on the technical information about alternative low-chromium compositions for stainless steel. Most of the available data was from laboratory investigations, with little information developed about processing and fabrication of these compositions, or about how they held up in service environments—essential information if industry were to use these substitutes during a protracted supply shortage. Subsequently, MPC has decided to focus on chromium substitution options for 18 percent chromium-8 percent nickel stainless steels used in room-temperature to moderately high-temperature (up to 1,2000 F) applications.[17] These applications comprise the highest volume uses for stainless steels, including many for which a decrease in corrosion resistance may be acceptable to some consumers in times of a supply shortage. MPC is now evaluating future steps, such as developing alternative compositions that duplicate all metallurgical and mechanical properties of the popular grades of steel, except corrosion resistance. MPC is preparing a survey to gain input from industry.

The AISI 400 series, accounting for about 20 percent of domestic stainless steel production, is the second largest class of stainless steels. Type 409, which contains approximately 11 percent chromium, is the second most popular stainless steel. It accounts for about half the production of 400 series grades and is used principally in the catalytic converter housings in automotive exhaust systems.

ARMCO is exploring several lower chromium alternatives to ferritic (400 series) stainless steels containing 12 percent chromium, These new alloys, still at the laboratory stage, may be promising substitutes for stainless steel used in the catalytic converter shell of automobiles, ARMCO reports that its 6.6 percent chromium alloy 6SR (scale resistant) is more oxidation- and creep-resistant than 409 stainless steel. Unlike, the other substitutes described above, the SR alloys (which also include 12SR, a potential 12 percent chromium substitute for some 18 percent chromium grades) are being researched in the producer industry. As a result, the institutional barriers to the acceptance of these SR alloys are relatively low[18] (table 7-4, item 7),

These substitutes are all in various stages of development. Other than the modified 9Cr-1Mo alloy, which is undergoing certification, the replacement alloys have not yet advanced beyond the laboratory level of investigation in the United States. The development of the chromium-free substitutes, such as the ferritic Fe-Al-Mo and the austenitic Fe-Mn-Al alloys, designed for elevated-temperature oxidation / corrosion-resistant service, probably involve the longest range, highest risk research. The low-chromium alloys also require additional study, but technical success is in general less speculative, Extensive additional testing of mechanical properties, phase stability, and other physical properties of any of the newly designed alloys, as well as ease of processing, could take several years. Even if these alloys overcome the initial hurdles, economic feasibility will remain in question. Without large markets in place, these alloys cannot be produced cheaply enough (due to poor economies of scale) to compete effectively with the current high-volume stainless steel products.

Advanced Surface Treatment Technologies and Processes

Most of the chromium in stainless steel is present solely for corrosion and oxidation resistance. Chromium's secondary roles can be met with the use of other alloying elements or processing techniques. Since corrosion and oxidation resistance is only needed at the surface, the chromium on the interior of the stainless

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[16] The Metal Properties Council, Inc., "Task Group on Critical Materials" (New York: The Metal Properties Council, Inc., 1983).

[17] Private communication with R. A. Lula and officials of the MPC.

[18] Joseph A. Douthett, "Substitute Stainless Steels With Less Chromium, " in Conservation and Substitution Technology *for* Critical Materials, vol. I, NBSIR 82-2495 (Springfield, VA: National Technical Information Service, April 1982).

steel is nonessential, Surface modification techniques can endow low- or no-chromium materials with corrosion and oxidation resistance sufficient to substitute for stainless steels in some applications, Advanced surface treatment techniques may also improve wear resistance, thus extending product life.

Existing fully developed surface treatment technologies—e.g., plating steels with chromium, nickel, cadmium, or zinc or welding a stainless steel overlay to nonchromium alloys—have been used for decades in a large number of applications, but there are constraints in their use. Fabricated parts and brittle metals cannot be clad, for example, and clad materials are difficult to weld. Claddings sometimes separate from the base metal, with potentially disastrous results.

A number of advanced processes now under development or in the early stages of commercialization may broaden applications for surface treatment. One advanced coating technique that can compete directly with stainless steels in some applications is the DILEX process, This technique involves the diffusion of chromium (or other elements) into the surface of a ferrous part that is placed in a lead bath. The surface alloy typically contains 25 percent or more chromium (and possesses excellent corrosion and oxidation resistance), while the underlying substrate contains little chromium. The cost of continuously processed DILEX strips is currently competitive with stainless steel products. In addition, parts and components that are difficult to fabricate from stainless steel can sometimes be produced more easily with the DILEX process.[19]

Surface alloying with lasers (by processes commonly referred to by their United Technologies trade names, LASERGLAZING and LAYERGLAZING) can provide corrosion and oxidation protection and wear resistance to materials. LASERGLAZING can improve erosion and corrosion properties through elimination of surface porosity, and can produce a wear-resistant surface that could extend the life of steels used in metal cutting and grinding. LAYERGLAZING can be used to build entire parts (e. g., turbine discs) through continuous melting of very thin layers of alloy at the surface. Such processes permit tight control over the composition of the alloy and can also reduce part rejections, since flaws detected in processing can be reglazed immediately. While laser techniques have impressive capabilities, these processes are not presently as cost effective as some of the more established surface modification practices, such as roll bonding.

A recent technological advance, ion implantation, holds long-term promise as a way of improving the wear- and corrosion-resistance of parts, thus helping conserve strategic materials through extending product life or reducing the need for chromium in corrosion-resistant applications. In ion implantation, high-energy ions of alloying elements are embedded into the surface of the workpiece to produce a surface layer of 100 to 1,000 angstroms that is an integral part of the substrate. Advantages of this technique include excellent coating-substrate adhesion (owing to the lack of a sharp boundary between the two), no dimensional alteration of the substrate, and low processing temperatures. Elements such as carbon, nitrogen, chromium, and nickel can be implanted, but the resulting properties are not as dependent on the type of ion as on the mechanical deformation it causes to the matrix surface. Therefore, the choice of an ion is based on its mechanical effect in the host material, not on its own inherent corrosion- or oxidation-resistant properties.[20]

Ion implantation has been shown to extend the life of cobalt-based cemented carbides and tool steels when carbon and / or nitrogen are applied. Implantation of yttrium in diesel fuel injection pumps reportedly dramatically improves wear resistance in comparison with chrome plating. Bureau of Mines-supported research has shown that ion implantation can

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[19] Ray J, Van Thyne, "Conservation of Critical Metals Utilizing Surface Alloy ing, ' 'as cited in *Conservation and Substitution Technology for Critical Materials*, vol. II, NBSIR 82-2495, April 1982.

[20] Charles River Associates, *New Metals Processing Technologies*, OTA contract report, December 1983, p. 46.

protect plain carbon steels against mild aqueous corrosion.

Ion implantation techniques, first developed in Great Britain, are fully commercialized in the semiconductor industry. For metallurgical applications, ion implantation is at the operational prototype stage—commercial machines are being developed, but there has been little market penetration.[21] Substantial technical and economic constraints impede its use for large-volume metallurgical uses. To be effective in providing corrosion resistance, ionic density must be much greater than in semiconductor applications. Commercial equipment capable of handling this higher beam density has yet to be developed and appears to be prohibitively expensive at this time. High capital costs and limited product size and production rates are key constraints acting against this technique's widespread use.

All surface treatment techniques have drawbacks, If the surface layer fails, the exposed substrate would be vulnerable to corrosion. Fabrication and construction with surface-treated materials is more difficult and costly than with monolithic materials. Special welding and joining techniques must be used to assure that the base material does not become exposed, Edges of the material must be treated to maintain protection. These welding and joining techniques are subject to separate research and development efforts. In addition, surface treatment can be very expensive, so there are major efforts aimed at improving the process economics of these techniques.

Surface treatments also face nontechnical and noneconomic hurdles, Designers and consumers often resist use of surface modification processes in new applications where solid monolithic alloys perform satisfactorily.

Chromium Substitution in Alloy Steels

About 15 percent of U.S. metallurgical chromium (10 percent of total domestic chromium) is consumed in alloy steels, Chromium is used in these steels primarily as a hardening agent. Although other elements, such as molybdenum, silicon, and nickel, can be used for this purpose, chromium and manganese are currently the most cost-effective hardenability enhancers, Because chromium's hardenability characteristics are more easily replicated than its corrosion and oxidation attributes, fewer technical problems exist in developing adequate substitutes for alloy steels than for stainless steels. In its 1978 Chromium Utilization study, the NMAB concluded that 80 percent of the chromium used in alloy steels could be replaced either now or after a short-term R&D effort.

The chromium contents of alloy steels typically range from less than 1 to 4 percent, although some grades have as much as 9 percent. Compared to carbon steels, these steels have improved strength, wear resistance, and hardenability. They are chosen when parts (e.g., bearings, gears, shafts) will be highly stressed over a long service life.

Several alternative chromium-free alloy compositions are under investigation as substitutes for large-volume alloy steels. These alloys have been designed to duplicate the most important properties of the steels they would replace, so that processing changes and design changes could be minimized if they were to be used as replacement steels.

Work at the International Harvester Co., sponsored by the Bureau of Mines, was aimed at the design of chromium-free substitutes for two alloy steels that together account for about 60 percent of the chromium used in constructional alloys, or about 6 percent of total U.S. chromium demand. These Cr-Mo grades (AISI 4100 series) and the Ni-Cr-Mo grades (8600 series) have been used for decades, and as a result, current designs for parts and manufacturing processes are adapted to these steels. The chromium in these grades was substituted with

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[21] Carnegie-Mellon University, Department of Engineering and Public Policy, Department of Social Sciences, and School of Urban and Public Affairs, The Potential of Surface Treatment Technologies in Reducing U.S. Vulnerability to Strategic Materials, Pittsburgh, PA, April 1984.

manganese, molybdenum, and nickel. Silicon, another common hardening agent, was not used because alloy steel producers have little experience with the high silicon levels (0,6 percent Si) required to achieve the desired hardenability. The compositions of the Mn-Ni-Mo and Mn-Mo replacement steels are shown in table 7-5.

To minimize the disruption entailed in shifting to new steels, the new chromium-free steels were designed to be produced using prevalent U.S. production practices. Moreover, the experimental substitutes have the same microstructure, heat treatment response, and mechanical properties as the steels they would replace, and therefore would provide equivalent engineering performance. So far, actual production of these steels has been limited to 100-pound” experimental test heats, thus the steels’ characteristics in large-scale commercial production have not been demonstrated.

The second phase of this program—to produce larger heats for testing–was delayed, owing to the financial status of the contractor. However, in 1984 the Bureau released a request for proposal which calls for about a 3,000-pound test heat. When completed, this phase of the program will provide better information for the possible transfer of this technology to industry.

In the original economic analysis (based on 1981 raw materials costs), these steels were not found to be cost effective. However, the Mn-Mo replacement for the 8600 series steels may become economical with the moderate chromium price increases that would be expected under steady economic and political conditions. The other replacements (Mn-Ni-Mo for 8600 and both Mn-Ni-Mo and Mn-Mo for 4100) would become economical only with the drastic price increases (on the order of tenfold for chromium ore and fourfold for ferrochromium) that would accompany severe chromium supply disruptions, such as a complete cutoff from South African supplies. To facilitate their use in such an emergency, the researchers recommended additional testing of these steels to determine equivalency of these steels under typical production practices by U.S. producers.[22]

Development of these alternative steels was facilitated through International Harvester’s CHAT (Computer Harmonizing Applications Tailored) system, which first identifies metallurgical properties needed for particular parts and then selects the least-cost alternatives from AISI and SAE steels that are available. Use of computerized information systems of this sort could facilitate the development of a strategic materials substitution information system that could be used in an emergency.

Reducing Cobalt and Chromium Used in Superalloy for High-Temperature Applications

Superalloys, used in jet engines, industrial gas turbines, and a widening spectrum of other industrial applications, account for 30 to 40

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[22] Carl J. Keith and V. K. Sharma, Development of *Chromium-Free* Grades of Constructional Alloy *Steels*, U.S. Department of the Interior, Bureau of Mines’ contract No. J01 13104, May 1983.

Table 7-5.—Ladle Analysis Ranges for the Chrome-Free Replacement Compositions for Standard 4118 and 8620 Steels (in percent)

	4100 type steel			8600 type steel		
Chemistry ladle range	AISI-4118 steel	Mn-Ni-Mo replacement	Mn-Mo replacement	AISI-8620 steel	Mn-Ni-Mo replacement	Mn-Mo replacement
Carbon.	0.18-0.23	0.16-0.21	0.16-0.21	0.18-0.23	0.16-0.21	0.16-0.21
Manganese	0.70	0.90	1.00-1.30	0.70-0.90	1.00-1.30	1.00-1.30
Chromium	0.40-0.60	r	r	0.40-0.60	r	r
Nickel	r	0.20-0.40	r	0.40-0.70	0.40-0.70	r
Molybdenum	0.08-0.15	0.15-0.25	0.25-0.35	0.15-0.25	0.25-0.35	0.35-0.45

r— residual

silicon range = 0. 15-().35°/0, sulfur = O 05°/0 maximum, phosphorus = 0.04°/0 maximum

SOURCE Carl J. Keith and V K Sharma, *Development of Chromium-Free Grades of Constructional Alloy Steels*, U S. Bureau of *Mines* contract No J01 13104, May 1983 percent of U.S. cobalt consumption. Only a small portion of U.S. chromium consumption goes into superalloys—about 3 percent in 1982. This amount is in the form of highly purified ferrochromium and chromium metal. Other materials used in superalloys include nickel, aluminum, titanium, and a number of minor alloying elements, including columbium (niobium) and tantalum—two second-tier strategic materials for which the United States is import-dependent.

While many superalloys do not contain cobalt, the use of cobalt has increased over time because it improves the weldability of some superalloys, contributes to their strength, and also enhances oxidation and corrosion resistance. Chromium is currently essential in all superalloy.

Importance of Superalloy to the Aerospace Industry

Improved jet engine performance has been highly dependent on development of new superalloys[23] that extend the maximum operating temperature of the engine yet are still able to withstand the high mechanical and thermal stress, oxidation, and hot corrosion that occurs in the hot section parts of a jet engine. Through complex adjustments in composition and processing, the temperature capability of superalloy has been extended from about 1,4000 F in 1940 to about 1,9500 F today (some superalloys now in use have operating temperatures of about 2,100° F), as shown in figure 7-1. In addition, the required life of various components (the minimum predictable time before overhaul or replacement) has also increased significant y.

Each individual component in the hot section of a jet engine, such as turbine blades, vanes, and discs, requires a superalloy with a different range of properties—so that development of an adequate substitute for one part does not mean that it can also substitute for other parts, In addition, each of the U.S. jet engine manufacturers maintain separate specifications for superalloy that can be used in each part. Today, there are well over 100 superalloys used domestically, but some of these may be certified for use only by one engine manufacturer, Table 7-6 shows representative superalloys used in the different parts of the hot sections of current jet engines,

As superalloy have become more specialized, their costs have escalated, so that it often takes a decade or more and several million dollars to bring a promising new alloy even to the engine testing stage. Initial development of a new superalloy in the laboratory for disc or blade applications constitutes only part of the total effort. Prior to engine qualification and use, a complete design data base, specifications and standards, component and machine testing, and commercial-scale heats must be demonstrated, Without a pressing need for substitutes, industry alone is unlikely to make this kind of commitment.

Substitution Prospects

From the standpoint of reducing U.S. vulnerability, backing out or reducing cobalt and chromium use in superalloy would be highly desirable–but only if they could be achieved without impairing the push toward higher performance in military applications. Continued increase in performance is the primary objective behind most government and industrial research aimed at developing new hot-section materials, although many of these materials could have the side benefit of reducing strategic materials requirements. Figure 7-2 shows NASA estimates of the approximate date for introduction of some of these higher temperature materials in aircraft. These materials are discussed later in this chapter.

Superalloys will almost certainly remain the primary structural material in turbine blades

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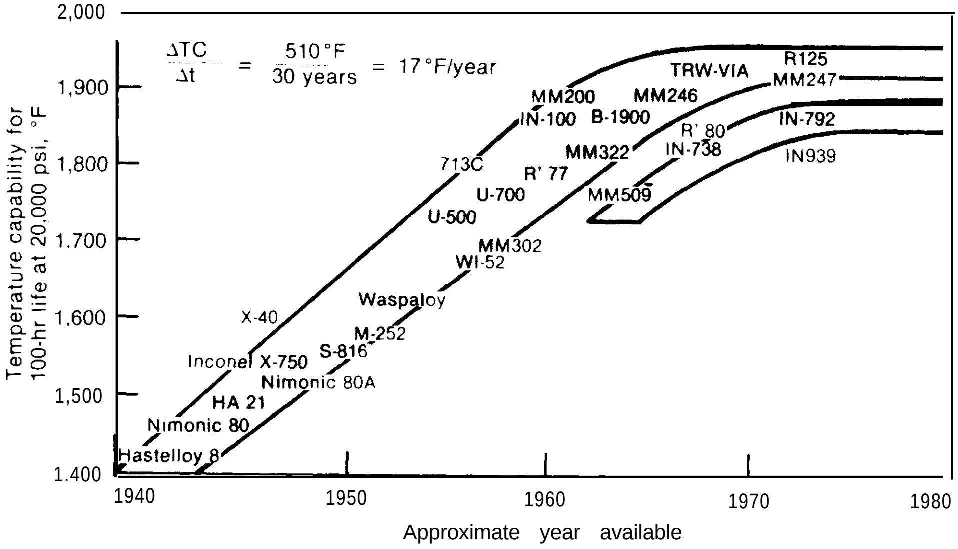
[23] The analysis of superalloy substitution potential in this section is drawn in large part from Richard C. H. Parkinson, Substitution *for Cobalt* and Chromium in the *Aircraft* Gas Turbine Engine, OTA staff background paper, September 1983. It should be noted that superalloy use is spreading to many nonaerospace applications, such as oil country tubulars, heavy duty tooling, pulp and paper production, medical and dental uses, and glass manufacture. In these applications, superalloy were substituted for other materials that could again be used in an emergency, although possibly with some performance costs. In the case of gas turbine engines used in jet aircraft, however, alternatives to superalloy are not currently available, and moreover are not likely to be developed in this century. Thus, aerospace uses remain the most demanding and critical superalloy applications.

Figure 7-1 .—Temperature Capability of Superalloy



SOURCE Garrett Turbine Engine Co

for at least the next 20 to 30 years. During this period, complete elimination of cobalt and chromium in jet engines is highly unlikely, although use of alternate alloys, wider use of coatings, and adoption of more efficient processing technologies could reduce use of these materials in individual applications.

In the long term, probably not before the second decade of the next century, a variety of nonmetallic materials (e. g., advanced ceramics and carbon-carbon composites) may be developed sufficiently to be widely used in some hot-section parts of human-rated jet engines. If so, chromium, cobalt, and other metals then may begin to be phased out of jet engines. Actual production dates for the first engines containing significant amounts of nonmetallic materials is likely to be well beyond the year 2000.

In the sections that follow, near-term (to 1990), medium-term (1990 to 2000), and long-term prospects for reduced chromium and cobalt usage in jet engines are selectively discussed, under the assumption that R&D efforts continue at approximately their present levels. Institutional factors that could affect the extent to which various substitution potentials are adopted are discussed in the concluding section of this chapter.

Near-Term Prospects for Cobalt Substitution (to 1990)

Cobalt supply insecurities in the late 1970s led U.S. jet engine makers to substitute already developed nickel-base superalloy for cobalt-base alloys wherever possible. A conspicuous example of this was the substitution of the already developed and qualified cobalt-free superalloy Inconel 718 for Waspaloy (13 percent cobalt) in turbine disk applications below 7000 C. Inconel 718, which contains a large amount of niobium, a strategic material imported largely from Brazil, continues to be used in these applications owing to its comparative cheapness and ease of fabrication. Other superalloy substitutions included replacement of cobalt-base vanes with cobalt-free nickel-base superalloy.

Cobalt prices are unlikely to stimulate further substitution in the near term. Easy to accomplish substitutions have already taken place, As a practical matter, adoption of lower chromium or cobalt substitutes by engine makers is not likely unless substantial improvements in properties, higher temperature capabilities, or ease in fabrication accrue, as well.

Processing Advances.—As a result, the greatest opportunities for cobalt and chromium conser-

Table 7-6.—Typical Structural Alloys Used for Hot-Section Components

		Composition (percent weight)					Nominal operating conditions	
Component	Alloy	Ni	co	Cr	Fe	Form	Stress	Surface temperature (oF)
						—Large grains—		
Combuster liner	Hastelloy X	48	1 5	*22*	18.5	Sheet	Low	1600
	HA-188	22	41	*22*	—	Sheet	Low	1600
						—Large grains—		
Turbine valve	MA-754	78	—	20	1	ODS + HIP, ODS + forge		1900+
	MAR-M 200	60	10	9	—	DS		1900
	MAR-M 247	60	10	8	—	CC, DS	Moderate 10 low	1800-1850
	MAR-M509	**10**	*55*	23.5	—	cc		1800 +
	X-40	105	*56*	25.5	—	cc		1800 +
	IN-713	72.5	—	13.5	—	cc		1600
	Rene-77	55	*15*	15	—	cc		1600
						–Large grains–		
Turbine blade	Alloy 454	*62.5*	*5*	10	—	se		1900
	MAR-M200	*60*	10	9	—	DS		1850
	MAR-M247	*60*	10	8	—	CC, DS		1800-1850
	B-1900	*65*	10	8	—	DS	High	1800
	Rene-80	*60.5*	9 5	14	—	cc		1750
	IN-713LC	*72.3*	—	12	—	cc		1600
	Rene-77	*55*	15	15	—	cc	1600	
						–Small grains–	–Rim	temperature–
Turbine disc.	IN-100	56	18,5	12.5	—	PM +HIP, PM +forged		1300
	MERL-76	54.1	18,5	12.4	—	PM +HIP, PM +forged		1300
	Astroloy	55.5	17	15	—	PM +HIP, PM +forged, forged		1300
	Waspaloy	*58*	13,5	19.5	—	Forged		1250
	Rene-95	*61.3*	9	14	—	PM +forged	High	1200
	IN-718	*53*	—	19	18	Forged		1200
	IN-901	*45*	—	12.5	**34**	Forged		1100
	A-286	*25.5*	—	15	55	Forged		1000
						–Small grains–		
Case	Waspaloy	*58*	13.5	19,5	—	Sheet, forged		1300
	IN-718	*53*	—	19	**18**	Sheet, CC, forged	High	1200
	IN-901	*45*	—	12.5	**34**	Forged		1100
	A-286	*25.5*	—	15	**55**	Forged		1000

NOTES: CC—Conventionally cast.
DS—Cast and directionally solidified polycrystal.
SC—Case and directionally solidified single crystal.
PM—Powder metallurgy.
ODS—Oxide dispersion strengthened.
HIP—Hot-isostatic pressing.
Alloy base compositions are shown in boldface type

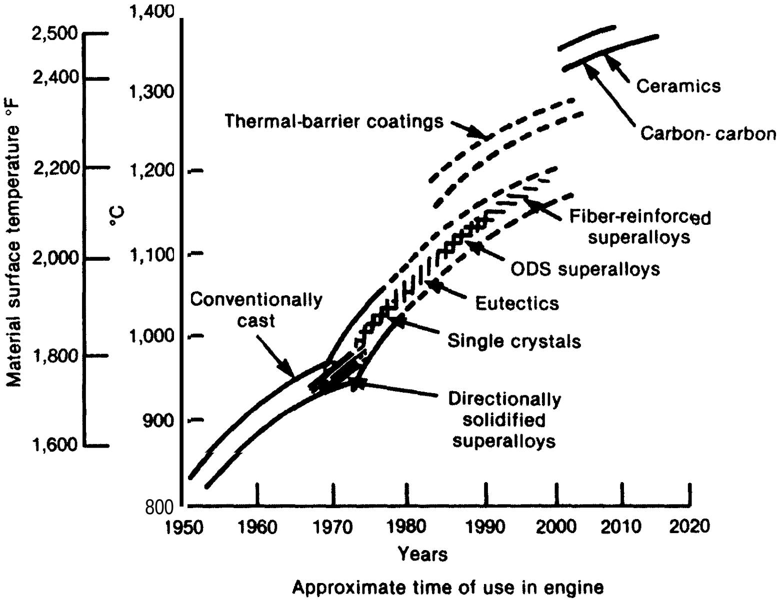
SOURCE: Office of Technology Assessment.

vation in superalloys in the near term lie in continued commercialization of advanced processing technologies, which have the incidental effect of improving cobalt or chromium yields in parts or of extending the life of components.

