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A Status Review of NASA's COSAM (Conservation Of Strategic Aerospace Materials) Program

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A STATUS REVIEW OF NASA's COSAM (CONSERVATION OF STRATEGIC AEROSPACE MATERIALS) PROGRAM

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ABSTRACT

NASA Lewis Research Center has undertaken a long-range program in support of the aerospace industry aimed at reducing the need for strategic materials used in gas turbine engines. The program is called "COSAM - Conservation Of Strategic Aerospace Materials." This program has three general objectives. These are to: (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 world-wide 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 engine markets. To achieve these objectives, the COSAM Program is developing the basic understanding of the roles of strategic elements in today's nickel-base superalloys and will provide the technology base upon which their

use in future aircraft engine alloys/components can be decreased. Technological thrusts in three major areas are underway to meet these objectives. These thrusts consist of strategic element substitution; advanced processing concepts; and alternate material identification. Based on criticality of need, initial efforts are concentrated on the strategic elements cobalt (97 percent imported), tantalum (91 percent imported), columbium (100 percent imported), and chromium (91 percent imported). This paper highlights the various research programs that have been undertaken within COSAM and the early progress that has been made.

INTRODUCTION

NASA Lewis Research Center (LeRC) has undertaken a long-range program in support of the aerospace industry aimed at reducing the need of strategic materials used in gas turbine engines (ref. 1). The program is called "COSAM - Conservation Of Strategic Aerospace Materials." This program has three general objectives. These are to: (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 world-wide 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 engine markets.

The need for a concentrated effort such as is underway in the COSAM Program is brought about by the fact that the United States is heavily reliant upon foreign sources for the supply of most metals required by today's military and civilian high performance aircraft gas turbine engines. For example, in the aerospace industry, the United States imports over 90 percent of such key metals as aluminum, chromium, cobalt, columbium, manganese, the platinum group metals, tantalum, tin, and titanium (ref. 2).

This reliance on the importation of so many of the strategic metals used in today's military and commerical aircraft engines poses a threat to the national security of the United States. This view has been expressed by many sectors of the materials industry. For example, E. F. Andrews, Vice President of Allegheny International, said "The national security and the economic survival of the United States depend upon the nation's capability to secure an uninterrupted flow of critical minerals from politically unstable third world nations" (ref. 3). Secretary of Interior James Watt was quoted as: "I considered energy to be the extreme problem of the '70s; minerals are going to be the problem of the '80s" (ref. 3).

Currently, the African Third World Nations of Zaire, Zambia, Zimbabwe, and South Africa play a major role in supplying such strategic materials to the United States as shown in figure 1. The potential for foreign cartels, political unrest, and production limitations is real and has lead to severe market availability/cost fluctuations, but could even lead to a total interruption of flow of such strategic metals in times of world crisis. Regions of possible instability (ref. 4) exist, however, in Africa from which some political groups might be able to wage "a long-term resource war against the U.S." (ref. 3).

The metals discussed herein also are vital to the welfare of the nation's economy since the sale of aircraft and engines of all types is a major positive contributor to our balance of payments (ref. 5). Thus, the continued availability of critical elements at a reasonable cost is a national issue which requires cooperative action between industry and appropriate government agencies. The aircraft engine industry, in particular, relies heavily upon imports for the key strategic metals chromium, cobalt, columbium, and tantalum. In order to offset or minimize possible future disruptions in supply, efforts to develop viable options must be pursued aggressively since a new material can take from 5 to 10 years of research and development efforts before qualifying for such aerospace service. Thus, a long term commitment to the creation of a sound technology base upon which to respond to interruptions or price fluctuations is in the best national interest.

The COSAM Program is aimed at helping to meet these needs. NASA plans to accomplish the general objectives of the COSAM program by creating the understanding needed to minimize the use of strategic metals in advanced aerospace systems. This program will be undertaken via three major research thrusts including: strategic element substitution; advanced processing concepts; and alternate material identification. Results from the research and any required supporting technology will help create the materials technology options needed to allow industry to make trade-offs in material properties for critical components versus the cost and availability impacts related to their strategic metal content. This paper is intended to present an overview of the COSAM Program as well as to briefly highlight early progress that has been made.

STRATEGIC METALS

As a working definition of strategic metals, the COSAM Program used the following: "those predominantly 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." As a result of meetings with the ASME Gas Turbine Panel in 1979 and a survey of aerospace companies in 1980, the COSAM Program was focused primarily on the aircraft engine industry's needs. Based on these and further discussions with several aircraft engine manufacturers, four elements emerged that were of particular concern. The alloys used to build the critical high temperature components for aircraft propulsion systems require the use of the four metals - cobalt, tantalum, columbium, and chromium. These metals are contained in superalloys, steels, and stainless steels that are used in engine manufacturing. The location of these metals in aircraft engine compressors, turbines, and combustors is illustrated in figure 2. The need for such metals has increased as the demands have grown for higher durability plus higher performance, fuel efficient aircraft turbine engines. Based on the essential nature of these metals and in order for the U.S. aircraft industry to maintain its competitive position, it is necessary that supplies be readily available at a reasonably stable cost. To achieve these requirements, domestic sources of key metals are desirable. However, the U.S. has never been self-sufficient in these metals. Today, we are almost totally dependent on foreign sources for these metals as shown in figure 3. In several of the countries listed in figure 3, political disturbances have led to supply interruptions. Therefore, the U.S. aircraft engine industry can be seen to be highly vulnerable to supply instabilities of the essential metals for engine manufacturing. Accompanying supply disruptions or increased demand are price changes of several hundred percent as shown in figure 4 (after ref. 6). These rapid price increases illustrate the vulnerability of the U.S. aircraft engine industry to cost fluctuations. The essential nature of chromium, cobalt, columbium, and tantalum along with their vulnerability to supply instabilities, and cost fluctuations combine to cause these metals to be classified as strategic aerospace metals. Their sensitivity to total disruption during a time of worldwide crisis is, of course, readily recognizable.

COSAM PROGRAM OVERVIEW

The three objectives of the COSAM Program enumerated in the Introduction are being accomplished by means of a systematic basic research and technology effort aimed at reducing the need for the use of strategic metals in advanced aerospace components. The COSAM Program is aimed at providing industry with options so that they can make their own property versus availability/cost trade-offs when selecting aerospace alloys. Initial emphasis was placed on the aircraft engine industry with initial focus on conservation of cobalt, columbium, tantalum, and chromium. Strategic metals such as titanium, the precious metals, and others could be brought into the COSAM Program, if required, and their minimization could also be pursued using the methodology currently being evolved.

The three-pronged approach to COSAM is shown in figure 5. It consists of research on strategic element substitution, advanced processing concepts, and alternate materials. Conservation, as well as reduced dependence on strategic metals, will be achieved 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 will help guide future material specifications if one or more of these metals becomes in short supply, and will create a powerful base of understanding that will benefit all future advanced alloy development. Conservation through advanced processing concepts research will 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, Cb, and Cr.

Current plans for the major areas of the COSAM Program are shown in figure 6. Activities underway or planned in each of the three thrusts of the program are shown extending over a five year effort. Efforts in the strategic element substitution thrust will concentrate on basic research into the roles of the strategic elements Co, Ta, and Cb in nickel base superalloys. Here research will work at identifying effective substitutes that will still allow the retention of the critical properties found in the high strategic metal content alloys. Advanced processing concepts research will focus on the potential of minimizing strategic metal usage by exploring dual alloy and multiple alloy concepts which emphasize the selected use of high strategic element content materials only in the portions of components where no other choice is possible. Alternate materials research involves a longer-range, higher-risk effort with the goal of totally replacing strategic element-rich materials in future aerospace applications.

The various efforts are being conducted under the overall programmatic management of NASA LeRC. Some of this work is being conducted in-house at LeRC. In addition, cooperative programs involving LeRC working together with both industry and universities in tripartied projects are underway 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 figure 7. Typical roles for each organization are shown. These roles will, of course, vary 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 LERC with a range of support from industry or a university. The subsequent section will outline some of the current projects and present the highlights of results obtained to date.

THE CURRENT STATUS OF COSAM RESEARCH ACTIVITIES

The initial emphasis of the COSAM Program has been in the major thrust area of strategic element substitution, with early attention on cobalt. Activities are also underway on projects seeking substitutes for tantalum and columbium in nickel-base superalloys. In addition, efforts have been initiated in the second major thrust area -- advanced processing concepts -- and in the third thrust area -- alternate materials. A brief summary of these current COSAM efforts is presented in subsequent paragraphs.

Strategic Element Substitution

Cobalt - As a reaction to the high cost of cobalt in 1978 and 1979, the United States has recently experienced a decline in cobalt usage (ref. 7). Figure 8 shows that 20 million pounds of cobalt were consumed in 1978 and that by 1981, usage was down to an estimated 13.6 million pounds, a reduction of about 1/3 in only 3 years. During this same time period, the use of cobalt to produce superalloys, primarily nickel-based alloys for aircraft engines, increased from 4 million pounds in 1978 to a peak of 7.2 million pounds in 1980, and then declined to an estimated 5.4 million pounds in 1981. The importance of cobalt to superalloy production is illustrated in figure 9. It should be noted that 40 percent of the 13.6 million pounds of cobalt consumed by the United States in 1981 went for superalloy production.

