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Superalloy Resources—Supply and Availability

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RESOURCES - SUPPLY AND AVAILABILITY

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I. INTRODUCTION

The superalloys are critical to the economic survival of the United States' aerospace industry. Therefore it is imperative that the raw material resources that are required for superalloy production are readily available to U.S. producers. During the initial years of superalloy development resources for iron, nickel, and to some extent chromium were available within the U.S. or from neighboring countries such as Canada and Cuba. However, in more recent years superalloy compositions have become more complex requiring 10 or more different elements in a single alloy; environmental restrictions and labor costs have pushed sources off-shore; and political and military changes have made once dependent countries for resources unreliable or even nonexistent. Because of these changes in the world economy, superalloy producers have had to assure reliable supplies of imported materials or in the event of a lack of availability of the alloying elements required in current superalloys, an alternative alloy would have to be available. One approach to alternative alloys is to substitute readily available elements for those alloying elements that are imported for superalloys. Obviously, this is not a simple solution since not only are the compositions of superalloys complex, but also their microstructures which are dependent upon a critical balance of alloying constituents, must be maintained to achieve desired properties. Because of shortages or limited availability of alloying elements over the years, e.g., cobalt in the 1950's, chromium in the 1970's, and cobalt and other elements in the late 1970's and early 1980's NASA Lewis Research Center undertook a program to address this continuing problem. This chapter will review some of the trends in superalloy development, define what is understood to be meant by the term strategic materials, summarize the current status of U.S. resources and reserves, discuss the supply sources and availability of strategic materials, and finally concentrate on the results achieved from the research program undertaken by NASA Lewis Research Center named Conservation Of Strategic Aerospace Materials (COSAM), Stephens (1981).

II. STRATEGIC MATERIALS

The United States has good supplies of such metals as copper, iron, and molybdenum; and stable/friendly foreign countries are sources for others e.g., nickel (Canada), titanium (Australia for rutile), aluminum (Jamaica, for bauxite), and tungsten (Canada) Bureau of Mines (1986). However, by examining our import dependence for other metals as shown in Fig. 1 it is apparent that we are a "have not" nation for many important metals. Of particular concern is the aerospace industry since it is highly dependent on imports for several key metals which are considered to be strategic materials. As a working definition of strategic materials for this chapter, the following is used: those predominately or wholly-imported elements contained in the metallic alloys used in aerospace components which are essential to the strategic economic health of the U.S. aerospace industry. Two approaches were used to identify the strategic materials most critical to the aerospace industry. One approach to obtaining a handle on the most strategic metals used in the aerospace industry was to establish an index of strategic metal vulnerability. Such a study was undertaken by Stalker et al., (1984). The index described 18 elements (aluminum, chromium, cobalt, copper, gold, iron, magnesium, manganese, molybdenum, nickel, niobium, platinum, rhenium, silver, tantalum, titanium, tungsten, and vanadium). Each metal was ranked 21 different ways, such as importance in relation to U.S. needs in a peace economy and in a war economy, in relation to U.S. reserves, and in relation to cost in dollars per pound.

Analysis of the data from this study shows that the 18 metals examined generally fall in three groupings. The most strategic elements have an index of about 8 or greater on a scale from 1 to 10 with 10 being the most strategic. The midgroup have numbers between about 5 and 8; and the least strategic metals have indices lower than 5. The breakdowns of the 18 metals are shown below:

Most strategic	Midgroup	Least strategic
Ta	V	Al
Cr	Re	Cu
Pt	Ti	Mo
Nb	W	Mg
Mn	Ag	Fe
Co	Ni	
	Au	

It should be noted that although the ranking above is in order of decreasing index for each of the three groups, the absolute rank within a group can be altered by using other data such as a more complete breakdown of resources and reserves (to be discussed later); and price volatility will affect known economic reserves as well as the weighting factors used. Regardless, it is doubtful that the most strategic list would change in composition. Table I summarizes the output of the study with data from all 21 categories listed. The rankings present the peacetime and wartime situations based on such factors as reserves, consumption, production cost, recyclability, and subjective judgments regarding the likelihood of a mineral cartel. Consideration of the needs of a wartime economy yielded slightly different normalized scores, but with major concern for the same six elements. In a further refinement, subjective weighting factors were applied to get a still more realistic appraisal. Weighting yielded significant increases in importance for manganese, copper, and aluminum, and a decrease in gold. However, the overall picture remained fairly much the same.

As can be seen, each of the most strategic metals has special capabilities, such that the U.S. economy will not function well without them. Unfortunately, the United States has a very limited reserve of each. It behooves us, therefore, to give attention to our dependence on foreign supplies for these strategic materials. Each element is special and each requires careful review of its role, in our case, in superalloys in order to develop short range and long range plans.

The second approach to identify the most strategic metals involved meetings with the ASME Gas Turbine Turbine Panel in 1979 and a survey of aerospace companies in 1980 which led to the need to focus primarily on the aircraft engine industry. Based on these and further discussions with several aircraft engine manufacturers, four elements emerged that were of particular concern, Stephens (1981). The alloys used to build the critical high temperature components for aircraft propulsion systems require the use of the three refractory metals Cr, Ta, and Nb plus a fourth strategic metal, Co. These metals are contained in superalloys which are located in engine compressors, turbines, and combustors as illustrated in Fig. 2. These four elements are among the six elements having the highest strategic indicies of the 18 metals evaluated by Stalker et. al., (1984). Although the other two elements were considered along with the less strategic metals, it was decided to focus on the four aforementioned metals in the NASA COSAM Program.

III. RESERVES AND RESOURCES

In order to have a thriving superalloy industry within the U.S., it is imperative that a readily available supply of the alloying ingredients be available. The ideal situation is for mining companies within the U.S. to be the primary suppliers to the alloy producers. Unfortunately, the U.S. is not blessed with ample reserves and resources of some of the required alloying elements in today's superalloys. Therefore, over the years the U.S. has become more and more dependent upon foreign sources for a number of strategic materials. In order to plan for future aerospace materials needs, an assessment of our reserves and resources is required. The principal distinction between reserves and resources is that reserves are based on current economical availability. Reserves are known, identified deposits of mineral-bearing rock from which the mineral or minerals can be extracted profitably with existing technologies and under economic conditions; whereas resources include not only reserves, but also other mineral deposits that may eventually become available--either known deposits that are not economically or technologically recoverable at present, or unknown deposits that may be inferred to exist, but have not yet been discovered, Brobst and Walden (1973).

Table II summarizes the estimated reserve and resource status of the U.S. for the 18 metals discussed previously. The U.S. is noted to rank first for rhenium and molybdenum and second for silver and copper. In comparison the USSR ranks first or second in six and South Africa in five. The domestic U.S. position presented in Table II is supported by further information that indicates negligible reserves of chromium, cobalt, columbium, and tantalum along with manganese--all vital to the aerospace and steel industries. Although the U.S. does not have reserves of a number of elements, it is still a leading producer of the metals as a result of importing the minerals and converting them into metals and alloys. Table III shows the U.S. ranking first or second in six metals: aluminum, copper, magnesium, molybdenum, titanium, and rhenium. The USSR holds this favorable position in nine metals: iron, manganese, aluminum, magnesium, titanium, tungsten, vanadium, gold, and platinum. One other important consideration is the domestic consumption and production of the metals needed for our economy. Table IV gives a picture of this factor for the 18 elements. It should be noted that foreign purchases were required for the four elements, Cr, Co, Nb, and Ta designated as strategic metals in the COSAM

Program. Manganese also fell into this category. In contrast there is a good match-up for Fe, Al, Cu, Mg, Ti, V, and Re while Mo production greatly exceeds consumption.

IV. THE SUPERALLOYS

Superalloys are the major materials of construction for today's high-temperature gas turbine engines used for both commercial and military aircraft. Nickel base superalloys along with iron base and cobalt base superalloys are used throughout the engines in wrought, cast, powder metallurgy, and cast single crystal forms to meet the demands imposed by the aircraft industry. Nickel-base superalloys had their beginning about the turn of the century with the addition of 20 wt % Cr in an 80 wt % Ni alloy for electrical heating elements, Stephens et al., (1984). In the late 1920's, small amounts of aluminum and titanium were added to the "80/20" Ni-Cr alloy with a significant gain in creep strength at elevated temperatures. It soon became apparent that iron and cobalt alloys would be more effectively strengthened by solid solution additions while nickel alloys were blessed with the ability to be strengthened by a coherent phase, γ'. Concurrently with these additions, carbon present in the alloys was identified to have a strengthening effect when combined with other alloying elements to form M_6C and $M_{23}C_6$ carbides. Other grain boundary formers such as boron and zirconium were added to polycrystalline materials to hold the material together. In the early development time period (1926), Heraeus Vacuumschmelze A.G. received a patent for a nickel-chromium alloy which contained up to 15 wt % and 12 wt % Mo, thus introducing the refractory metals into superalloys. The purpose of the refractory metals additions was to raise the yield point. By the 1930's there were two Fe-base "heat-resisting alloys" containing either W or Mo additions and the use of W and Mo was widely accepted in Co-base alloys. Commercial exploitation of Mo additions awaited the introduction of Nimonic 100[*] in 1955. In the early 1950's, the alloys being introduced in the United States, such as Waspaloy,[†] were alloys containing about 5 wt % Mo. Inconel 713C (a cast alloy) containing 2 wt % Nb was available in the late 1950's. The only commercially significant alloy to use vanadium is IN-100, which became available in about 1960. In the early 1960's, W and Ta were widely accepted for alloying in Ni-base alloys, Finally, the demonstration of the effectiveness of Re additions to Ni-base alloys occurred in the late 1960's.

The original 20 wt % Cr level in superalloys was increased to 25 wt % or higher in some alloys to gain oxidation resistance, but because of its perceived deleterious effect on strength, it was reduced to as low as 10 wt % in favor of Al for oxidation protection, Sims (1972). However, reducing chromium led to the onset of hot corrosion--enhanced oxidation resulting from sodium and sulphur in the fuel and exhaust gas stream. Ingestion of sea water spray into helicopter engines used in the Viet Nam war wrecked havoc in low-chromium turbine blades, leading to a reevaluation of the use of Cr in superalloys.

The trend for increasing usage of refractory metals is shown in Fig. 3 and Table V. It is apparent that, on a weight basis, the refractory metal content of Ni-base alloys tended to steadily increase from the mid-1940's to about 1980. On an atom basis, Fig. 3 (b) shows the use of refractory metals increased from 1 to about 6 wt % in less than a decade. With this increasing trend in the use of refractory metals in superalloys the concern for the availability of those that have been determined to be strategic in nature, Cr, Nb, and Ta becomes apparent.

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[*] Nimonic and Inconel are trade names of the International Nickel Company.

[†] Waspaloy is a trade name of United Technologies Corporation.

Cobalt is used in a variety of both Co-base and Ni-base superalloys. The largest usage in terms of pounds consumed, however is in Ni-base alloys. Several Ni-base and Co-base superalloys are listed in Fig. 4 which shows the range of Co content in these alloys. It was the sharp rise in cost of cobalt more than any other factor that brought on the need of the COSAM Program. Cobalt that was selling at around $5.50/lb in 1977 increased to over $30.00/lb in 1979 with spot prices as high as $55.00/lb. A historical rule-of-thumb has been that the price of cobalt is typically higher than that of nickel by a factor of two to three times. In 1980 that factor was in excess of seven times. Primarily because of the spiraling cost of cobalt, the United States experienced a decline in cobalt usage. Fig. 5 shows that 20 million lb of cobalt were consumed in 1978 and that in 1980 usage was down to 16 million lb, Stephens (1981). During this same time period the use of cobalt to produce superalloys, primarily for aircraft engines, increased from 4 million lb in 1978 to 7.2 million lb in 1980. This increase in cobalt usage in superalloys can be attributed to the increased orders of aircraft over this time period. The aircraft industry is a major factor on the positive side of the U.S. balance of payments, thus a healthy aircraft industry is of utmost importance to the United States. Because of this the COSAM Program as well as industry activities were undertaken.

Table VI presents a list of several superalloys that have been used in gas turbine engines or are emerging as promising replacements to gain increased operating temperatures and higher efficiencies for aircraft of the future. These alloys are used in a variety of forms and serve a multitude of needs in gas turbine engines such as turbine blades, vanes, and disks; compressor components; and ducting components. The next section of this chapter will focus on the NASA COSAM Program and some of the technical accomplishments achieved from the various research efforts that were undertaken in the program.