Several of these new metals processing technologies are currently being adopted by industry, as is discussed in chapter 6. Powder metallurgy, with its potential to produce parts that are close to their final shape, can dramatically reduce reject rates and scrap generation in fabrication of engine components. Two powder metallurgy processes used in conjunction with each other—hot isostatic pressing (HIP) and isothermal forging—are now used commercially, although equipment costs are high.

Improved material utilization would be achieved if HIP parts did not have to be hot worked. This is now essential in order to over-

Figure 7-2.—Temperature Capabilities of Turbine Blade Materials



SOURCE' National Aeronautics and Space Administration

come fatigue problems, but reduces product yields. The U.S. Air Force Office of Scientific Research is supporting research in this area to improve the final quality of superalloy components.

Hot isostatic pressing can also be used to rejuvenate turbine vanes and blades, potentially doubling the operating life of parts. So far, HIP rejuvenation has been used primarily in industrial gas turbines but is not yet widely used for worn aircraft parts. As discussed in chapter 6, life cycle extension techniques are under intensive investigation by the Air Force, and some jet engine parts are now being saved (rather than sold as scrap), pending possible improvements in rejuvenation technologies. Most obsolete jet engine parts, however, continue to be sold as scrap, and most of the scrap is downgraded to less demanding uses.

By the end of the 1980s, additional jet engine applications for cobalt-free oxide dispersion strengthened (ODS) superalloy are probable. These nickel- and iron-based superalloys are produced through a mechanical alloying process, first developed in 1968. Although still considered an emerging technology, rapid growth in ODS production is expected as new applications are accepted.

All currently available ODS superalloys are cobalt free and are marketed by the Inco Alloy Products Co. One ODS alloy, MA-754, has been used for years in high-pressure turbine vanes of military aircraft produced by General Electric. New applications for ODS alloys in combustor linings and turbine blades are being investigated as part of NASA's Materials for Advanced Turbine Engine [MATE) Program.

NASA and Pratt & Whitney Aircraft are currently evaluating another cobalt-free ODS alloy (MA-956) for use in combustor linings. Early results suggest that MA 956, coupled with design changes, could extend the operational life of these linings by up to four times compared to existing linings. It can also be used at a higher temperature than a commonly used liner material, Hastelloy X (which contains 1.5 percent cobalt).

Although ODS alloys are superior at high temperatures (i.e., 2,100° F), their poorer performance in intermediate temperature ranges (i.e., 1,4000 to 1,600° F) has so far prevented their use in turbine blades. However, NASA, in conjunction with the Garrett Turbine Engine Co., is evaluating the recently developed cobalt-free ODS alloy MA-6000, for turbine blade applications. Research suggests that an increase in surface metal temperature of 1500 F over the best current superalloy blade material may be feasible.

ODS alloys are more expensive than conventional superalloy. With expanded markets, however, finished part costs have declined. Additional price reductions could arise if the market expands into turbine blade and industrial applications. Current production of these alloys is about 120,000 pounds per year, but is growing rapidly.

Coatings.—Continuing near-term progress in enhancing the surface properties of hot-section components through use of coatings is also expected. Coatings of one sort or another have been used since the 1960s and have extended the life of parts significantly. Thermal barrier coatings (TBCs), now used on combustor linings and vane platforms, provide oxidation and hot corrosion resistance through a metallic bond coat (often containing chromium), which, in turn, is covered with a thin ceramic coat to provide thermal insulation. TBCs have yet to be applied to turbine airfoil surfaces because peeling problems have not been completely overcome. However, they may may be used on airfoil surfaces by the end of the decade.

Coatings (or other surface treatments) may some day permit reduced use of chromium in superalloys—although near-term prospects are very limited. Chromium's primary function in superalloy is to provide oxidation and hot-corrosion resistance at the surface of components. Most superalloy contain several times as much chromium as strictly needed to provide this surface protection. As an insurance measure, chromium is added throughout the alloy, even though it is only needed at the surface.

Aside from its absolutely essential role in corrosion resistance, the high levels of chromium throughout monolithic superalloy may not be needed. In theory, conservation of chromium and improved mechanical properties could be achieved if a safe way could be found to put chromium only at the surface of components, leaving the rest of the part chromium free. Presently, coating or cladding of a chromium-free base alloy is not acceptable, owing to the possibility of a disastrous crack forming in the coating. Other advanced surface treatment processes have yet to be applied for the specific purpose of reducing chromium content.

From the above discussion it would appear that prospects for cobalt substitution in superalloy are quite limited in the near term, and that few available alternatives are ready for use by engine manufacturers, Chromium substitution prospects are even more limited.

Medium-Term Prospects for Further Cobalt and Chromium Substitution (1990-2000)

Over the next 10 to 15 years, only substitute materials that are now approaching qualification and approval for jet engine use are likely to be useful in reducing U.S. dependency on imported strategic materials, The long lead time entailed in testing and certification of new materials and the time it takes for designers to become familiar with them make it unlikely that new materials or processes not now being actively developed will be in commercial use before the last half of the 1990s.

Several cobalt-free or low-cobalt alternative materials have been investigated under NASA sponsorship (Conservation of Strategic Aerospace Materials Program, established in 1981, and pre-COSAM research activities.) These substitutes could provide alternative compositions for six widely used superalloy. Table 7-7 shows currently used superalloys selected for substitution research. Preliminary laboratory experiments suggest that cobalt may not be needed in the high-volume Udimet 700 type superalloy (18 percent cobalt) which is used in turbine discs and blades. One evaluation of the initial COSAM research hypothesized that

Table 7-7.–Nickel-Base Superalloy Selected for Cobalt Substitution Research by NASA

Alloy	Typical engine application	Form	Remarks	Cobalt content (% weight)
WASPALOY . . .	Turbine disc	Forged	Highest use wrought alloy in current engines	13.5
UDIMET-700 . . .	Turbine disc	Forged	Similar alloys used in various forms and applications	18.5
(LC) ASTROLOY	Turbine disc	as-hip-powder		
(RENE 77)	Turbine blades	Cast		
MAR-M247	Turbine blades and wheels	Cast	Conventially cast, DS and single crystal	10,0
RENE 150	Turbine blades	DS-Cast	Highly complex directionally cast alloy	12.0

SOURCE Adapted from Joseph R Stephens, *A Status Review of NASA COSAM (Conservation of Strategic Aerospace Materials) Program*, NASA Technical Memorandum 82852 (Springfield, VA National Technical Information Service, May 1982)

while definite conclusions are premature, it may be possible to cut by one-half or even eliminate cobalt now used in some nickel-based superalloys with little or no effects on mechanical properties or environmental resistance. (An estimated 2.15 million pounds of cobalt was contained in nickel-based superalloy primary products in 1980, according to the NMAB. This comprised about one-eighth of total apparent cobalt consumption in that year.)[24]

The COSAM substitutes are still in the laboratory stage of development and are many years away from actual use in a jet engine. In theory, the COSAM alternatives could be brought on line more quickly than an entirely new material, since only slight adjustments in manufacturing processes may be needed to produce the low-cobalt substitutes. However, to commercialize these alloys fully could still require 6 to 7 years and $6 million to $9 million per application—a commitment that engine makers will find difficult to justify, given current low-cobalt prices. Hence, their post-COSAM development may be delayed until a perceived need arises.

Over the next 10 to 15 years, strategic materials conservation could also be a side benefit from several advanced superalloy production techniques that are approaching commercialization—simply because some of the experimental prototypes and research materials happen to contain little or no cobalt. These processes may not necessarily conserve strategic materials over the long run, however, if it turns out that cobalt provides a performance benefit over the experimental prototypes.

One group of these new processing methods is “rapid solidification, ” in which metals are solidified so quickly that the resulting distribution of elements is nearly homogeneous, having few inclusions that could initiate fatigue cracks. Moreover, previously unattainable alloy compositions with superior properties can be obtained in some cases, Experimental cobalt-free superalloy powders produced through various rapid solidification processes have been shown in early experiments to have some advantages over conventionally processed alloys. Detailed information on rapid solidification processes and their prospects as substitutes for strategic materials is provided in the Advanced Materials section of this chapter.

The capability to produce directionally solidified eutectic superalloy is another of the recent processing advances. Over the past two decades considerable effort has been devoted to developing this technique. When superalloy are produced in this manner, they are strengthened by the formation of microscopic carbide or intermetallic fiber reinforcements. Most of the experimental alloys have comparatively low levels of chromium and cobalt—4 percent and 3 to 10 percent respectively. As with other advanced processes and materials, the key objective of eutectics development is not to conserve strategic materials, but to increase temperature capabilities of turbine blades and vanes. Eutectic superalloy could increase the allowable operating temperature of these components by about 100° F compared to currently available single-crystal alloys.

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[24] National Materials Advisory Board, *Cobalt Conservation Through Technological Alternatives*, National Research Council, Publication NMAB-406 [Washington, DC: National Academy Press, 1983), pp. 24 and 47.

Although work on eutectic alloys is progressing, they have yet to receive qualification for engine use. Technical problems include inferior transverse properties and poor oxidation and corrosion resistance. Cost of these alloys is high because the processing times are high; a eutectic blade can be withdrawn from the furnace at only about one-fourth inch per hour, However, eutectic R&D has had active support by engine producers (General Electric and United Technologies) as well as scientific support at government laboratories and universities.

The medium-term (1990-2000) prospects for reducing cobalt and chromium in jet engines are difficult to assess because new materials will be used as new jet engines are introduced into military and civilian aircraft. The selection of these materials will be performance driven, and while some materials may contain little or no cobalt, others almost certainly will. Development of the COSAM alternatives to the point of commercial use is possible over this period, but these materials will serve as substitutes for currently used superalloys which will comprise a declining portion of superalloy use. It is also possible that, over this period, a breakthrough in basic science will occur which will lead to a better understanding of the precise role of cobalt in superalloy, with possible reductions of cobalt in the design of new alloys. Improved understanding of the role of cobalt and other strategic materials in superalloy is a key purpose of the COSAM program.

Long-Term Prospects

Over the long term, several classes of new materials that are completely free of cobalt or chromium may come into use. These alternatives are being actively pursued because of their potential to extend the maximum operating temperatures (and thus performance) of turbine blades beyond the current limits of around 1,150° C or 2,100° F. These materials include ceramics, composites, and monolithic intermetallic compounds (or long-range order materials) and are discussed in detail in the next section. Table 7-8 summarizes potential applications for these advanced materials in the hot section of jet engines,

Table 7-8.—Use of Structural Materials Under Development to Reduce Cobalt and Chromium Usage in Hot-Section Parts

	Composition (percent weight)		
Material	Co	Cr	Suitable components
Rapid solidification processed superalloy	Varies	Varies	Combustor liners; cases; turbine blades, vanes, discs, seals.
Long-range order (intermetallics):			
Ni	—	—	HP turbine discs (combustor liners; HP turbine vanes, blades)
Ti	—	—	LP turbine discs, blades, vanes; cases,
Fe	—	—	Combustor liners; LP turbine discs, blades, vanes; cases
Directionally solidified eutectics	3-10	4	Turbine blades, vanes
Oxide dispersion strengthened superalloys	—	15-20	Turbine vanes; (combustor liners, turbine blades).
Fiber-reinforced (metal matrix composite) superalloy	—	15 (matrix)	Turbine blades, vanes; combustor liners; cases
Monolithic ceramics	—	—	Turbine discs, vanes, blades, seals; cases; combustor liners
Ceramic-ceramic composites	—	—	Turbine vanes, blades, cases
Carbon-carbon composites	—	—	Combustor liners; cases; afterburners; nozzles; turbine discs, vanes, blades

KEY” HP = High pressure
LP = Low pressure.
( ) = Less likely application
— = Minimal or none

SOURCE: Office of Technology Assessment.

Advanced Materials

There is currently a great deal of interest in the development of advanced materials such as rapid solidification processed materials, long-range order intermetallics, ceramics, and composites. This interest is driven by the impressive array of properties these new materials offer. They not only offer enhanced properties, but often entirely *new* combinations of properties, as well, A side benefit of advanced materials is their use of little or reduced amounts of strategic materials.

Many advanced materials are still undergoing R&D and have thus far seen limited commercialization, In selected component applications, some advanced materials are now being used. The number of applications for advanced materials should increase appreciably during the next 5 to 20 years—especially where major design modifications are not needed. In most critical applications where performance standards tend to be exacting, however, they will require much more R&D before they see widespread use,

Although growth in the use of advanced materials is expected, the overall effect of their use on future strategic material needs is unclear. Some major technical problems (e.g., the brittleness of ceramics, difficulties in repairing composites, etc.) must be solved before they can be used in many critical applications. Moreover, advanced materials will not necessarily be used as direct replacements for existing materials. In many applications, these new materials are so different from the alloy substitutes described previously that redesign of entire systems is often necessary to benefit fully from their properties. In addition, use of strategic materials may just as easily increase as decrease as these new materials are adopted. For example, using advanced materials in the hot section of a gas turbine engine to raise its operating temperature may increase the temperature in a cooler section of the engine to a point where it requires the use of strategic materials. Yet, using advanced materials (e. g., composites) to make an aircraft lighter may allow the use of smaller engines containing less amounts of strategic materials. In an economic sense, advanced materials and materials containing strategic elements may be both substitutes and complements.

The various industries involved in developing and producing advanced materials are doing so because of a belief in the promise of future economic benefit from the introduction of these materials in existing and entirely new applications, not because they foresee a role for them as materials substitutes. The advanced materials industry has the potential to make a large contribution to future U.S. gross national product (GNP), The U.S. market for advanced ceramic materials, for instance, has been projected at $5.9 billion by the year 2000, an amount 10 times the 1980 market.[25]

This emerging U.S. advanced materials industry faces global competition, especially from Japan and Western Europe, in materials development, processing, and commercialization. Today, some processed ceramic materials and components of composites are only available from foreign sources. In some instances, the United States is credited with the basic research on some material components for which Japan now holds most of the processing capacity. In others, process licensing has been made available to U.S. firms for foreign patented materials.

Compared to their metallic counterparts, advanced materials have relatively brief histories of use, and this absence of a proven track record often makes designers and their industries reluctant to use them. Different societies approach institutional barriers to commercialization in different ways. In the United States, the standard engineering education still provides little, if any, formal training in the use of advanced materials, Industry must bear the cost of continuing education. In Japan, indus-

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[25] U.S. Department of Commerce, A *Competitive* Assessment *of* the U.S. Advanced Ceramics Industry [Washington, DC: U.S. Government Printing Office, March 1984), p. xiii.

tries are willing to introduce advanced materials to the marketplace at a lower level of confidence in their eventual success than in the United States. The risk of failure is reduced by testing new materials in everyday items such as scissors or high-value glamour products, such as sporting goods.

The following sections present the current state of the art of these advanced materials, and, where known, potential areas for strategic material savings. It must be kept in mind, however, that many unknowns exist, and the rapid advance of the science of these materials could change their prospects in only a short time.

Ceramics

Advanced ceramic materials are an emerging technology with a very broad base of current and potential applications and an ever-growing list of material compositions (see table 7-9). While this dynamic situation makes it difficult to quantify their future impact, it does not appear that advanced ceramics will replace any substantial portion of the U.S. demand for first-tier strategic materials within the next decade. Beyond 2010, a larger potential for substitution exists if ceramic rotating parts are successfully applied in gas turbine engines. In order for this major materials substitution to be technically feasible, however, the brittleness tendency of ceramic materials must be overcome by improvements in material properties and processing technologies and the use of ceramics must be integrated with system designs that reduce the ways in which stresses are loaded on ceramic parts.

Most ceramic raw materials (see table 7-10) are not considered potential strategic materials because they are available in large quantities from domestic sources. However, the United States is competing with other countries in advanced ceramics R&D, and loss of a leadership role in the development and use of ceramic materials could ultimately result in a dependence on international sources (primarily Japan) for processed ceramic materials and products.

While a potential decrease in U.S. consumption of strategic materials is an important benefit of ceramic use, the promise of performance improvements is the main force driving the development of advanced ceramic materials. The sought-after properties of advanced ceramics include wear resistance, hardness, stiffness, corrosion resistance, and relatively low density (providing a weight savings that can translate into energy savings), A major attraction, however, is a high melting point and accompanying mechanical strength at high temperatures. Ceramics offer one of the best possibilities for raising the operating temperature of heat engines and power generating equipment; and as the operating temperature in these systems is increased, system efficiency in energy conversion can increase, resulting in cost savings. The metallic superalloy currently used in jet engines limit operating temperatures to about 2,000° F, whereas ceramic materials can withstand temperatures up to about 2,500° F. Complicated and energy-consuming cooling systems now must be used—even in relatively low-temperature engines such as automobiles—to maintain the integrity of metals at operating temperatures. Ceramic materials can also be used to increase the energy efficiency of many high-temperature processing systems. The excellent wear-resistance properties of ceramics could increase productivity in the machining, chemical, and metal processing industries, where wear and corrosion resistance are critical. Box 7-A provides detailed information on the properties of ceramics and on the processes for making them.

Although research into some areas of advanced ceramics is still in the development stages, new roles in electronics and wear-resistance applications are being filled by ceramics. Neither the economic viability nor the technical capability of using ceramics in many of the structural applications (e.g., heat engines) has yet been demonstrated. Although the basic ceramic raw materials (e. g., silicon, alumina, magnesium) are plentiful and inexpensive, the procedures necessary for converting the raw material into a usable form (usually an ultrafine powder) and then a final product can be expensive. It has been estimated that from 25

Table 7-9.—Current and Prospective Uses for Advanced Ceramics

Ceramic material	Current and potential applications	First-tier strategic materials substitution opportunities
Electric:		
Insulating (Al_2O_3, BeO, MgO)	IC circuit substrate, package, wiring substrate, resistor substrate, electronics interconnection substrate,	—
Low-firing and/or glass ceramics, ferroelectrics ($BaTiO_3$, $SrTiO_3$)	Ceramic capacitor.	Low-temperature firing permits use of copper instead of tungsten, moly or PGM wires, nickel instead of PGM electrodes.
Piezoelectric (PZT)	Vibrator, oscillator, filter, transducer, ultrasonic humidifier, piezoelectric spark generator.	—
Semiconductor ($BaTiO_3$ SiC, AnO-Bi_2O_3, V_2O_5, and other transition metal oxides)	NTC thermistor: temperature sensor, temperature compensation,	—
	PTC termistor: heater element, switch, temperature compensation.	—
	CTR thermistor: heat sensor element.	—
	Thick film thermistor: infrared sensor.	—
	Varistor: noise elimination, surge current absorber, lighting arrestor.	—
	Sintered CdS material: solar cell.	Pt, Pt-Rh heaters, Ni-chrome heaters
	SiC heater: electric furnace heater, miniature heater.	—
Ion conducting (β-Al_2O_3, ZrO_2)	Solid electrolyte for sodium battery.	—
	ZrO_2 ceramics: oxygen sensor, pH meter fuel cells.	
Magnetic:		
Soft ferrite	Magnetic recording head, temperature sensor.	Ceramics for Co-Sin magnets
Hard ferrite	Ferrite magnet, fractional horsepower motor, powders for tapes and discs (σ-Fe_2O_3, CrO_2).	Ceramics for AlNiCo magnets
Optical:		
Translucent alumina	High-pressure sodium vapor lamp.	—
Translucent magnesium oxides, mullite, etc,	For a lighting tube, special-purpose lamp, infrared transmission window materials,	—
Translucent Y_2O_3-ThO_2 ceramics	Laser material.	—
PLZT ceramics	Light memory element, video display and storage system, light modulation element light shutter, light value.	—
Chemical:		
Gas sensor (ZnO, Fe_2O_3, SnO_2)	Gas leakage alarm, automatic ventilation fan; hydrocarbon, fluorocarbon detectors.	Reduced use of Pt-group catalyst
Humidity sensor ($MgCr_2O_4$-TiO_2)	Cooking control element in microwave oven.	—
Catalyst carrier (cordierite)	Catalyst carrier for emission control.	—
Organic catalyst	Enzyme carrier, zeolites, other ceramics.	Catalytic processes may replace Co, Pt
Electrodes (titanates, sulfides, borides)	Electrowinning aluminum, photochemical processes, chlorine production.	—
Thermal:		
ZrO_2-based Al_2O_3-based Si-based	Infrared radiator, thermal barrier coatings.	Reduced use of W, Cr, Co, Ni

Table 7-9.—Current and Prospective Uses for Advanced Ceramics—Continued

Ceramic material	Current and potential applications	First-tier strategic materials substitution opportunities
Mechanical:		
Cutting tools (Al_2O_3, TiC, TiN, others)	Ceramic tool, sintered SBN. Cermet tool, artificial diamond. Nitride tool.	WC-Co cemented cutting tools and high-speed steels (Cr)
Wear resistant (Al_2O_3, ZrO_2)	Mechanical seal, ceramic liner, bearings, thread guide, pressure sensors.	Hard facing alloys (Cr, Co, Mn)
Heat resistant (SiC, Al_2O_3, Si_3N_4, ZrO_2, others)	Ceramic engine, turbine blade, heat exchangers, welding burner nozzle, high-frequency combustion crucibles.	Superalloy (Co, Cr)
Biological:		
Alumina ceramics implantation Hydroxyapatite bioglass	Artificial tooth root, bone, and joint.	Bone and tooth implants (Pt, Co, Cr-based

SOURCE' Elaine P. Rothman, George B Kenney, and H. Kent Bowen, MIT Materials Processing Center, *Potential of Ceramic Materials to Replace Cobalt, Chromium, Manganese, and Platinum in Critical Applications,* OTA contract study, January 1984.