Because of the importance of cobalt to the aircraft engine industry and its high cost and lack of availability in 1979 and 1980, several programs were initiated to identify substitutes for cobalt in a variety of nickel-base superalloys. It was felt that due to the criticality of cobalt for aerospace use, the development of a clear understanding of the role of cobalt in superalloys and potential substitutes for it would have long term national benefits. In addition, it was felt that the methodology developed in this study would serve as a model for future efforts aimed at other strategic elements.

Four nickel-base superalloys were selected for the COSAM investigation on cobalt (ref. 8). The four alloys are listed in figure 10 along with their typical applications in the aircraft engine industry, the forms in which the alloys are used, and remarks as to why they were selected for the COSAM activity. Applications include turbine disks as well as low pressure and high pressure turbine blades. A variety of product forms are represented by the applications of the four alloys as noted in figure 10. The selection of the four alloys was based primarily upon the considerations given in this figure. Waspaloy* was selected because it represented the highest tonnage of cobalt in commercial aircraft engines. Selection of Udimet-700* was based on the fact that this alloy has a composition similar to many of the cobalt-containing nickel-base superalloys and is used in the as-cast, as-wrought ingot, as-wrought powder, and as-HIP powder metallurgy fabricated conditions. Thus composition vs. processing study opportunities were great. The potential for determining the impact of cobalt on both conventionally-cast as well as on D.S. polycrystalline, and single crystal turbine blades was the reason for selecting Mar-M 247*. Rene' 150* was chosen because it is an advanced directionally solidified alloy.

Figure 11 shows the participants in the COSAM activities on cobalt substitution. These initial research efforts were planned for a three-year period and consist of cooperative research programs involving universities, industry, and in-house NASA LeRC programs. Nominal compositions of the four alloys given in figure 11 indicate that cobalt content ranges from 10 percent in Mar-M 247 to 19 percent in Udimet-700. In addition, the γ' strengthening phase ranges from 20 percent in Waspaloy to 65 percent in Rene' 150. The first step in each research effort involved substituting the less strategic element, nickel, for cobalt in incremental steps to a zero cobalt content.

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*Trademarks
Waspaloy : United Technologies Corporation
Udimet : Special Metals Corporation
Mar-M : Martin Marietta Corporation
Rene' : General Electric Corporation

The effects of this substitution on properties and phases present, such as γ', made up the major portion of the research effort in the first year of each program element. Subsequent efforts are directed at identifying and optimizing alloying elements as substitutes for cobalt in the alloys so as to maintain their key properties.

The cooperative nature of the research being conducted on Waspaloy and Udimet-700 is illustrated in figure 12. The role of industry as represented by Special Metals Corporation is to characterize and optimize fabrication and heat treating procedures for the reduced cobalt Waspaloy and Udimet-700 alloys. Columbia University's role in this effort and that of Purdue University are also shown in figure 12. Columbia University is conducting mechanical property characterization, structural stability, microstructural feature evaluation, and theoretical formulations to identify future alloy modifications, if required, for the second portion of the project. Purdue University is primarily responsible for microstructural and microchemistry characterization of the reduced cobalt content alloys. To round out the program, NASA Lewis Research Center is involved in special mechanical and physical metallurgy characterization of the alloys as shown in figure 12. The output of this cooperative effort is expected to be a clearer understanding of the role of cobalt in nickel-base superalloys.

Some preliminary results on the effects of reducing cobalt in Waspaloy (a 13 percent cobalt alloy) were reported by Maurer, et. al. (ref. 9) of Special Metals Corporation. Highlights of that study are shown in figure 13. 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 of this study is presented in figure 14. 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 (ref. 10) is examining the effect of cobalt on the oxidation resistance of Waspaloy. Initial results, shown in figure 15, indicate that based on specific weight change data to $1100^{\circ}C$, 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 (ref. 11). This investigation focused on the microstructure of the alloys and on metallographic studies of extracted γ' and carbide precipitates. A summary of the findings of this study is presented in figure 16. 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 (ref. 9); 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 are also under investigation as part of the cooperative program involving Special Metals Corporation, Columbia and Purdue Universities, and NASA Lewis Research Center. Fabricability has been investigated by Jackman and Maurer, Special Metals Corp., (ref. 12) and mechanical properties and metallurgical properties by Jarrett and Tien, Columbia University, (ref. 13). The results of these two studies are summarized in figure 17. Fabricability, based on Gleeble and high strain rate tensile tests corresponding to rolling temperatures in the 1000^{o}-1100^{o}C range show no cobalt effect on the high temperature ductilities (ref. 12). Of particular interest is the work of Jarrett and Tien on the effect of the disk (partial γ' solutioning) and blade (complete γ' solutioning) heat treatments on stress rupture and creep properties a summarized in figure 17 (ref. 13). Rupture life as a function of cobalt content is shown in figure 18 for the two heat treated Udimet-700 conditions. The disk heat treatment resulted in a reduction in rupture life below 9 percent 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. Engel (ref. 14) has examined the microchemistry of the low/no cobalt Udimet-700 alloy specimens. His results are summarized in figure 19. The increase in γ-γ' mismatch with decreasing cobalt content is significant as shown in figure 20.

Barrett of NASA Lewis (ref. 10) has also investigated the cyclic oxidation resistance of the low/no cobalt Udimet-700 alloys. Initial results of this study are shown in figure 21. At 1100^{o}C, removing cobalt from Udimet-700 improved the cyclic oxidation resistance based on specific weight change data, but confirmatory metallographic analyses of the depths of attack have yet to be conducted. Tests at 1000°C and 1150°C revealed a similar behavior. Hot corrosion resistance of the low/no cobalt Udimet-700 alloys are also under investigation at NASA LeRC. Initial qualitative results by Deadmore and Lowell (ref. 15) 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 figure 22 where the improved corrosion resistance for the lower cobalt concentrations is evident.

Harf of NASA LeRC (ref. 16) is conducting a parallel program on hot isostatic pressed (HIP) powder metallurgy (PM) Udimet-700. Results to date tend to confirm the observations discussed previously on the wrought material. No major differences in properties have been attributed to processing history of the alloys. In addition to these studies, tests are underway to investigate the low cycle fatigue (Halford, NASA LeRC (ref. 17)) and thermal fatigue (Bizon, NASA LeRC (ref. 18)) behavior of the low/no cobalt Udimet-700 alloys.

Effects of removing cobalt from Mar-M 247 have been investigated as part of a cooperative program (figure 23) involving TRW, Teledyne CAE, Case Western Reserve University, and NASA LeRC. This was a no fund transfer contract program with Teledyne CAE which arose strictly from the mutual interest of the participants. NASA's role was in coordinating the industrial effort and in supporting the NASA funded grant research at Case Western Reserve University.

The industrial application was related to an integral cast rotor, therefore, casting mold and pouring temperatures were selected to simulate blade and hub conditions. Major findings by McLaughlin, Teledyne (ref. 19) and Kortovich, TRW (ref. 20) are summarized in figure 24. A parallel in-depth study on cobalt effects on Mar-M 247 mechanical properties was undertaken by Nathal (ref. 21), a graduate student at Case Western Reserve University, whose research was conducted at NASA Lewis Research Center. This study explored in more depth the mechanisms associated with the effects of cobalt on mechanical properties. The results of Nathal's studies are summarized in figure 25. Typical creep rupture properties are shown in figure 26 for alloys tested at 871 ^{o}C. Nathal postulated that reduction in γ' weight fraction and carbide formation as a grain boundary film were responsible for the deliterious effects on creep-rupture properties. It was proposed that reducing the carbon level in the 5 percent cobalt alloy may result in an alloy with properties comparable to Mar M-247, but with the conservation of 50 percent of the cobalt normally used in this alloy. More recently, Nathal (ref. 22) has shown that, based on weight change data, removing cobalt from Mar-M 247 improves the cyclic oxidation resistance of this alloy at 1100 ^{o}C (figure 27). Similar to Udimet-700 test results, hot corrosion testing of alloys based on Mar-M 247 chemistry (ref. 15) revealed that reducing cobalt also improved corrosion resistance. Post-test photographs of the specimens at the three cobalt levels shown in figure 28 support this finding.

Nathal has further shown (ref. 22) 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 material. The single crystal findings by Nathal supported previous results reported by Strangman, et al (ref. 23) where 0 percent cobalt levels in single crystal alloys had longer rupture lives than the 10 percent cobalt Mar-M 247 single crystals. However, a 5 percent cobalt level was required for alloy stability with respect to formation of the μ phase.

A program underway at NASA LeRC by Scheuermann (ref. 24) is examining the role of cobalt in single crystal alloys based on R'150 chemistry. Cobalt levels of 12, 6, and 0 percent will be investigated primarily by creep-rupture and tensile testing. Initial DTA results (unpublished results of Scheuermann) indicate the solvus temperature is about 1250 $^{\circ}$C and independent of cobalt content.

Based on all the COSAM studies to date on the role of cobalt in nickel-base superalloys, several major effects have emerged which are summarized in figure 29. The metallurgical factors contributing to the mechanical property changes are also listed in figure 29. For the low/no cobalt alloys, the disk heat treatment of U-700 resulted in a reduction in rupture life with a concomitant reduction in the fine, strengthening γ' volume fraction. In contrast, the blade heat treatment produced an increase in rupture life and no change in volume fraction of γ'. These results suggest that, as might be expected, γ' volume fraction may be the controlling strengthening mechanism in this alloy. In single crystal Mar-M 247 alloys, stress rupture properties appear to improve with decreasing cobalt content. These alloys are free of carbides. In contrast, polycrystalline Mar-M 247 alloys with carbide strengtheners exhibited a decrease in rupture life with cobalt removal and a change from discrete carbide particles to a grain boundary carbide film. These results suggest that carbide strengthening may be a controlling mechanism in Mar-M 247.