V. COSAM PROGRAM SUMMARY

The COSAM Program had three general objectives which were: (1) contribute basic scientific understanding to the turbine engine "technology bank" so as to maintain our national security in possible times of constriction or interruption of our strategic material supply lines; (2) help reduce the dependence of United States military and civilian gas turbine engines on disruptive worldwide supply/price fluctuations in regard to strategic materials; and by these research contributions, (3) help minimize the acquisition costs as well as optimize performance of such engines so as to contribute to the United States position of preeminence in world gas turbine markets. To achieve these objectives a three-pronged approach was undertaken as shown in Fig. 6, Stephens (1981). It consisted of research on strategic element substitution, advanced processing concepts, and alternate materials. The intent was to achieve conservation, as well as reduced dependence on strategic metals, in the area of strategic element substitution by systematically examining the effects of replacing cobalt, columbium, and tantalum with less strategic elements in current, high use engine alloys. This would help guide future material specifications if one or more of these metals becomes in short supply, and create a powerful base of understanding that will benefit all future advanced alloy development. Conservation through advanced processing concepts research can be achieved by creating the means to use dual alloys and multiple alloy tailored-structures that can minimize strategic material input requirements--use them only where mandatory--and thus lower total usage. And in the longer term, the development (higher risk) of alternate materials that can replace most strategic metals with others readily available in the U.S. could lead to a dramatic reduction in the U.S. dependence on foreign sources. Both of the later two technology areas will help conserve all four strategic metals: Co, Ta, Nb, and Cr.

The various efforts of the COSAM Program were conducted under the overall programmatic management of NASA Lewis Research Center. Some of this work was conducted in-house at NASA Lewis. In addition, cooperative programs involving NASA Lewis working together with both industry and universities in tripartied projects to optimize the utilization of the expertise at each of the various organizations and to seek synergistic results from these combined efforts. This method of research cooperation is depicted graphically in Fig. 7. Typical roles for each organization are shown. These roles, of course, varied from program-to-program. For example, one project can involve an industry contract or a university grant to conduct the bulk of the effort with a range of supporting contributions from the other partners. Alternatively, another project may be conducted mainly in-house at NASA Lewis with a range of support from industry or a university. The subsequent sections will present the highlights of results obtained from the program.

A. Substitution

1. Cobalt in Waspaloy and Udimet-700.* Waspaloy, which contains 13% Co, is used as in turbine disks and because of this component's size and weight, a major portion of the cobalt consumed in gas turbine engines is found in this alloy. Udimet-700 containing 17% Co can be used for both disks and blades, depending on processing history and heat treatment.

Results on the effects of reducing cobalt in Waspaloy were reported by Maurer et al., (1980) of Special Metals Corporation. Highlights of that study are shown in Fig. 8. Tensile strength decreases only slightly as the amount of cobalt in the alloy decreases. However, rupture life decreased substantially with decreasing amounts of cobalt in Waspaloy. A summary of the major findings

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*Udimet-700 is a tradename of Special Metals Corporation.

of this study is presented in Fig. 9. In addition to the slight decrease in amount of γ' in the alloy, the major effects of removing cobalt on mechanical properties were attributed to a possible higher stacking fault energy of the matrix and to changes in carbide partitioning in grain boundaries.

Barrett (1982) examined the effect of cobalt on the oxidation resistance of Waspaloy. Results, shown in Fig. 10, indicate that based on specific weight change data to 1100 °C, cyclic oxidation resistance is essentially independent of cobalt content.

A further study of the reduced cobalt composition Waspaloy alloys was conducted at Purdue University by Durako (1981). This investigation focused on the microstructure of the alloys and on metallographic studies of extracted γ' and carbide precipitates. The effect of removing cobalt in Waspaloy on mechanical properties was attributed by Durako to be due in part to: the decrease in volume percent γ' in agreement with Maurer (1982); to the reduction in γ-γ' mismatch, hence increasing dislocation mobility; and to an indirect increase in the matrix stacking fault energy resulting from matrix chromium depletion caused by the formation of massive $M_{23}C_6$ chromium-rich carbides. Both Durako and Maurer suggested that alloy modifications might allow the reduction or removal of cobalt from Waspaloy.

Effects of removing cobalt in wrought Udimet-700 alloy were extensively studied as part of a cooperative program involving Special Metals Corporation, Columbia and Purdue Universities, and NASA Lewis Research Center. Fabricability has been investigated by Jackman and Maurer and Sczerenie and Maurer (1982), Special Metals Corporation and mechanical properties and metallurgical properties by Jarrett and Tien, (1982), Columbia University. Fabricability, based on Gleeble and high strain rate tensile tests corresponding to rolling temperatures in the 1000 to 1100 °C range show no cobalt effect on the high temperature ductilities. Of particular interest is the work of Jarrett and

Tien (1982) on the effect of the disk (partial γ' solutioning) and blade (complete γ' solutioning) heat treatments on stress rupture and creep properties. Rupture life as a function of cobalt content is shown in Fig. 11 for the two heat treated Udimet-700 conditions. The disk heat treatment resulted in a reduction in rupture life below 9% Co. In the blade heat treated condition, specimens exhibited an increase in rupture life with decreasing cobalt content at the lower stress level and were insensitive to cobalt content at a higher stress level. Creep rates, as expected, showed similar trends with cobalt content and heat treatment as presented in Fig. 12. The results of Jarrett and Tien (1982) are summarized as follows:

(1) Room temperature tensile yield strength and tensile strength were only slightly decreased in the disk alloys and basically unaffected in the blading alloys as cobalt was removed.

(2) Creep and stress rupture resistance (at 760 °C) were found to be unaffected by cobalt level in the blade alloys and decreased sharply only when the cobalt level was reduced below about eight vol % in the disk alloys.

(3) Microstructure was found to be very heat treatment sensitive. After the fine grain, disk heat treatment, fine strengthening γ' precipitates fraction decreased as cobalt was removed because of a corresponding increase in undissolved γ' fraction. No such change occurred after the higher temperature, coarse grain heat treatment during which all γ' particles were initially dissolved.

(4) Cobalt was observed (through STEM/EDS) to partition mostly to the γ matrix phase.

(5) Cobalt also changed the relative stability of the various carbides, and destabilized rather than stabilized the alloy with respect to sigma phase formation after long-time aging. It did not significantly alter γ' coarsening kinetics.

(6) Correlation of the detailed microstructural and microchemistry information with yield strength and creep rate formulisms specially developed for particle strengthened systems showed that the slight decrease in yield strength was due to γ' fraction and APB energy considerations. The significant drop in creep and stress rupture resistance in the low cobalt and cobalt-free disk alloys is due to a change in the fine γ' volume fraction and is relatively unaffected by matrix composition and stacking fault energy factors.

Harf (1985) of NASA Lewis conducted a parallel program on hot isostatic pressed (HIP) powder metallurgy (PM) Udimet-700. Initial results confirmed the previous results of Jarrett et al., (1982) on the cast plus wrought (CW) material. Harf (1986) then focussed on modifying the disk heat treatment to improve the creep-rupture properties of the zero cobalt alloy. In the original concept of comparing the properties of Udimet-700 type alloys with decreased cobalt levels, the comparison was made with minimum of change in heat treatment between the various compositions. A major compromise in the disc type heat treatments had been to adjust the partial solutioning temperature to maintain a nearly constant temperature difference from the γ' solvus, in particular in the HIP-PM alloys. However, since the γ' solvus increased with decreasing cobalt content, this meant that the thermal gap between the partial solutioning temperature and the subsequent aging temperatures (which were the same for all cobalt contents) increased with decreasing cobalt content. Harf (1986) modified the aging temperatures to keep the thermal gap for the zero cobalt alloy similar to that used for the 17% Co Udimet-700 alloy. His results showed that this technique was successful in improving the rupture life and creep resistance of the 0% Co alloy at 650 °C. He attributed this improvement to the microstructure which contained an increased quantity of ultra-fine, 20 nm, γ' particles as shown in Fig. 13 where the standard heat treatment (Fig. 13(a)) has fewer particles than for the modified heat treatment (Fig. 13(b)). In the CW alloy, substantial improvements in creep-rupture properties also were observed at 760 °C as a result of a similar modification in heat treatment for the 0% Co alloy.

Barrett (1982) has also investigated the cyclic oxidation resistance of the low/no cobalt Udimet-700 alloys. Results of this study are shown in Fig. 14. At 1100 °C, removing cobalt from Udimet-700 improved the cyclic oxidation resistance based on specific weight change data. Hot corrosion resistance of the low/no cobalt Udiment-700 alloys was also investigated. Results by Deadmore (1984) from tests using NaCl-doped flames in a Mach 0.3 burner rig indicate that corrosion resistance increases with decreasing cobalt content. Photographs of exposed specimens are shown in Fig. 15 where the improved corrosion resistance for the lower cobalt concentrations is evident. In contrast, Zaplatynsky (1985) found that the alloys with an aluminide coating exhibited improved oxidation resistance with increasing cobalt content based on a weight loss criteria during testing in the Mach 0.3 burner rig. Leis et al. (1983), of the Battelle-Columbia Laboratories investigated the creep fatigue behavior of low cobalt PM and CW Udimet-700 alloys and saw no correlation between fatigue resistance and cobalt content. It is concluded that an alloy based on Udiment-700 in which all the cobalt has been substituted for by nickel is a viable superalloy for use in turbine applications. This statement applies to both the cast plus wrought and the hot-isostatically-pressed pre-alloyed powder processed alloy. Jarrett et al., (1982) had previously reported that the alloy, when given a different heat treatment, might also qualify for use in turbine blades. It is suggested that this alloy be considered for future use in aerospace and land-based turbine applications.

2. Cobalt and Tantalum in Mar-M 247*. Mar-M 247 is an advanced nickel base superalloy used in polycrystalline, directionally solidified (DS), and single crystal form.

Effects of removing cobalt from MAR-M 247 have been investigated as part of a cooperative program involving TRW, Teledyne CAE, Case Western Reserve University, and NASA Lewis. The potential industrial application was related to an integral cast rotor, therefore, casting mold and pouring temperatures were selected by Teledyne CAE to simulate blade and hub conditions. Major findings by McLaughlin (1981), Teledyne and Kortovich (1981), TRW are summarized in Fig. 16. A parallel in-depth study on cobalt effects on Mar-M 427 mechanical properties was undertaken by Nathal (1981). This study explored the mechanisms associated with the effects of cobalt on mechanical properties of polycrystalline materials. Nathal postulated that reduction in γ' weight fraction and carbide formation as a grain boundary film were responsible for the deleterious effects on creep-rupture properties. It was proposed that reducing the carbon level in the 5% cobalt alloy may result in an alloy with properties comparable to Mar-M 247, but with the conservation of 50% of the cobalt normally used in this alloy. Nathal also showed that, based on weight change data, removing cobalt from Mar-M 247 improves the cyclic oxidation resistance of this alloy at 1100 °C. Similar to Udimet-700 test results, hot corrosion testing of alloys based on Mar-M 247 chemistry revealed that reducing cobalt also improved corrosion resistance, Deadmore (1984).

Nathal et al., (1982) has further shown that in single crystal form, removing cobalt from Mar-M 247 appears to increase rupture life and decrease creep rate--trends that are opposite to those observed for the polycrystalline

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*Mar-M is a trademark of Martin Marietta Company.

material. The single crystal findings by Nathal supported previous results reported by Strangman et al., (1980) where 0% cobalt levels in single crystal alloys had longer rupture lives than the 10% cobalt Mar-M 247 single crystals. However, a 5% cobalt level was required for alloy stability with respect to formation of the μ phase.

Nathal and Ebert (1985) studied the influence of composition on the tensile and creep strength of [001] oriented nickel-base superalloy single crystals at temperatures near 1000 °C. Cobalt, tantalum, and tungsten concentrations were varied according to a matrix of compositions based on the single crystal version of Mar-M 247. For alloys with the baseline refractory metal level of 3 wt % Ta and 10 wt % W, decreasing the Co level from 10 to 0 wt % resulted in increased tensile and creep strength. Substitution of 2 wt % W for 3 wt % Ta resulted in decreased creep life at high stresses, but improved life at low stresses. Substitution of Ni for Ta caused large reductions in tensile strength and creep resistance, and corresponding increases in ductility. For these alloys with low Ta plus W totals, strength was independent of Co level. Figures 17 and 18 show the yield stress and creep-rupture properties of the reduced cobalt and tantalum alloys. The results of their extensive studies on microstructure and mechanical properties are summarized in the following paragraphs.