Table 7.10.—Some Advanced Ceramics Material Families

Families	Chemical formula	Elements
Alumina	Al_2O_3	Aluminum, oxygen
Aluminum silicate	AlSi	Aluminum, silicon
Barium titanate	$BaTiO_3$	Barium, titanium, oxygen
LAS		Lithium, aluminum, silicon
Magnesium silicate	MgSi	Magnesium, silicon
MAS (cordierite)	$2MgO \bullet 5SiO_2 \bullet 2Al_2O_3$	Magnesium, silicon, oxygen, aluminum
Magnesia	MgO	Magnesium, oxygen
Silicon carbide	SiC	Silicon, carbon
Silicon nitride	Si_3N_4	Silicon, nitrogen
SiAlON	(various alloys of silicon nitride and alumina)	
Zirconia	ZrO2	Zirconium, oxygen
PZT (partially stabilized zirconia)		Zirconia with particles of calcia, magnesia or yttria

SOURCE: Office of Technology Assessment.

to 75 percent of the production cost of ceramic components is due to a high rejection rate caused by the poor reproducibility of current processing steps.[26] As new manufacturing technologies mature and the ability to design with brittle materials increases, prices are projected to become competitive with existing metallic technologies. As yet, however, mass production of many advanced ceramics does not yet occur. Scaling up an experimental process to a commercial manufacturing level of production, while retaining the desired properties of the materials and obtaining production reliability, has not often been achieved.

Ceramics as a Strategic Material Substitute

A growing market for advanced ceramics exists in a number of applications, with limited implications for the use of strategic materials, Strategic material substitution, however, may have a higher potential in the long term (2010 and beyond), particularly in the eventual use of advanced ceramics in aircraft gas turbine engines and, to a lesser extent, as components in automotive gas turbine and heavy vehicle diesel engines.

As shown in table 7-11, ceramic materials are displacing some first-tier strategic materials in

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[26] Elaine p, Rothman, George B. Kenney, and H. Kent Bowen, Materials Processing Center, Massachusetts Institute of Technology, Potential *of* Ceramic Materials to Replace Cobalt, Chro*mium,* Manganese, and *Platinum* in Critical Applications, OTA contract report, January 1984, p. 240.

Box 7-A.—Ceramics Primer

Ceramics, derived from the Greek word "keramos," meaning "burnt stuff," is a general term for inorganic,[27] nonmetallic materials processed or consolidated at high temperatures. Traditionally, ceramics has referred to the family of earthenware, brick, glass, porcelain, and enamels in common use. The field now encompasses a wide range of materials and applications.

Traditional types of ceramics are made from natural raw materials such as clay, silica, and feldspar and produced using relatively simple chemical processing, forming, and firing steps. Advanced ceramic products, on the other hand, are produced from ultrafine powder forms of synthetic materials derived from the natural raw minerals. The powder production phase of advanced ceramics processing has become increasingly critical. Purity, particle size, shape, and distribution of particles and how they agglomerate must be rigidly controlled in order to produce reliable, reproducible components, To attain such high-quality, new techniques such as sol-gel, coprecipitation, and laser synthesis have been added to conventional powder production and agglomeration methods.

Because a great number of materials are classified as ceramics, a wide range of properties are available; and ceramic materials have many characteristics that distinguish them from metals. They are generally more stable chemically and thermally and are better insulators than metals. On the other hand, they are much stronger in compression than in tension and do not have the same ductility, or "forgiving" nature, of metal. Ceramics are harder and more rigid than either metals or plastics and are more stable (retain their low-temperature properties) at high temperatures.

Owing to their lack of ductility, ceramic products cannot be formed by the stamping or forging processes used for metals. Instead, they are generally processed directly from highly refined raw material by the consolidation of powder. (Melt formation is used to form glass and single crystal ceramics.) The powder is first formed to the desired shape. Forming methods include isostatic pressing, injection molding, and slip casting. This "green body" preform is then further densified by the application of heat (sintering) or the simultaneous application of heat and pressure (two such processes are hot-pressing and hot-isostatic pressing). Reaction bonding and reaction sintering are special sintering processes during which the final composition of the ceramic material is obtained along with densification. The combination of processes selected to produce a ceramic material will affect its ultimate properties.

Ceramics are brittle and fracture with little or no warning. This characteristic has been the material's major barrier to expansion into a wide range of applications, both technically and institutionally. Ceramics must be considered and used in ways different from those taught traditionally to designers and engineers schooled in the use of metals. Because metals bend and deform prior to reaching a point of fracture, ceramics cannot usually be directly substituted for metal alloys on a one-for-one basis. Instead, redesign of components and systems to eliminate or minimize load-bearing (stresses) are often necessary in order to substitute a ceramic material.

A considerable amount of the research in ceramics centers around how to reduce, cope with, or design around this brittleness. Research takes three approaches: 1) basic research to increase the knowledge base and understanding of the behavior of the materials, 2) improvement of processing technologies to reduce the probability of brittle failure, and 3) investigation of how varying material compositions can affect ceramic properties.

Brittle failure results from microscopic flaws (cracks), solid inclusions, and voids in the microstructure[28] of finished products inevitably introduced to a ceramic material during processing. The likelihood of brittle failure increases with the size of such flaws, and tension loading on a part will lead to the

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[27] Substances that do not contain carbon except as a minor constituent.

[28] The detailed arrangement (size, nature, and distribution) of phases (combinations of elements) that constitute the overall material.

growth of existing flaws (crack propagation). New processing techniques aim at reducing flaw size and population by the use of homogeneous powders and forming procedures. Greater processing reproducibility is another goal.

Another, complementary method of decreasing the probability of fracture of ceramics is to increase the energy required to extend a crack in the material. Such a barrier to crack propagation is provided by introducing toughening mechanisms into the powders before processing. Examples include zirconium oxide particles embedded in aluminum oxide and calcia, magnesia, or yttria added to zirconia to create partially stabilized zirconia (PSZ).

The ability to identify the flaws cm increase the reliability of ceramic products. Nondestructive evaluation (NDE) techniques are being developed (by both industry and the Federal Government) to determine flaw size, shape, concentration, and type with an aim toward predicting when component failure will occur. As yet, there is no "perfect" method for detecting all types of flaws in ceramics. Many methods are not applicable to the production line or are simply too costly and time-consuming, NDE techniques include ultrasonic, radiography, optical, and thermographic methods.

wear-resistant applications such as cutting tool tips, pump seals, bearings and nozzles, and in heat-resistant applications such as heat exchangers. Turbochargers with ceramic rotors may be offered by one Japanese automobile manufacturer within the next few years.

Wear-resistant parts today are often made from cemented tungsten carbide materials in which cobalt is used as a binder. This material accounts for 9 percent of the annual U.S. consumption of cobalt, more than half of which is estimated to be used in these wear-resistant applications. (Another major end use is machine dies.) In heat-resistant applications, ceramic materials such as silicon carbide, silicon nitride, and aluminum silicates can replace stainless steels and other heat-resistant alloys containing chromium, cobalt, and some manganese. While it is difficult to quantify the individual quantities of these metals used in wear- and heat-resistant applications, the overall amounts are thought to be small. The substitution of ceramic materials will, therefore, result in minor strategic material savings. Additional indirect savings may be generated by higher temperature operations, energy savings, and weight reductions made possible by the use of ceramics.

If successfully introduced in the rotor section of turbochargers, advanced ceramics will find their first commercial rotating, structural use and will replace nickel superalloys and nickel-iron alloys containing cobalt and chromium, respectively. With 100 percent penetration in the automotive market, ceramic materials would replace less than 1 percent of current U.S. cobalt and chromium annual consumption, but may inhibit a growing use of strategic materials.

Current automotive engines consume a negligible amount of first-tier strategic materials, but operating engine conditions require air pollution control devices that consume 1.5 percent of the chromium and 34 percent of the PGMs consumed annually in the United States. It has been suggested that the use of ceramic gas turbine and diesel automobile engine technologies may alter these pollutants, thereby changing the material requirements for catalytic converters. In aircraft gas turbine engines, on the other hand, a direct material substitution could occur with the replacement of superalloy containing cobalt and chromium currently consumed in portions of such engines. (The aviation industry annually consumes approximately 40 percent of the U.S. cobalt demand

Table 7-11. —Potential of Advanced Ceramics to Substitute for First-Tier Strategic Materials

Application	Current strategic material use estimated percent of annual U.S. consumption	Ceramic materials currently used or under consideration	Advantage to use of ceramics	Primary factors affecting adoption			Extent occurrent commercialization U S and world
				Technical	Economic	Institutional	
Near term (before 1995):							
Wear resistance.							
Cutting tool tips	Cobalt, as binder m tungsten carbide 5 percent	Alumina, silicon nitride, sialon	Increased productivity	Overcoming Inadequate fracture toughness	Appears competitive with tungsten carbide	Most U S machine tools cannot accept ceramic bits Lack of information within machine tool industry	2% of U.S. market Higher in Japan and West Germany
Seals, bearings, nozzles, etc	Cobalt, as binder m tungsten carbide 3 percent	Alumina-zirconia, silicon carbide	Improved wear and corrosion resistance	No significant barriers	Competitive with tungsten carbide except large (>8 inch diameter seals)	Need to standardize parts Consumer awareness and lack of desire to change; pumps are a replacement parts market, longer seal life is not seen as an advantage to producers	20% of U.S. and world market
Heat exchangers Large Industrial Small single burner recuperators	Small amounts of chromium in high-temperature stainless steels	Silicon carbide Cordierite	Energy savings Longer furnace life	Improved joining technology (ceramic/ceramic. ceramic/metal) and reproducibility of SIC tubes in processing	Higher initial capital investment than metallic heat exchangers High cost of SiC tubing	Change over to electrical induction heating which does not use recuperators. Depressed state of the domestic steel industry and metal processing industries has inhibited change	< 5% of U.S. market Possibly higher in Japan
Turbochargers (automotive)	Superalloy containing Chromium. (0.02 percent) Cobalt: (0.4 percent)	Silicon carbide, silicon nitride	Higher temperature capability with lower mass Potential for tower costs	Overcoming difficulties in ceramic/metal joining; improving reproducibility of the ceramic rotors	Current cost of producing the ceramic rotor is high, but economies of scale are predicted	Ceramics will be used if they demonstrate superior performance	Expected limited introduction by Japanese soon, possible market penetration by 1990
Long term (after 1995):							
Automotive diesel engine (cylinder, pistons, sensors)	Some chromium and cobalt in heat resistant and specialty steels; in addition, chromium: 1 5 percent, PGMs 34 percent in automobile catalytic converters (Use of ceramic parts will alter operating temperatures of engines, causing possible change in converter material requirements)	Silicon, silicon carbide, silicon nitride, zirconia	Higher engine efficiencies potential. Lightweight engine components	Improved fracture toughness, reproducibility and reliability of parts	Only prototype parts are currently produced, generally, hot pressed prototype parts require diamond machining which is an expensive mass production technique. New processing techniques could generate significant economies of scale	Almost revolutionary change in engine style is required to fully realize ceramics potential	Only several demonstration engines so far
Automotive gas turbine combustors, shrouds, and rotors	(same as above)	Silicon carbide, silicon nitride, sialon, lithium, aluminum silicate	Higher engine efficiencies, ability to burn any fuel, lower mass Potentially lower cost	improved fracture toughness, thermal shock resistance, reproducibility and reliability	High cost of processing due to current techniques and limited production volumes	"Proof of concept" engines follow-on design will need thorough, exhaustive road testing to overcame brittle image of ceramics	Only prototypes and demonstration testing

NOTE These applications are not meantto be all inclusive but represent key potential applications

SOURCE Elaine P Rothman, George B Kenney, and H Kent Bowen MIT Materials Processing Center *Potential of Ceramic Materials to Replace Cobalt Chromium* Manganese *and Platinum In Critical Applications* OTA contract study, January 1984 and less than half a percent of its chromium demand, and most of this material is used in the manufacture of jet engines.)

Owing to their higher temperature capabilities, resistance to corrosive environments, low inertial mass, potentially low cost, and the ready availability of raw materials, ceramics could become an integral part of future power generating technologies. In contrast to current and near-term applications, however, major technical barriers must be overcome before ceramic components for diesel and gas turbine engines can advance from demonstration projects to commercialization. Improvements are needed in material properties (most significantly, fracture toughness), processing and fabrication techniques, ceramic-ceramic and ceramic-metal joining capabilities, testing procedures, and design methodologies. Ceramic components must be reliably produced and manufacturing processes must be capable of a high degree of reproducibility, neither of which is possible at the current state of the technology.

The Ceramics Market and Industry

The worldwide market for advanced ceramics in 1980 was estimated to be $4.25 billion.[29] Electronic components represent the primary market for ceramics, with cutting tools and wear parts second and third, respectively. Roughly half of the present overall demand is being met by Japanese companies, whose sales exceeded $2 billion in 1980.[30] While the electronic segment now accounts for more than two-thirds of the total market and offers significant growth potential, it may eventually be dwarfed by the ultimate size of the high-temperature applications market.

Indicative of a high level of uncertainty, projections made to estimate the value of the advanced ceramics market by 2000 vary widely. An American Ceramics Society study[31] projected a $20 billion world market, half of which would be domestic. The U.S. Department of Commerce was more conservative in a study released in ***1984.*** It projected total domestic shipments (as equivalent to future market potential) of advanced ceramics of $5.9 billion. Included were electronics shipments of $3.5 billion; heat engines, $840 million; cutting tools, $960 million; and wear parts, $540 million.[32] In yet another estimate, advanced ceramic usage in automotive engines alone was projected to reach $30 billion on a worldwide basis by the year 2000.[33]

Except in electronics, advanced ceramic materials have penetrated a very small share of their recognized end use markets worldwide, primarily due to the state of the technology and relatively high costs of its products. While low-volume production adds to these high costs, demonstrated technical performance will not necessarily create markets for advanced ceramics. Roughly half of the cost of a typical ceramic component is estimated to be due to production rejects.[34] An incremental introduction into most markets is expected until ceramic component mass production techniques are developed which can reproducibly fabricate reliable products and customer acceptance can be firmly established. In automobile markets, revolutionary ceramic engine designs may have to await a lengthy proving process prior to successful commercialization. If it is successful, the ceramic turbocharger—the first commercial structural heat engine use of advanced ceramics—can provide invaluable information for this process and the beginnings of institutional acceptance of the structural capabilities of advanced ceramics.

The essence of the advanced ceramics business is that common starting materials are con-

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[29] Rothman, et al., op. cit., p. 238.

[30] Ibid., Japanese firms were estimated to hold 52 percent of the worldwide ceramic powders market; 61 percent of electronic IC packages/substrates; 91 percent, piezoelectrics; 43 percent, capacitors; 63 percent, thermistor/varistors; 79 percent, ferrites; 11 percent, gas/humidity sensors; 44 percent, translucent ceramics; 12 percent, cutting tools (carbide, cermet); and 48 percent, structural ceramics (heat and wear resistant).

[31] Ibid.

[32] U.S. Department of Commerce., op. cit., p. 13. The Department of Commerce cautioned in its study that it is too early in the history of this new industry to predict its future with a high level of confidence.

[33] According to Kent Bowen of MIT, as quoted in Rothman, et al., op. cit.

[34] Ibid.

verted into high value-added commodities and components by sophisticated, high-technology processing and manufacturing systems. Exacting standards require extensive quality control. Generally, material producers in the ceramics industry have been and still remain vertically integrated; thus, raw materials are processed and fabricated into component parts within a single company. Relatively few producers supply ceramic raw materials, and even fewer supply new advanced ceramic powders. The evolving advanced ceramics industry consists of traditional ceramics firms expanding into new applications, new end users taking on the task of being materials suppliers, and conventional materials firms expanding into the ceramics arena.[35]

The United States is not alone in its interest in advanced ceramic materials. It already is competing with and will continue to encounter stiff competition from Japan and Western Europe in tapping future markets. The Japanese industry is currently the sole source for some high-grade ceramic powders (e. g., silicon carbide) and has eclipsed the rest of the world in supplying the electronics market. se A British firm, which holds numerous patents for sialons (a ceramic composed of oxides and nitrides of silicon and aluminum), now licenses others to manufacture these materials.

Japan began its comprehensive advanced ceramics R&D program only in 1977, but its government-industry-university collaborative effort is widely regarded as the best organized and financed in the world, The Japanese are, of course, more materials and energy import-dependent than the United States; and a prime goal of their research efforts is to ease that dependence. But they also view advanced ceramics as a technology which will be part of an industrial base for the future. In an issue of *The Japan Industrial & Technological Bulletin*[37] in 1983, R&D in ceramics is recognized as involving "huge investment risks" and requiring "a relatively long lead time before the commercialization of these materials. " As such, the study concluded that the Japanese government "should take the main role in promoting advanced and fundamental research as well as development. " And, the primary objectives of the Fine Ceramics Office set up in July 1982 under the auspices of the Ministry of International Trade and Industry (MITI) are to "get a comprehensive picture of the domestic fine ceramics industry, systematize the industry, consolidate the industry's foundation and adopt comprehensive policies designed to promote the industry's sound growth. "

While the United States, Japan and Western Europe have all followed interdisciplinary approaches in their independent research efforts, the U.S. effort has leaned toward basic research and design methodologies while others have emphasized materials supply and processing. As a consequence, some feel that the United States may end up lagging behind in the implementation and exploitation phases of advanced ceramics technology. In advanced ceramics (as in other new technologies), the Japanese seem willing to take the risk to apply state-of-the-art materials to consumer products. This provides field testing for improvement of the knowledge base of the technology production experience and cost reductions and income to finance further research efforts , all the while gaining customer acceptance for new materials,

If one assumes that the Japanese rather than the United States becomes the dominate factor in an all-important future automobile ceramic engine market, the United States could be adversely affected by a decline in the GNP, loss of employment opportunities, shift in the

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[35] For a review of the status of the U.S. advanced ceramics industry and the firms involved, see the U.S. Department of Commerce, *A Competitive Assessment of the U.S. Advanced Ceramics Industry,* op. cit.

[36] Not all such sales in the United States are imports, however. Kyocera International, a subsidiary of Kyoto Ceramic Co. of Japan, established production facilities in San Diego in 1971 which now supply 70 percent of the U.S. demand for ceramic packaging for integrated circuits. See "The Japanese Score on a U.S. Fumble, " *Fortune* magazine, June 1, 1981, pp. 68-72,

[37] Japan External Trade Organization, *The Japan Industrial & Technological Bulletin: The Development of Structural Fine Ceramics in Japan,* Special Issue, No. 15. 1983, pp. 6-7. Note that Japan uses the term "fine ceramics" for what is commonly referred to as "advanced ceramics" in the United States.

balance of trade, and loss of savings in energy costs.[38]

One aspect of the expanding ceramics industry for which there is little data is the possible environmental, health, and safety effects on the communities and workers where the processing occurs. While some may assume that these processes may be "cleaner" than those of existing metal production, the statistics as they are now collected and aggregated by the Environmental Protection Agency and the Occupational Safety and Health Administration based on the traditional ceramics industry do not correspond to the future industry,

Research in Ceramics Applications

Ceramics is an ancient art. Despite—or because of—the age old and common use of ceramics, it remained essentially an art until recently, when more exacting standards were asked of the materials. One major engineering textbook on ceramics states in its 1976 edition that:

> . . . until a decade or so ago, ceramics was in large part an empirical art, Users of ceramics procured their materials from one supplier and one particular plant of a supplier in order to maintain uniformity. Ceramics producers were reluctant to change any detail of their processing and manufacturing (some still are), The reason was that the complex systems being used were not sufficiently well known to allow the effects of changes to be predicted or understood, and to a considerable extent this remains true.[39]

British scientists conducted much of the original research in the 1950s and 1960s in ceramics theory, raw materials development, and processing methods. Not until the 1970s were ceramics developed to the point where they could be considered engineering materials in that their chemical and physical properties could be altered to match intended functions in various applications. This short period of development time probably contributes to the relatively low rate of usage of advanced ceramic materials so far,

Following is a discussion of the current status of the research and use of advanced ceramics in cutting tool, wear resistance, heat exchanger, and heat engine applications.

CUTTING TOOLS[40]

Cutting tool applications represent a limited but growing and potentially valuable market for ceramic materials. At present the total U.S. market for cutting tools has been estimated at $2.2 billion per year. Advanced ceramic cutting tools hold 2 to 3 percent of this market (compared to tungsten carbide at 45 percent).[41] Nine percent of the annual U.S. consumption of cobalt is used as a binder in tungsten carbide material.[42]

New cutting tools are continually being sought to increase manufacturing productivity by attaining higher cutting speeds and reducing the downtime of cutting machinery through improved lifetime of tool inserts. Ceramic materials have proven feasible in this application and may offer higher performance than existing cutting tool materials; but they must compete with new metal alloys, coatings, and processing methods (e.g., powder metallurgy) for market penetration. No one material meets all cutting requirements in all applications, and advanced ceramic cutting tools tend to be higher in cost than conventional tools,[43] owing to their smaller volume production and more complex processing. This higher initial cost, however, can be mitigated by the higher cut-

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[38] L.R. Johnson, A, P. S. Teotia, and L. G. Hill, *A Structural Ceramic Research Program: A Preliminary Economic Analysis.* ANL/CNSV-38. Argonne National Laboratory, March 1983.

[39] W. D. Kingery, H. K. Bowen, and D. R. Uhlmann, *Introduction to Ceramics,* 2d ed. (New York: John Wiley & Sons, 1976), p. 1.

[40] Cutting tools are insert pieces—the cutting edge—held and guided by machine tools. The process of machine tooling shapes and removes excess materials from manufactured products to produce desired tolerances.

[41] U.S. Department of Commerce, Op. Cit., P. 35.

[42] Rothman, et a]., op. Cit., p. 168.

[43] According to an interim draft report (January 1984) by Charles River Associates for the National Bureau of Standards, *Technological and Economic Assessment of Advanced* Ceramic *Materials: A Case Study of* Ceramic *Cutting Tools,* a typical silicon nitride cutting tool is currently sold in the $18 to $20 range, whereas typical tungsten carbide cutting tools are priced at $4 to $5.

ting speeds, if downtime due to lower reliability is not excessive,

An increase in the use of advanced ceramics is dependent on improvements in ceramic materials and the machine tools in which they are used. Advanced ceramic materials have greater abrasion, wear, and creep resistance than their carbide counterparts, but less strength, fracture toughness, and thermal shock resistance. The attributes of ceramic materials provide superior performance at high cutting speeds (especially demanded by the automotive and aerospace industries), which can translate into productivity gains. But widespread conversion to advanced ceramic cutting tools will require investments in new machine tools as many of those still in use have neither the speed, power, nor rigidity needed to use ceramic cutting tools effectively.