In addition to the results reported herein, other investigators outside of the COSAM program have also recently examined the role of cobalt in nickel base superalloys; e.g., Law, et al, in MERL 76 and AF115 (ref 25) and Tawancy in C-263 (ref. 26). Both investigations obtained results similar to those summarized in figure 29.

Columbium - Columbium is considered to be a strategic aerospace metal because the United States imports 100 percent of it and because of the increasing importance of this metal as an alloying element in nickel-base superalloys. The price of columbium has held near $30 per pound during the last few years. The aerospace industry's response to the cobalt shortage in 1978-79 was, in some instances, to switch to columbium containing alloys as substitutes for cobalt bearing alloys; e.g., INCONEL 718* (5 percent Cb-0 percent Co) for Waspaloy (0 percent Cb-13 percent Co). The importance of columbium to the aerospace industry is illustrated in figure 30 where superalloys are again noted to be the largest single user of columbium. High-strength low-alloy steels and carbon steels are also major consumers of this strategic metal. If columbium containing superconductors begin to penetrate the electric power generation/transmission market, even further economic pressure will be placed on supplies of this element.

Within the aerospace industry, INCONEL 718 is probably the largest consumer of columbium. INCONEL 718 is used as a turbine disk material -- disks are large, heavy components that thus contain the bulk of the columbium

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*INCONEL, Trademark of International Nickel Company used. The increased demand for columbium in the aerospace industry has focused attention on identifying potential substitutes for it in nickel-base superalloys. A program has recently been initiated to identify potential substitutes for columbium in INCONEL 718. This program is primarily a university grant with Case Western Reserve University. Special Metals Corporation has prepared the modified composition alloys and NASA LeRC is involved in evaluation of alloy properties. The program organization is illustrated in figure 31. Composition modifications based on INCONEL 718 alloy chemistry are being investigated in the first portion of the program. These are listed in figure 32. Since this program is just getting underway, there are no data to report at this point in time.

Tantalum - The cost of tantalum as indicated in figure 4 increased dramatically in recent years. However, the price has recently dropped from a peak near $130 per pound to about $40 per pound in today's market. Tantalum is being used in advanced nickel-base superalloys primarily to improve oxidation resistance and increase strength. The increased use of tantalum in the aerospace industry and the fact that the U.S. imports over 97 percent of it makes this element strategic and also of concern for the long term. The use of tantalum within United States industries is distributed as shown in figure 33. Its major usage is for capacitors -- another high national priority application, while the total use of tantalum in superalloys constitutes only about 6 percent of total U.S. consumption. However, tantalum is critical to advanced nickel base superalloys. A joint Michigan Technological University/ GE-Corporate Research Dept./NASA LeRC program is just beginning to determine the role of tantalum in nickel-base superalloys. The program organization is shown in figure 34. Primary initial emphasis is on exploring the effects of reducing tantalum in conventionally cast, D.S. polycrystalline, and single crystal Mar-M 247, an alloy that contains 4 percent tantalum. In addition, some limited studies will be conducted on B-1900+Hf, an alloy which contains 4.3 percent tantalum. Material for this part of the program is being supplied by TRW, who has conducted some independent studies of the role of tantalum on mechanical properties and microstructure of B-1900+Hf (ref. 27). Their results indicated that tensile strength decreased with decreasing tantalum content upon testing at room temperature and at 760^{o}C. Stress rupture testing at 760^{o}C/650MPa indicated that the rupture life increased with decreasing tantalum content while at 980^{o}C/200MPa rupture exhibited a maximum at a 50 percent reduction in the normal tantalum content. TRW stress-rupture results and tensile results at 760^{o}C are shown in figure 35.

Coatings for COSAM Alloys - Since many of the high temperature gas turbine engine airfoil alloys are used with protective coatings, reducing one or more of the strategic metals of an alloy could be expected to effect coating performance and durability. An in-house program at NASA LeRC by Zaplatynsky and Levine (ref. 28) is investigating the effects of alloy composition on coating life. The program has a twofold approach. The first approach involves investigating the low/no cobalt or tantalum alloys within the current COSAM Program. The second approach involves investigating a separate series of alloys (by means of a statistically designed experiment) to establish any synergistic effects of varying the amounts of chromium, cobalt, and tantalum, as well as aluminum in nickel base alloys on coating life. Coatings to be examined are plasma sprayed NiCoCrAlY and aluminide coatings. Evaluation will include cyclic oxidation and hot corrosion in a Mach 0.3 burner rig.

Advanced Processing

Turbine disks constitute a major portion of the weight of superalloys (and thus strategic materials) used in gas turbine engines. These components typically operate at higher temperatures in the rim and at lower temperatures in the hub area. In addition, creep is the primary deformation mechanism in the rim while fatigue resistance is required in the hub. Monolithic disks currently used are fabricated and heat treated to compromise the creep resistance that can be achieved with a large grain size material and fatigue resistance of fine grain size material. An alternate approach would be to fabricate dual property disks (different heat treatments at the bore and rim) or dual alloy disks to optimize the required properties at the rim and hub. The concept of joining two P.M. nickel-base superalloys to achieve this goal was investigated by Kortovich (ref. 29) in a NASA LeRC sponsored program. The COSAM Program will carry this technique further by studying the feasibility of HIP joining a nickel-base alloy rim material and an iron-base alloy (low strategic metal content) hub material (Harf, NASA LeRC (ref. 16)). The dual alloy joining concept is shown schematically in figure 36 along with the planned extension of this process to conserve strategic materials. Emphasis will be placed on HIP joint integrity, microstructural stability, and mechanical properties as compared to the base alloys. INCOLOY 901 was initially selected for the hub alloy. This alloy contains 13 percent chromium and no cobalt, columbium, nor tantalum. Rim alloys initially selected are Rene'95 and Low Carbon Astroloy.

A second approach to conserving strategic materials by advanced processing is the concept of multiple alloy components. An example of such a concept is illustrated in figure 37. Again the idea is to use alloys that contain high strategic element concentrations only in those areas of a component where they are essential -- such as for only the leading and trailing edges of an airfoil. A NASA Lewis Request For Proposals has been issued in this area in order to contractually investigate the benefits and problems associated with applying this concept to a variety of advanced gas turbine components, as well as to examine the fundamentals of advanced joining/processing techniques.

Both the in-house and proposed contract programs are aimed at investigating the fundamentals of joining technologies of dissimilar alloy compositions for advanced aircraft engine components. Evaluation will focus on joint integrity, stability, and microstructure.

Alternate Materials

The third major COSAM Program thrust, Alternate Materials, has the potential of eliminating most or all of the cobalt, tantalum, and columbium containing alloys and of also replacing some of the strategic element chromium that is now used in gas turbine engines. Chromium is critical to currently used superalloys because of the oxidation/corrosion resistance it provides, although its use in superalloys is small compared to total U.S. consumption as shown in figure 38.

Intermetallic Compounds - This aspect of the COSAM Program is focusing on the equiatomic iron and nickel aluminides (i.e., NiAl and FeAl) 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 emphasizes 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 pay-off if materials evolve which permit conserving all four currently identified strategic metals -- Co, Ta, Cb, and Cr. 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.

Figure 39 illustrates the organizational structure of the current intermetallic compound program. The in-house program is focused on understanding the slow plastic deformation behavior of extruded powder metallurgy, polycrystalline aluminides in terms of existing deformation models and structural parameters. Some initial results by Whittenberger (ref. 30) of compressive creep testing of the three aluminides are shown in figure 40 along with data for two commercial superalloys for comparative purposes. In addition to creep testing, thermal expansion and lattice parameter measurements are also being evaluated. Transmission electron microscopy evaluation of dislocation interactions in deformed specimens is being conducted in-house on the iron-aluminides. In support of these high temperature deformation studies, a grant at Stanford University will explore similar dislocation interactions in the nickel and cobalt aluminides.

A COSAM investigation is being conducted at Dartmouth College by Schulson on the low temperature deformation mechanisms of nickel aluminide. Emphasis centers on grain size effects and microalloying to improve low temperature ductility. The effect of decreasing grain size on tensile elongation at 295^{o}C is shown in figure 41 (ref. 31). Results indicate that below a grain size of about 10μm diameter, tensile ductility at this temperature can be achieved in nickel aluminide. Various microalloyed materials have been prepared and they are being tested.

Iron-Base Alloys - With the successful development of high strength nickel-base superalloys (and to some extent cobalt-base superalloys) over the last thirty 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 has just been 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 is a joint program involving the University of Connecticut, United Technologies Research Center (UTRC), and NASA LeRC. Roles of the participants are illustrated in figure 42. The potential of these iron-chromium-manganese aluminum type alloys is illustrated in figure 43 where rupture lives determined by Lemkey (ref. 32) are compared with other iron, nickel, and cobalt base alloys.

Composites - A third area of alternate materials technology is underway as an in-house program which is aimed at determining the potential of silicon carbide reinforced low strategic element content iron-base matrix composites.

This program, by Petrasek and Signorelli of NASA LeRC (ref. 33), focuses 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 Alternate Materials thrust will focus on basic research aimed at understanding fundamental materials properties. This long-range, high-risk program will extend over the currently planned five year effort of the COSAM Program. It is anticipated that this thrust will generate basic information on mechanical, physical, and environmental properties of the alternate materials: intermetallic compounds, advanced iron base alloys, and composites.