Removal of Ta and W from the baseline 3Ta-10W alloys to form the 0Ta-9W alloys caused large reductions in γ' solvus temperature and γ' volume fraction. Substitution of W for Ta to form the 0Ta-12W alloys resulted in intermediate reductions in solvus temperature and volume fraction. The amount of γ' was independent of Co level, although the γ' solvus temperature increased significantly as Co content was reduced from 10 to 0%. The partitioning of elements between the γ and γ' phases did not vary appreciably as the alloy composition varied. Tantalum and Ti partitioned almost totally to γ'; Al and W partitioned preferentially to γ'; and Co, Cr, and Mo partitioned preferentially to γ.

The γ' lattice parameter was independent of Co content but increased as the total refractory metal level increased. At the 0% Co level, the 3Ta-10W alloy exhibited a room temperature lattice mismatch $\delta = -0.0037$, and the 0Ta-12W alloy exhibited $\delta = -0.002$. The 0Ta-9W alloys and all alloys with 5 and 10% Co possessed mismatch values below the detection limit.

For the alloys with γ' that remained coherent during aging, the unstressed γ' coarsening rate increased as Co level was reduced from 10 to 0%. The alloys with high lattice mismatch possessed γ' that became semi-coherent during aging and exhibited anomalously low coarsening rates.

Oriented γ' coarsening which resulted in lamellae perpendicular to the applied stress was very prominent during creep. Alloys with higher magnitudes of lattice mismatch exhibited faster directional coarsening rates and a finer spacing of misfit dislocations at the γ-γ' interfaces.

Substitution of Ni for Co caused large increases in creep resistance for alloys with high Ta plus W totals. This was consistent with an increase in γ-γ' lattice mismatch. High values of lattice mismatch resulted in a finer dislocation network at the γ-γ' interface, thus providing a more effective barrier for dislocation motion. Substitution of Ni for Ta and W to form the 0Ta-9W alloys caused large reductions in creep resistance, which were related to the decreases in γ' volume fraction, γ-γ' mismatch, and solid solution hardening. Substitution of W for Ta to form the 0Ta-12W alloys resulted in a decrease in creep resistance at high stresses and an increase in creep strength at low stresses. This crossover in creep resistance between the 3Ta-10W and 0Ta-12W alloys was not easily explained. The decreased creep life of the 0Ta-12 Walloys at high stresses was attributed to the slight decreases in

γ' volume fraction and γ-γ' mismatch, although it remains unclear as to why W appears to be a more effective solid solution strengthener than Ta at low stresses.

Decreases in Co level from 10 to 0% caused significant increases in the 1000 °C yield and ultimate tensile strengths of the 3Ta-10W alloys, but the effect of Co was much less for alloys with other refractory metal contents. The influence of Co on the strength of the 3Ta-10W alloys was attributed to coherency strain hardening associated with the increased lattice mismatch as Co level decreased. Reduction of Ta and W content to form the 0Ta-9W alloys caused large reductions in tensile strength, and substitution of W for Ta caused intermediate decreases in strength. These changes in tensile strength with refractory metal level were related to the increases in γ' volume fraction and solid solution hardening which resulted from high Ta plus W totals.

3. Tantalum in B-1900+Hf. B-1900+Hf represents a high strength nickel base superalloy used in turbine blade applications. Kortovich (1982) conducted some independent studies of the role of tantalum on mechanical properties and microstructure of B-1900+Hf. His results indicated that tensile strength decreased with decreasing tantalum content upon testing at room temperature and at 760 °C. Stress rupture testing at 760 °C/650 Mpa indicated that the rupture life increased with decreasing tantalum content while at 980 °C/200 Mpa rupture exhibited a maximum at a 50% reduction in the normal tantalum content. TRW stress-rupture results and tensile results at 760 °C are shown in Fig. 19.

Janowski (1985) studied the microstructure of B-1900+Hf alloys tested by Kortovich. Figure 20 shows the γ-γ' partitioning ratios for the various tantalum levels. The partitioning ratios of Co, Cr, and Ni are constant with Ta variations, consistent with Mar-M 247 results. In addition, the partitioning ratios for Al, Mo, and Ti are also independent of Ta content. However, the Hf and Ta partitioning ratios are very sensitive to Ta content; the partitioning ratios of Hf and Ta decrease and increase, respectively, as Ta is removed from the alloy. The change in the Hf distribution was postulated to be a consequence of more Hf becoming available to the matrix phases as a result of Ta replacing part of the Hf contained in the MC carbides.

4. Niobium in Inconel 718. Inconel 718 is used for disks in gas turbine engines and on a pound basis, is the most frequently used superalloy. Ziegler and Wallace (1985) explored a series of Inconel 718 alloys with reduced niobium contents. Alloys had Nb contents of 5.1 (Inconel 718 composition), 3.0, and 1.1 wt %. Substitutions of 3.0% W, 3.0% W+0.9% V, and Mo from 3 to 5.8% were investigated. Two additional alloys, one containing 3.49% Nb plus 1.10% Ti and a second containing 3.89% Nb and 1.27% Ti also were studied. Additions of solid solution elements to a reduced Nb alloy had no significant effect on the properties of the alloys under either process condition. The solution and aged alloys with substitutions of 1.27% Ti at 3.89% Nb had tensile properties similar to those of the original alloy and stress-rupture properties superior to the original alloy. The improved stress-rupture properties were the result of significant precipitation of Ni_3Ti-γ' in the alloy, which is more stable than γ'' at the elevated temperatures. At lower temperatures this modified alloy benefits from the γ'' strengthening. Much more information is needed to fully characterize the modified alloy, but these initial results suggest that with more precise control and proper processing, the reduced Nb direct-age alloy could substitute for Inconel 718 in high-strength applications.

B. Advanced Processing

Advanced processing--tailored fabrication and dual alloy concepts were initially planned for the COSAM Program. Because of funding limitations and the focus on substitution, very little work was undertaken in this area as a part of the COSAM Program. However, industry has independently investigated dual alloy concepts to improve properties.

A turbine disk is a good candidate for the dual alloy concept because of its weight and its operating characteristics. The rim of a disk operates at higher temperatures and requires a nickel-base superalloy for creep resistance. However, the hub of a disk operates at lower temperatures where fatigue resistance is of importance and thus an iron-base superalloy with lower strategic metal content may suffice. The key to this dual alloy concept is the interface between two alloys of widely different compositions. Harf (1985) has studied the interface properties of Alloy 901 combined with three nickel-base superalloys--Rene 95, Astroloy, and MERL 76. His preliminary results showed that the alloys could be joined by the HIP-PM process and form a strong, integral bond. Stress rupture properties of the alloy combinations with heat treatments for each of the alloys are shown in Fig. 21. Failure was always in Alloy 901 indicating the superior strength of the bond and the rupture lives were always equal to or greater than that for Alloy 901. These results imply that a dual alloy concept is viable for enhancing the local properties of gas-turbine components and of conserving costly strategic materials.

C. Alternate Materials

The third major COSAM Program thrust, Alternate Materials, has the potential of making a major contribution to the conservation of the four strategic elements studied in this program, including chromium which is critical to currently used superalloys because of the oxidation/corrosion resistance it provides. Materials investigated in this phase of the program are described in the following paragraphs.

1. Intermetallic compounds. This aspect of the COSAM Program focused on the equiatomic iron and nickel aluminides (i.e., FeAl and NiAl) as potential alternatives to nickel base superalloys. Cobalt aluminide is being carried along for comparative purposes since it has unusual mechanical properties and phase equilibria. This program emphasized a basic research approach toward understanding the deformation mechanisms that control high temperature creep as well as those that control the lack of room temperature ductility. By necessity, the program is a long-term, high-risk effort, but offers the potential of a high payoff if materials evolve which permit conserving all four currently identified strategic metals--Co, Ta, Nb, and Cr. The research program on the aluminides was conducted in-house at NASA Lewis Research Center and at Dartmouth College, Stanford University, Texas A&M University, and Case Western Reserve University, Stephens (1984). These binary aluminides have the advantages of (1) they exist over a wide range of compositions and have a large solubility for substitutional third element additions; (2) have a cubic crystal structure; (3) have very high melting points (except for FeAl which has a somewhat lower melting point); (4) contain inexpensive, readily available elements; and (5) possess potential for self protection in oxidizing environments. Their chief disadvantage is the lack of room temperature ductility.

Some of the highlights on FeAl, Gaydosh and Nathal (1986) and Mantravadi et al., (1986), are shown in Figs. 22 and 23. Fig. 22 shows that the room temperature tensile elongation of Fe-40Al is about 1 or 2%. With the addition of Zr and B 5 to 6% elongation was achieved. The fracture for alloys without B was intergranular while alloys containing B exhibited transgranular fracture. The creep strength of the Fe-40Al - 0.1 Zr - 0.41 B alloy is compared with several commercial iron-nickel base superalloys in Fig. 23. Results indicate that this alloy has promising properties at elevated temperature.

Schulson (1984) described the effects of grain size on the tensile ductility of NiAl (ref. 30). His work is based on the models of Cottrell (1958) and Petch (1958) which state that the stress required to nucleate microcracks in coarse-grained materials is more than enough to propagate them. In contrast, for fine-grained materials the stress required to nucleate cracks is less than that required to propagate them. In the first case, coarse-grained materials will fail in a brittle manner while fine-grained material must undergo permanent deformation and work hardening prior to failure. The conclusion is therefore, that a critical grain size should exist for plastic flow. This does indeed appear to be the case for Ni-49 Al at 295 °C as illustrated by the results shown in Fig. 24 where the critical grain size is ~20μm. At lower temperatures the critical grain size becomes even smaller.

Vedula et al., (1984) have shown that Ta rich precipitates in a Ni-48 at % Al-2 at % Ta alloy can produce an increase in creep strength of nearly two orders of magnitude over the simple equiatomic binary NiAl. Dislocations interacting with the precipitates during creep testing are shown in Fig. 25. This alloy is comparable to some nickel-base superalloys at 1025 °C.

2. Iron-base alloys. With the successful development of high strength nickel-base superalloys (and to some extent cobalt-base superalloys) over the last 30 years, there has been little recent interest in developing iron-base alloys for the higher temperature gas turbine engine components. However, with the threat of strategic material supply disruptions or interruptions, iron-base alloys with low strategic metal contents are attractive as alternative materials for U.S. industrial consideration. A program was initiated to investigate iron-base superalloys with aligned carbides for further strengthening as potential alternatives to current high strategic element content nickel and cobalt base superalloys. This was a joint program involving the University of Connecticut, United Technologies Research Center (UTRC), and NASA Lewis. The

potential of these iron-chromium-manganese aluminum type alloys is illustrated in Fig. 26 where rupture lives determined by Lemkey and Bailey are compared with other iron, nickel, and cobalt base alloys.

3. Composites. A third area of alternate materials technology conducted in-house at NASA Lewis was aimed at determining the potential of silicon carbide reinforced low strategic element content iron-base matrix composites. This program, by Petrasek (1986), focused on understanding matrix/fiber interface compatibility in the 760 to 900 °C service range for turbine engine components. This concept offers the potential of not only conserving strategic materials, but also of either reducing component weight due to the potential strength of the fibers and their high volume fraction or of maintaining weight and extending service life. The results of this program can be summarized as follows: (1) A low temperature fabrication process, hollow cathode sputtering, can be successfully utilized to produce single filament composites from B_4C-B and SiC filaments and iron-base matrix alloys while retaining high fractions of the filament strength. No evidence of filament/matrix reaction was observed due to processing. (2) Single fiber composites of B_4C-B and SiC filament reinforced iron base alloys have stress-rupture strengths at 870 °C that are superior to those of the strongest superalloys. The 1000 hr rupture strength projected for a 50 vol % B_4C-B filament reinforced iron base alloy composite at 870 °C is 455 MPa which represents a 30% increase in strength compared to single crystal CMSX-2. Much more impressive however is that the 50 vol % fiber content B_4C-B iron base alloy composite is projected to have a 1000 hr rupture strength to density ratio at 870 °C twice that of CMSX-2 as shown in Fig. 27. (3) The potential for B_4C-B and SiC filament reinforced iron-base alloy composites for use at intermediate temperatures appears promising if similar processing technologies can be developed for multi-ply composites. The successful accomplishment for developing this technology for

turbine components would reduce turbine blade weight. A 40% weight reduction could be obtained in a composite blade using this material while also increasing blade life. In addition, for a 50 vol % fiber content, a significant savings in strategic materials can be achieved compared to nickel-base superalloys.