While approximately two-thirds of current ceramic tool sales are alumina (Al_2O_3), introduced in the 1960s, the newest cutting tools in use today are based on the silicon family. (Silicon nitride exhibits twice the fracture toughness of alumina.) Rapid development of silicon nitride ceramics has been the result of accelerated research activity over the past decade on high-temperature structural ceramics for use in advanced energy conversion systems. Ford Motor Co., for instance, is now moving toward commercialization of its “S-8” material, which was developed during research on materials for gas turbine rotors.

Most of the direct research in cutting tools in the United States is conducted by private industry and has been estimated at $1 million per year.[44] Indirect benefits may accrue, however, from the much heavier investments by government, industry, and academia in structural ceramics R&D.

Japan and Western Europe are considered to be ahead of the United States in the development and utilization of ceramic cutting tools. (About half of the advanced ceramic tools sold in the United States are imported from Japan.) The difference in higher usage has been attributed to the fact that in the United States’ older machine tool industry equipment is outdated and must be modernized or replaced before ceramic tools can be used to their full advantage.[45]

WEAR APPLICATIONS

Wear applications are often in low-temperature environments in which resistance to abrasion and corrosion are the primary performance goals. Applications include ball and roller bearings, valves and pipefitting, industrial fasteners, and pumping equipment such as seals, liners, and nozzles. The traditional materials for those applications are cemented tungsten carbide and wear-resistant steels (in which chromium is used as an alloying agent for its hardenability). Up to about 3 percent of U.S. cobalt consumption may be used in all wear-resistant applications and about 2 percent of chromium. Thus, strategic materials savings could result from more extensive substitution of ceramic materials in wear applications.

While the technical feasibility of wear parts made from ceramics (primarily aluminum oxides, and silicon carbides, silicon nitrides) has been demonstrated, the Department of Commerce has estimated that ceramics currently hold less than 1 percent of the annual $3.3 billion U.S. market.[46] The extent to which they will assume a greater share of these markets will be strongly affected by performance versus cost tradeoffs. The current state of processing and fabrication techniques for ceramic wear parts (rather than raw materials costs) leads to the higher initial costs than those for metal parts, Ceramics can, however, provide longer service life than metals.

The potential to resist fatigue, corrosion, high temperatures, and loss of lubrication better than metals make ceramic materials attractive for ball and roller bearing uses, Their high cost of fabrication, however, makes them imprac-

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[44] Ibid., p. 45.

[45] E. Dow Whitney, “Process in Ceramics Research for Cutting Tools in the U. S., West Germany, Japan and Sweden, ” paper given at the National Science Foundation conference on Substituting Non-Metallic Materials for Vulnerable Minerals, June 1983, p. 1.

[46] Department of Commerce, Op. cit., p. 35.

tical in many applications. Ceramic bearings tend to be consumed primarily by petroleum and chemical industries, which have demanding performance standards (e. g., in corrosive environments) and in specialized aerospace applications, all of which can absorb the high initial cost.[47] Pump seals are the largest wear application market now held by ceramics. The properties required are hardness, low friction, high resistance to corrosion, and high-temperature capability. Ceramics (especially, silicon carbide and silicon nitride) have been shown to be superior to metals in performance in this application and, with improved manufacturing techniques and reduced costs, are expected to assume more of the market. Nozzle parts must withstand high wear and abrasion resistance properties which the hardness of ceramics provides.[48]

Research in wear applications for ceramics is primarily conducted by the private sector, much of which remains proprietary, resulting in little transfer of technology. The research is concentrated on improving the properties of the materials, on manufacturing techniques to reduce costs, and on nondestructive evaluation methods to gain reliability.

HEAT EXCHANGERS

Competitive pressure in high-temperature industrial processes, as well as the rising cost of energy and the reduced availability of high-grade fuels in the 1970s, have led to the development and expanded use of energy conservation devices such as heat exchangers.[49] As in other high-temperature applications, the use of advanced ceramic materials in heat exchanger technology allows for improved performance over metals and often makes the technology possible. In addition, ceramics can provide better oxidation and corrosion resistance, which can result in longer component lifetime. Constraints to the expanded use of ceramics in this application are those specific to individual types of heat exchangers, but include the need for improved materials properties such as thermal shock resistance and resistance to certain corrosive environments, the development of joining and sealing technologies, and low confidence in the reliability of the ceramic components. The use of ceramics is still not cost effective vis-a-vis metal alloys in some heat exchanger designs, especially for large industrial furnace and power systems, which are constructed from an array of thin-walled ceramic tubes, Processing technologies are still being refined to provide high reproducibility for long (greater than about 8 feet) tubes. In addition, sealing against leakage between the hot and cold streams has not been fully successful.

Because of their high temperature and often corrosive environments, heat exchangers have been predominantly fabricated from stainless steels and superalloy; therefore, substitution of ceramic materials will result in some savings of chromium and cobalt, although the amount is difficult to quantify due to lack of specific end use reporting. On the other hand, much recent heat exchanger technology has been made possible by new ceramic materials, and the resultant growth in the use of ceramic materials are not as replacement materials. The use of ceramic materials, such as high-temperature cordierite (a magnesium alumina silicate commonly referred to as “MAS”), silicon carbide, silicon nitride, aluminum oxide, and lithium-alumino-silicate (LAS) in this application will be driven by energy costs faced by users and the unit cost of fabricating ceramic components.

The use of ceramics in recuperators, a type of heat exchanger that allows a furnace to operate more efficiently by recycling its waste heat to preheat incoming combustion air, has received a considerable amount of attention. Both development and commercialization research in ceramic recuperators was contracted by DOE’s Conservation Office through GTE Sylvania and the Carborundum Co. As a result, small ceramic recuperators are now commer-

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[47] Ceramic bearings cost about $100 while similar steel bearings cost from $1 to $3,50.

[48] Rothman, et al., op. Cit., p. 191.

[49] “Heat exchanger” is a generic term for any device that transfer heat from a fluid flowing on one side of a barrier to another fluid flowing on the other side of the barrier. Here, the term refers to the use of such devices in combination with industrial furnaces, stationary power generators, and engines.

cially available and are economically viable. They can be retrofitted to existing furnaces with the modification of furnace burners to cope with the higher temperatures generated. The performance advantage of ceramic recuperators is expected to encourage their use in new furnaces and as add-ens to unrecuperated furnaces; but a changeover in large industrial systems will be slow owing to the high investment costs of such installations coupled with the current stabilization of energy costs. The GTE "Super Recuper" is reported to save some industrial furnaces 30 to 60 percent in fuel by enabling furnaces operating at 2,500° F to preheat incoming air to 1,600° F. Unlike the long tubular array systems, GTE's counterflow plate design heat exchanger does not present any major ceramics processing problems. But materials properties improvements are needed in order for the device to be applicable in certain highly corrosive environments such as those in the glass industry,

A variety of other heat exchanger applications are being investigated by both the private sector and DOE. They include ceramic regenerator cores for inclusion in gas turbine engine designs and specific designs for use in cogeneration and combined-cycle power generation equipment.

HEAT ENGINES

Ceramic materials are under active investigation by both the Federal Government and industry for use in the propulsion of automobiles, trucks, military equipment (tanks and missiles), and aircraft as well as stationary uses, such as power-generating equipment. Research in these applications is being conducted to achieve significant advantages over the use of metal alloys, including fuel economy, improved performance, reduced maintenance, and possible reduction of pollution emissions, with savings of strategic materials a secondary objective.

Private sector R&D is focused primarily on advantages of ceramics that could translate into direct cost savings or improved product competitiveness. A review of the government-sponsored research in ceramic heat engines in table 7-11 shows that the main focus of that effort has concentrated on the gas turbine engine for automotive applications.

The ceramic materials being applied today to these technologies are generally termed "structural ceramics." They include monolithic forms of the silicon carbide (SiC), silicon nitride (Si_3N_4), zirconia (ZrO_2), and aluminum silicate (AlSi) families of ceramic materials. Ceramic composites are also being considered for engine applications because of their superior strength and hardness, low thermal expansion, and wear resistance, which may allow them to overcome the fracture problems of the monolithic ceramics. However, ceramic composites have been found to lose their strength at higher temperatures, a problem that has not yet been resolved,

Ceramics are likely to see service in the hot sections of engines, progressively, as follows :[50]

- Turbochargers: static parts and rotors,
- Small stationary electric power generators, similar to airplane auxiliary power units (APUs).
- Large stationary electric power generators, then mobile (ground and marine) APUs.
- Short-life turbojet and turbofan engines for missiles.
- Heavy-duty turboshaft vehicular propulsion engines; military truck, tank, off-road vehicular, marine engine.
- Automobile propulsion,
- Human-rated aircraft propulsion and utility electric power generation.

Technical advances gained from continuing research efforts are necessary before ceramic materials can serve in these applications.

VEHICLES

Ceramic materials are being considered either as direct substitutes for selected components of existing gasoline and diesel engines or for use in engines designed specifically to benefit from the properties of ceramic materials.

Component substitution in gasoline engines offers only minor improvements in fuel econ-

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[50] Parkinson, op. cit.

omy or power production over conventional all-metal engines. As such, while selected components (cylinder liners and heads, exhaust and intake ports, valves, bearings) of such engines may be fabricated from ceramics, a "ceramic gasoline engine" is not considered a possibility, Ceramic diesel engines, on the other hand, can provide a 10- to 30-percent reduction in fuel economy and improved reliability due to the elimination of cooling systems. Since only minor amounts of strategic materials are used in conventional engines, ceramic components substitution can only marginally affect the use of strategic materials. One possibility, as yet unproven, is that the pollutants emitted by such hybrid metal-ceramic engines will be lower, owing to higher operating temperatures, and that strategic materials savings could occur with a shift in the materials requirements (now, PGMs and chromium) consumed by automotive catalytic converter systems.

Turbochargers.—Turbocharger rotors, now made primarily of nickel-based superalloys and nickel-iron alloys, could be a significant near-term use of ceramics. This technology[51] is one of the few heat engine applications being investigated with mostly private rather than government funding and is driven by a desire to combine the fuel economy of today's small cars with the performance of yesterday's larger engines, As this competition for greater fuel economy / performance increases in the automotive industry, the inclusion of ceramic rotors in turbochargers may retard an otherwise growing market for superalloy. The main candidate material for ceramic rotors is silicon nitride.

The primary attraction of the ceramic rotor is the improved performance provided by its low rotational inertia, which enables a quick response by the turbocharger at low engine rpms. The higher weight of metal alloys causes a delayed response called turbo lag. Secondly, there are expected material cost savings to be gained from the use of ceramics, along with overall weight savings (providing additional fuel economy). The high-temperature characteristics of ceramics are not a prime factor.

Two technical problems constrain mass production of ceramic rotors for turbochargers: the difficulties in joining ceramics and metals and uncertain reliability and reproducibility in materials processing. Nevertheless, ceramic turbochargers may be offered—to a limited extent—by the Japanese automobile industry within the next few years. Two Japanese firms reportedly began delivering sample turbochargers to Japanese car companies in mid-1983 for testing purposes. One of these firms announced plans to begin production in late 1984 and predicted that its ceramic turbines will be mass-produced within 3 to 4 years. The major U.S. turbocharger manufacturer, Automotive Products Division of AiResearch, competes in international markets and expects to have its ceramic rotor turbocharger ready by 1986 for the 1987 model year, If the ceramic turbocharger is successfully marketed by the Japanese industry, the U.S. automobile industry is expected to compete by offering similar turbochargers on their specialty market automobiles, where such gains in performance are desirable and the consumer may be willing to absorb added costs (both initial and maintenance).

The ceramic turbocharger is seen as a precurser to the use of ceramics in gas turbine engines where the rotor must withstand higher stresses. Successful commercialization of the ceramic turbocharger could provide valuable information to accelerate the application of ceramics to gas turbine engines.

Gas Turbines and Diesel Engines.—Research in new automotive engine designs to incorporate ceramic materials has been a major beneficiary of government support. Technologies now being investigated under contract to industry are the "adiabatic" (or, minimum heat loss) diesel and gas turbine engines. Industry also supports R&D in engine technologies through cost sharing on government contracts and its own private basic research. While various government projects have been funded sporadically since the 1940s, the heaviest support has occurred

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[51] A turbocharger, added to a standard internal combustion engine, pumps hot air (compressed by action of a turbine spun by hot exhaust gases) into the engine. Other options for fuel economy are available through redesign of the standard engine to improve its performance by reducing the amount of waste heat.

during the last decade.[52] NASA was directly involved in the early research with the Department of Defense and the Department of Energy (DOE) now taking the lead. The current major projects are DOE's Automotive Gas Turbine (AGT) program to develop a gas turbine engine by fiscal year 1986 and the U.S. Army Tank Automotive Command (TACOM) program with Cummins Engine Co. to develop the adiabatic diesel engine for use in military vehicles. It is believed that this diesel engine technology will eventually be transferred to the private sector for use in heavy-duty trucks. Automotive use of both the diesel and the gas turbine engines, if commercialized, is not expected until after 2000.

The benefits foreseen in use of the adiabatic diesel engine are increased fuel economy (due to the reduction of lost energy and the elimination of the need for a cooling system), reduction in weight and inertia, and greater engine reliability and maintainability. Energy loss may be reduced as much as 50 percent, and fuel consumption, 25 percent over conventional diesel engines with a significant increase in power.

The TACOM/Cummins research project started with development of ceramic components for conventional diesel engines. A second phase followed to design and test an uncooled, nonadiabatic diesel engine with ceramic and metal parts. R&D is now proceeding on an adiabatic diesel engine, combining both a ceramic combustion system and a turbocompound unit (to utilize waste heat). Remaining technical issues include the need for further materials research and the development of component manufacturing methods that are cost effective and provide reproducibility.

After Congress passed the Automotive Propulsion Research and Development Act (Title III of Public Law 95-238) in 1978, DOE and NASA initiated the AGT program. Two contracts were awarded: one to General Motors (Allison and Pontiac divisions) for the AGT 100 and another to the Garrett Corp. and the Ford Motor Co. for the AGT 101. Each of these contracts involve the design, development, and testing of an advanced ceramic automotive gas turbine engine. In the final versions the engines will have been designed from scratch to exploit fully the material properties of ceramics. Since its inception in 1980, the AGT program has been revised to take the development of the ceramic engine through to the proof-of-concept stage. A probable decrease in funding in fiscal year 1985 will require another shift in the overall program goals or organization.

Both the AGT 100 and 101 have successfully passed an initial testing phase. The models tested were designed using ceramics for static components, retaining metal for rotary parts. The phase now underway will test versions designed with ceramic rotary parts.

One of the largest technical problems foreseen with the application of ceramics as engine components is that of gaining reliability and reproducibility in the large-scale production that commercial automotive application will require, The ultimate phase required for bridging a tough attitudinal barrier ("ceramics are brittle") and to ensure transfer of this new engine technology will be to convince engineers, designers, the automobile industry management, and consumers that ceramics can indeed serve in these capacities. This will require rigorous testing of ceramic engines in real environments—in automobiles subjected to daily use over long periods of time.

Again, the benefits of strategic material savings from these new automobile engines will be minor except for the possible changes in materials now used for catalytic converters. Results from the use of advanced ceramic materials in vehicle applications and the knowl-

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[52] According to a draft interim report (November 1983) by Charles River Associates for the National Bureau of Standards, *Technological and Economic Assessment of Advanced Ceramic Materials: A Case Study of Ceramics in Heat Engine Applications:*

> Since 1976, total U.S. Government support for R&D in ceramic heat engines has exceeded $10 million per year. In 1981, 74 percent of total government funding was provided by DOE, 23 percent by DOD, and about 3 percent by NASA. In addition, Charles River Associates have estimated that private funding of structural ceramics R&D is roughly equal to the amount of funding received by the private sector from the government in this area. However, little information is available about the focus of this private funding, i.e., what amounts are devoted to heat engine applications.

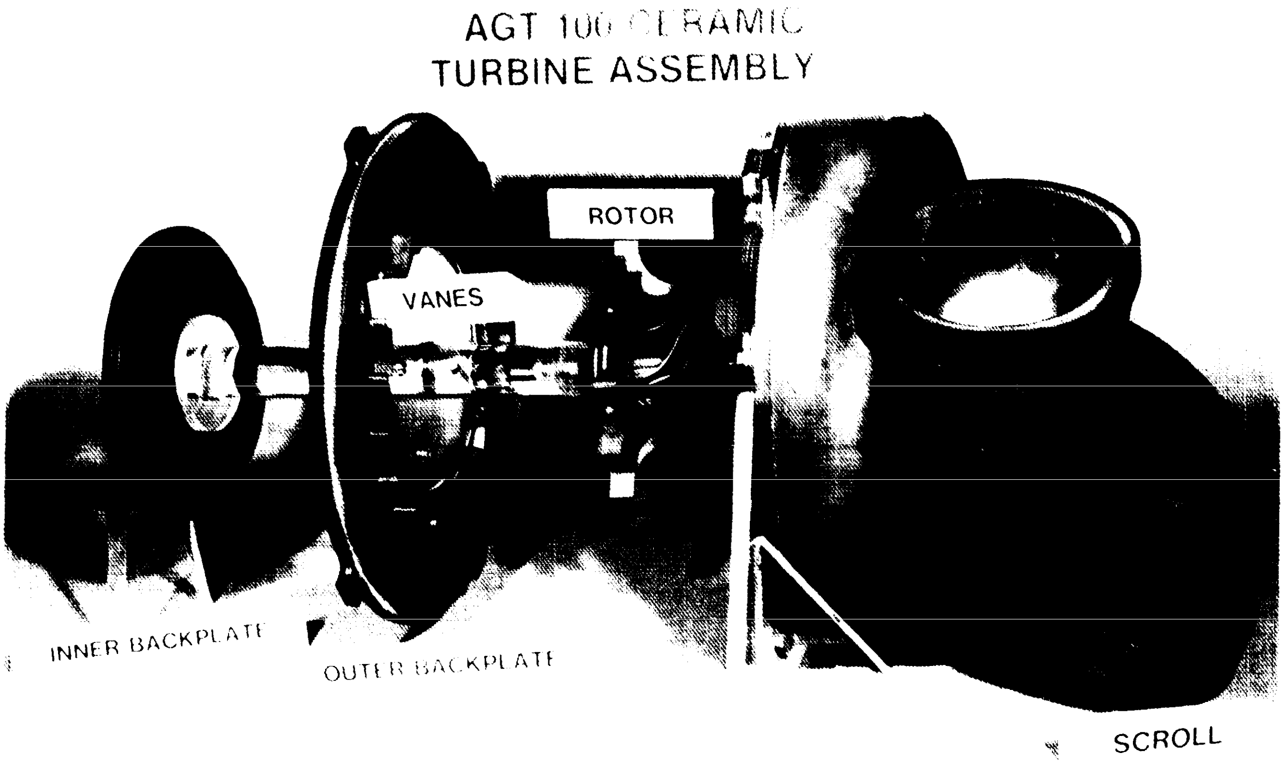

Photo credit: Allison Division, General Motors

Ceramic components are being evaluated in the advanced gas turbine being developed by Allison Division of General Motors for the U.S. Department of Energy and NASA

edge gained in processing of those materials will undoubtedly benefit the development of aircraft gas turbine engines, where real strategic materials savings may be realized from the substitution of ceramics for superalloy (chromium and, especially, cobalt).

AIRCRAFT TURBINE ENGINES

The use of ceramics in gas turbine engines for human-rated aircraft is believed to be one of the most challenging and difficult applications for advanced materials, owing to high performance demands and the extremely high risk of use involved. It is, however, an area in which the private sector is acutely interested because of a continuing desire to increase the performance of jet engines. This performance, which translates into fuel economies, increases as the inlet temperatures for a gas turbine engine increases. The current materials—superalloys—used in the hot sections of the engine have operating limits over time of about 1,9500 F. Ceramics, on the other hand, can withstand operating temperatures up to about 2,500° F. This higher thermal efficiency allows for a reduction in airflow through the engine and a corresponding smaller engine size. NASA has estimated possible introduction of monolithic ceramics as turbine blades in this application around the year 2010.[53]

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[53] Parkinson, op. cit.

Both the Air Force and NASA[54] have maintained a continuing interest in ceramic gas turbine engine development, In the private sector, both Pratt & Whitney and General Electric Co. have contributed to basic research on structural ceramics for potential aircraft engine applications. The Air Force Materials Laboratory has sponsored small research programs on the evaluation of ceramics and ceramic composites with potential use in aircraft systems. NASA's Lewis Research Center, in addition to managing DOE's AGT programs, has sponsored small research programs on structural ceramics. NASA has also developed an overall program to augment its current research efforts in ceramics. This program, with its focus on the aircraft engine, is intended to broaden the technological base of advanced ceramics by coordinating research in the various technical needs (e. g., materials processing, nondestructive testing, design methodologies). The development of this plan was coordinated with other government agencies and industry but was not included in the final NASA fiscal year 1985 budget proposal.

Much work remains in developing monolithic ceramics and processing techniques and gaining applications experience before these materials will be acceptable for human-rated aircraft. The advantages of ceramics with regard to engine performance and, to a lesser extent, the potential for reducing the overall use of first-tier strategic materials are incentives that will help promote the still-substantial research, development, and commercialization tasks ahead.

STATIONARY ENGINES

Stationary engines being considered for ceramic materials applications are primarily gas turbines for industrial and household use, including accessory power units for emergency or peak load service. The possible development of these small generators for near-term use have benefited from research sponsored by DOE and the private sector. In the longer term, both General Electric Co. and Westinghouse are investigating the application of advanced ceramics in large gas turbines for electric powerplants. It is believed that the thermal efficiencies obtainable with the use of ceramics can result in considerable energy savings. To be economic, the ceramic materials will have to withstand long component lifetimes. These large units are not expected for use until 2000. Strategic materials savings could be realized through reduced use of wear- and corrosion-resistant materials, such as chromium alloy steels.

Composites

Two or more materials, when combined into a composite, can yield a product with very impressive properties, including high strength and stiffness, low weight, and good corrosion and chemical resistance. In addition, composites offer engineers unparalleled opportunities to tailor materials to particular applications. Most composites contain little or no strategic metals, As a result, the anticipated growing market for composites has the potential to displace some strategic metal use.

Technically, a composite is any material composed of two or more physically distinct phases. This category includes, among other materials, filled plastics, laminated materials, dispersion-strengthened alloys, and fiber-reinforced materials. Of these, the latter two are most likely to affect strategic materials usage. Dispersion-strengthened alloys were covered in the superalloy substitution section, so the discussion here will be limited to fiber-reinforced materials (commonly called advanced composites). The basic characteristics of fiber-reinforced composites are outlined in box 7-B.