In addition to this work within COSAM, two somewhat allied programs (refs. 34 and 35) have been underway for sometime that are being managed by NASA LeRC under Department of Energy (DOE) sponsorship. These programs are aimed at developing low cost cast iron-base alloys as substitutes for the much higher cost cobalt-base alloy HS-31 currently used for high temperature cylinders and heat exchanger housings in prototype automotive Stirling engines. These contract efforts are also managed by members of the COSAM team. Here the basic goal is one of conserving strategic metals along with cost reduction. In addition, some of the material property requirements are similar.

CONCLUDING REMARKS

This paper has presented the basis for initiating the NASA's COSAM Program and has summarized some of the early major results of the program. The primary points made about this program are summarized below:

1. The long-term threat of a strategic materials supply disruption, significant cost increase or total cut-off because of geopolitical actions in southern Africa as well as other world areas makes it imperative that the United States have a strong technological back-up position well in hand.
2. The COSAM Program is aimed at providing the aerospace industry with the necessary understanding upon which to select alternative materials and processing concepts in the event of future strategic material shortages or excessive price increases.
3. The COSAM Program is constructed so as to develop expanded cooperative research efforts with industry, universities, and NASA Lewis Research Center in order to exploit the expertise of each in pursuing these aims.
4. Cooperative research efforts are currently underway in each of the three major thrust areas of strategic element substitution, advanced processing concepts, and alternate materials. The strategic element substitution thrust, in particular the efforts on cobalt, has been underway the longest and will soon be focused on identifying substitutes other than nickel for cobalt in nickel-base superalloys.

This paper is intended as an "executive status report" on the various programs. More detailed information will be disseminated in a timely manner as individual projects are completed.

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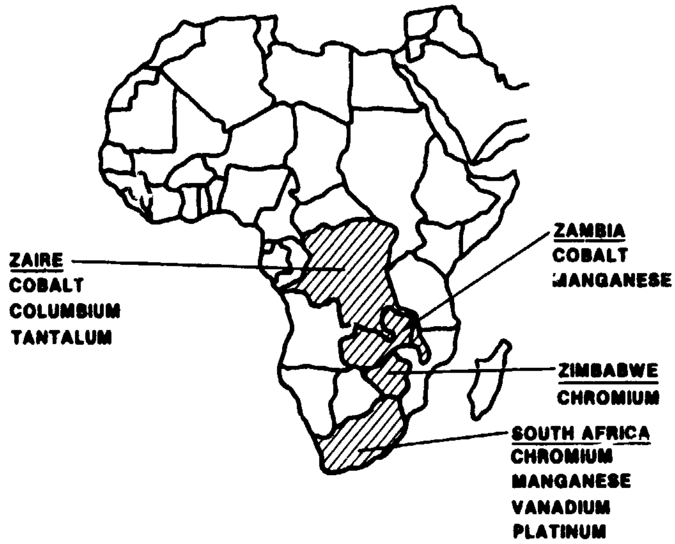
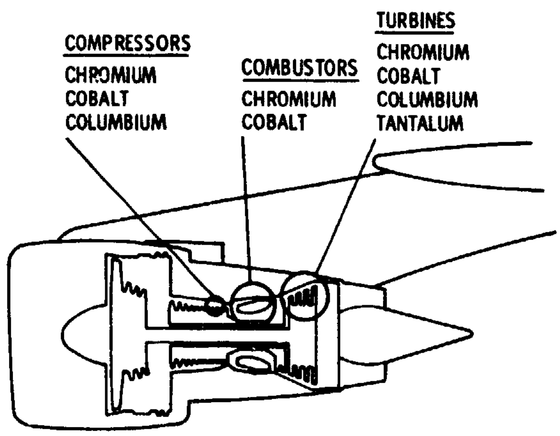


Figure 1. - Strategic material resources in Africa.



NEEDED FOR PERFORMANCE AND LONG LIFE

COBALT - HIGH TEMPERATURE STRENGTHENER
COLUMBIUM - INTERMEDIATE TEMPERATURE STRENGTHENER
TANTALUM - OXIDATION RESISTANCE
CHROMIUM - CORROSION RESISTANCE

Figure 2. - Gas turbine engines depend on strategic metals.

METAL	% IMPORTED	MAJOR FOREIGN SOURCES
COBALT	97	ZAIRE, ZAMBIA
COLUMBIUM	100	BRAZIL, CANADA
TANTALUM	97	THAILAND, MALAYSIA
CHROMIUM	91	SOUTH AFRICA, ZIMBABWE

Figure 3. - U. S. aerospace is vulnerable to supply instabilities.

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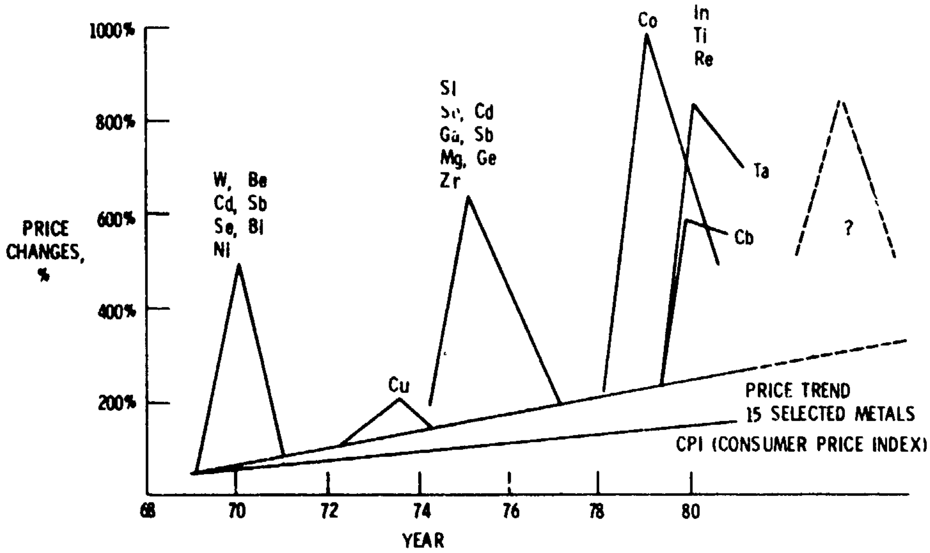

Figure 4. - Strategic material prices are volatile and unpredictable.

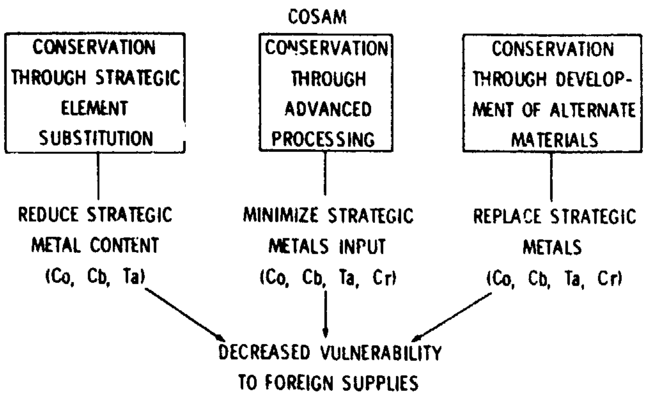

Figure 5. - Conservation of strategic aerospace materials.

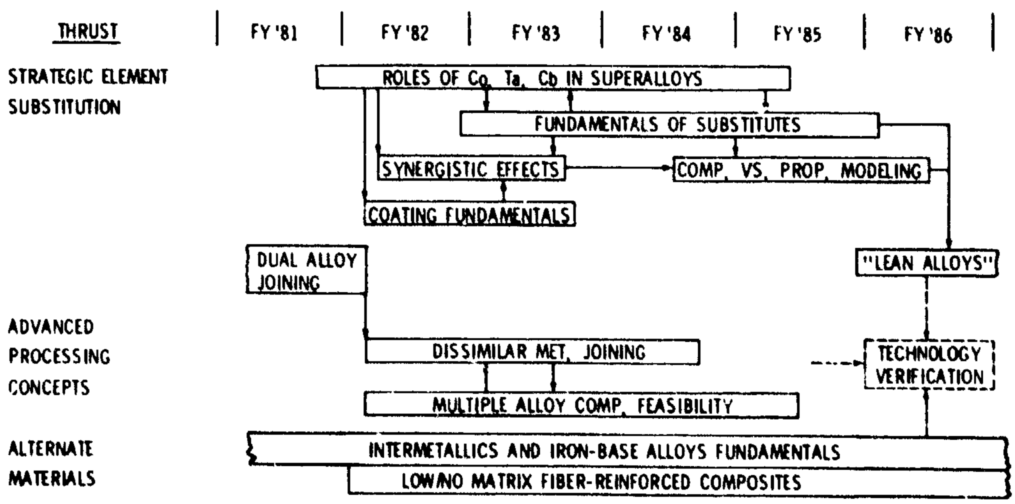

Figure 6. - Strategic materials program plan

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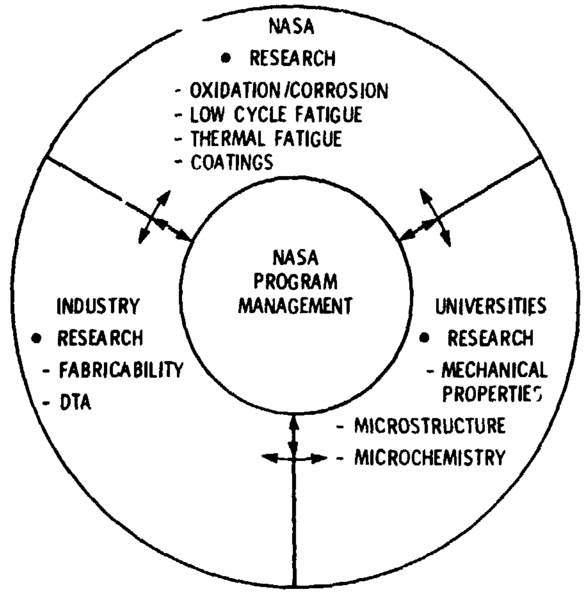

Figure 7. - Cooperative NASA-industry-university programs.