VI. CONCLUDING REMARKS

The COSAM Program began in 1980 and continued through 1983. Because of the drop in cost of cobalt, niobium, and tantalum and the immediate threat of a strategic materials shortage being significantly lessened, funding for the program was terminated in 1984. However, research initiated under the COSAM Program continues today, being funded under other NASA programs because of the technical promise shown by the materials that evolved from the COSAM Program. This is especially true of the alternate materials.

Comparing the results that were achieved in the short time that the COSAM Program existed with the initial objectives stated in the first paragraph in Section V, we find that a significant "technology bank" was established in the area of a substitution for strategic materials in nickel-base superalloys. This is especially true for cobalt where our knowledge of the physical metallurgy of lower and zero cobalt alloys was characterized in terms of composition, microstructure, heat treating, and thermomechanical processing. Mechanical and environmental properties were described in detail. A similar argument for tantalum substitution also can be made while niobium substitution was much less clearly defined. Transfer of this technology to flight hardware must overcome significant barriers as discussed by Stephens and Tien (1983) and illustrated in Fig. 28. A commitment of both time and money is required to overcome these barriers as illustrated in Fig. 29. Experience in the aircraft engine industry has shown that 10 yr with a minimal expenditure of $1 million/yr is not uncommon. Since the threat of a strategic materials shortage is currently not a threat to aircraft engine producers, such a commitment will in all probability not be fourthcoming to move one or more of the lower strategic metal content alloys into flight operation.

Since the COSAM Program was not carried to fruition we cannot make the claim that a reduced dependence on disruptive foreign sources was achieved. However, in future supply or cost disruptions the "on-the-shelf" knowledge gained from the COSAM Program may contribute to reducing the impact of such disruptions.

The third objective of reducing costs as well as optimizing performance of aircraft engines may well be realized in future advanced aircraft where lightweight temperature materials are of utmost importance. The continuing alternate materials research on the aluminides and metal matrix and more recently intermetallic matrix composites may well lead to improved engines for such vehicles as hypersonic aircraft. Because of the technical requirements of such aircraft, these low or no strategic metal content materials with potential for meeting these needs, may overcome the transfer barriers from research to flight hardware if their advantages can be realized and their disadvantages overcome. In addition, research on the iron-base alloys has been spun-off to potential terrestrial applications for the heater head of experimental automotive Stirling engines, Stephens and Titran (1985).

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TABLE I. - STRATEGIC METALS INDEX ANALYSIS FOR PEACETIME AND WARTIME ECONOMIES

Ranking in relation to:	Economy	Metal index values																		Weighting factor
		Al	Cr	Co	Nb	Cu	Au	Fe	Mg	Mn	Mo	Ni	Pt	Re	Ag	Ta	Ti	W	V	
USA needs	Peace	17	15	13	7	12	2	18	6	11	10	16	4	1	3	5	14	9	8	1X
	War	17	14	12	11	7	5	18	2	8	13	16	4	1	3	6	15	10	9	2X
World reserves	-----	3	5	12	11	6	17	2	1	4	10	8	16	18	14	15	7	13	9	1X
North American reserves	-----	7	18	11	9	2	15	1	3	5	8	6	17	16	13	14	4	10	12	2X
USA reserves	-----	4	15	8	17	3	12	2	1	18	5	6	14	13	11	16	7	9	10	5X
World production	Peace	3	4	12	14	5	15	1	7	2	8	6	17	18	13	16	9	10	11	1X
	War	3	4	12	10	5	15	1	13	2	7	6	17	18	16	14	8	9	11	1X
North American production	Peace	2	18	13	9	3	15	1	6	4	7	5	16	17	11	14	8	10	12	1X
	War	2	13	11	9	3	18	1	6	5	7	4	16	17	15	14	8	10	12	1X
USA production	Peace	2	16	14	17	3	11	1	4	15	5	7	13	12	10	18	6	9	8	2X
	War	2	17	14	16	3	11	1	4	15	5	7	13	12	10	18	6	9	8	5X
Availability in USA consumption	Peace	2	5	11	14	3	17	1	7	11	4	6	16	18	13	15	9	10	12	1X
	War	2	14	10	13	3	17	1	4	11	5	6	12	18	16	15	8	7	9	1X
Reliability of supply source	Peace	4	14	15	18	6	9	5	3	16	1	12	13	11	2	17	8	10	7	1X
	War	4	18	16	14	6	8	5	3	15	1	9	13	7	2	17	12	10	11	2X
Stockpile versus goal	War	17	10	9	12	16	3	2	1	8	4	18	11	5	6	13	14	7	15	5X
Price	Peace	3	5	12	13	4	17	1	6	2	10	7	18	16	14	15	8	11	9	1X
Recyclability	Peace	6	15	9	14	1	2	5	10	16	11	7	4	18	3	17	8	12	13	1X
	War	6	12	11	15	1	2	5	10	16	9	7	4	18	3	17	8	13	14	2X
Probability of mineral cartel	Peace	6	15	14	12	10	3	1	2	17	4	5	18	9	8	13	11	7	16	3X
	War	6	17	15	12	10	3	1	2	16	4	5	18	9	8	13	11	7	14	5X
Ranking point totals, normalized[a]	-----	2.7	8.5	8.1	8.6	2.5	6.7	1.0	2.1	6.4	3.5	4.8	8.9	8.8	5.7	10.	5.5	6.1	7.2	--
Weighted ranking point totals, normalized[a]	-----	3.7	9.1	7.8	8.9	3.5	5.2	1.0	1.5	8.2	3.2	5.2	9.0	7.3	5.4	10.	5.9	5.7	7.4	--

[a] Normalized on 1 to 10 sliding scale; lower the number, better the ranking.

TABLE II. - WORLD AND UNITED STATES RESERVES AND UNITED STATES RESOURCES OF 18 METALS IN 1980

Metal	Reserves		Location of top two reserves		U.S. resources, 10^3 ton
	World, 10^3 ton	USA, 10^3 ton	No. 1	No. 2	
Re	3.5	1.3	USA	Chile	5
Au	42	2.5	South Africa	USSR	9
Pt	50	0.042	South Africa	USSR	3
Ta	67	---------	Zaire	Nigeria	1.7
Ag	338	62	Canada	USA	160
W	2 850	137	China	Canada	2900
Co	3 400	350	Zaire	Zambia	1400
Nb	3 800	---------	Brazil	Canada	400
Mo	10 850	5 900	USA	Chile	9500
V	17 400	115	South Africa	USSR	294x10^3
Ni	59 800	2 700	New Caledonia	Canada	149x10^3
Ti	133 000	2 000	Brazil	Australia	3400
Cu	542 300	101 000	Chile	USA	122x10^3
Mg	2 785 000 +	10 000 +	China	USSR	unlimited
Cr	3 700 000	---------	South Africa	Zimbabwe	189x10^3
Mn	5 400 000	---------	USSR	South Africa	2450x10^3
Al	25 080 000	44 000	Guinea	Australia	70x10^5
Fe	105 000 000	5 800 000	USSR	Brazil	60x10^6

TABLE III. - WORLD PRODUCTION IN 1980

Metal	Production, 10^3 ton	Top two producers	
		No. 1	No. 2
Re	0.011	USA	Chile
Pt	0.281	South Africa	USSR
Ta	0.500	Canada	Brazil
Au	1.592	South Africa	USSR
Nb	12.25	Brazil	Canada
Ag	14.15	Mexico	Canada
Co	29.80	Zaire	Zambia
V	40.35	South Africa	USSR
W	54.75	China	USSR
Ti	92.60	USSR	USA
Mo	120.50	USA	Chile
Mg	352	USA	USSR
Ni	721	Canada	New Caledonia
Cu	8 250	USA	Chile
Cr	10 000	South Africa	Philippines
Al	16 900	USA	USSR
Mn	25 300	USSR	South Africa
Fe	791 000	USSR	Japan

TABLE IV. - UNITED STATES PRODUCTION AND CONSUMPTION IN 1980

Metal	Production, 10^3 ton	Consumption, 10^3 ton	Top two foreign suppliers	
			No. 1	No. 2
Re	0.005	0.005	Germany	Chile
Au	0.039	0.017	Canada	USSR
Pt	0.0003	0.123	South Africa	USSR
Ta	-------	0.74	Thailand	Canada
Nb	-------	3.7	Brazil	Canada
Ag	1.333	4.125	Canada	Mexico
V	5.05	5.905	South Africa	Chile
Co	-------	8	Zaire	Belgium
W	3.5	11	Canada	Bolivia
Ti	25	27	Japan	USSR
Mo	73.5	31	Canada	Chile
Mg	170	110	Norway	Netherlands
Ni	16	197	Canada	Norway
Cr	-------	530	South Africa	USSR
Mn	-------	1 170	South Africa	France
Cu	1 292	2 057	Chile	Canada
Al	5 050	5 000	Canada	Ghana
Fe	111 300	109 500	Japan	Europe

TABLE V. - REFRACTORY METAL CONTENT OF SELECTED NICKEL-BASE SUPERALLOYS AND YEAR OF AVAILABILITY

Alloy	Nominal refractory metal content, wt%							Year[a]
	Cr	Mo	W	Nb	Ta	Re	V	
Nimonic 80A	20	0	0	0	0	0	0	1942
Waspaloy	19	4.4	↓	↓	↓	↓	↓	1951
Nimonic 100	11	5	↓	↓	↓	↓	↓	1953
M-252	20	4.0	↓	↓	↓	↓	↓	1953
Inconel 713C	12	4.5	↓	2.0	↓	↓	↓	1956
Inconel 718	19	3	↓	5.0	↓	↓	↓	1960
TRW-NASA VIA	6.1	2	5.8	.5	9	↓	.5	1968
René 150	5	1	5	0	6	2.2	3	1978
P&WA 454	10	4	0	0	12	0	0	1980

[a] Approximate year of availability.

TABLE VI. - COMPOSITIONS OF SELECTED Fe-, Ni-, AND Co-BASE SUPERALLOYS

Alloy	Fe	Ni	Co	Cr	V	Nb	Ta	Mo	W	Re	Zr	Al	Ti	B	C	Hf
Fe-Base alloys																
A-286	53	26	----	15	0.2	---	----	1.25	----	---	----	0.2	2.15	-----	0.05	---
N-155	30	20	20	21	---	1	----	3	2.5	---	----	----	---	-----	0.15	---
CG-27	38	38	----	13	---	0.6	----	5.5	----	---	----	1.5	2.5	0.01	0.05	---
Ni-Base alloys																
IN-718	19	53	----	19	---	5.2	----	3	----	---	----	0.6	0.8	0.006	0.05	---
Mar-M 247	--	62	10	8.2	---	---	3	0.6	10	---	0.09	5.5	1.4	0.001	0.006	---
Udimet-700	--	53	19	15	---	---	----	5.2	----	---	----	4.3	3.5	0.03	0.08	---
CM SX-2	--	66	4.6	8	---	---	5.8	0.6	7.9	---	----	5.6	0.9	-----	0.005	---
IN 713C	--	74	----	12	---	2	----	4.2	----	---	0.1	6.1	0.8	0.012	0.12	---
PWA 1480	--	63	5	10	---	---	12	----	4	---	----	5	1.5	-----	-----	---
Waspaloy	--	58	13	19	---	---	----	4.3	----	---	0.06	1.3	3	0.006	0.08	---
N-4	--	63	7.5	9.2	---	0.5	4	1.6	6	---	----	3.77	4.25	-----	0.005	---
René 150	--	58	12	5	3	---	6	1	5	2.2	0.03	5.5	----	0.015	0.06	1.5
Co-Base alloys																
HS-188	3	22	39	22	---	---	----	----	14	---	----	----	----	-----	0.1	---
X-40	--	10	54	25	---	---	----	----	7.5	---	----	----	----	-----	0.5	---