Advanced composites can be made from several different combinations of matrix and reinforcement materials, but are generally classified by matrix material. Table 7-12 shows the most common matrix and filament combinations. Organic (polymeric) matrix composites (including fiberglass reinforcements) are the only composite materials in widespread com-

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[54] The budget for NASA's Ceramic Technology for Aerospace Heat Engines was an estimated $3.3 million in fiscal year 1983 and $4.4 million in fiscal year 1984.

Box 7-B.--Fiber-Reinforced Composites

Fiber-reinforced composites, which are continuous filaments or whiskers embedded in a binding matrix, exhibit properties that exceed those of its constituents taken alone. Each constituent serves a special function. The filaments provide the strength and stiffness, while the matrix provides the body of the finished composite product and transfers the stresses and loads to the fibers.

The mechanical properties of a composite depend on the composition of both the matrix and the fibers, the relative proportion of each, the orientation of the fibers, and the length of the fibers. By varying these parameters, the strength of a composite can be optimized for the loads encountered during its service.

The filaments, which account for 25 **to** 80 percent of the composite by weight, can be either continuous or discontinuous (whiskers). Composites with continuous fibers have outstanding directional properties, while those with discontinuous fibers lend themselves more readily to such conventional metalworking operations as forging, extrusion, squeeze casting, and welding.[55]

In addition to strength and stiffness, the filaments enhance other properties of the composite. Often, the filaments will increase the maximum service temperature by adding high-temperature strength to the composite. Also, certain filaments can enhance thermal stability because they do not expand greatly when heated (i.e., low coefficient of thermal expansion).

Since most of the load-bearing responsibility falls on the fibers, the importance of the strength characteristics of the matrix material is diminished. In fact, composites with the weaker, but lighter matrices such as plastics, carbon, and aluminum can have good strength. Therefore, composites are known to have good strength and stiffness for their weight (i.e., high specific strength and modulus).

The matrix provides more than the body of the composite. In unidirectional composites, which have all the filaments aligned in a single direction, the matrix provides most of the transverse (perpendicular to the fiber direction) and shear properties. Additionally, the matrix is responsible for much of the corrosion and oxidation resistance and for providing the visual and textural appearance of the finished composite product.

Although matrices and fibers serve different functions, they are not independent. The thermal expansion mismatch between matrix and fiber must below to minimize thermal fatigue problems. Also, both phases must be chemically compatible at both fabricating and operating temperatures in order to prevent interdiffusion and the concomitant degradation of fiber strength. In some cases where such compatibility is inconvenient, barrier coatings can be applied to the fibers to inhibit interdiffusion.

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[55] Robert R. Irving. "Metal Matrix Composite Pose a Big Challenge to Conventional Alloys," *Iron Age*, Jan. 12, 1983, p. 35.

mercial use. Carbon/carbon composites are in limited production for aerospace applications. Metal and ceramic matrix composites have yet to be commercialized, except in highly specialized applications.

prospects for composites to displace strategic materials varies by composite class, Organic or polymeric composites—the only composites now in widespread use—will seldom directly replace the first-tier strategic materials considered in this report, but the indirect effects of their use could be significant, as was brought out at a recent National Science Foundation workshop:

> It is unlikely that this country will witness any wholesale and direct substitution of composites for critical and strategic materials unless some national emergency dictates such steps. Rather, composite materials will make inroads in those areas where weight and/or cost are the primary drivers. Most of the critical materials, namely cobalt, chromium, platinum, tungsten and tantalum are used because of their unique resistance to high temperature,

Table 7-12.—Advanced Composite Materials Options

	Reinforcement										
	Carbon/graphite										
Matrix	Rayon Base	PAN Base	Pitch Base	S-glass	Aramid	Boron	Alumina	Silicon carbide	Quartz	Boron nitride	Tungsten
Organic											
Epoxy	⊗	⊗	X	⊗	⊗	⊗					
Phenolic	⊗	⊗							⊗		
Polyimide		⊗	X	⊗					⊗		
Bismaleimide		X									
Polysulfonate		X									
Carbon											
CVD	⊗	⊗	⊗								
Resin pyrolyzed	⊗	⊗	⊗								
Pitch pyrolyzed	⊗	⊗	X								
Metal											
Aluminum		X	X			X	X	X			
Magnesium			X				X	X			
Copper		X	X								
Lead		X					X				
Titanium						X		X			
Steel								X			X
Superalloys											X
Ceramic											
Silica									⊗		
Boron nitride										X	

NOTE Circles indicate composites which have been or are now in production status

SOURCE Stanley L Channon, *Industrial Base and Qualification of Composite Materials and Structures (An Executive Overview)* (Alexandria. VA. Institute for Defense Analyses, March 1984), working paper, p 3

corrosion or their catalytic phenomena. In no way can the composite materials we ordinarily consider, graphite, glass, or Kevlar with epoxy, polyimide, or thermoplastic resins be considered for direct substitution. The impact of composites will come indirectly in secondary effects. An example is a gas turbine in which the weight reduction by the use of composites for stationary, low-temperature components will cascade into downsizing of high-temperature components and result, not in elimination of the critical metals, but in a significant reduction in the amount of strategic material needed.[56]

Carbon/carbon composites, used primarily in aerospace applications, may also have indirect effects on strategic materials through redesign of products. Metal and ceramic/glass matrix composites may eventually be used in very high-temperature superalloy applications.

The high cost of advanced composite materials is an important deterrent to their widespread use. Table 7-13 shows the high relative raw material costs of various advanced composites. Moreover design, fabrication, testing, and inspection costs are often higher for composite materials than for monolithic materials. These costs can be expected to decrease as the materials come into more widespread use and as processing and fabrication problems are overcome. Figure 7-3 shows the decrease in graphite fiber costs since 1970.

The advanced composites industry has rapidly become internationalized, with the United States, Japan, Great Britain, France, and other countries participating in individual segments of the industry. Very often, separate fabrication steps needed in the manufacture of par-

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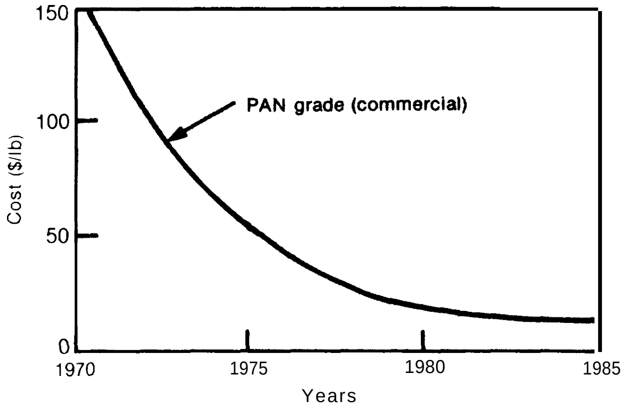
[56] William E. Winters, "Use of Composites in High Performance Structural Application s," *Materials and* Society, vol. 8, No. 2, 1984, p. 313.

Table 7-13.—Price Range of Selected Composite Raw Materials

Reinforcement	*1985* cost/pound
Graphite grades:	
Rayon precursor fibers (woven cloth)	$70 to $80
PAN precursor (commercial and large-volume aerospace orders)	$17 to $40
Pitch grade (high-volume aerospace)	$35 to $275
Graphite fiber prepreg (PAN grade, 60 percent fiber)	$36 to $40; up to $100/lb for specialty products
Boron:	
Tungsten core	$365 to $375
Boron fiber prepreg (carbon core fiber):	
250° cure	$270 to $300
350° cure	$310 to $340
Kevlar:	
Type 29	$5.40 to $39.25
Type 49	$12.55 to $48.20

SOURCE Various Industrial producers contacted by the Office of Technology Assessment

Figure 7-3.—Graphite Fiber Cost



SOURCE: **1970-1980 data:** *Commercial Opportunities for Advanced Composites, A* A Watts (ed.) (Philadelphia, PA. American Society for Testing and Materials, 1980), publication 704, p 90; **1985 data** provided by industry producers.

ticular composites are undertaken in separate countries. Although advanced composites are not strategic materials in the ordinary sense of the term, a growing concern in the defense community concerns U.S. dependency on foreign processing capacity to fabricate key composite components. Until recently, for example, the United States depended on Japan and Great Britain for virtually all carbon fiber reinforcements made from polyacrylonitrile (PAN), one of three possible precursor materials for carbon fiber. The United States now produces some carbon fiber using foreign PAN precursor materials. Also, Union Carbide has opened a domestic PAN production facility that reduces U.S. dependence on foreign PAN to 70 percent of domestic needs. However, this domestic precursor is not yet qualified for all defense programs, so in many critical applications dependence on foreign supplies is still near 100 percent. France, similarly, is the source of all quartz fibers and of an important curing agent used in epoxy resin formulations.[57] It has been estimated that, in most segments of the composites industry, U.S. production capability could be doubled within 2 years if the need arose.[58]

Polymer (Organic) Matrix

Polymers, such as polyesters, epoxies, and polyamides, are by far the most developed of all composite matrix materials. They are most frequently reinforced with (fiber) glass, graphite, or aramid (commonly referred to by its Dupont tradename, Kevlar) filaments. Polymeric composites can have performance capabilities that are commonly thought unattainable by plastics. For example, polyimide composites are capable of continuous operation at 7000 F in some applications. Organic

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[57] Stanley L. Channon, *Industrial Base and Qualification of Composite Materials and Structures [An Executive Overview)* (Alexandria, VA: Institute for Defense Analysis, March 1984), p. 10 (working paper).

[58] Ibid., p. 16.

composites are attractive because they combine these good physical properties with lightweight and ease of fabrication. Consequently, these materials may reduce the need for strategic materials—not via direct substitution, but through the cascading effects of downsizing and redesign allowed by the decreased weight and innovative fabrication.

The total U.S. consumption of polymer composites in 1982 approached 1 million metric tons (tonnes). Of this, 618,000 tonnes of polyester/glass (fiberglass) was the largest share, Additionally, 106,000 tonnes of reinforced thermoplastics and 28,000 tonnes of epoxy resins (equivalent to approximately 90,000 tonnes of epoxy-based composites) were consumed.[59] U.S. consumption of composite reinforcing filaments in 1982 was: glass, 280,000 tonnes; aramid, 900 tonnes; carbon (graphite), 800 tonnes; and other, 10 tonnes,

Fiberglass-reinforced organics (which are not generally considered advanced composites) dominate current markets. High-volume applications include boat hulls, plumbing and bathroom fixtures, and automotive body and trim panels, which are often made from polyester/glass composites. Low raw material costs and automated, high-speed production processes have made possible the widespread use of polyester/glass composites. Figure 7-4 shows selected applications for different fiberglass composites.

Because of their high price, use of other polymer composites has been largely limited to aerospace applications, sports equipment, and automotive applications. Low-volume aerospace applications for polymer composites have increased since 1968, when an epoxy/ boron horizontal stabilizer for the F-14 jet was first used on an experimental basis. In 1970, the Grumann Corp. approved this application for limited production.

Since then, air frames, air panels, satellite structures, and sporting goods have been built from advanced composites, Table 7-14 shows recent aerospace applications for advanced polymeric composites. In each of these applications, advanced composites were selected for their high specific properties. Specific properties refer to common materials properties (e.g., strength), normalized to the weight of the material. Organic composites have very good strength and stiffness for their weight and are therefore said to have high specific strength and stiffness.

Aside from polymer/glass composites, the polymeric composites with the greatest potential for continued growth appear to be epoxy/graphite and epoxy/aramid. Epoxy/boron (despite its early use) is no longer seen as promising, owing to difficulties in processing the extremely hard and brittle boron fibers, to high costs associated with producing the fibers, and to effective competition from the graphite and aramid systems.

Carbon Matrix

A carbon matrix reinforced with carbon or graphite fibers is commonly known as a carbon/carbon composite. They are high-cost materials used in specialty applications and are, for the most part, in early developmental stages. To date, commercial applications include rocket nozzles and exit cones, re-entry vehicle nosetips, and aircraft brakes.[60]

These materials are very strong and tough, and have the potential for maintaining these properties at temperatures up to 4,500° F. Moreover, carbon/carbon composites are very light—somewhat less than 25 percent of superalloy density and about 50 percent of ceramic (monolithic or ceramic/ceramic composite) density—dimensionally stable, wear resistant, and free of strategic metals,

There are, however, several disadvantages which must be addressed. Controlled environments or impervious coatings must be used to prevent oxidation problems in high-temperature applications, and special weaves of graphite fibers are needed to prevent surface fatigue cracking caused by low interlaminar strength.

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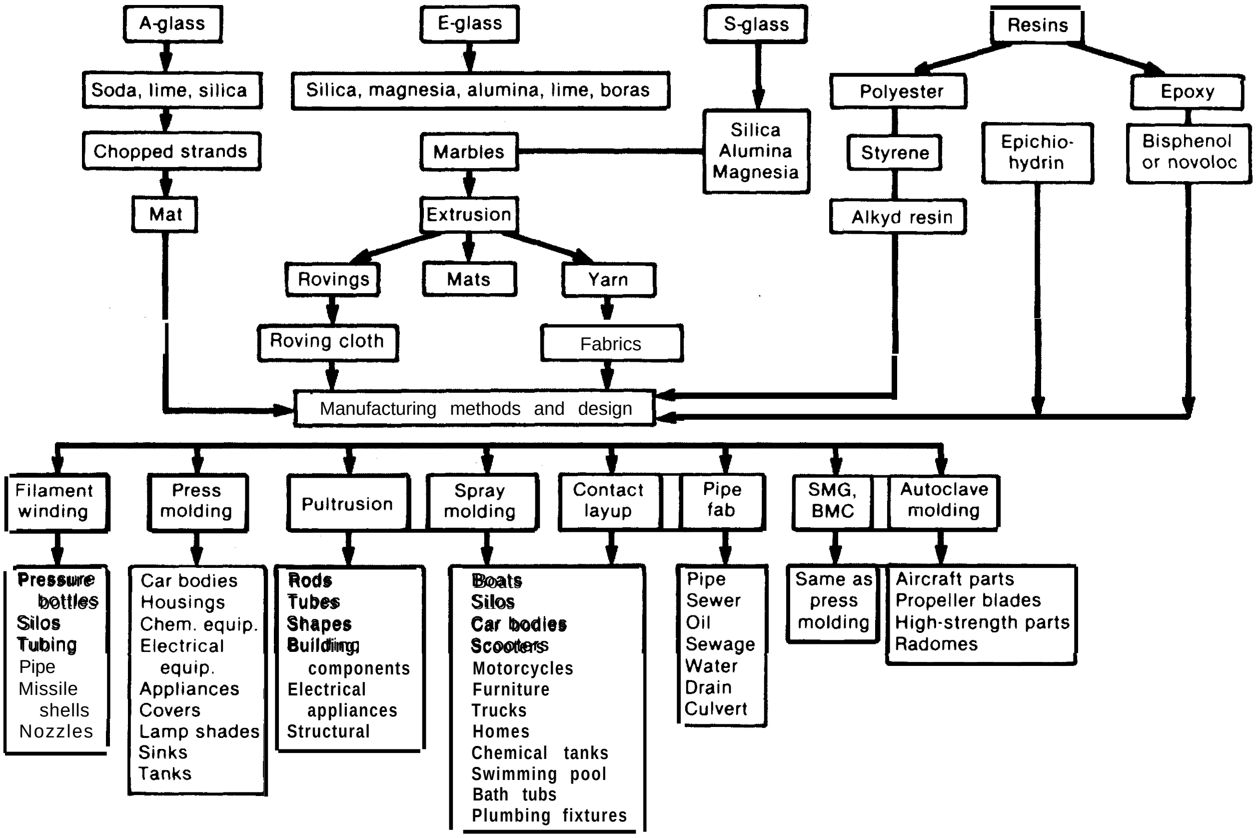
[59] Joel Clark, *Potential of Composite Materials to Replace Chromium, Cobalt, and Manganese in Critical Applications,* OTA contract report, 1984.

[60] Channon, op. cit., p. 36.

Figure 7-4.— Fiberglass Composite Applications



SOURCE: *Commercial Opportunities for Advanced Composites,* A. A. Watts (cd.) (Philadelphia, PA: American Society for Testing and Materials, 1980), publication 704, p. 112.

In addition, carbon/carbon composites are very expensive as a result of the complex weaving procedures, long processing times, and high energy consumption involved in processing. As with most developing materials, the cost is expected to decrease as the technology emerges and production rates increase.

Development work at NASA and in industry is aimed at reducing the high fabrication costs of carbon/carbon composites. Improving composite strength and stiffness and increasing the reliability of coatings and oxidation-inhibiting matrix additives are also goals of this work.

U.S. carbon/carbon composite use is expected to grow rapidly, primarily because of defense and aerospace needs. In 1982, an estimated 200,000 pounds of carbon/carbon was consumed in the United States. One survey of government and industry experts found an expected need for 800,000 pounds of carbon/carbon by 1990—a quadrupling in demand in an 8-year period.[61] As already discussed, some concern exists about U.S. reliance on Japan for most of its carbon fibers made from PAN. Although rayon- and pitch-based carbon fibers exist, PAN-based fibers are used in most current applications. Figure 7-5 projects defense and civilian needs for carbon/carbon composites through 1990; this may be an overestimate, due to changed program priorities.

Ceramic/Glass Matrices

Monolithic ceramics and glasses are brittle and exhibit low fracture toughness. The toughness of these materials can be improved by

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[61] The 1982 estimate and the 1990 projection were made by Channon, op. cit., p. 42.

Table 7-14.—Current Aircraft Applications for Advanced Composite Materials

Component	Source	Remarks
Wing:		
F-15 composite wing	McDonnell Douglas	Graphite/epoxy used to form wing ribs and spars over much of the wing substructure; target weight savings for entire wing, 25°/0
C-5A leading edge slat	Lockheed-Georgia	Basic design is graphite/epoxy skins over aluminum honeycomb core: weight savings, 22%
F-5 main landing gear door. . .	Northrop	Weight savings, 36°/0
737 spoilers	Boeing	Basic design is graphite/epoxy skins over aluminum honeycomb core with aluminum and fiberglass fittings, edgemembers and ribs: 108 units (27 ship sets) have been fabricated and service tested: weight savings, 15%
A-4 landing flap.	McDonnell Douglas	Basic design is graphite/epoxy skins over aluminum honeycomb with aluminum edgemembers except for a molded graphite/epoxy actuator rib: weight savings, 47 %
F-5 leading edge flap	Northrop	Weight savings, 32%
B-1 leading edge slat	Lockheed-Georgia	Basic design is graphite/epoxy skins over aluminum honeycomb core with aluminum and fiberglass ribs and trailing edge close-out. Front beam is molded graphite/epoxy along with the leading edge structure: weight savings, 15%; cost savings, 35%
Empennage:		
A-4 horizontal stabilizer	McDonnell Douglas	Basic design is multishear web/solid-laminate skin concept; shear web constructions are both graphite/epoxy laminates and fiberglass core-graphite/epoxy skin honeycomb structure: weight savings, 28%
F-5 horizontal stabilizer	Northrop	Basic design is graphite/epoxy skins over aluminum honeycomb core with aluminum close-out ribs, integral spar, and torque tube fitting: weight savings, 23°/0
F-4 rudder	McDonnell Douglas	Used graphite/polymide in leading edge spar; other high-temperature materials used were fiberglass olyimide honeycomb core, boron/polyimide prepreg. titanium, and high-temperature adhesive
DC-10 upper aft rudder , ...	McDonnell Douglas	Graphite/epoxy rudder is 32 ft^2 rib-stiffened-skin design manufactured in a co-cured assembly; composite component weight is 57 lb: weight savings, 37%
L-101 1 vertical fin	Lockheed	Graphite and Kevlar composite box beam and skins to replace 9 x 25 ft primary structure; composite component weight is 640 lb (17°/0 metals): weight savings, 25°/0
Fuselage:		
A-7 speed brake	Vought Aeronautics	Built-up molded laminate design using graphite/epoxy elements bonded with structural adhesive: weight savings, 400/0
F-5 speed brake	Northrop	Weight savings, 23°/0

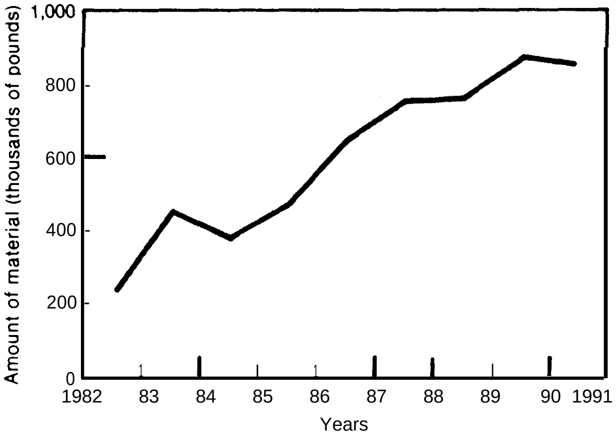
CONVERSION FACTORS 1 ft^2 – O 1 m^2
1lb = O 45 kg
If! = 03 m

SOURCE *Commercial Opportunities for Advanced Composites*, A. A Watts (cd.) (Philadelphia, PA American Society for Testing and Materials, 1980), publication 704, p 104

reinforcing them with ceramic fibers to limit the growth of cracks. Currently, glass matrix composites are more developed than their ceramic counterparts. Ceramic matrix composites are still confined to experimental applications–-they are not currently used commercially,

Most glass compositions (e.g., lead, quartz, borosilicate, and boron oxide) have been reinforced on a laboratory scale. They have been allied with a variety of filaments, including alumina, silicon carbide, graphite, and tungsten, in order to improve their toughness and high-

Figure 7-5.—Carbon/Carbon Composite Needs[a]



[a] These estimates, reported in 1982, reflect anticipated use in weapons systems, aircraft brakes, and engines at that time. Recent changes in program planning indicate that these needs may be overestimated.

SOURCE: Stanley L Channon, *Industrial Base and Qua/if/cation of Composite Materials and Structures (An Executive Overview)* (Alexandria, VA: Institute for Defense Analyses, March 1984), working paper, p 43

temperature strength. One promising example is United Technologies' lithium aluminum silicate glass, reinforced with silicon carbide fibers, This material has roughly 10 times the fracture toughness of the unreinforced glass up to about 2,0000 F.

Ceramic matrices that have been examined experimentally include alumina, boron nitride, zirconia, silicon nitride, and silicon carbide, Reinforced with either inorganic materials or metal wires, these ceramics could possibly be used in applications with temperatures exceeding 3,0000 F. As with glasses, ceramics are reinforced to improve their toughness. They do not, in general, benefit from any improvement in high-temperature properties.

Reinforcement of higher temperature ceramics has been relatively unsuccessful to date because of fiber strength losses due to fiber and matrix interaction at high fabrication temperatures, fiber recrystallization, and fiber fracture due to abrasion and stress during processing. As a result of these problems, NASA research has been redirected to ceramic composites employing weak bonding between the fiber and the matrix and to developing processing technologies that employ lower temperatures and no pressing, Clearly, ceramic/ceramic composites will need substantial additional research and development. They may eventually be used for turbine vanes, blades, and cases.