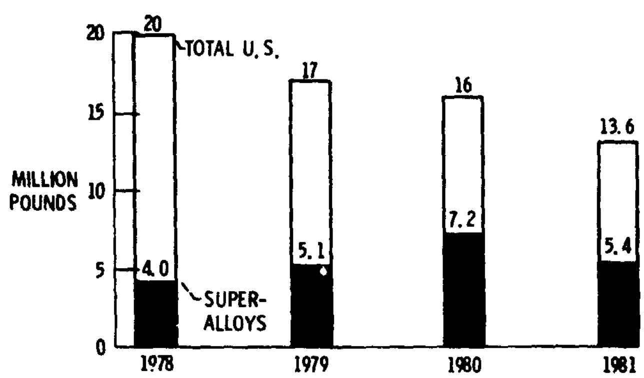

Figure 8. - Recent trends in U. S. and aerospace cobalt usage.

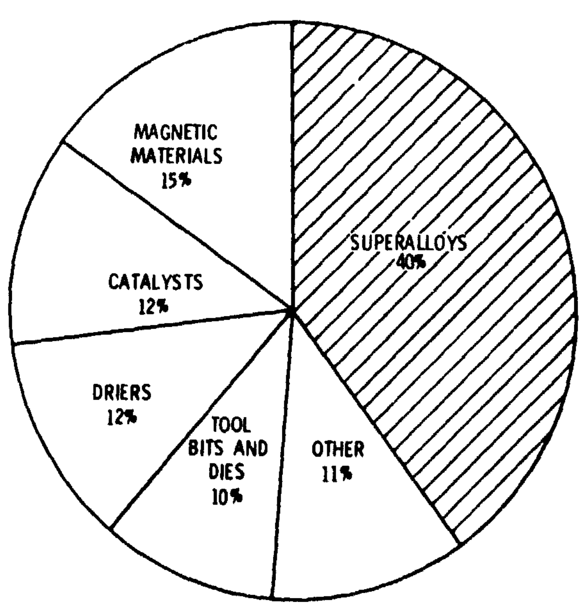

Figure 9. - Distribution of 1981 U. S. cobalt consumption - 13.6 million pounds.

ALLOY	TYPICAL ENGINE APPLICATION	FORM	REMARKS
WASPALOY	TURBINE DISK	FORGED	HIGHEST USE WROUGHT ALLOY IN CURRENT ENGINES
UDIMET-700	TURBINE DISK	FORGED	SIMILAR ALLOYS USED IN VARIOUS FORMS AND APPLICATIONS
(LC) ASTROLOY	TURBINE DISK	AS-HIP-POWDER	
(RENÉ 77)	TURBINE BLADES	CAST	
MAR-M247	TURBINE BLADES & WHEELS	CAST	CONVENTIONALLY-CAST, D.S. AND SINGLE CRYSTAL
RENÉ 150	TURBINE BLADES	DS-CAST	HIGHLY COMPLEX DIRECTIONALLY-CAST ALLOY

Figure 10. - Superalloys selected for cobalt substitution.

PARTICIPANTS	ALLOY	NOMINAL COMPOSITION Ni	Cr	Co	Mo	W	Ta	Re	Al	Ti	Hf	γ'
COLUMBIA UNIV.	WASPALOY	58	20	13	4	-	-	-	1.3	3	-	20%
PURDUE UNIV.												
SPECIAL METALS												
NASA-LEWIS												
COLUMBIA UNIV.	UDIMET-700	53	15	19	5	-	-	-	4.3	3.5	-	40%
PURDUE UNIV.	(WROUGHT,											
SPECIAL METALS	CAST)											
NASA-LEWIS												
NASA-LEWIS	(P. M.)											
CASE-WESTERN RESERVE UNIV.	MAR-M247	60	8	10	.6	10	3	-	5.5	1	1.4	55%
TELEDYNE, TRW												
NASA-LEWIS												
NASA -LEWIS	RENÉ 150	59	5	12	1	5	6	3	5.5	-	1.5	65%

Figure 11. - Scope of cobalt substitution program.

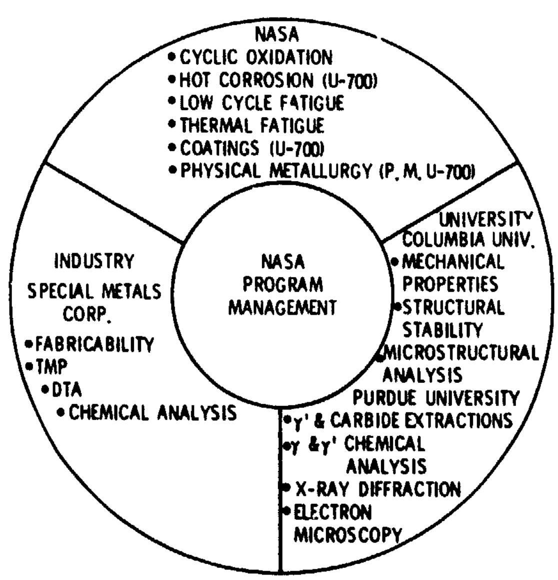

Figure 12. - Participants' roles in cooperative program on Waspaloy & Udimet 700.

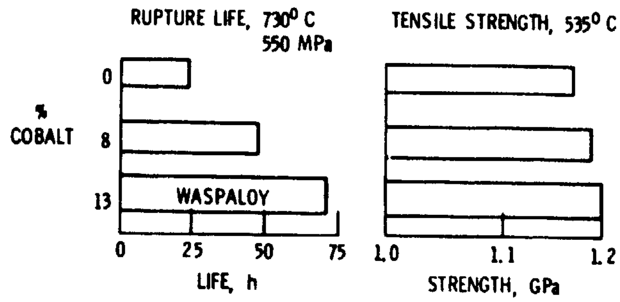

Figure 13. - Effect of cobalt content in Waspaloy on rupture life and tensile strength.

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 14. - Effects of removing cobalt from Waspaloy.

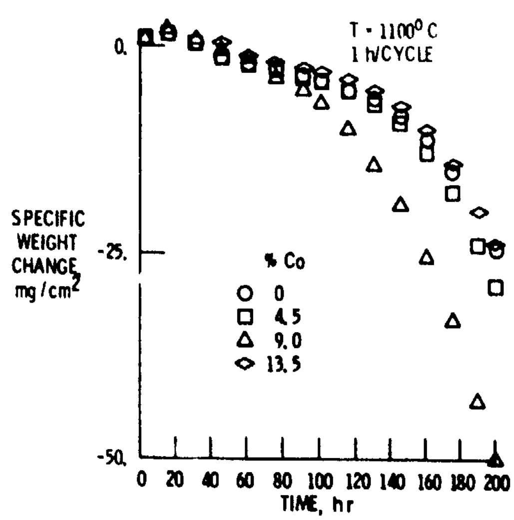

Figure 15. - Effect of cobalt on cyclic oxidation resistance of Waspaloy.

ITEM	RESULT
TITANIUM SOLUBILITY IN γ	INCREASE
CARBON SOLUBILITY IN γ	DECREASE
γ' - LATTICE PARAMETER	DECREASE
- VOLUME FRACTION	DECREASE
γ - LATTICE PARAMETER	INCREASE
γ - γ' MISMATCH	DECREASE

Figure 16. - Microchemical effects of removing cobalt from Waspaloy.

ITEM	RESULT
HOT WORKABILITY - HEATING	NO CHANGE
- COOLING	NO CHANGE
TENSILE - STRENGTH (DISK & BLADE)	SLIGHT DECREASE - NO CHANGE
- DUCTILITY (DISK & BLADE)	SLIGHT DECREASE
STRESS RUPTURE LIFE - DISK	17 $\rightarrow$ 9% Co NO CHANGE 9 $\rightarrow$ 0% Co DECREASE
- BLADE	INCREASE
CREEP RATE - DISK	INCREASE
- BLADE	NO CHANGE
γ' - SOLVUS TEMPERATURE	INCREASE
- VOLUME FRACTION - DISK	INCREASE IN COARSE γ' DECREASE IN FINE γ'
- BLADE	NO CHANGE
- CHEMISTRY	DECREASE Al, Ti,
CARBIDES - CHEMISTRY	MORE $M_{23}C_6$
- MORPHOLOGY	COARSER
LONG TIME STABILITY	INCREASE

Figure 17. - Effects of removing cobalt from Udimet 700.