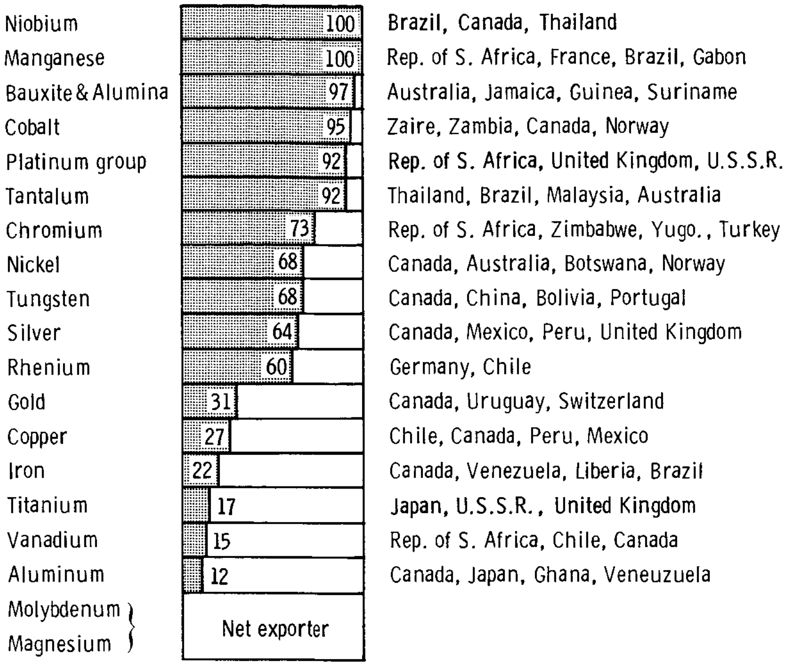
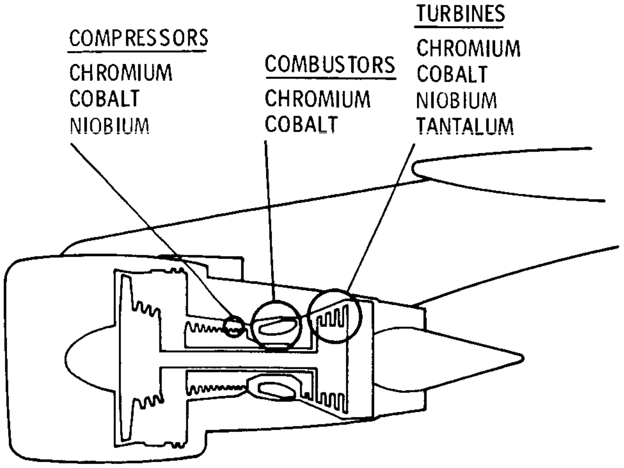


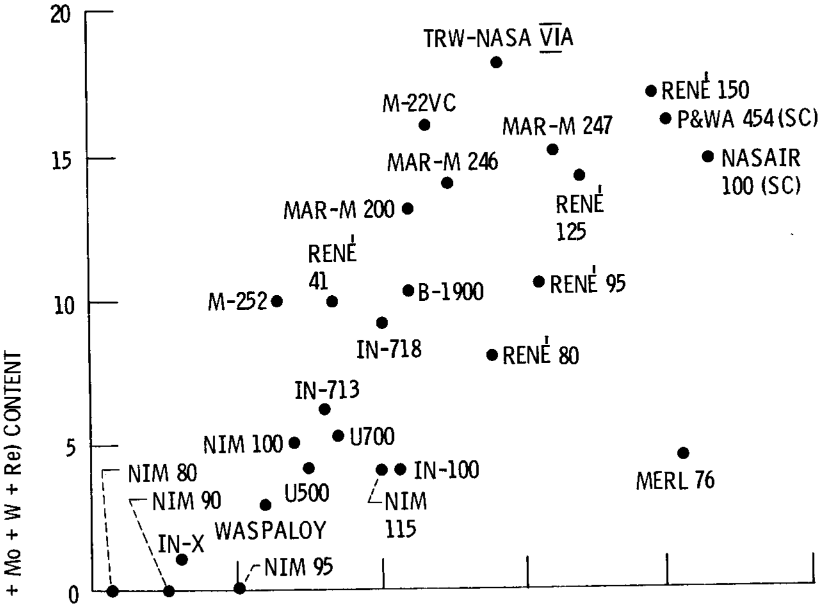
Figure 1. - 1985 estimated net import reliance of selected nonfuel mineral materials as a percent of apparent consumption, where Net import reliance = Imports - Exports + Adjustments for Government and industry stock changes.



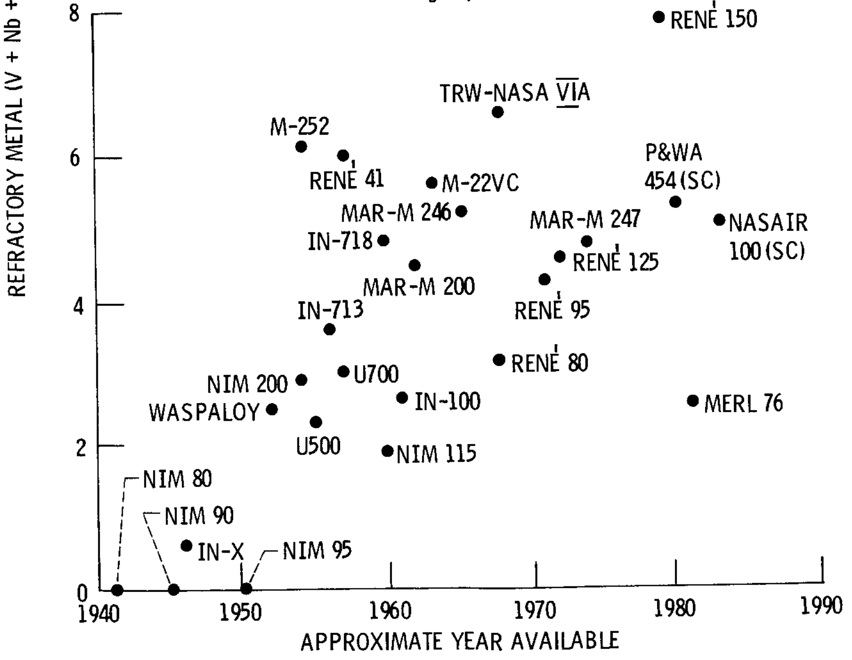
NEEDED FOR PERFORMANCE AND LONG LIFE

COBALT - HIGH TEMPERATURE STRENGTHENER
NIOBIUM - INTERMEDIATE TEMPERATURE STRENGTHENER
TANTALUM - OXIDATION RESISTANCE, STRENGTHENER
CHROMIUM - CORROSION RESISTANCE

Figure 2. - Current gas turbine engines depend on strategic metals for several major components.



(a) Weight percent.



(b) Atom percent.

Figure 3. - Increased use of refractory metals in nickel-base superalloys.

ALLOY DESIGNATION	% COBALT NOMINAL
CAST	
HS - 31	55
MAR-M509	55
IN - 100	15
B - 1900	10
IN - 738	8
WROUGHT	
L - 605	55
S - 816	45
HA - 188	39
U - 700	19
WASPALOY	14
MAR-M247	10
POWDER METALLURGY	
1056	19
U - 700	19
R - 95	8

CS-81-2608

Figure 4. - Cobalt content of typical superalloys.

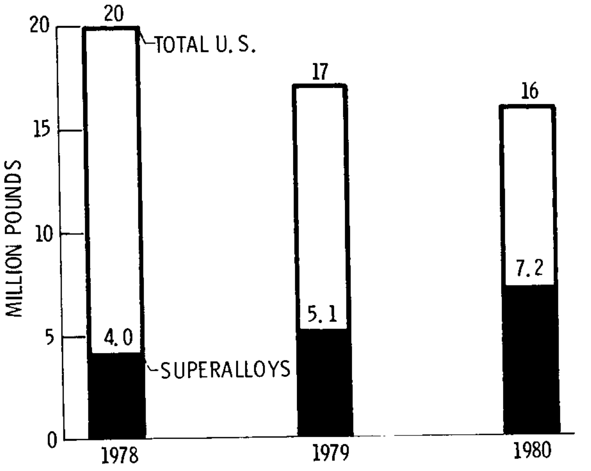


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Figure 5. - Recent trends in U. S. and aerospace cobalt usage.

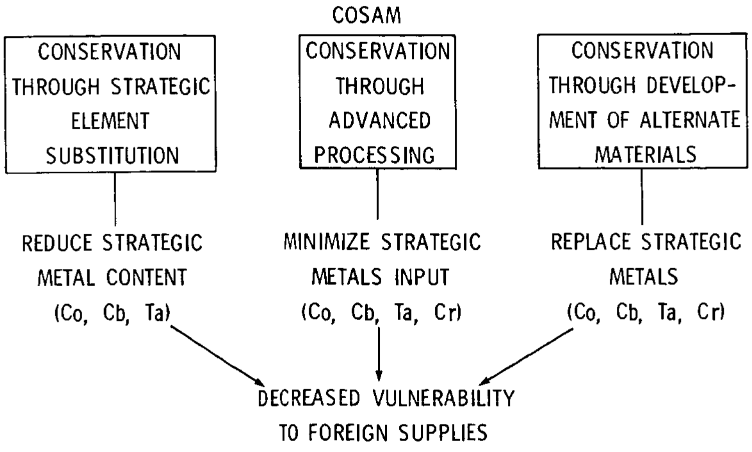


Figure 6. - Conservation of strategic aerospace materials.

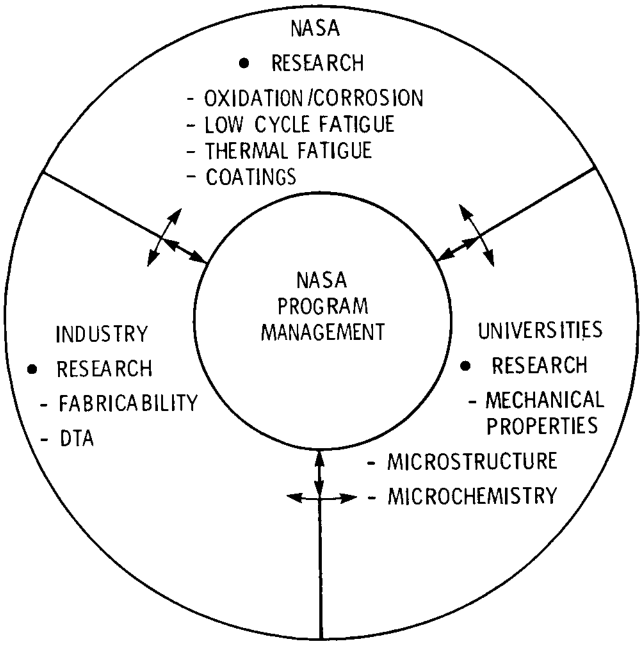


Figure 7. - Cooperative NASA-industry-university programs.

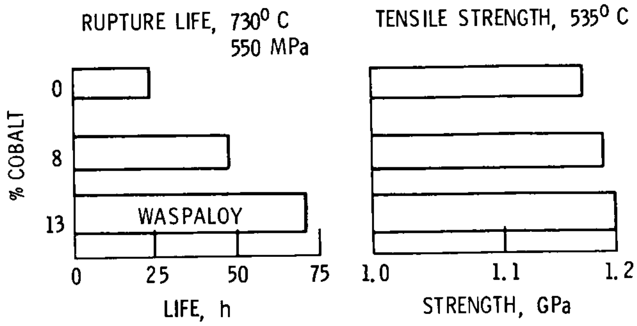


Figure 8. - Effect of cobalt content in Waspaloy on rupture life and tensile strength.

ITEM	RESULT
HOT WORKABILITY - HEATING	NO CHANGE
- COOLING	DECREASE
TENSILE - STRENGTH	SLIGHT REDUCTION
- DUCTILITY	NO CHANGE
STRESS RUPTURE LIFE	MAJOR DECREASE
CREEP RATE	SIXFOLD INCREASE
γ' - SOLVUS TEMPERATURE	NO CHANGE
- VOLUME FRACTION	SLIGHT DECREASE (18% TO 16%)
- CHEMISTRY	DECREASE - Cr, Ti INCREASE-Al
CARBIDES - CHEMISTRY	MORE MC AS - ROLLED
	MORE $M_{23}C_6$ 843° AGING
- MORPHOLOGY	COARSER

Figure 9. - Effects of removing cobalt from Waspaloy.