Metal Matrix

Metal matrix composites are relatively new structural materials. Many metals, including lead, titanium, stainless steel, magnesium, copper, nickel, and zinc, have been experimented with, but the most highly developed are aluminum matrix composites. Virtually any metal can be reinforced; benefits include increased specific strength compared to conventional metals, improved wear resistance, and higher allowable operating temperatures. However, the gains from reinforcement are often insignificant when compared with the costs.

Metal matrix composites are still primarily laboratory materials. However, some successful commercial applications exist. Toyota Motor Co. has developed an aluminum/alumina composite for reinforcing the piston ring groove in production diesel engines and is developing composite pistons and cylinder heads. In such applications, improved performance is highly valued, and this has been the justification for developing metal matrix composites, Table 7-15 shows some potential commercial applications of metal matrix composites,

Copper composites are under consideration for use in transmission lines. Lead is reinforced for use in batteries because in certain applications lead lacks the strength to support its own weight. Aluminum matrices, containing boron, alumina, or silicon carbide fibers are designed to compete with titanium. Reinforcing an aluminum alloy can raise its allowable service temperature by 2000 F, permitting its utilization in many applications where it otherwise could not be used. Aluminum/graphite and aluminum/boron composites have been developed for use at 525° F.

Fiber-reinforced superalloy (FRS) technology is under development in the NASA Metal Matrix Composite Program, The aim of this program is to develop the technology to fabricate an FRS turbine blade capable of operating at a surface temperature of 1,100° to 1,200° C

Table 7-15.—Potential Commercial Applications of Metal Matrix Composites

Application	Desired properties	Suggested composite systems
Aerospace:		
Space structures.	lightweight, stiffness	B/Al, B/Mg, Gr/Mg
Antennae ., ...	lightweight, stiffness	B/Al, B/Mg, Gr/Mg
Aircraft:		
Airplanes:		
Pylons	lightweight, stiffness, heat resistance	B/Al, SiC/Al
Struts	lightweight, stiffness, strength	B/Al, SiC^a/Al
Fairings	lightweight, stiffness	B/Al, SiC^a/Al, Gr/Al
Access doors	lightweight, stiffness, strength	B/Al, SiC^a/Al
Wing box	lightweight, stiffness, strength	B/Al, SiC^a/Al
Frames	lightweight, stiffness, strength	B/Al, SiC^a/Al, Gr/Al
Stiffeners ., ...	lightweight, stiffness, strength	B/Al, SiC^a/Al, Gr/Al
Floor beams	lightweight, stiffness, strength	B/Al, SiC^a/Al, Gr/Al
Fan and compressor blades	strength, stiffness, heat resistance, impact resistance	B/Al, SiC^a/Al, Gr/Al
Turbine blades	strength, stiffness, heat resistance, impact resistance	tungsten or tantalum fiber-reinforced superalloys
Turbine blades	strength, stiffness, heat resistance, erosion resistance	directionally solidified eutectics Ni_3Al-Ni_3Cb, Ni_3Al-Ni_3Cb-N i, Ni-Mo wire
Helicopters:		
Transmission cases	lightweight, stiffness, strength	Al_2O_3/Mg, Gr/Al, Gr/Mg, Al_2O_3/Al
Truss structures	lightweight, strength, stiffness	B/Al, SiC^a/Al, Al_2O_3/Al
Swash plates	lightweight, strength, stiffness	Al_2O_3/Al, SiC^a/Al
Push rods.	lightweight, stiffness, strength	SiC^a/Al, B/Al
Trailing edge of tail rotor blades	lightweight, stiffness, strength	Gr/Al, SiC^a/Al
Automotive:		
Engine blocks	lightweight, heat resistance, strength, stiffness	SiC^b/Al
Push rods	lightweight, heat resistance, strength, stiffness	SiC^a/Al, B/Al
Frames, springs	lightweight, strength, stiffness	SiC^b/Al
Piston rods	lightweight, strength, stiffness	SiC^b/Al
Battery plates	stiffness	Gr/Pb
Electrical:		
Motor brushes	electrical conductivity, wear resistance	Gr/Cu
Cable, electrical contacts	electrical conductivity, strength	GrlCu
Utility battery plates.	stiffness, strength, corrosion resistance	Al_2O_3Pb, Gr/Pb, fiberglass/Pb
Medical:		
X-ray tables, prosthetics	lightweight, stiffness, strength	B/Al,, SiC^a/Al
Wheelchairs	lightweight, stiffness, strength	B/Al, SiC^a/Al
Orthotics	lightweight, stiffness, strength	B/Al, SiC^a/Al
Sports Equipment:		
Tennis racquets ... , ...	lightweight, stiffness, strength	B/Al, Gr/Al, SiC^b/Al
Ski poles	lightweight, stiffness, strength	B/Al, Gr/Al, SiC^b/AL
Skis	lightweight, stiffness, strength	B/Al, Gr/Al, SiC^b/AL
Fishing rods	lightweight, strength, flexibility	B/Al, Gr/Al, SiC^b/AL
Golf clubs	lightweight, strength, flexibility	B/Al, Gr/Al, SiC^b/AL
Bicycle frames	lightweight, strength, stiffness	B/Al, Gr/Al, SiC^b/AL
Motorcycle frames	lightweight, strength, stiffness	B/Al, Gr/Al, SiC^b/AL
Textile industry		
Shuttles	lightweight, wear resistance	B/Al, Gr/Al, SiC^a/AL
Other:		
Bearings	—	Gr/Pb
Chemical process equipment	—	Al_2O_3/Pb
Abrasive tools	—	B/Al_2O_3, SiC/Al_2O_3

[a] SiC whisker and/or continuous SIC filament

[b] SiC whiskers only

SOURCE Commercial *Opportunities for Advanced Composites*, A A Watts (ed) (Philadelphia, PA American Society for Testing and Materials, 1980), publication 704, p 119.

(2,000° to 2,200° F). FRS development has been carried out almost solely through NASA sponsorship. With no end user deeply committed to the material, its development pace has been slow.[62]

NASA's development prototype is a cobalt-free (15 percent chromium) iron-based tungsten fiber-reinforced superalloy (TFRS). This experimental material has been successfully fabricated into a turbine blade, but has not yet been engine tested. Cobalt- and nickel-based superalloys can be used as a matrix material, but only if a protective barrier is provided to prevent tungsten/matrix interdiffusion. Hence, the first FRS material likely to be commercialized will probably be cobalt free.

In addition to their high-temperature properties, TFRSs are good substrates for thermal barrier coatings (TBC), which also raise engine temperature capabilities. The thermal expansion coefficient of TFRSs is low compared to superalloy and approaches that of current TBC. Such coatings applied to TFRS components would, therefore, show less tendency to span (i. e., crack and flake particles off the surface) than they do with present superalloy, (Spalling problems prevent TBC from being applied to present superalloy blade and vane air foils.) Further, regardless of the application of a TBC, the high thermal conductivity of TFRSs permits the use of simpler internal blade geometries for cooling air, thereby lowering manufacturing costs,

Several major technical problems currently limit the prospects for widespread use of TFRSs in turbines. The expansion coefficient of the tungsten fibers is approximately one-third that of the matrix. This induces thermal fatigue in a TFRS blade, considerably reducing its life. Also, tungsten fibers oxidize rapidly at turbine operating temperatures if exposed to the hot gas, Accidental exposure of the fibers in service could lead to rapid failure of the blade. At present, insufficient confidence exists that the probability of such exposure can be kept acceptably low, even with the application of a coating,

Ceramic whiskers and fibers also have been used to strengthen metal matrices. Such reinforcement is attractive because ceramic whiskers and fibers have high strength at ambient and elevated temperatures, high elastic modulus, good oxidation resistance, and low density, It has been found that ceramic reinforcement, usually as chopped fibers, can significantly improve the wear resistance of certain metals. However, results of research with both the whiskers and the long single crystal fibers have been disappointing so far.

One of the major advantages of metal composites over polymer composite systems is that there is not as large a difference between transverse and longitudinal strength. Transverse strength in metal composites is essentially equal to the strength of the matrix metal. An additional advantage, which can be important, is that metal matrix composites are electrically conductive.

Generally, the cost of metal composites is on the order of 10 times the cost of the matrix metal alone. Much of this differential is due to the high raw material cost of the reinforcement. Also, processing complexities add significantly to the total cost. For this reason, metal matrix composites are only considered for applications where the value of their added performance is great,

Prospects for the Future

Advanced composites are now entering a period of rapid growth. Much of this increased use will occur in the transportation industry, where there are significant incentives to decrease the weight and increase the performance of materials. Over the next 10 years, the aerospace industry could represent over 50 percent of the total high-performance composites market, Significant growth in the automobile and industrial sectors may occur in the late 1980s.[63]

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[62] Parkinson, op. cit.

[63] Clark, op. cit., p. 1.

Aerospace Applications

Most aircraft applications of composite materials do not require high-temperature performance and can be satisfied by polymer or aluminum matrix composites in such applications as airframe and structural parts. The use of aluminum matrix composites in these applications represents the largest foreseeable market for metal matrix composites, The downsizing and redesign, made possible through the reduction in weight, has the potential to reduce strategic materials usage.

Weight reduction in aircraft translates into fuel savings, lower operating costs, and increased profits for commercial aircraft; increased range, payload, and maneuverability for military aircraft; and reductions in manufacturing due to parts consolidation in both cases. The impetus for substitution of composite materials for conventional materials comes from market forces alone rather than from any desire to substitute strategic materials. Constant economic pressure can be expected to stimulate materials innovation.

Metal matrix composites, like advanced ceramics, ceramic composites, and carbon/carbon composites also have some potential for use in the jet engine industry, where the use of composite materials is expected to be performance- and market-driven. Cost considerations for jet engine materials will be of secondary importance relative to the overall cost of the engine.

While substantial technical problems must be overcome, these advanced materials could boost operating temperature above 2,500° F, far beyond even the most advanced superalloys now under development, However, use of these nonmetallic materials is not expected by NASA for human-rated engines until after the year 2010—roughly the same period as for advanced ceramics.

Tungsten fiber-reinforced superalloys will, in all likelihood, be used in jet engines only in the event of a prolonged crisis in the cobalt market. They have not satisfied important reliability criteria necessary for serious long-term consideration as substitutes for conventional superalloys or directionally solidified eutectics. They have not yet seen active operating service and would require a serious testing commitment before acquiring the confidence for industrial implementation,

Today, carbon/carbon composites can be fabricated into forms that may be useful in the gas turbine for combustor liners, cases, afterburners, and nozzles. A one-piece bladed turbine disc has also been formed, Industrial-research is at such an advanced stage for low- stress applications that jet engine afterburners made of composites could be in use in 5 years. High-stress applications are 10 or more years away. The complex qualification procedures used in the composites industry could affect timing, as well. These procedures are discussed in the concluding section of the chapter.

Carbon/carbon composites, despite their advantages in low-stress applications, cannot be expected to satisfy high-temperature, high-stress requirements for jet engine applications for another 10 to 20 years. Use of these materials will depend on developments in oxidation inhibitors and nondestructive testing methods, While materials prices are of negligible importance when compared to the overall cost of an engine, efficient implementation of these materials in jet engines will require a major overall redesign effort that will be both costly and risky, Industry seems to believe that government risk-sharing will be necessary to promote a rapid development of these novel technologies.

It is not expected that engine blades will be made of carbon/carbon composite materials, if only because reliability criteria for rotating high-stress parts are far from met, and testing has been far from sufficient. [64]

Automotive Applications

Currently, all the major automotive manufacturers have active development programs investigating the use of advanced composites in

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[64] Clark, op, cit., p. 75.

automotive structures. A wide variety of prototypes have been fabricated of advanced composites, including hinges, brackets, leaf springs, drive shafts, doors, and door guard beams. Many of these components have been tested in actual service over the last few years and have been found to perform well. Composite parts equivalent to steel parts in performance have been built. Significant redesign of these components has been accomplished to take advantage of the design flexibility which composites offer. Table 7-16 shows the potential automotive applications for Kevlar-reinforced composites.

Composites will also see increased use in automobile engines. Toyota has used aluminum reinforced with polycrystalline aluminum oxide fibers for the connecting rods in an experimental engine. Advantages of composite use in engines could include increased fuel efficiency, faster engine response, and reduced engine vibration.[65]

Large-scale use of composites by the automotive industry could occur as broader consumer acceptance, lower production costs, and design concepts lead to a general expansion of composite materials markets and lower prices. Corporate Average Fuel Economy (CAFE) regulations have been instrumental in creating an environment for novel new concepts of automotive designs and materials usage. However, these pressures have been relieved by automotive downsizing to meet CAFE standards in the short run. If CAFE requirements become more stringent and make downsizing less profitable in the U.S. market, polymeric and metal matrix composites could be a very important means of achieving weight reduction. New auto body parts production and assembly technologies, which are likely to affect the use of composites in automotive structures, are expected to see implementation over the next 10 years. Use of composites in substantial quantities is not expected to increase before the 1990s. The impact of composites technology on critical materials (mostly chromium) will be largely indirect, through weight reduction and performance enhancement.

Table 7-16.-Potential Automotive Applications for Composites of Kevlar 49 Aramid

Potential application	Reasons for use
Leaf springs	reduced weight, stiffness, fatigue resistance
Transmission supports	reduced weight, stiffness, vibration damping
Drive shafts	reduced weight, stiffness, fatigue strength
Bumper beams	reduced weight, stiffness, damage resistance
Radiator supports. . .	reduced weight, stiffness
Anti-intrusion beams.	reduced weight, damage resistance
Wheels	reduced weight, damage resistance
Body parts	reduced weight, stiffness, damage resistance
Clutch faces, brake linings	strength, wear resistance, high temperature, frictional properties

SOURCE: Commercial *Opportunities for Advanced Composites,* A. A. Watts (cd.) (Philadelphia, PA" American Society for Testing and Materials, 1980), publication 704, p. 119.

Barriers to the Adoption of Composites

Composites have some major technical problems which counter the attractiveness of many of the properties described above and inhibit the introduction and effective use of these materials. There is little doubt that many of these problems will be overcome as the technology matures,

Use of composites in many potential applications has been discouraged by the lack of established design practices and insufficient design data, Additionally, when composites are selected for use, they are often used as direct substitutes for conventional materials without redesign. The performance of composites in such circumstances is often less than optimal. The implementation of sophisticated computer-aided design algorithms promises to reduce greatly the complexity of designing for composite structures and allow more effective use of composites,

Another problem of composites is the high cost of raw materials, especially high-performance reinforcements such as boron, graph-

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[65] *Metal Progress*, February 1984, p. 14.

ite, and aramid. Prices for these reinforcements range from $20 per pound to well over $100 per pound. For this reason, advanced composites (those with specific properties exceeding steel) are selected only for applications where their special properties are highly valued.

Contributing to the high cost is the poor productivity of composite product fabrication. Processing composites is generally labor-intensive and time-consuming. While innovative techniques for automated, high-speed processing have been developed, their use is not widespread and is usually limited to forming specific types of goods. Moreover, once a nonmetallic composite is fabricated, the integrity of the structure is difficult to assess without destroying the component. This drawback is being overcome with the advent of nondestructive tests based on ultrasound and laser holography and with improved design procedures and increased experience in end uses.

Long-Range Order Intermetallic Materials

Materials in which two elements are arranged in an ordered pattern throughout the entire crystal lattice are known as long-range order intermetallics. Although there are many types of intermetallics, three families are particularly interesting with respect to the use of strategic materials:

Nickel aluminizes , , ., ... , ...	NiAl and Ni_3Al
Titanium aluminizes	TiAl and Ti_3Al
Iron aluminizes . . . ., ...	FeAl and Fe_3Al

None of the above materials contains any cobalt or chromium, but other compounds could contain strategic materials. Very little information concerning long-range order materials is publicly available, making it difficult to assess the state of the technology or determine when it will be commercialized.

Each of these six materials has low density as well as excellent high-temperature stability, strength, and oxidation resistance. These properties have been known for many years, but the materials have seen little service because of brittleness problems. Their poor ductility, particularly at low temperatures, results in fabrication problems, low impact strength, and low thermal shock resistance. Recent research, however, has shown that the ductility can be improved by microalloying and thermomechanical treatment, This raises the prospect of using the intermetallics in high-temperature applications, such as gas turbines, where strategic materials are currently used.

Nickel Aluminizes

Single crystals of Ni_3Al exhibit good ductility, but polycrystalline Ni_3Al is very brittle. Because of the cost and inconvenience of single crystal-technology, monolithic Ni_3Al is unattractive for most applications.[66] Research at Oak Ridge National Laboratory has demonstrated that small additions of boron (around 0.05 percent) to the polycrystalline form removes the ductility problem.[67] Microalloying (doping) with boron makes it possible to extrude, forge, and cold roll these materials, In addition to being fabricable, these boron-doped aluminizes have tensile strengths that compare favorably with those of Waspaloy, Hastelloy X, and 316 stainless steel.

Possessing high-temperature strength and oxidation resistance, and adequate ductility and fabricability, boron-doped Ni_3Al alloys have potential as structural materials. The aircraft gas turbine industry is beginning to evaluate the material for various applications. Polycrystalline forms are being considered for discs—operating temperatures up to 1,250° C, or 2,280° F, seem possible. Combustor liners and turbine vanes are other possible uses. A single crystal Ni_3Al turbine blade is also of interest.

The good oxidation resistance of Ni_3Al results from the formation of aluminum oxide scales, which protect the alloy, Recent work has shown that alumina-forming materials

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[88] Ni_3Al is most commonly known as the dispersion phase [gamma prime) that imparts high-temperature strength to nickel-based and iron-nickel-based superalloy.

[67] C. T. Liu and C. C. Koch, "Development of Ductile Polycrystalline Ni_3Al for High-Temperature Application s," *Technical Aspects of Critical Materials Use by the Steel Industry, Volume 1113,* NBSIR **83-2679-2**, June **1983**, op. cit.

have excellent hot-corrosion resistance in coal energy conversion systems. Such findings suggest that aluminizes may be useful as structural materials in sulfiding environments.

Titanium Aluminizes

The ductility problems of Ti_3Al are overcome by microalloying with columbium (niobium), a second-tier strategic material. Ti_3Al is being studied in the United States for use in aircraft gas turbine engine compressor rotors and blades and in low-pressure turbine discs, blades, and vanes. These materials are potential (albeit expensive) substitutes for some superalloy (e.g., Waspaloy and Inco 713.)[68]

Iron Aluminizes

Pratt & Whitney Aircraft has studied these materials in conjunction with rapid solidification rate processing.[69] The inherent ductility problem was removed and an increase in tensile strength achieved by microalloying with titanium diboride (TiB_2). The particular interest in these materials is for use as sheet for combustor liners—up to temperatures of 1,800° to 2,0000 F. Iron aluminizes are also of interest for turbine discs, blades, and vanes at lower temperatures, and for cases.

Nickel, titanium, and iron aluminizes are all in relatively early stages of development. While they have shown great promise to date, much remains to be learned concerning the full range of their material properties.

Rapid Solidification

Many new and potentially useful materials are being developed using technologies that solidify molten alloys extremely quickly. These rapid solidification (RS) technologies enable materials engineers to improve current alloys and to explore previously unattainable alloy compositions and microstructure. The effects of this new technology on the use of strategic materials are as yet unknown. As emphasized in a 1983 NMAB study:

> Work is continuing in the field of rapid solidification and its applicability to the reduction of strategic elements. Work to date indicates that this method of processing holds much promise for attaining at least a degree of independence from such elements as cobalt and chromium in various systems of alloys. However, it must again be emphasized that, for critical alloy applications, the principal motivation in alloy and process development is the achievement of improved mechanical, physical, or chemical properties, Whether the successful application of RS technologies will be accompanied by a reduction of the use of strategic elements cannot be foreseen at this time.[70]

Rapid solidification refers to the chilling of molten materials into solids at very high cooling rates. Materials are considered rapidly solidified when they have been cooled fast enough to assume microstructure that cannot be generated by conventional solidification techniques. Cooling rates obtained with RS processes are often on the order of millions of degrees Celsius per second.

Because of the heat transfer characteristics needed to attain the requisite high cooling rates, RS materials must have high surface area-to-volume geometries. This requirement limits the shapes of RS products to powders, flakes, and ribbons. These are rarely used in the as-cast form; usually, consolidation and mill working operations are needed. The casting, consolidation, and mill working processes are described in box 7-C.

RS in Strategic Materials Substitution

A vast number of alloy systems have been rapidly solidified in the course of scientific inquiry, but commercial interest in RS has been limited to only a few classes of alloys. Of these, transition metal-based glasses and aluminum-, nickel-, and iron-based crystalline alloys seem to have the greatest commercial potential.[71] In

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[68] Parkinson, op. cit., p. 49.

[69] Joseph Moore and Colin Adam, “Potential of Rapid Solidification for Reduction of Critical Element Content of Jet Engine Components, ” *Conservation and Substitution Technology for Critical Materials, Vol. II,* NBSIR 82-2495 (Springfield, VA: National Technical Information Service, April 1982).

[70] NMAB-406, op. cit., p. 68.

[71] J. V. Woods, “Rapid Solidification Processes and Perspective Part I I,” *Materials and Design, vol. 4,* April/May 1983, p. 712.

Box 7-C.—Rapid Solidification Technologies

Several methods have been devised to achieve the high cooling rates associated with rapid solidification. In all of them, molten metal is quenched at rates varying anywhere from 10^3 to 10^7 degrees Celsius per second. The powder, flake, or ribbon produced by these methods can be either crystalline or amorphous, depending on the alloy compositions and cooling rates used. Other parameters affecting the viability of the various processes include: the sizes, shapes, distribution, and handling characteristics (cost, safety, cleanliness) of the particulates, the production rates, and the production mode (batch or continuous).

A number of processes involve breaking up liquid alloy streams into molten droplets, with subsequent solidification of these droplets in flight. Among these processes are: gas or air atomization, ultrasonic atomization, rapid solidification rate process (centrifugal atomization), rotating electrode process, and soluble gas process. The quench rate can be increased appreciably by allowing the molten metal to impinge directly on a cooled substrate. The substrate quenching methods include: spray rolling, double roll quenching, melt extraction, transmet flaking, and self-substrate cooling.

Once a mix of metal and alloy powder is rapidly solidified, it is usually consolidated into a billet and then rolled, machined, extruded, forged, or otherwise mechanically shaped. As a first step, the particulate is densified by vibratory packing and by mechanical cold or hot compacting. This compact is then preheated in a vacuum to remove most of the surface oxides and hydrates formed during particulate production, storing, and handling. Following the preheat, the compact is further consolidated, by either mechanical hot pressing or hot isostatic pressing, to increase density prior to hot working in mill operations. Because these processes rely partially on heat to induce densification, they can be damaging to the RS microstructures. These problems can be avoided with dynamic compaction processes which use explosives or high-velocity projectiles to effect consolidation. More development work is needed, but dynamic compaction is a promising method of consolidating RS powders.