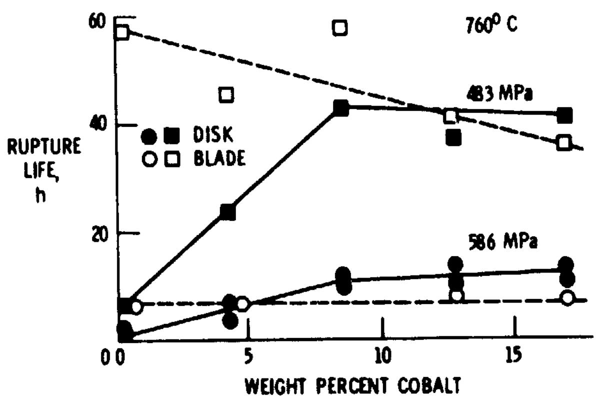

Figure 18. - Effect of removing cobalt and heat treatment on rupture life of Udimet 700 alloys.

ITEM	RESULT
γ LATTICE PARAMETER	DECREASE
γ' LATTICE PARAMETER	DECREASE
γ - γ' MISMATCH	INCREASES
CARBIDE CHEMISTRY	MC $\rightarrow M_{23}C_6$ (G. B.) $\rightarrow M_{23}C_6$ (MASSIVE)
BORIDE WEIGHT FRACTION	SLIGHT INCREASE
γ' WEIGHT FRACTION	NO CHANGE PRIMARY - INCREASED SECONDARY - DECREASED
LONG TERM AGING - STABILITY	INCREASES
- γ' WEIGHT FRACTION	INCREASES PRIMARY - NO CHANGE SECONDARY - INCREASES

Figure 19. - Microchemical effects of removing cobalt in Udimet-700.

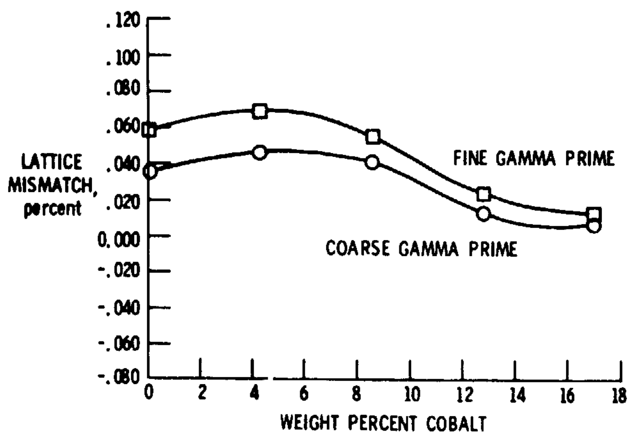

Figure 20. - Effect of cobalt on lattice mismatch of gamma/gamma prime in Udimet-700 disk material.

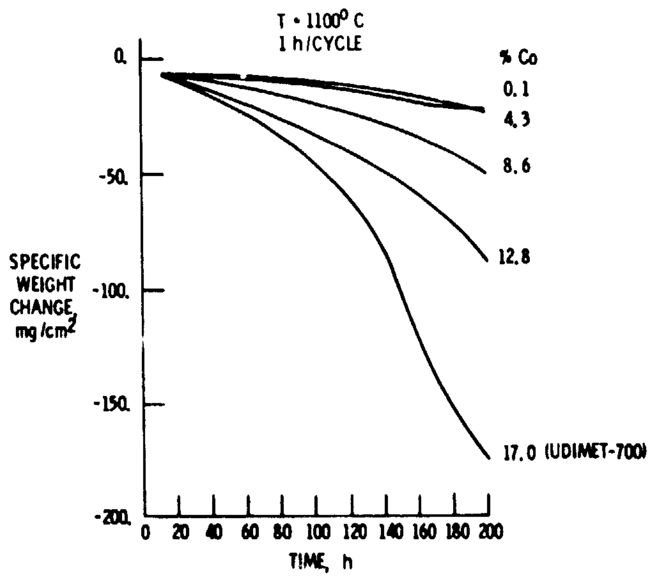

Figure 21. - Effect of cobalt on cyclic oxidation resistance of Udimet-700.

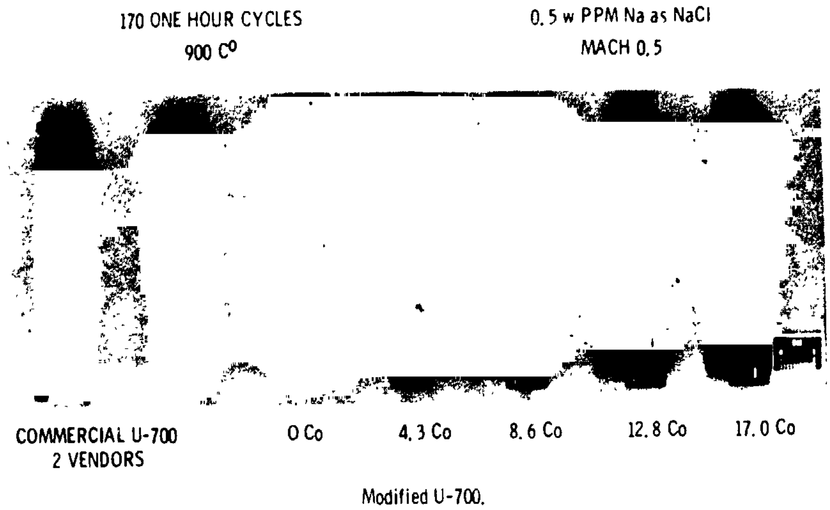

Figure 22. - Effect of cobalt on hot corrosion.

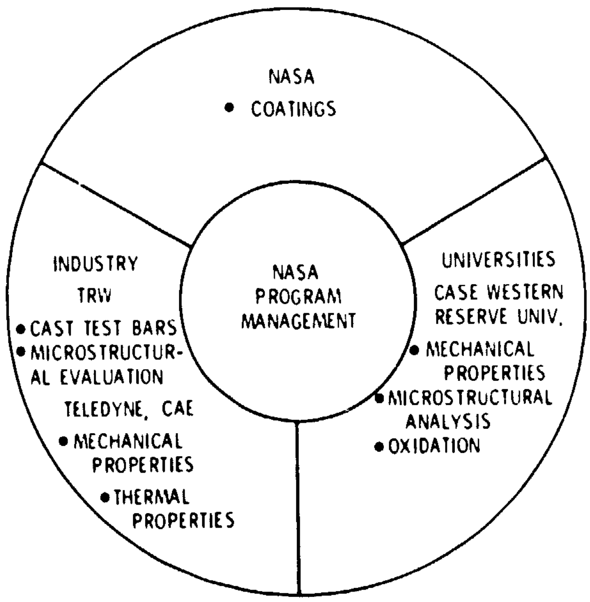

Figure 23. - Participants' roles in cooperative program on cobalt in MAR-M247.

ITEM	RESULT BLADE	RESULT 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 24. - Effects of removing cobalt from MAR-M 247 blade & hub.

ITEM	RESULT
YIELD STRENGTH	PEAK AT 5% COBALT - AT 650° & 760° C
RUPTURE LIFE	SLIGHT DECREASE 10→5% COBALT DECREASE 5→0% COBALT
CREEP RATE	NO CHANGE 10→5% COBALT INCREASE 5→0% COBALT
γ' - SOLVUS	SLIGHT INCREASE
- WEIGHT FRACTION	DECREASE
- SIZE	INCREASE
- LATTICE PARAMETER	SLIGHT DECREASE
- COMPOSITION	INCREASE - W, Ti
γ - COMPOSITION	DECREASE - Cr, Al, W
CARBIDES - SOLUBILITY (C)	DECREASE
- WEIGHT FRACTION	INCREASE
- MORPHOLOGY	DISCRETE PARTICLES → G. B. FILM
- COMPOSITION	NO CHANGE

Figure 25. - Effects of removing cobalt from MAR-M 247.

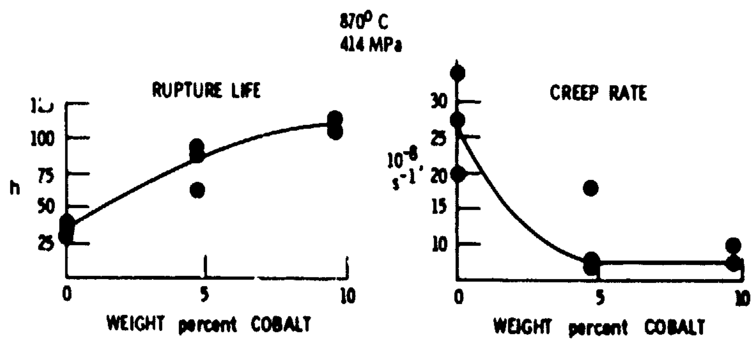

Figure 26. - Creep-rupture properties at 871° C and 414 MPa as a function of Co level in MAR-M247.