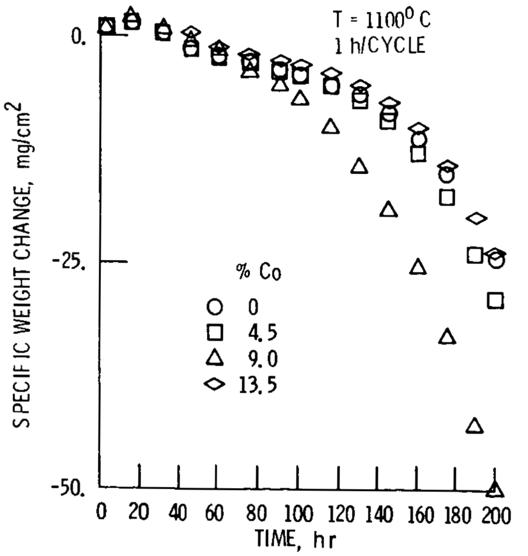
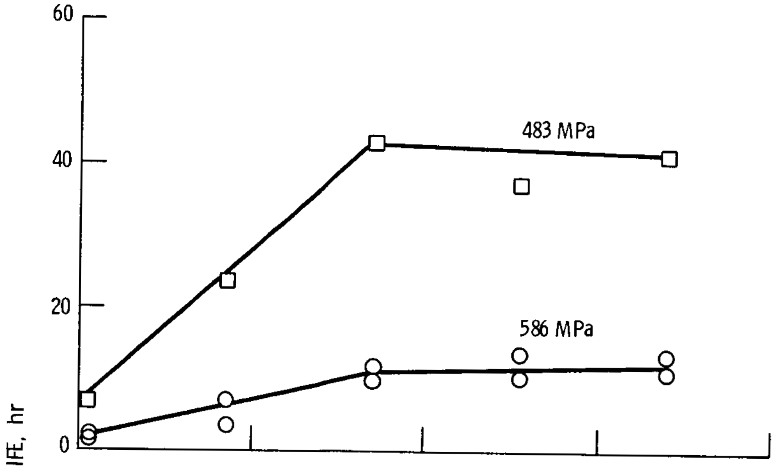
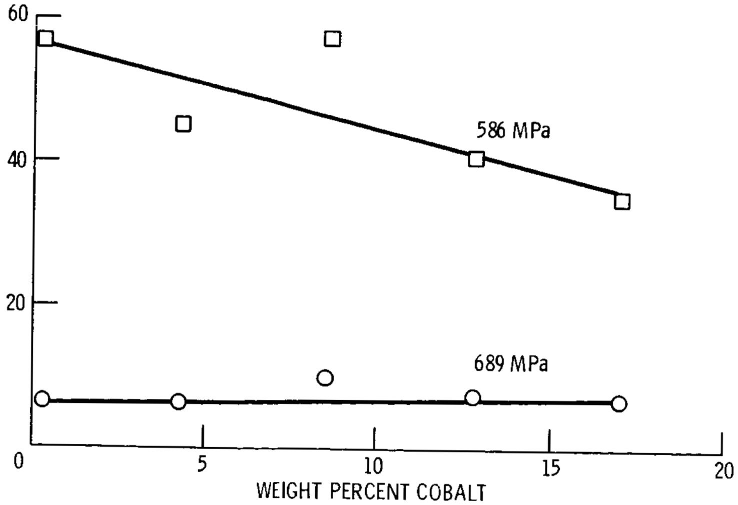


Figure 10. - Effect of cobalt on cyclic oxidation resistance of Waspaloy.

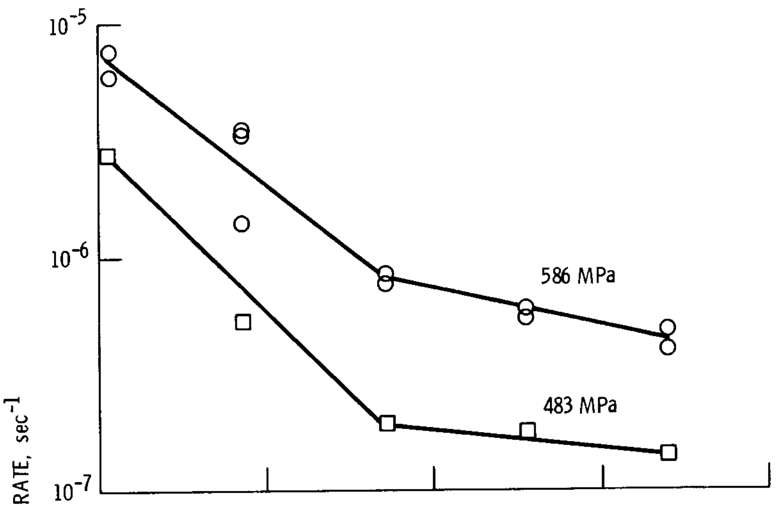


(a) Disk heat treatment.

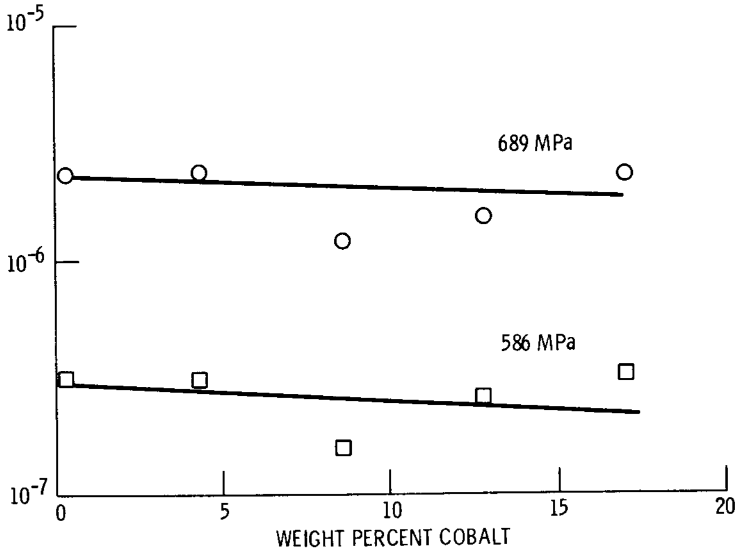


(b) Blade heat treatment.

Figure 11. - Stress rupture life of Udiment 700 at 760 °C versus cobalt content.

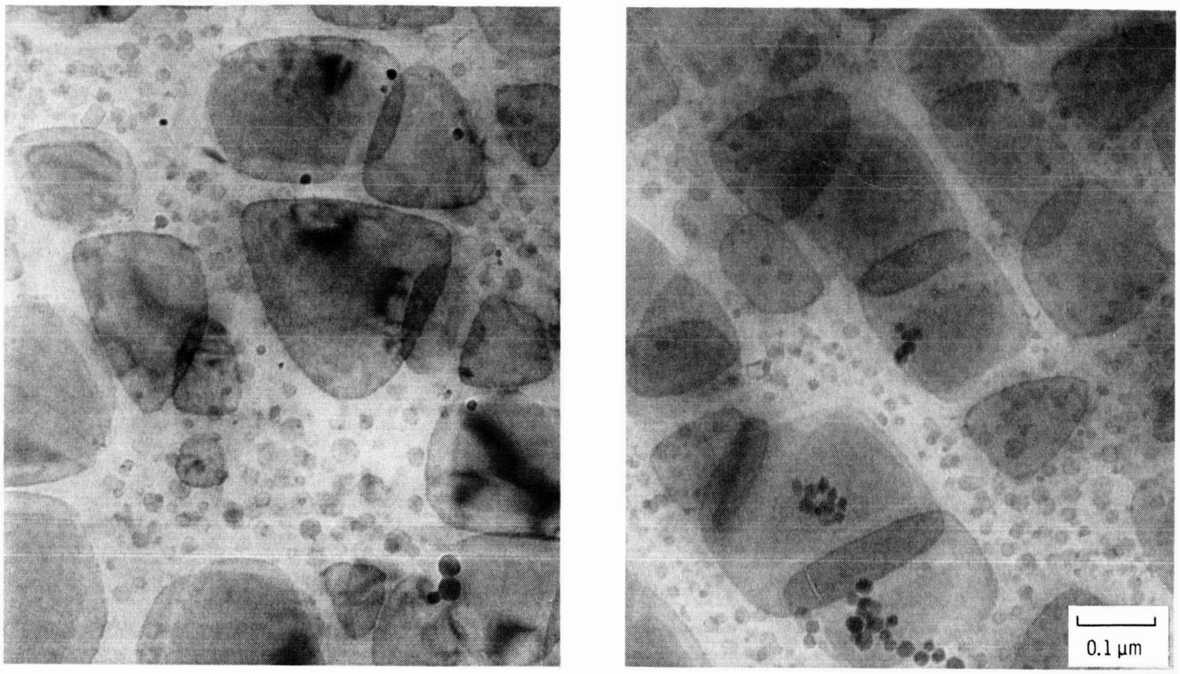


(a) Disk heat treatment.



(b) Blade heat treatment.

Figure 12. - Creep rates at 760 °C as a function of cobalt content.



(a) Standard heat treatment.

(b) Modified heat treatment.

Figure 13. - Transmission electron micrographs comparing ultrafine particles in Udimet 700 type alloys with 0 percent cobalt content.

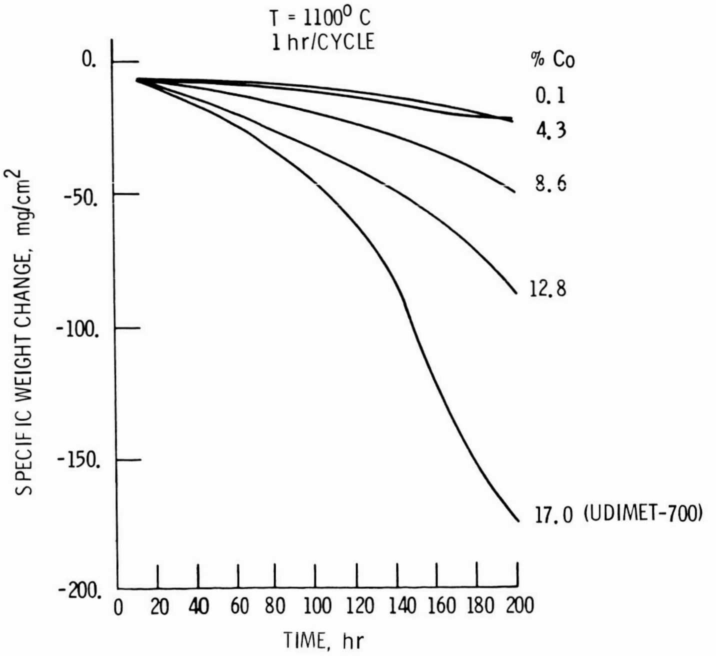
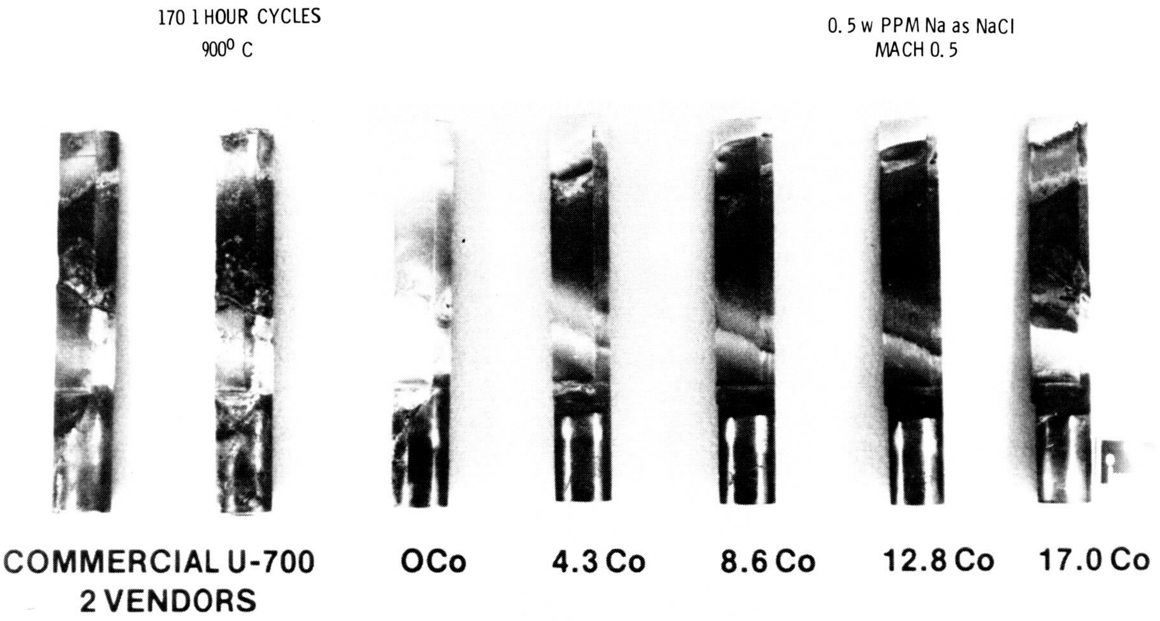


Figure 14. - Effect of cobalt on cyclic oxidation resistance of Udimet-700.