The principal mill product processes include sheet and plate rolling, extrusion, and forging. Secondary processes may involve operations such as rod and wire drawing, swaging, and tube drawing. Process parameters such as temperature, percent reduction, and forming rate must be established and controlled in a way that minimizes grain and inclusion growth and phase separation, which deteriorate the desired properties, but this is not likely to require the development of new technology.

Direct powder-to-hot-work processes could be used if the surface oxides and hydrates formed during particulate production and handling could be suppressed. If this becomes possible, much of the consolidation stage may be eliminated, thus leading to optimum process simplification and minimum cost. Except for the Reynolds Aluminum direct sheet rolling production program, the work in this area is still experimental.

general, glassy materials are most interesting for their magnetic or electrical properties, while crystalline alloys are of interest for structural applications. Some of the potential applications of RS materials include:

Aluminum alloys for aerospace structures. RS aluminum would compete with polymeric- and, possibly, aluminum-matrix composites and titanium in these applications.[72][73]

Nickel alloys with abnormally high refractory metal concentrations for gas turbines.

Steels with submicron-sized phase dispersions for higher speed bearings.

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[72] National Materials Advisory Board, *Rapidly Solidified (RS) Aluminum Alloys—Status and Prospects*, National Research Council, Publication NMAB-368 (Washington, DC: National Academy Press, 1981). This unclassified document contains information which is subject to special export controls. It should not be transferred to foreign nationals in the U.S. or abroad without a validated export license. Distribution is limited to U.S. Government organizations. Other requests for the document must be referred to DARPA/TIO, 1400 Wilson Blvd., Arlington, VA 27709.

[73] C. Blankenship, panel/Workshop on Critical Questions in Rapid Solidification Processing, *Rapid Solidification Processing, Principles and Technologies, III*, Proceedings of the Third International Conference on Rapid Solidification, Reston, VA, 1983.

> Amorphous (glassy) eutectic iron alloys with unusual electrical and magnetic properties for power transformers and magnetic applications. Use of RS alloys with good magnetic permeability coupled with high resistivity can cut transformer core losses by 60-70 percent. This can greatly reduce energy wastage during power distribution.[74] [75]

Commercial use of RS is still limited primarily for cost reasons. Auto industry experts estimate it will be 10 to 15 years before the technology reaches their area. Entry should be sooner in aerospace where a lo-percent improvement in strength-to-weight ratio warrants a twofold to threefold increase in raw material price. T’ Based on information gathered at the first Workshop on Rapid Solidification Technology held at the National Bureau of Standards (NBS) in 1981, the NMAB concluded that:

> The primary application of RS crystalline alloys at this time are superalloy disks for aircraft engines and high speed tool steels . , , and near-term opportunities for commercial applications of RS aluminum alloys appear limited to the aerospace industry. [77]

Limited commercial acceptance notwithstanding, RS research enjoys substantial support from industry. Pratt & Whitney Aircraft, with the considerable support of the Defense Advanced Research Projects Agency (DARPA), has played a major role in promoting RS alloy development, Production of RS superalloy material has reached the level of a few thousand pounds per year and some discs made from RS material have been incorporated into jet engines.[78] [79] If processing difficulties can be overcome, it is possible that the suitability of different RS alloys for other engine applications could be determined in 5 years (with an expenditure of $5 million for each application).[80]

Cobalt-free superalloy powders produced through various rapid solidification processes have been shown in early experiments to have some advantages over conventionally processed alloys. One promising example is an experimental, cobalt-free superalloy being developed by Pratt & Whitney Aircraft for turbine airfoils. The alloy, which chiefly contains nickel, molybdenum, and aluminum, offers superior creep resistance compared to some other hot-section alloys. Moreover, with addition of 3 percent chromium as well as smaller amounts of hafnium and yttrium, the RS alloy has oxidation resistance exceeding that of alloy 454 (10 percent chromium), now used in the turbine blades of the F-100 jet engine. The RS alloy “offers approximately 1500 F advantage in temperature capability over our current (directionally solidified polycrystalline) metals in the stress range critical for blade design.”[81] Depending on the design strategy, the increased temperature capability can be used to improve the performance, durability, or cost of the engine. R&D with this RS superalloy continues, but neither the results nor an estimate of the possible year of introduction are available.[82]

The development of rapidly solidified iron-based alloys has received support from DARPA and the Army Materials and Mechanics Research Center (AMMRC). These two organizations have sponsored a program at Marko Materials Inc. aimed at developing RS iron-based alloys for potential high-temperature structural applications in the intermediate temperature range of 800° to 1,200° F. These new

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[74] ’’ Glassy Metals Move Into Production, ” *High Technology,* March/April 1982, p. 80,

[75] ‘‘Glass-Like Metals Cut Cost and Energy Use, ” *Machine Design,* Apr. 26, 1984.

[76] *Metal Progress,* “Trends in Powder Metallurgy Technology,” January 1984, p. 58.

[77] National Materials Advisorv Board, *Rapid Solidification Processing, Status and Facilities;,* National Research Council, Publication NMAB-401 (Washington, DC: National Academy Press, 1982), p. 3. This unclassified document contains information which is subject to special export controls. It should not be transferred to foreign nationals in the U.S. or abroad without a validated export license. Distribution is limited to U.S. Government organizations. Other requests for the document must be referred to DARPA/TIO, 1400 Wilson Blvd., Arlington, VA 27709.

[78] NMAB-401, op. cit., p. 16.

[79] Charles River Associates, New *Metal Processing Technologies,* OTA contract report, 1983, p. 53.

[80] John K. Tien and Robert N. Jarrett, *Potential for the Development and Use of New Alloys to Reduce the Consumption of Chromium, Cobalt, and Manganese for Critical Applications,* OTA contract report, 1983, p. 9.

[81] Moore and Adam, op. cit.

[82] Parkinson, op. cit., p. 48.

RS alloys will be specifically developed to evolve as potential replacements for conventional precipitation-hardenable (PH) stainless steels, titanium alloys, and iron-based superalloys.[83]

Rapid solidification particulate technology offers great potential for the production of a new family of aluminum alloys that have properties superior to those of ingot alloys. According to NMAB, realistic property improvements likely between 1985 to 1990 include: 10-percent reduction in density, lo-percent increase in tensile strength, 15-percent increase in fatigue strength, 10-percent increase in modulus of elasticity (stiffness), and usable properties at elevated temperatures (450° F).[84] Improvements in corrosion and stress corrosion cracking resistance are also likely. These alloys are not expected to replace many strategic materials directly. Furthermore, the new aluminum alloys may contain cobalt and manganese as alloying elements. However, RS aluminum alloys will probably change the need for strategic materials because of design relationships in the applications where they are likely to be used.

Though actual in-service experience has not been accumulated, use of these new alloys is foreseen in a variety of aircraft, missile, armored vehicle, and space structure applications. Because of weight savings, significant reductions in fuel costs would be achieved, a’ Effective use of the expected improved properties will make these materials potentially competitive with various composite materials and titanium alloys for selected applications. Near-term opportunities for commercial applications, other than aircraft, are limited. Significant commercial applications have not been identified, or at least verified, with any degree of confidence.[86]

Two RS aluminum alloys have achieved production status and are being offered as extrusions, die forgings, and hand forgings. These are alloys 7090 and 7091, air-atomized 700()-series powder alloys that are modified with cobalt additions and have been developed by Alcoa.[87] The mechanical properties of 7090 and 7091 have been evaluated in several industry and government programs. In addition to good strength and fracture toughness, these alloys have excellent exfoliation and stress corrosion cracking resistance. This combination of high strength and corrosion resistance is superior to that of any existing ingot alloy. Two 7090 die forgings will be used as a main landing gear support link (an 85-pound finished forging) and an actuator component for the main landing gear doors on the Boeing 757 air transport. The components offer a 15-percent weight savings over the same parts designed with conventional alloys.[88]

The Air Force Materials Laboratory is currently working on the development of advanced second-generation alloys with improved strength and ductility properties, improved fatigue and fracture properties, increased modulus and decreased density, and improved elevated temperature properties for service at temperatures ranging from 450° to 6500 F. Scale-up to production status will be initiated when adequate properties are demonstrated and is expected to be completed by 1990.[89]

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[83] Ran jan Ray, Viswa nathan panchanathan, and Saul Isserow, “Microcrystalline Iron-Base Alloys Made Using a Rapid Solidification Technology, ’ *Metals Progress,* June 1983, p. 30,

[84] NMAB-368, op.cit. The improved properties of RS aluminiure alloys derive from very small grain sizes, extended solubility or supersaturation of solute alloying elements, and very fine dispersions of dispersoid and insoluble particles,

[85] A.L. Bement and E.C. van Reuth, “QUO Vadis—RSR, ” *Rapid Solidification Processing; Principles and Technologies 11,* R.Mehabrian, B. H. Kear, and M. Cohen (eds.) Baton Rouge, LA: Claitors [publishing Division, 1980).

[86] N MA B-368, op. cit., p. 5.

[87] 7090 Aluminum—8. (1 Zinc—2. 5 Magnesium- 1.0 Copper—1 1.4 Cobalt
7091 Aluminum—6,5 Zinc—2.5 Magnesium-1.6 Copper—0.4 Cobalt.

[88] Stephen Ashley, “RS Alloys Gaining Acceptance,’ *American Metal Market, 9/12/83,* p. 13.

[89] NMAB-368, op. cit., p. 2.

Institutional Factors in Substitution

The potential role of direct substitutes and advanced materials in reducing U.S. strategic material needs depends not only on resolution of technical problems, but also on overcoming several institutional barriers that may impede their development. Several institutional issues are discussed below, including the general need for improved material data management, qualification and certification processes involved in substituting one metal alloy for another in critical applications, and factors affecting development of advanced ceramics and composites.

Information Availability and Substitutes

Limited access to materials properties information inhibits the use of substitute and advanced materials in many applications. The lack of a publicly accessible material property data base not only discourages direct substitution, but also frustrates the design process. In a recent study on material properties data management, the NMAB found that:

> Materials properties combined with structural analysis form the basis of modern industrial design. International competitive pressures are driving virtually all structural design in the direction of greater complexity and increased economies of production and operation. If the U.S. industrial design process is to remain competitive in this environment, engineers must have rapid access to a well organized materials properties data base.[90]

Handbooks, the traditional method of presenting material properties data, are increasingly unable to keep up with developments in a timely manner. Moreover, their methods of organizing the data are too limited. The computerized material information sources that exist are bibliographic services that search according to material properties. However, the information they provide is often cumbersome to use. According to NMAB:

> . . . the citations for a given material are frequently so numerous as to render compilation and evaluation for relevancy a very time-consuming and expensive task. Further, the interpretation of relevant data often is complicated by the lack of a standard format for presentation and the absence of sufficient information to properly characterize the material.[91]

To make the most of the wealth of materials information being generated, an on-line material properties data base with concise, thorough, and validated data would be desirable. This base would provide engineers with easy access to important information regarding substitution and design. Benefits of such a system, according to the NMAB study, would include "stimulation of innovative design, decreased design costs, and increased component reliability, and, as a result, the U.S. position in the international markets would improve."[92]

Such an on-line data base would greatly enhance the design process, especially that based on computer-aided design (CAD) and computer-aided manufacturing (CAM) systems. Also, it would disseminate a great deal of useful information to small businesses, which may not be able to support a staff of materials engineers.

There seem to be no technical barriers to the development of such a data base. A recent workshop sponsored by NBS, the Committee on Data for Science and Technology of the International Council of Scientific Unions (CODATA), Fachinformationzentrum, and Oak Ridge National Laboratory (ORNL) found that the major problem is selecting the best organization to lead the effort, raise the necessary funds, and coordinate the required technical expertise.[93]

Finally, it should be mentioned that the dearth of easily accessible properties data is a particularly acute problem for advanced materials, such as composites and ceramics. The

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[90] National Materials Advisory Board, *Materials Properties Data Management–Approaches to a Critical National Need,* NMAB-405 (Washington, DC: National Academy Press, 1983).

[91] Ibid., p. 3.

[92] Ibid., p. 33.

[93] Ibid., p. 3 and 102.

great potential of these new materials lies in the innovative structural designs that they make possible. However, in order to examine a wide array of structural configurations and to use most effectively the special capabilities of the materials, the design process must be computer assisted, An on-line material properties data base would be an integral part of such a design system, However, not only are machine-readable data not widely available, but information in any form is difficult to come by. Much of the development work on advanced materials is done by end users (as opposed to suppliers) who have no interest in promoting the material outside their company or industry. Therefore, properties data are often unavailable for use in other applications.

Qualification and Certification of Alloy Substitutes

Currently, many promising alloy substitutes are under development that have potential to reduce strategic materials requirements. Actual use of these materials by industry is problematic. Many of these substitute materials will not be tested and developed to the point where they can be considered on-the-shelf technologies that will be immediately available in a supply disruption.

A major reason for this is that industry is not likely to commit resources to qualify and certify new materials that it does not have immediate plans to use. Qualification and certification is needed in many critical applications—those in which substitution could be most important to reduced import vulnerability—yet few substitutes will be taken through this process because of the time and cost involved. This barrier appears greatest when there is no evident economic driving force to entice industry to engage in the process. Such is the case for many strategic materials substitutions—government, not industry, is the party with the most concern for making sure that the new alloy gains customer acceptance. In addition, owing to their critical applications, the certification process for strategic materials substitutes is more demanding of time and data, which translates into cost.

Two examples of alloy certification processes —one for stainless steel, the other for superalloys—are discussed below.

Stainless Steel

As the earlier section on substitution prospects suggests, several promising low- or no-chromium alloys could serve as alternatives to currently used stainless steels and nonstainless alloy steels. Actual use of technically promising, lower chromium substitutes will depend on acceptance of these new materials by producers and end users. For many consumer and decorative steel applications, substitution of a new material is a comparatively simple matter—often entailing a decision to switch by a manufacturer. For critical applications, however, extensive testing and certification is essential before widespread use.

In contrast to superalloys, in which company-oriented qualification of materials predominates, certification of new stainless steels and alloy steels is usually undertaken through committees of professional societies or trade associations, often through voluntary donation of time and facilities by producers and end users, Such activities may take 10 years or more if the immediate need is small, and can slow the process of user acceptance of replacement materials,

An instructive example of the steps entailed in qualifying a new material in a critical application is provided by the ongoing effort by DOE to qualify a new alloy as a boiler and pressure vessel material. The initial steps toward development of the alloy began in 1974, when a task force set up by DOE (then called the Energy Research and Development Administration) recommended a program to develop reference structural alloys for use in the liquid metal fast breeder reactor.[94] The alloy development process was sponsored through two offices in the DOE under an Oak Ridge Na-

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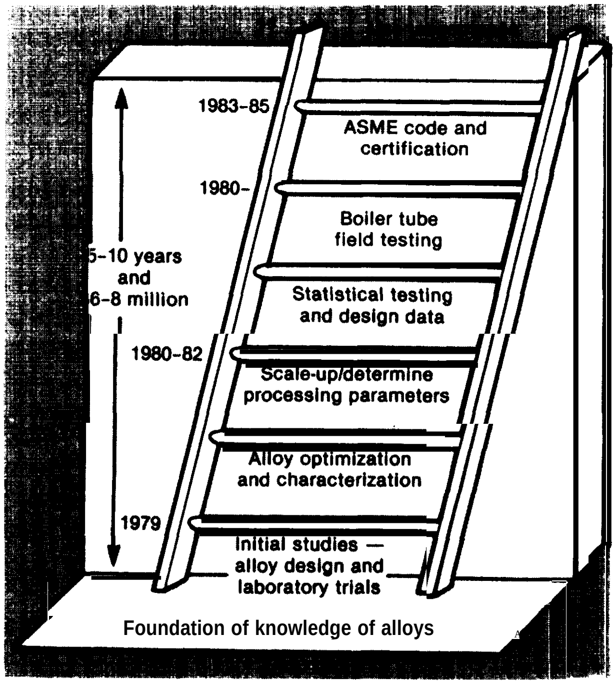
[94] The history of the 9- I alloy is discussed in P. Patriarca, E. E. Hoffman, and G. W. Cunningham, "Historical Background" in P. Patriarca, compiler, *ORNL Technology Transfer for Meeting A New Chromium-Molybdenum Steel for Commercial Applications* (Oak Ridge, TN: Oak Ridge National Laboratory, Apr. 7, 1982].

tional Laboratory contract with Union Carbide Corp., and in conjunction with Combustion Engineering, Inc. After studying several alternative alloys, a modified 9Cr-1Mo alloy was selected for further development, Data development for qualification began in 1979, but the alloy has yet to be approved for widespread commercial use. The purpose of the effort was not to conserve chromium, but rather to provide a uniform construction material for boilers and pressure vessels. Figure 7-6 shows the development "ladder" for this alloy.

Once initial laboratory work had been undertaken, the need to demonstrate reliable transfer of properties through scale-up and field testing arose. Under arrangements with several alloy producers, commercial heats (ranging from 0,5 to 15 tons) were made using several commonly used processing practices (e. g., AOD and vacuum induction melting). The commercial heats were then formed into plates, bars, tubes, and pipes, using a variety of fabrication processes. To provide additional test data, modified 9Cr-1Mo alloy replacements for 18-percent stainless steel tubes have been put in service in six conventional powerplants located in the United States, Canada, and Great Britain, as shown in table 7-17.

Figure 7-6.— Development of Modified 9Cr-1Mo Steel for Fossil Fuel and Nuclear Power Applications



SOURCE. John K. Tien and Robert N. Jarrett, *Potential for the Development and Use of New Alloys to Reduce the Consumption of Chromium, Cobalt, and Manganese for Critical Applications,* OTA contract report, September 1983.

Widespread, nonexperimental use of this substitute in powerplant applications is dependent first on approval of its specifications by the American Society for Testing of Materials (ASTM), followed by its inclusion in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code,

In May 1981, an application was made to ASTM to approve specification of the modified 9Cr-1Mo alloy for use in plate and tube products, followed a year later by a similar request for forgings, pipings, and fittings. The specifications are currently working their way through the ASTM approval process, as shown in table 7-18. A data package for inclusion of the material in the ASME Boiler and Pressure Vessel Code pertaining to nonnuclear applications was provided in June 1982, Additional data will have to be collected before the substitute material can be considered for possible use in nuclear powerplants.

By early 1984, the alloy had been approved for certain limited uses in conventional (nonnuclear) powerplants. Additional applications for the alloy can be expected to be approved sometime in 1985—9 years after initial design of the alloy. Estimated costs for the post-laboratory alloy development through the end of 1983 are $5 million by the government (an estimated $2 million has been donated in services by industry).[95]

Superalloy

As suggested previously, several current and prospective materials and technologies could be used to reduce cobalt and, to a lesser extent, chromium use in the hot sections of gas turbine engines. Some, perhaps most, of these may have the technical potential to reduce stra-

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[95] Information provided by V. Sikka, Oak Ridge National Laboratory.

Table 7-17.—Current Status of Testing of Modified 8Cr-1Mo Steel Tubes in U.S. and Foreign Steam Powerplants

Utility	Plant	Tube location	Operating temperature (“c)	Tubes being replaced	Number of tubes	Date installed	Status
Tennessee Valley Authority	Kingston Steam Plant, Unit 3	Superheater	593	Type 321	8	May 1980	Operating
American Electric Power	Tanners Creek Unit 3	Secondary superheater	593	Type 304	10	April 1981	Operating
Detroit Edison	St. Clair Unit 2	Reheater	538	Type 347	2	February 1981	Operating
Central Electric Generating Board (U K)	Agecroft Power Station	Superheater	590-620	2¼ Cr-1 Mo	6	April 1982	Operating
Ontario Hydro (Canada)	Lambton TGS	Reheater	538	Type 304H	9	May 1983	Operating
		Reheater	538	Standard 9 Cr-1 Mo	9		
Ontario Hydro (Canada)	Nanticoke TGS	Secondary superheater	538	2¼ Cr-1 Mo	11	April 1984	Planned

SOURCE V K Sikka and P Patriarca, *Data Package for Modified 9Cr-1Mo Alloy* (Oak Ridge, TN Oak Ridge National Laboratory December 1983), p 28

Table 7-18.–Status of Specifications for Modified 9Cr-1 Mo Alloy

Specification number	Description	Status as of December 1983
A-213 T91	Seamless ferritic and austenitic alloy-steel, boiler, superheater, and heat-exchanger tubes	Approved and available as separate
A-387 GR91 . . .	Pressure vessel, plates, alloy steel, chromium-molybdenum	Approved by Main Committee and awaiting Society Ballot
A-182 F91	Forged or rolled alloy-steel pipe flanges, forged fittings, and valves and parts for high-temperature service	Approved by Main Committee and awaiting Society Ballot
A-234 WP91 . . .	Piping fittings of wrought carbon steel and alloy for moderate and elevated temperatures	Approved by Main Committee and awaiting Society Ballot
A-335 P91	Seamless ferritic alloy steel pipe for high-temperature service	Approved by Main Committee and awaiting Society Ballot
A-336 F91	Steel forgings, alloy, for pressure and high-temperature parts	To be submitted for AI.06 Subcommittee approval
A-199 T91	Seamless cold-drawn intermediate alloy-steel heat-exchanger and condenser tubes	To be submitted for AI.10 Subcommittee approval
A-369 FP91 . . .	Carbon and ferritic alloy-steel forged and bored pipe for high-temperature service	To be submitted for AI.10 Subcommittee approval

SOURCE: V K. Sikka and P Patriarca, *Data Package for Modified 9Cr-1Mo Alloy* (Oak Ridge, TN: Oak Ridge National Laboratory, December 1983), p. 5

tegic materials without impairing the advances in performance so critical to the military. However, aside from those that are already fully developed, most of these potential substitutes still face massive R&D costs, and, if they prove viable, large scale-up and qualification costs. Given industry's little incentive to assume these costs itself, unless clear performance and cost benefits would also accrue, most of the resources available for qualifying new superalloy are dedicated to prospective materials to be used in the next generation of jet engines.

Successful commercialization of a new superalloy for the hot section of a gas turbine engine can take two decades, beginning with the researcher's idea, through laboratory proof-of-concept, to engine testing and eventual commercial application. Many research ideas never reach the laboratory stage, and of those that do, only some show technical promise.