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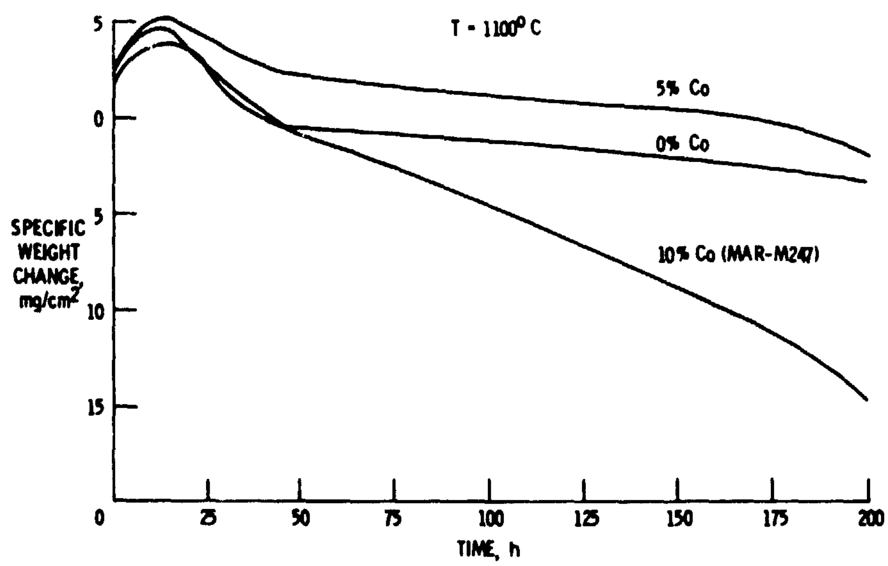

Figure 27. - Effect of cobalt on oxidation resistance of MAR-M 247.

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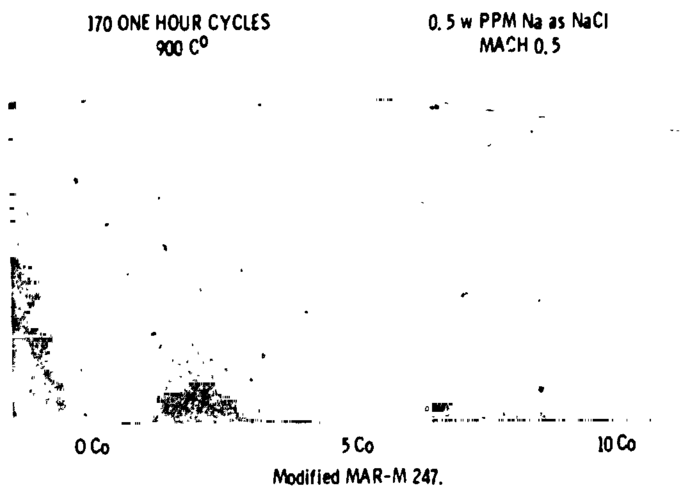

Figure 28. - Effect of cobalt on hot corrosion.

PROPERTY	REDUCING COBALT
TENSILE PROPERTIES	MINIMAL EFFECT
RUPTURE LIFE	50% REDUCTION - SLIGHT DECREASE TOTAL REMOVAL - MAJOR DECREASE
CREEP RATE	50% REDUCTION - SLIGHT INCREASE TOTAL REMOVAL - MAJOR INCREASE
OXIDATION RESISTANCE	IMPROVES
CORROSION RESISTANCE	IMPROVES
LONG TERM STABILITY	IMPROVES

CONTRIBUTING FACTORS

γ' VOLUME FRACTION

CARBIDE MORPHOLOGY & COMPOSITION

STACKING FAULT ENERGY

γ - γ' MISMATCH

Figure 29. - Role of cobalt in nickel-base superalloys.

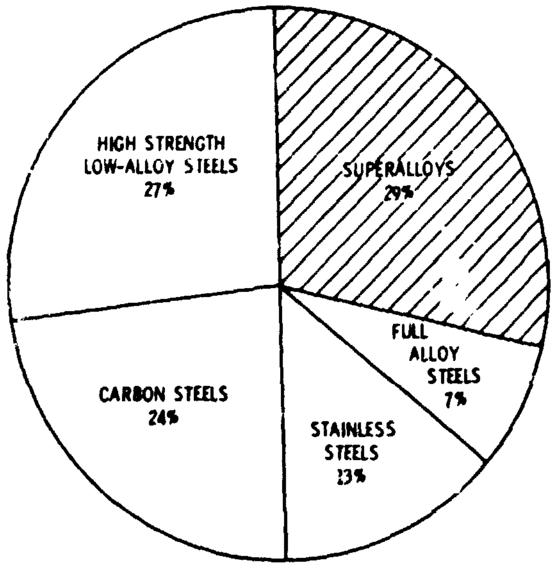

Figure 30. - Distribution of 1980 U. S. Columbium consumption - 6.5 million pounds.

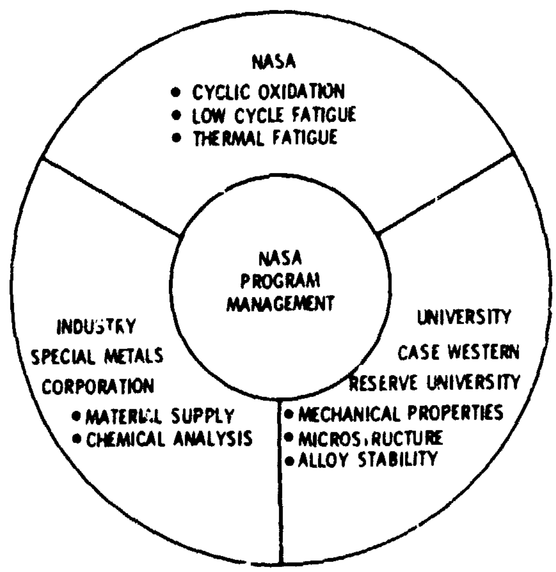

Figure 31. - Participants' roles in cooperative program on Columbium in Inconel 718.

COMPOSITION, WEIGHT PERCENT

ALLOY NO.	Ni	Cr	Fe	Cb	Mo	Al	Ti	W	V	Zr	B
1	BAL	19	19	4	3.5	.6	1.3	1	-	-	-
2				3	4	.7	1.7	2	-	-	-
3				3		.7	1.7	2	-	.05	.005
4				2.5		.6	1.5	-	1.75	-	-
5				2		.8	2.1	3	.8	-	-
6				2		.8	2.1	2	.8	.05	.005
7				1.5		.85	2.2	2	.8	-	-
8				1		.9	2.3	3	1.3	-	-
9				0		1.0	2.5	3	2	.05	.005

Figure 32. - Columbium modified composition Inconel 718 alloys.

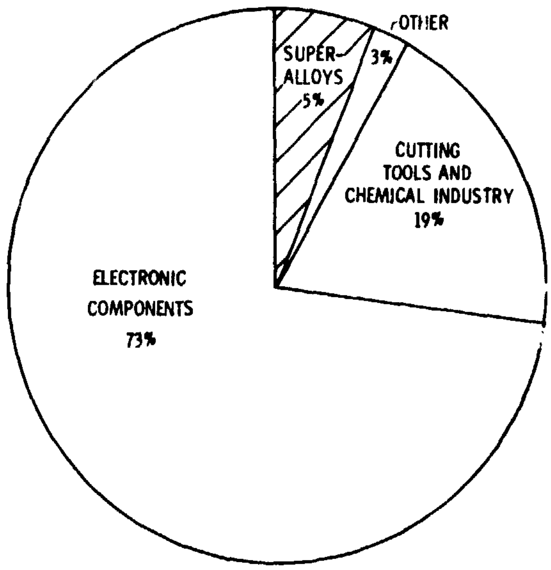

Figure 33. - Distribution of 1981 U. S. Tantalum consumption - 1.3 million pounds.

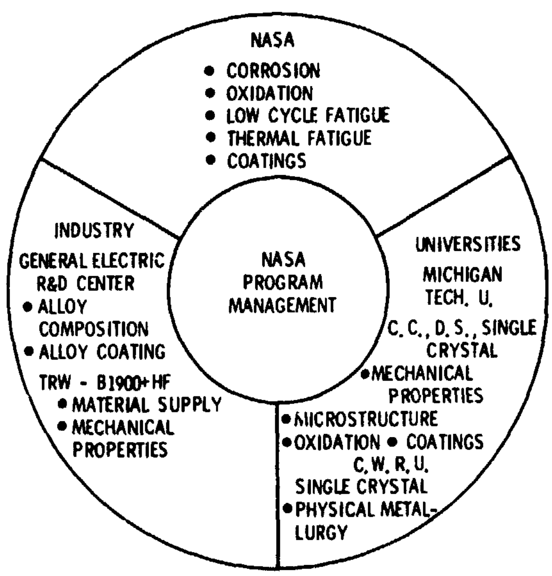

Figure 34. - Participants' roles in cooperative program on tantalum in superalloys.

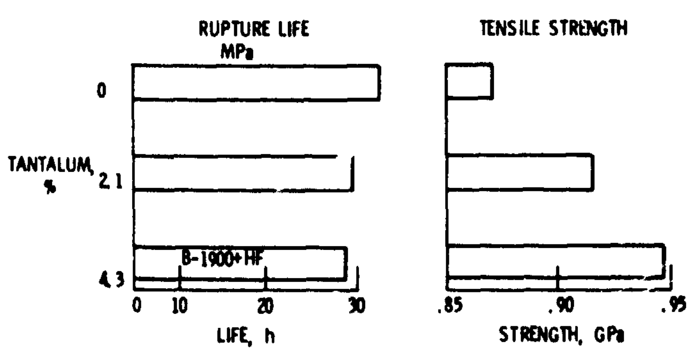

Figure 35. - Effect of tantalum on 760° C mechanical properties of B-1900+HF.