Modified U-700

Figure 15. - Effect of cobalt on hot corrosion.

ITEM	RESULT	
	BLADE	HUB
YIELD STRENGTH	SLIGHT DECREASE	SLIGHT DECREASE
ULTIMATE TENSILE STRENGTH	DECREASE	DECREASE
TENSILE DUCTILITY	DECREASE	SLIGHT DECREASE
STRESS RUPTURE LIFE	DECREASE	DECREASE
OXIDATION RESISTANCE	NO CHANGE	NO CHANGE
THERMAL SHOCK	NO CHANGE	NO CHANGE
FRACTURE MODE - TENSILE	FROM TRANSCOLONY	TO INTERCOLONY
- STRESS RUPTURE	FROM TRANSCOLONY	TO INTERCOLONY

Figure 16. - Effects of removing cobalt from MAR-M 247 blade and hub.

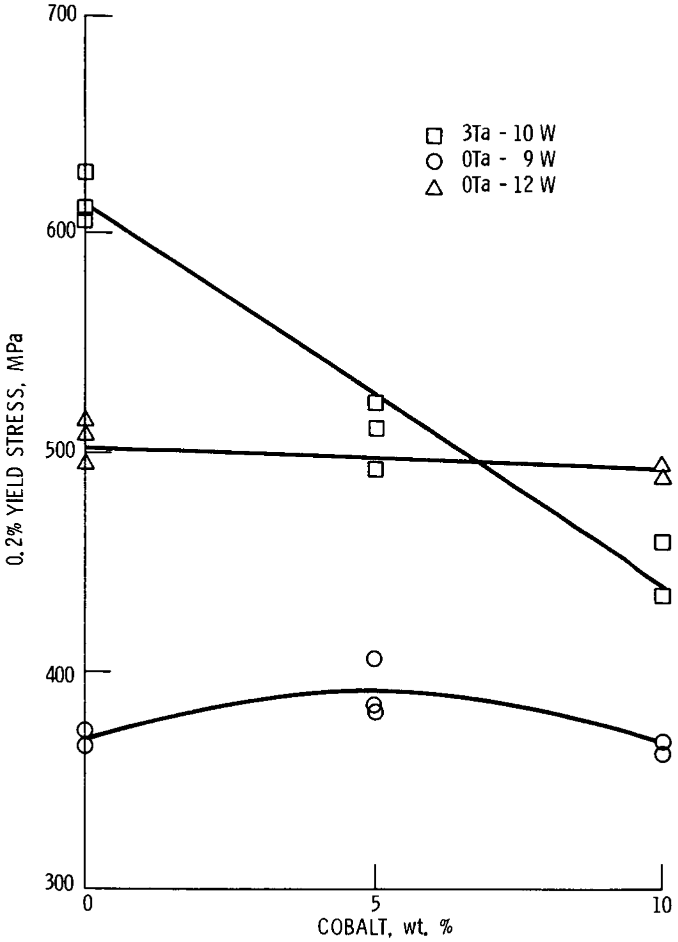


Figure 17. - The 0.2 percent yield stress at 1000 °C for single crystal alloys.

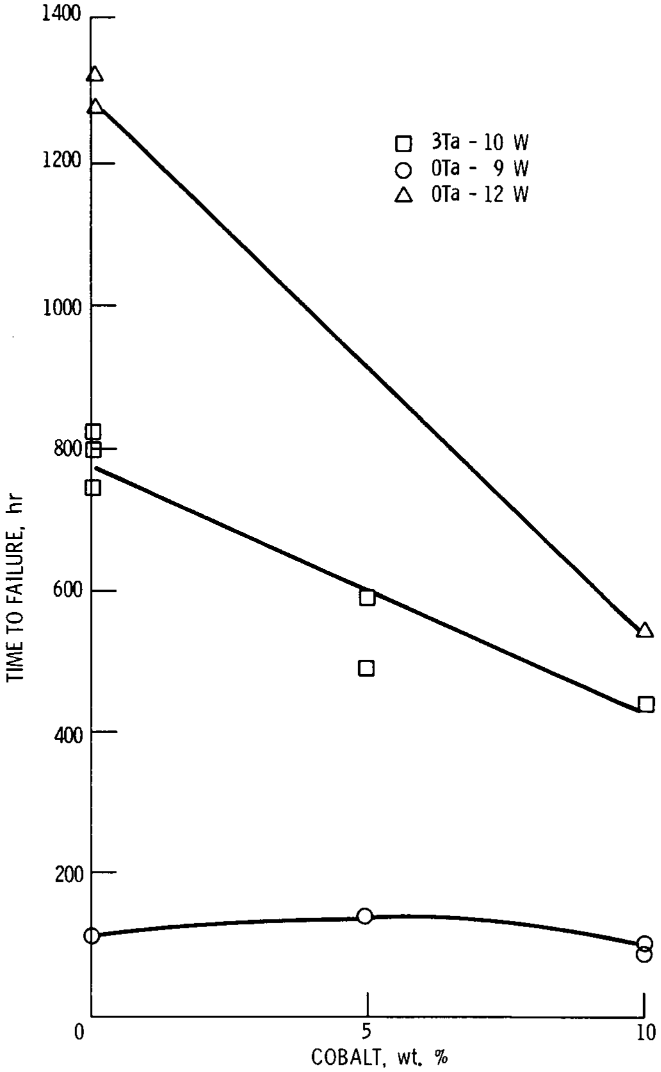


Figure 18. - Rupture lives of single crystal alloys at 1000 °C and 148 MPa.

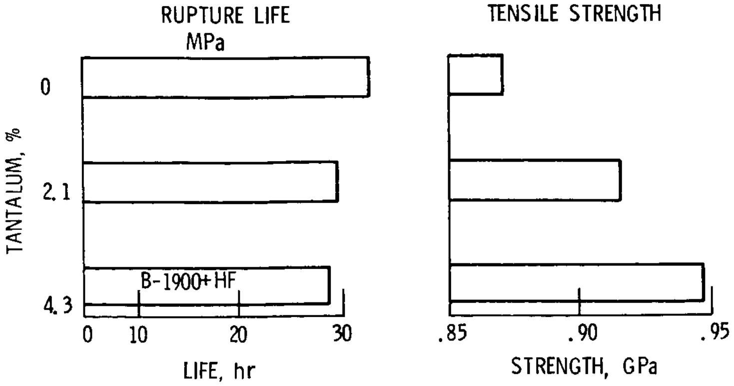


Figure 19. - Effect of tantalum on 760 °C mechanical properties of B-1900+Hf.

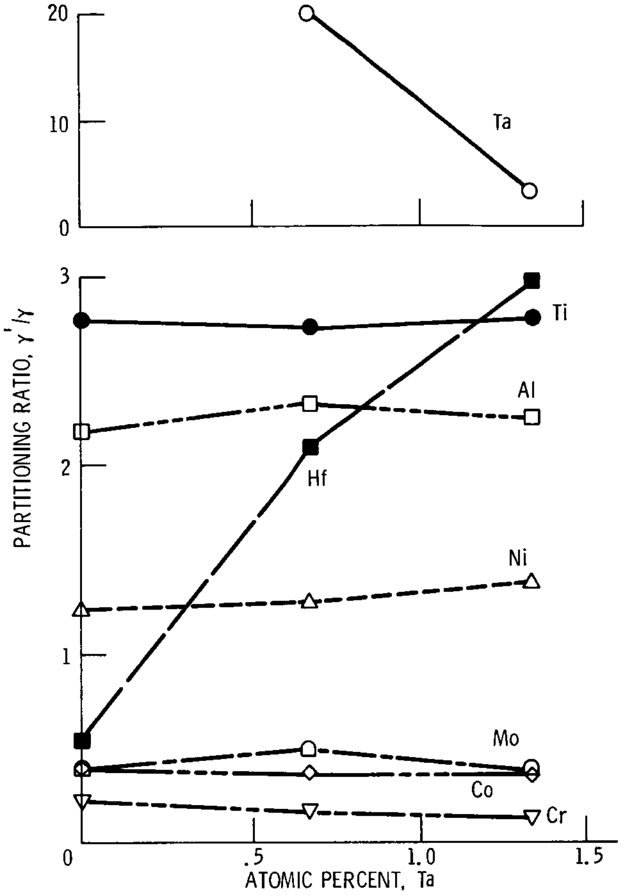


Figure 20. - Gamma prime/gamma phase elemental partitioning ratios for the B-1900 + Hf-type alloys as a function of Ta content.

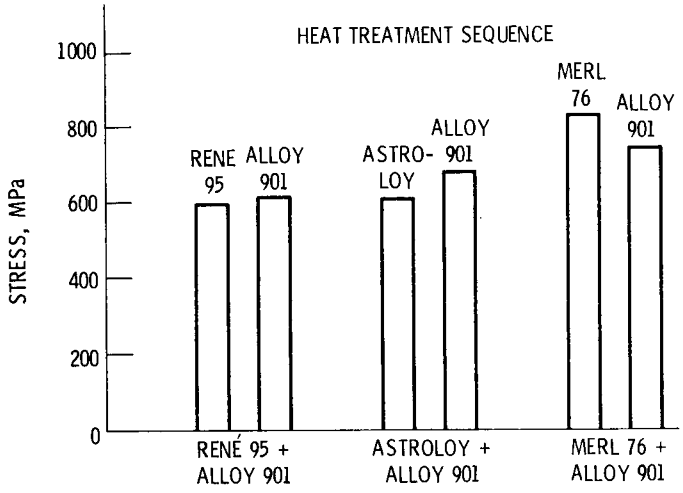


Figure 21. - Stress to rupture superalloy mixtures in 100 hr at 650 °C.

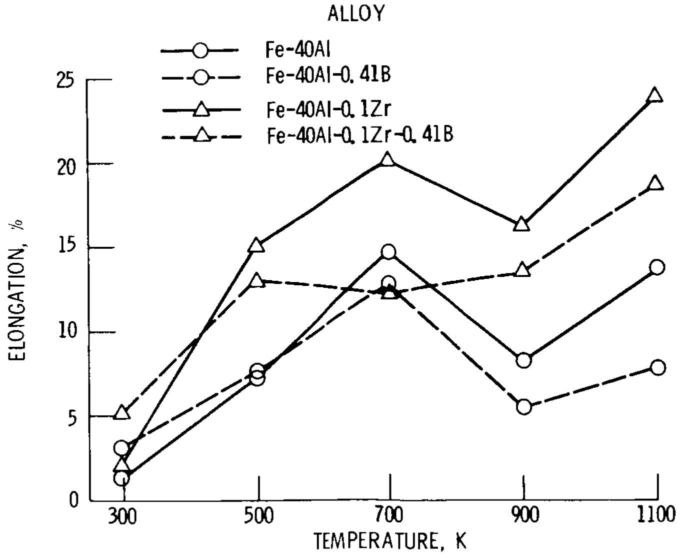


Figure 22. - Ductility of Fe-40Al alloys.

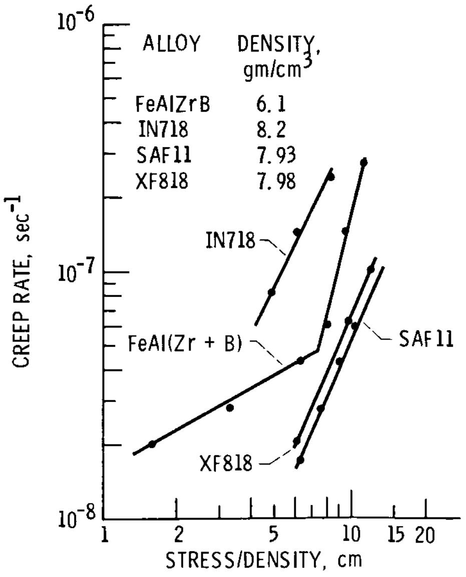


Figure 23. - Creep strength of Fe-40Al-0.1Zr-0.41B alloy compared to commercial iron-nickel base superalloys.