Even when technical problems can be overcome, institutional barriers can add appreciably to development time or can indefinitely delay work on the project. Given the protracted time period involved, what may have been initially seen as a clear need for a new material may not be relevant a decade later. Many superalloy development efforts are cost-shared between government and industry, which adds to the risk that R&D priorities will change during the course of the project. Coordination of research may also be difficult. By the time commercialization of a superalloy is successfully reached, several different government agen-

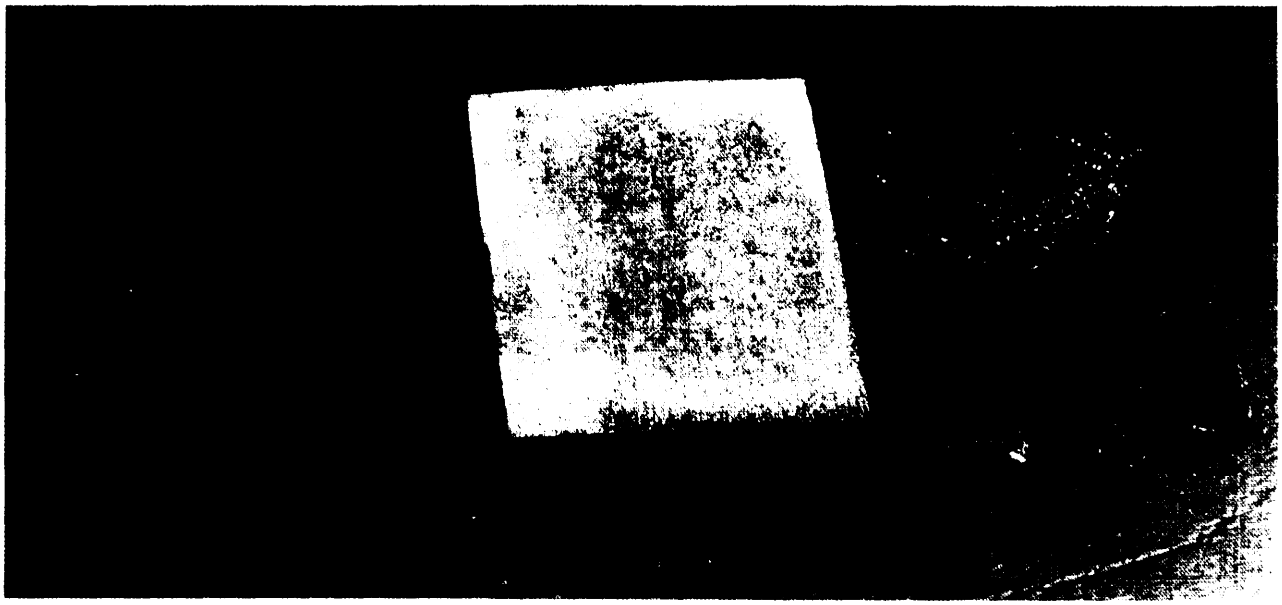


Photo credit: U.S. Department of the Interior, Bureau of Mines

Aluminum and silicon can reduce the need for chromium in stainless steels for high-temperature applications. A 5-percent aluminum addition to a Bureau of Mines 17Cr-8Ni research alloy (center) enormously improves oxidation resistance after 380 hours at 1,000° C compared to type 304 (18Cr-8Ni) and type 316 (18Cr-12Ni) stainless steels. The research alloy is under investigation as a possible high-performance alternative to the 25 percent Cr-20 percent Ni stainless steels

cies, universities, and companies may become involved—each with its own specific objectives, personnel, and priorities.

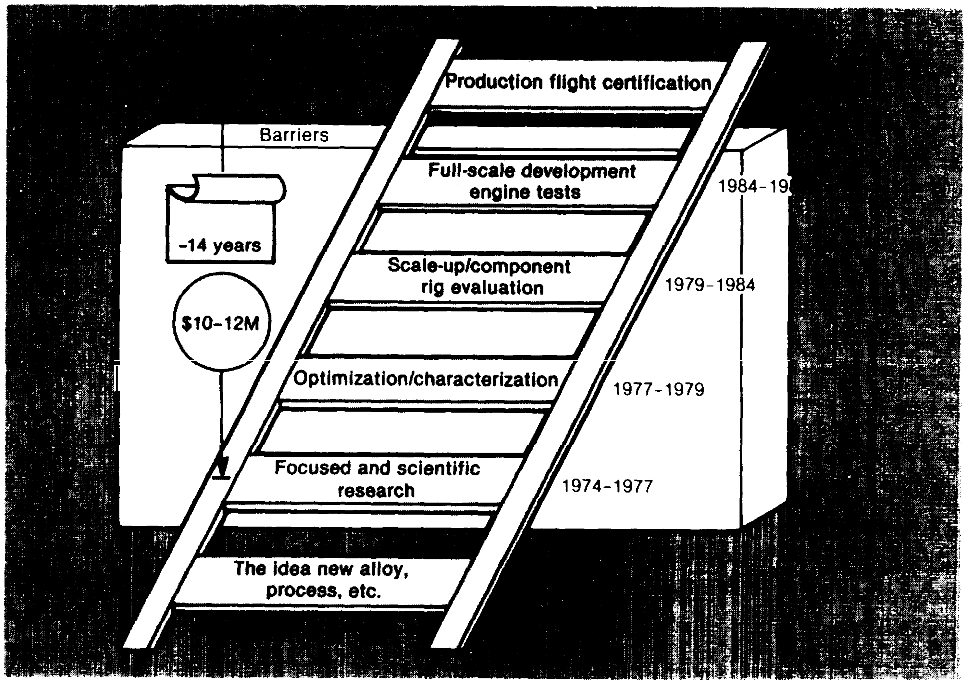
Typically, laboratory findings must be verified in large-scale industrial heats. It is only at this stage that the technical validity and manufacturing practicality of the process can be known with assurance, and it is only at this stage that the expensive and time-consuming process of engine qualification can begin. Designer and user acceptance of the new material will occur only when there is confidence about its reliability and performance at acceptable costs.

Figure 7-7 shows key steps that must be overcome in the successful commercialization of a new superalloy, using Inconel MA 6000 as an example. Inconel MA 6000 contains no cobalt, but its initial development had nothing to do with conservation of strategic materials. Rather, the key objective was to develop a turbine blade material able to operate at a higher temperature than other superalloy, while avoiding the performance penalties associated with the need for cooling air.

The origins of Inconel MA 6000 date back to 1968, with the invention by a researcher at the International Nickel Co. of a mechanical alloying process for producing oxide dispersion strengthened superalloy. In 1974, NASA entered the picture by providing Inco with support to design an alloy composition that became MA 6000. In time, university researchers and several manufacturers of jet engines became participants in the project as it advanced through scale-up to its present status—preparation for engine testing. If successful, it will probably be another 5 years before MA 6000 is actually used for turbine blades and vanes in human-rated jet engines. Using 1974 as a starting date, 15 or more years—and an estimated $10 million to $12 million—will have been consumed in the development of this one cobalt-free superalloy.

Development costs associated with an entirely new superalloy may be greater than for

Figure 7-7.—Technology Transfer Ladder for ODS MA 6000



SOURCE: Joseph R. Stephens and John K. Tien, Considerations Of Technology Transfer Barriers *in the Modification of Strategic Superalloys for Aircraft* Turbine *Engines,* NASA Technical Memorandum 83395 (Springfield, VA: National Technical Information Service, 1983)

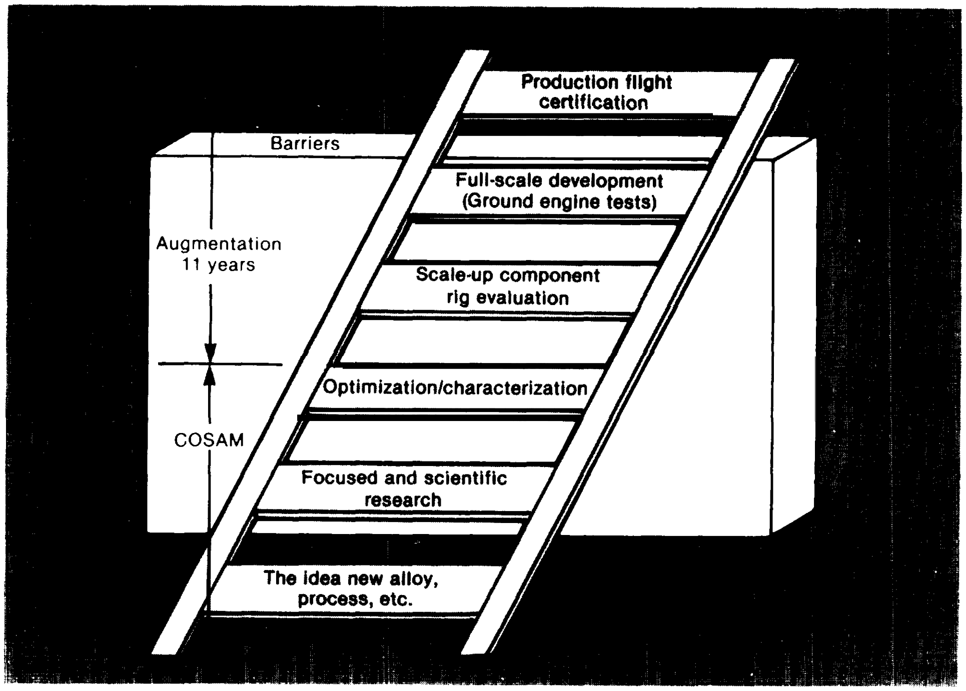
a superalloy with a modified composition. For example, the low- or no-cobalt COSAM alternatives are intended as substitutes for existing superalloy. If the alternative materials were commercially used, it is probable that only minor adjustments in manufacturing and fabrication processes would be needed, In this regard, NASA's proposed fiscal year 1985 budget earmarks $50,000 for preparing several test heats of one of its four low-cobalt, alternative superalloy. Figure 7-8 shows steps taken to date and additional development required for the COSAM superalloy.

Institutional barriers to continued development of the materials are formidable, even if their technical promise is favorable. In the case of the low-cobalt COSAM alternative superalloy, post COSAM augmentation efforts could require 6 to 7 years and $6 million to $9 million, assuming real-time testing requirements and typical scale-up activities for each modified alloy. Since the COSAM alternative superalloy would substitute for already used, widely accepted, higher cobalt superalloy, no single company is likely to be committed to assuming such a development effort simply for the purpose of contingency planning for a hypothetical future cobalt shortage.

Institutional Barriers and Advanced Materials

Advanced materials face a number of institutional barriers before being adopted on a major scale. As comparatively new technologies and new industries, they need the support of more complete and reliable data than is currently available and of innovative design which uses the materials to their best advantage. In the end, final acceptance of advanced materials by engineers, designers, and consumers will come only from experience in use. The Federal Government's efforts focused on these new materials can assist in this adoption process and promote the growth of new industries.

Figure 7-8.—Technology Transfer Ladder for COSAM Strategic Material Substitution



SOURCE Joseph R Stephens and John K Tien, *Considerations of Technology* Transfer *Barriers in the Modification* of *Strategic Superalloys for Aircraft Turbine Engines*, NASA Technical Memorandum 83395 (Springfield, VA National Technical Information Service, 1983)

Ceramics Data Base Requirements, Standards, and Qualification Processes

The properties of ceramic components and the materials from which they are made—and thus their usefulness for any particular application—can vary depending on their chemical formula and the methods by which they are produced. One of today's largest single institutional constraints to expanded structural usage of ceramics is the poor quality and limited availability of information on these variable material properties. The technology needs not only the application of standardized test procedures (specific to materials and processing and the effect of different temperature and chemical environments over time) and a systematic collection of available information but also research efforts devoted to producing the information.[96]

Designer Preference and Education

Product design engineers select materials on the basis of past experience and available data. Few structural design engineers have experience with ceramics (less so with composites). As stated above, reliable data about material properties are scarce, and in general, formal codes and specifications do not yet exist, Such data bases normally serve as guides for engineers working with unfamiliar materials,

In general, the formal education received by engineering students is deficient both in knowledge obtained about advanced materials and in how to incorporate that knowledge into design work. For instance, materials courses are not generally required of mechanical engineering students, and if they are, the emphasis is on metals. Educational institutions are reluc-

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[96] The National Bureau of Standards recently announced the establishment of a Ceramic Powder Characterization Laboratory (*NBS Update*, June 11, 1984). The laboratory will help manufacturers by providing them with information on powder characteristics.

tant to adjust long-established curricula to eliminate such deficiencies and may often be constrained by budgets from doing so. In a broader context, the base of 10 to 15 universities in the United States with programs in ceramics may be insufficient to meet the future research needs of a rapidly expanding industry,

Industry in Transition

The advanced ceramics industry is being created out of discrete parts of other industries. The mature traditional ceramics industry, conservative because of a history of stable and profitable years, is only now examining new possibilities. This change in perspective may be a result of recent depressed conventional markets (linked to the steel industry) and talk of future competition from abroad. Most of the innovations in the industry, however, appear to come from end users rather than from the producers. Much of the research conducted by end users naturally leads them into becoming materials processors in order to maintain the necessary tight control over this critical step. Other segments of this emerging industry are the expansion into advanced ceramics by conglomerates and conventional materials firms that sense future market changes.

This merging process means that there is no focal point, no industrial champion for advanced ceramics. As yet, no industrial association or organization is charged with research, development, or product data specification. The established professional association—the American Ceramics Society—provides a forum for the exchange of technical information. It does not, however, have a technical section dealing with advanced ceramics as a separate issue. Recently, it has begun to collect data on industry production of advanced ceramics and form a standardized data bank. With little information yet available about the organization of the industry and its participants, government data collection centers, such as those of the Department of Commerce,[97] EPA, and OSHA, do not yet aggregate advanced ceramics data separate from that of the traditional ceramics industry.

Government Research

Currently, several agencies are involved in many aspects of advanced ceramics research: primarily, DOE, Department of Defense, NASA, and NSF. Those interested in the advancement of the technology express concern over the uncertainty from year to year over adequacy of funding, the direction of funding, and possible lack of coordination which may lead to duplication of effort.

The bulk of the research effort is focused on the high potential (in terms of market size, energy efficiencies, and strategic materials substitution) heat engine applications. While this may be appropriate from an applications point of view, questions remain as to whether concentration on major development projects is the best way to advance the science of advanced ceramics and whether this approach will contribute to the building of a firm, broad base of technical knowledge for the support of a competitive domestic industry. Supporters of the concept argue that the technological base is broadened by focusing on the development of a major application, since success requires an iterative process in which researchers must continually return to basic science in order to solve problems encountered in the development phase. Others worry that, by pushing the development phase at the expense of basic research, application failures which occur will result in generating negative impressions of the ultimate capabilities of the technology.

The current contractors on the ceramic heat engine projects have plans to commercialize the technology eventually, but a technology gap will exist after the proof-of-concept stage is reached by government R&D efforts. The skills developed in designing the ceramic components of experimental engines will be transferable to engines designed with the consumer in mind. But industry will have to be firmly convinced of the technology's viability to be willing and able to take on expensive and lengthy

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[97] Information is beginning to emerge, however. See, for instance, U.S. Department of Commerce, *A Competitive Assessment of the U.S. Advanced Ceramics Industry*, March 1984.

development costs before ceramic heat engines are ready for the marketplace.

Until recently, there was no Federal office with a specific mission to promote, coordinate, and focus the government's R&D efforts in advanced ceramics. (As is discussed in chapter 8, the National Critical Materials Act of 1984 establishes a council in the Executive Office of the President that is to formulate a Federal program plan for advanced materials.) It is currently difficult to obtain a comprehensive overview of the R&D efforts of the various agencies and to determine whether there is any overlap of effort. Table 7-19 provides a breakdown by agency of estimated Federal Government R&D for structural ceramics technology. This reflects internal shifts of program emphasis and is a result of a growing awareness in many sectors of the important role that advanced ceramic technology could play in future U.S. economy.[98]

DOE has initiated some steps to cope with the lack of available information. Its Oak Ridge National Laboratory (ORNL), in its Ceramic Technology for Advanced Heat Engines Program Plan,[99] provides a breakdown of the funds committed by various agencies for R&D in advanced ceramics considered applicable to heat engine technology. The Advanced Materials Development Program at DOE is developing a computer-based data system which, when completed, will provide continuing—and systematically collected—information on the R&D efforts in structural ceramics of Federal Government agencies.

Even with these statistics available, overlap of effort is difficult to assess. The difficulty lies, in part, in the large and growing number of advanced ceramic materials, each designed with specific properties for specific applications (similar to metallic alloys). While the knowledge gained from success in one application, if transferred, can advance the use of similar ceramic materials in another application, a material designed for a specific application cannot necessarily serve "as is" elsewhere.

Table 7.19.—Structural Ceramic Technology Federal Government Funded R&D (in millions of dollars)

	Fiscal year 1982	Fiscal year 1983	Fiscal year 1984	Fiscal year 1985
Department of Energy:				
• Conservation and renewable energy:				
— Heat engine propulsion	$9.3	$14.6	$15.5	$13.6
— Industrial programs	1.5	1.0	2.3	2.7
— Energy utilization research	0.3	0.5	0.6	2.0
• Fossil energy:				
— Advanced research and technology development	1.2	1.0	1.0	1.0
— Advanced energy conversion systems	1.9			
• Energy research:				
— Basic energy science	2.0	3.0[a]	3.0	3.0
NASA:				
• Lewis Research Center[b]	1.8	3.0	3.5	4.6
NSF	2.7	2.9	3.3	3.6
Department of Defense:				
• Defense ARPA	2.0	7.7	9.5	7.7
• U.S. Air Force	1.7	3.0	3.4	4.7
• U.S. Army	1.3	4.7[c]	6.0[c]	2.5[c]
• U.S. Navy	1.0	1.2	1.3	1.4
Total	$26.7	$42.6	$49.4	$46.8

[a] Reflects increase in portion of budget applied to structural ceramics.
[b] Includes salaries for manpower.
[c] TACOM included.

SOURCE: U.S. Department of Energy, Advanced Materials Program, October 1984

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[98] Robert B. Schulz, Program Manager, Advanced Materials Development Program, Department of Energy, personal communication, Oct. 4, 1984,

[99] Oak Ridge National Laboratory, *Ceramic Technology for Advanced Heat Engines Program Plan,* ORNL/TM-8896, June 1984.

Despite the lack of official oversight, coordination among agencies has apparently improved in recent years. The ORNL program plan on ceramic heat engine technology was developed to identify technology base needs; develop a multi-year technical and resource agenda; and coordinate activities with other industry, government, and university programs. NASA holds regular and frequent meetings with DOE that now include DARPA and the Air Force. Each fall, an interagency meeting is held for all the participants from government, industry, and academia working on ceramics in heat engines,

NASA's Lewis Research Center has also developed a new comprehensive ceramics program proposal but funding was not included in the fiscal year 1985 budget, The program's goal, while focused on the aircraft engine as the application, was to broaden the ceramics technology base in general.

The National Science Foundation, under its industry and university cooperation program, has funded the Center for Ceramic Research at Rutgers University. This center has been granted public funding for 5 years with the intent that it will be able to generate sustaining private funding of its research efforts within that period. Research areas in which the Center is involved include, among other things, powder processing technologies and improvement of materials properties.

Qualification, Certification, and Standardization of Composites[100]

Composites are engineered materials, and as such are very sensitive to a multitude of structural and processing factors. This characteristic is very beneficial, because it gives designers great control over the properties of composites, allowing the tailoring of these materials to individual applications. However, with the greater design flexibility also comes the need for strict materials and processing tolerances during production runs, Addressing the concerns arising from the sensitivity of composites to each manufacturing step, the composites industry has adopted elaborate certification and qualification schemes. These procedures are needed to ensure the quality and uniformity of the various materials, through the many times they change hands, used in the production of composites.

Qualification and certification is more complex for composites than for traditional materials for several reasons,

The composites industry is very fragmented–there is very little vertical integration. There are many processing steps entailed in the production of composites, and rarely, if ever, does one company engage in all these segments of the business. Most composites companies are specialized, each concentrating on a segment of the industry,

While this may not increase the amount of testing needed to ensure product quality and uniformity, it causes confusion with regard to testing needs and data interpretation.

Composites are fundamentally different in their structure and behavior than traditional materials. The well established testing and characterization techniques used for traditional materials are not suited for composites. Appropriate composites testing techniques have been developed, but on an ad hoc basis with little industrywide agreement.

There is no uniform procedure for certifying and qualifying composite materials and structures; every product is handled differently, on a company-by-company basis.

The composites industry has no industry association to pursue the interests of the composites industry as a whole. There is no organization through which the industry can work on qualification, certification, and standardization problems common to many of the involved companies.

Developing the data package necessary for qualification of composite materials and struc-

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[100] This section draws heavily on Stanley L. Channon, ' 'Industrial Base and Qualification of Composite Materials and Structures (An Executive Overview)" (Alexandria, VA: Institute for Defense Analysis, May 1984). Presented as a working paper for a Department of Defense-sponsored colloquium/workshop on Composite Materials: Standardization, Qualification, Certification, Washington, DC, May 1984,

tures is very time-consuming and expensive (especially considering the small quantities of materials often associated with composite orders). The battery of tests required to qualify a material may cost $20,000 to $200,000 or more, depending on the scope of testing. While these costs are borne by the composites user for the initial supplier's material, alternate suppliers may be required to assume part or all of their qualification costs. The new suppliers may be required to perform costly full-scale tests if bench-scale evaluation suggests significant differences between their material and the primary material. Qualification of a new supplier for an existing material may require 3 to 6 months for most structural applications. Whenever any change is made in the composites used in rocket nozzles, full-scale testing—taking up to a year—is required. This costly testing limits the number of suppliers for any given application.

In addition to being costly, the complexity of the qualification process may discourage innovation. Once a composite has been qualified for a particular use, changes in the material or its production are usually disallowed for that application. This, along with designers' preference for proven materials, tends to restrict the number of available qualified materials.

There is also a need for standardization of material specifications and test methods for composites, Standards are currently generated by a variety of government and industry groups, but it is customary to rely on specifications from fiber and resin suppliers. The government specifications are rarely used because they are too broad or out of date. Industry groups such as the American Society for Testing and Materials (ASTM), the American National Standards Institute (ANSI), the Society of Automotive Engineers (SAE) and others generate composites standards, but the process is slow and often includes compromises accepted in order to broaden the applicability y of the specifications. ASTM test methods find frequent use in industry, but many companies develop their own test methods because of preferences in testing equipment and procedures.

Regarding the need for standardization of composite materials, a recent industry survey concluded:

> Although the majority of industry and government personnel would prefer to see standards adopted for the composites industry, it is recognized that this will not be accomplished easily. A major resistance to standardization emanates from the suppliers of materials who fear that the identity of their materials would be lost. , . Some opponents to standardization feel that this would retard technological innovation in the industry whereas proponents feel that the industry will advance more rapidly if standards are adopted. Some feel that the timing is inappropriate for standardization because the industry is still in a dynamic state. [101]

Composites technology also faces other institutional barriers similar to those for ceramics, although it is probably far ahead in most aspects, The technology has found its major application in the aircraft and automotive industries and has been supported and pushed by those industries and by the government. The extensive government research in composites has been centered primarily in the Department of Defense. The interest in composites for use in military aircraft, and the accompanying lack of public information, however, has been blamed for slowing technology transfer between the government, academia, and industry.

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[101] Ibid., p. 22.