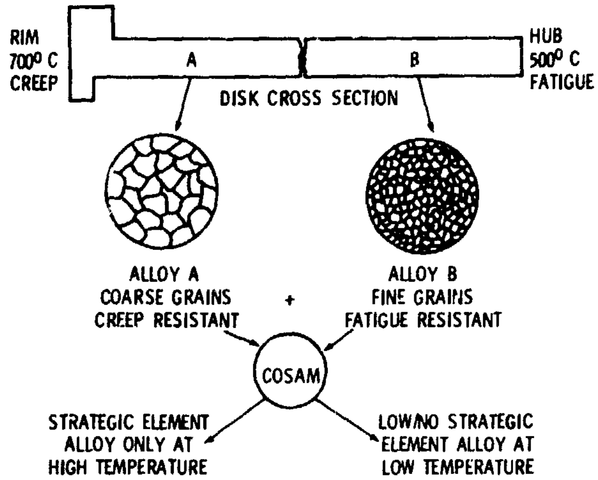

Figure 36. - Dual alloy joining technology for turbine disks.

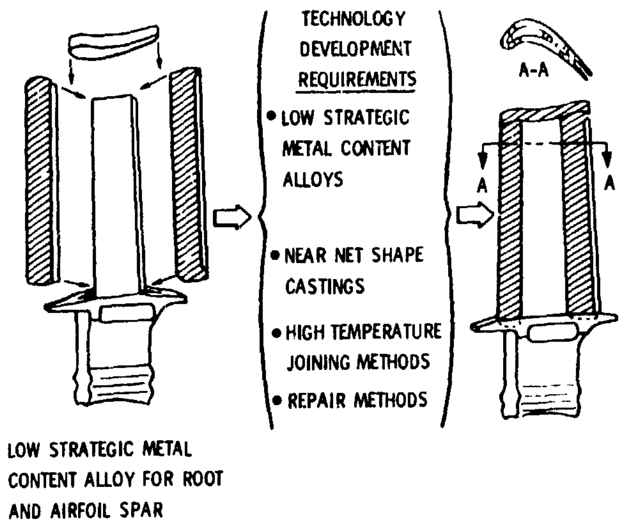

Figure 37. - Multiple alloy components joining technology.

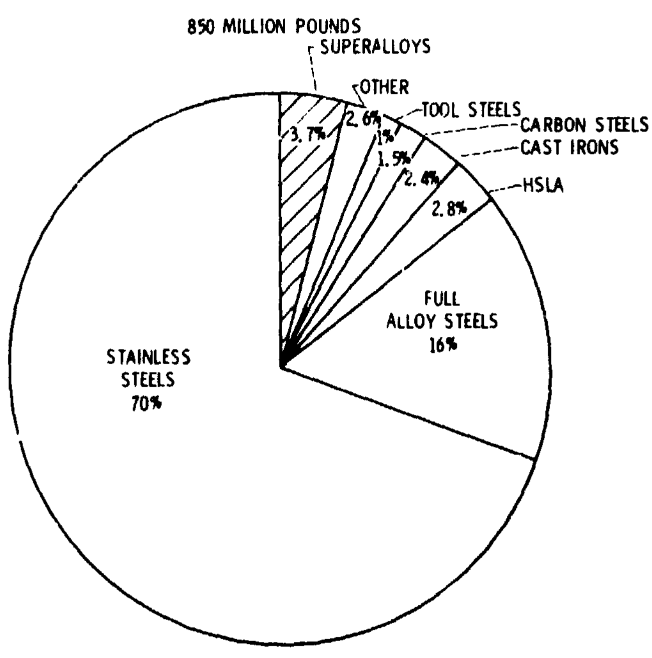

Figure 38. - Distribution of 1981 U. S. chromium consumption.

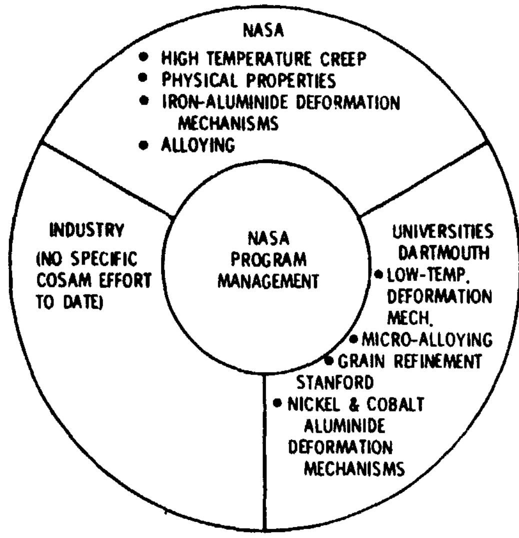

Figure 39. - Participants' roles in cooperative intermetallic compound program.

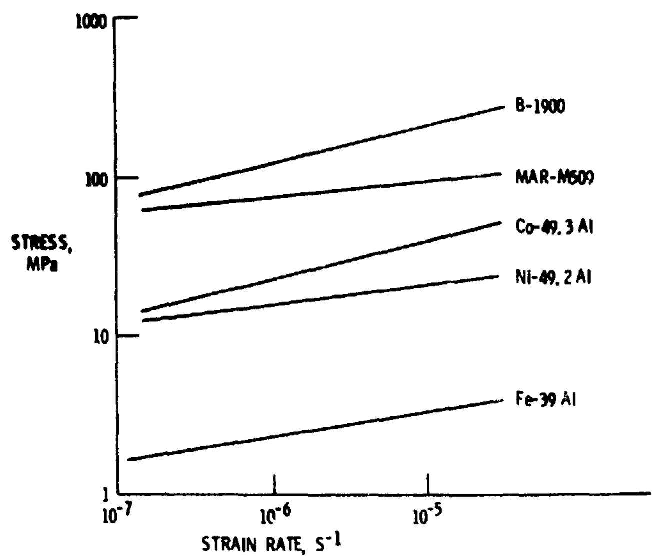

Figure 40. - Creep behavior of aluminides at 1125° C.

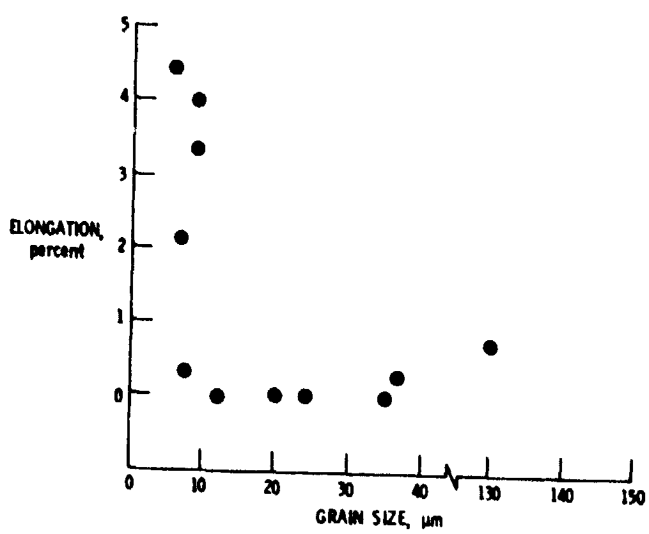

Figure 41. - Grain size effects on ductility of nickel aluminide at 295° C.

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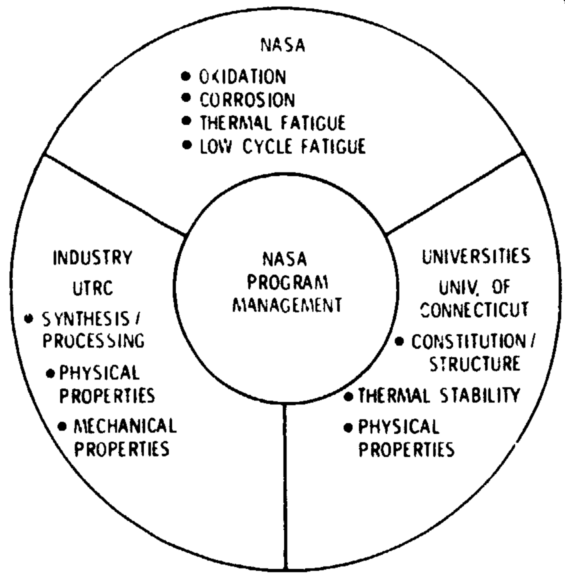

Figure 42. - Participants' roles in cooperative iron-base alloy program.

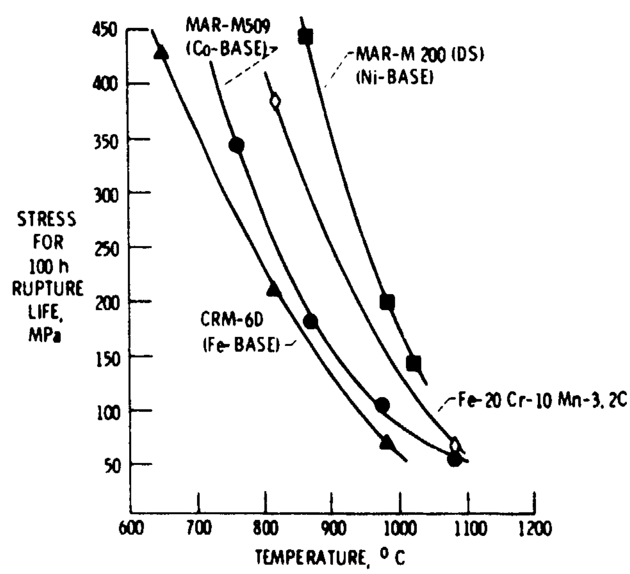

Figure 43. - Stress-rupture potential of Fe-20Cr-10Mn-3.2C alloy.