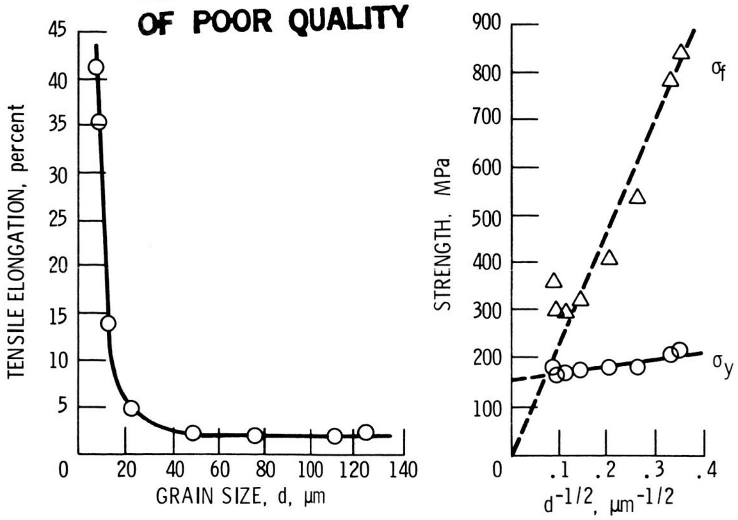


Figure 24. - Effect of grain size, d on tensile elongation, yield strength, σ_y and fracture strength, σ_f of NiAl at 400 °C.

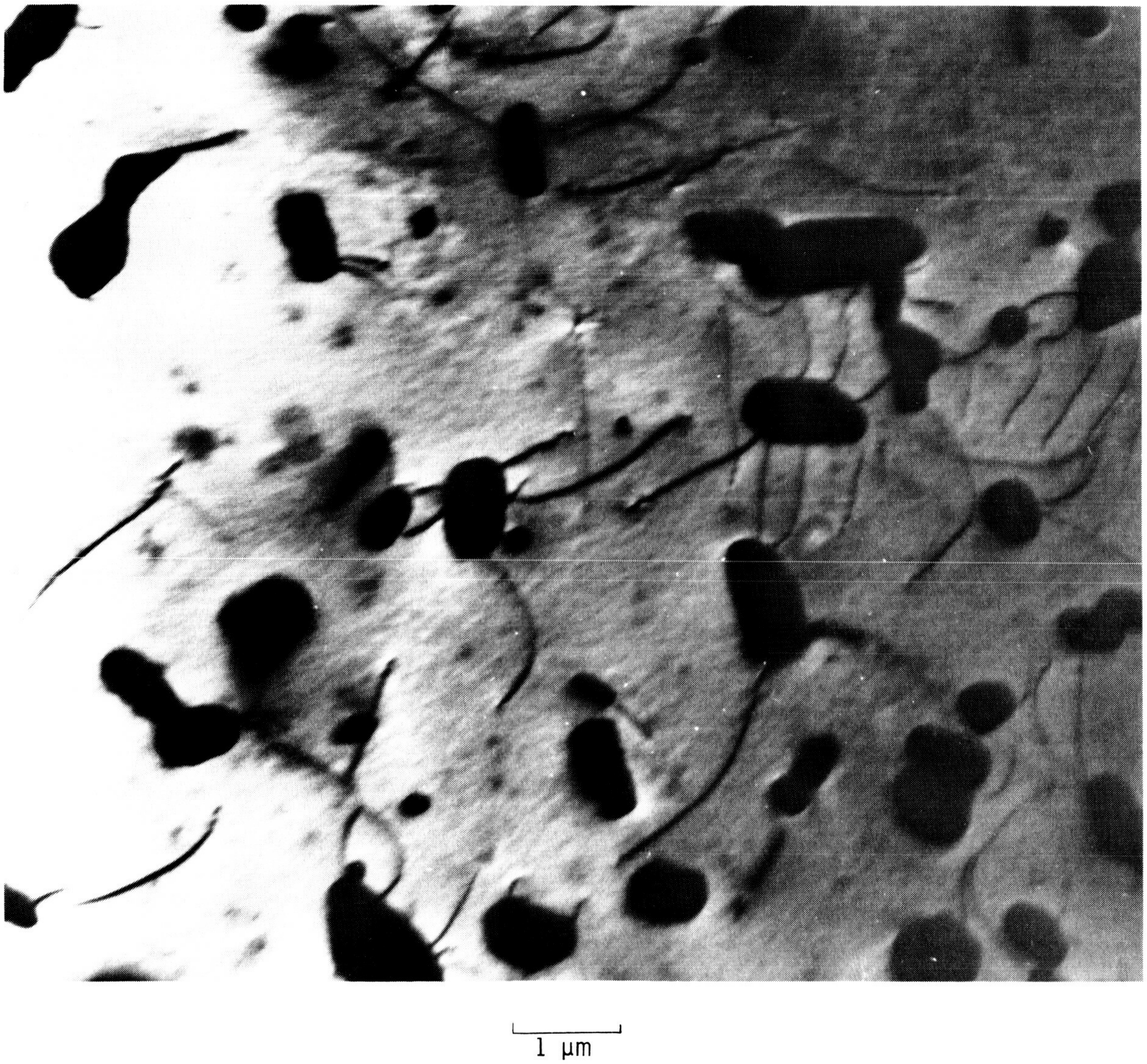


Figure 25. - Transmission electron micrograph of NiAl-2-at% Ta specimen deformed in hot compression at 1300 K to about 7% strain.

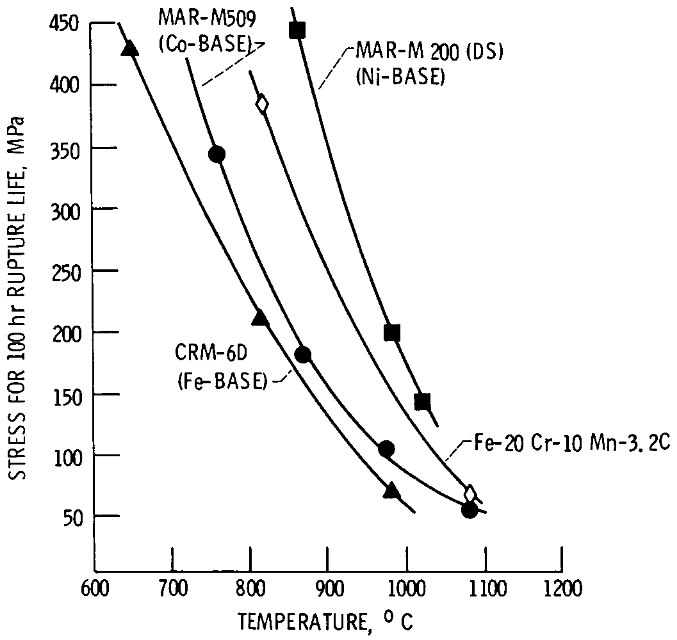


Figure 26. - Stress-rupture potential of Fe-20Cr-10Mn-3.2C alloy.

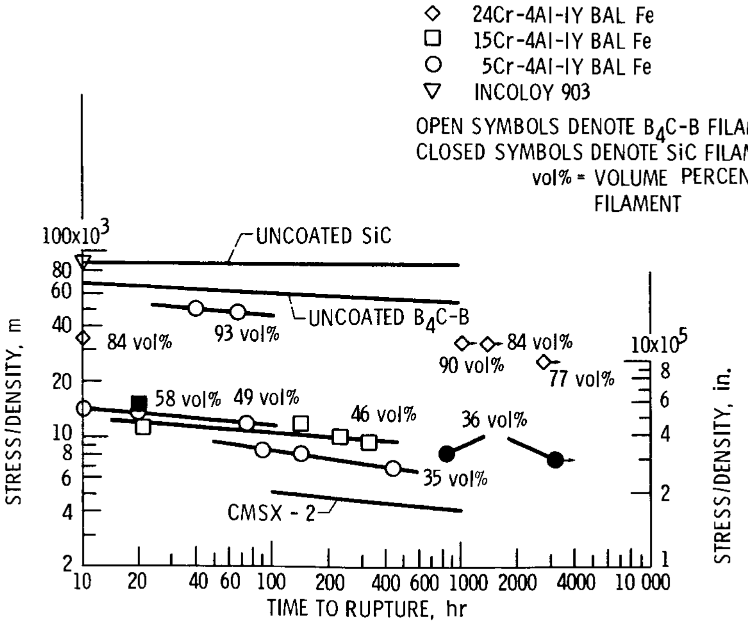


Figure 27. - Stress rupture to density ratio for uncoated and coated filaments compared to CMSX - 2 at 870 °C (1600 °F).

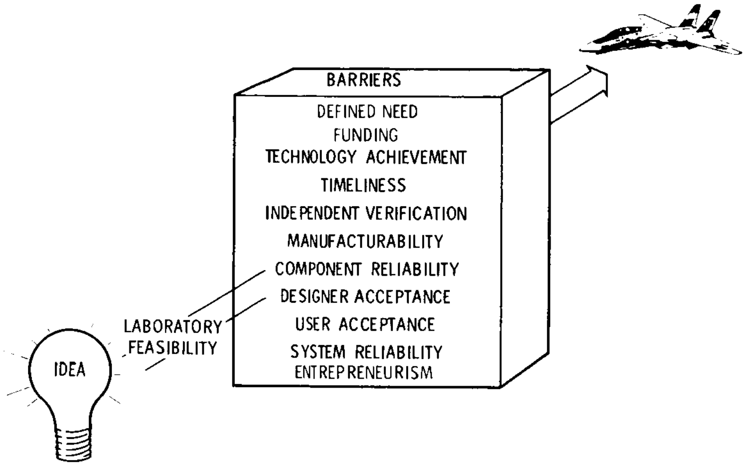


Figure 28. - Technology transfer barriers.

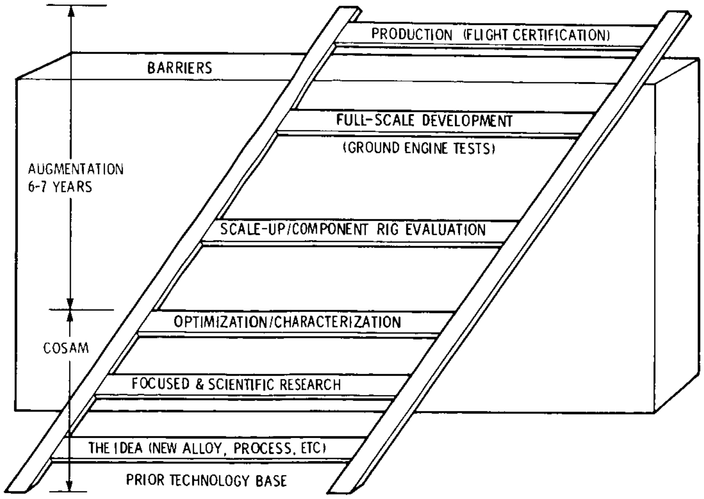


Figure 29. - Technology transfer ladder for strategic material substitution.

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16. Abstract
Superalloys are critical to the economic survival of the United States' aerospace industry. Therefore it is imperative that the raw material resources that are required for superalloy production are readily available to U.S. producers. Over the past several decades there have been shortages of strategic materials because of our near total import dependence on such metals as chromium, cobalt, and tantalum. In the late seventies and early eighties cobalt prices increased tenfold and U.S. producers were put on a supply quota basis because of political and military unrest in Zaire, at that time the major U.S. supplier. In response to the continued vulnerability of U.S. superalloy producers to these disruptions in resource supplies, NASA undertook a program to address alternatives to the superalloys that contain significant quantities of the strategic materials such as chromium, cobalt, niobium, and tantalum. The research program called Conservation Of Strategic Aerospace Materials (COSAM) focused on substitution, processing, and alternate materials to achieve the goals of the program. In addition to NASA Lewis Research Center, universities and industry played an important role in the COSAM Program. This paper defines what is meant by strategic materials in the aerospace community, presents a strategic materials index, and reviews the resource supply and availability picture from the U.S. point of view. In addition, research results from the COSAM Program are highlighted and future directions for the use of low strategic material alloys or alternate materials are discussed.

17. Key Words (Suggested by Author(s))
Strategic materials; Superalloys; Cobalt; Chromium; Tantalum; Niobium; Intermetallics; Resources; Reserves

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