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Cobalt, A Vital Element in the Aircraft Engine Industry

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ABSTRACT

Recent trends in the United States consumption of cobalt indicate that superalloys for aircraft engine manufacture require increasing amounts of this strategic element. Superalloys consume a lion's share of total U.S. cobalt usage which was about 16 million pounds in 1980. In excess of 90 percent of the cobalt used in this country was imported, principally from the African countries of Zaire and Zambia. Early studies on the roles of cobalt as an alloying element in high temperature alloys concentrated on the simple Ni-Cr and Nimonic alloy series. The role of cobalt in current complex nickel-base superalloys has not been well defined and indeed, the need for the high concentration of cobalt in widely used nickel-base superalloys has not been firmly established. This paper will review the current cobalt situation as it applies to superalloys and describe briefly the opportunities for research to reduce the consumption of cobalt in the aircraft engine industry--a field of research being addressed by NASA's COSAM (Conservation of Strategic Aerospace Materials) Program.

INTRODUCTION

Periodically the United States metallurgical industry is faced with shortages of strategic materials that are critical to the economical health of our country. In the early 1970's the potential reduction of chromium supply, brought about in part by U.S. government sanctions against Rhodesia (now Zimbabwe), led to a number of studies,[1] workshops,[2] and research efforts.[3,4] NASA Lewis Research Center's research efforts focused on reducing chromium in 304 stainless steel which constitutes the largest single use of chromium in this country. Results indicated that substituting aluminum and molybdenum for a portion of the chromium produced an austenitic alloy with comparable properties to that of 304 stainless steel and with the potential of conserving one-third the chromium in this alloy.[3]

In the late 1970's another strategic metal shortage occurred in this country which had a major impact on superalloy producers. Because of political instabilities in Zaire, cobalt supply to the United States was disrupted. Producer cobalt supply to alloy melters in 1978 and 1979 was put on an allotment of 70 percent of 1977 usage. In addition to these disruptions, a titanium sponge shortage plagued U.S. alloy producers in the late 1970's.

Recent developments indicate that official policies of the United States are now taking materials shortages seriously. The National Materials Policy Act[5] was passed into law during 1980. This Substitution Workshop, sponsored by the Department of Commerce, is in direct response to this Act and a report of this Workshop and other activities will be delivered to the Congress by the Department of Commerce later this year. It is interesting to note that the Department of Commerce chose the aerospace industry as its case study of strategic materials. We at NASA Lewis Research Center have formulated the COSAM (Conservation of Strategic Aerospace Materials) Program[6] with special interest on the four strategic elements cobalt, columbium, tantalum, and chromium. Initial research efforts, underway since early 1980, are concentrated on determining the role of cobalt in superalloys. Superalloys constitute the single largest U.S. usage of cobalt. Therefore, the papers presented in this two-part session on cobalt are very timely and of extreme interest to the United States economy. An indication of the importance placed on cobalt by the current administration is the recent announcement that $100 million would be used to build-up the U.S. stockpile.[7] Cobalt was singled out as the first commodity to be purchased under this plan.

This paper will present the cobalt situation in the U.S. as it exists now, describe the role of cobalt in nickel-base alloys, and describe the initial COSAM Program on cobalt which was undertaken in 1980.

GEOGRAPHICAL CONSIDERATIONS

In planning and establishing our COSAM Program, strategic materials were defined as those predominantly or wholly imported elements contained in the metallic alloys used in aerospace components which are essential to the strategic economical health of the U.S. aerospace industry. Cobalt was identified as being within this definition of a strategic material. The United States imports over 90 percent of the annual consumption of cobalt. Figure 1 shows the leading producers of cobalt. The African countries of Zaire and Zambia are noted to be the leading cobalt producers. Also listed in figure 1 are the sources of U.S. imported cobalt in 1980.[8] Zaire and Zambia supply over 70 percent of the U.S. imports. This producer and supplier situation places the United States in an extremely vulnerable position if supplies are cutoff for any length of time. An example of this occurred in 1978 and 1979 because of the political disruptions that Zaire experienced in those years.

The objective of the COSAM Program is to provide technology options which will support the aerospace industry in making strategic economic decisions aimed at significantly reducing strategic metal (such as cobalt) consumption. This Workshop along with other activities will help focus attention on our non-fuel strategic material situation.

ECONOMICAL CONSIDERATIONS

Most of you are aware of the price increase in cobalt that has taken place since 1977. Cobalt metal that was selling at around $5.50 per pound in 1977 increased to over $30.00 per pound during 1979 with spot prices as high as $55.00 per pound. 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.

It is interesting to compare the price increase in cobalt with that of oil, a commodity that most of us are concerned with. The average prices for the year 1972 were chosen as a basis of comparison since this was just before oil prices skyrocketed. The price of cobalt was $2.45[9] per pound while OPEC oil sold for $2.28 per barrel.[10] Figure 2 shows that OPEC oil experienced a rapid rise in price during 1974 and again in 1979 and 1980. Interestingly enough, cobalt price increase has kept pace with that of oil over the past eight years. Just as oil price increases have influenced the use pattern of this commodity, the price of cobalt has brought about changes in the use pattern of this commodity as well. Some of the trends in cobalt usage will be discussed in a later section of this paper.

Even though the changes in prices of oil and cobalt have been similar over the last eight years, the response by the American public and press has been quite different. There has been a strong demand for conservation of and substitution for oil, but the cobalt situation has received only minor attention. The reason is the difference between the place of oil and cobalt in the economy. A cutoff of oil for a few months could severly cripple our economy particularly in the area of transportation and home heating. In contrast the average consumer would not even know a cutoff of cobalt had occurred unless it extended for a prolonged length of time.

A second reason is the tremendous demand for oil in this country compared to most any other commodity. Annual consumption of oil is compared to that of cobalt in figure 3 along with two other mineral commodities. Oil[11] is consumed by a factor of over five orders of magnitude compared to cobalt.[8] Iron ore, the largest used nonfuel mineral commodity, is overshadowed by oil consumption. With the volume of oil imported (over one-half of consumption) a significant effect on the balance-of-payments exists with a slight increase in price. In contrast, with the relative small amount of cobalt imported (even though over 90 percent is imported), a price increase comparable to that of oil has a negligible effect on the balance-of-payments. These factors suggest that the concentrated users of cobalt must take the lead in identifying effective substitutes for cobalt that will permit the United States to remain competitive in the world market.

USAGE CONSIDERATIONS

Primarily because of the spiraling cost of cobalt, the United States has experienced a decline in cobalt usage since 1978. Figure 4 shows that 20 million pounds of cobalt were consumed in 1978 and that in 1980 usage was down to 16 million pounds, a 20 percent reduction in usage in only 2 years. During this same time period the use of cobalt to produce superalloys, primarily for aircraft engines, increased from 4 million pounds in 1978 to 7.2 million pounds in 1980. This change represents an 80 percent increase in cobalt usage in superalloys in only two years. The numbers are from the Department of Interior's Mineral Industry Surveys.[12]

The importance of cobalt to superalloy production is illustrated in figure 5. It should be noted that 45 percent of the 16 million pounds of cobalt consumed by the United States in 1980 went for superalloy production. So even though total U.S. usage is down, superalloy usage continues to grow. The shift away from cobalt usage has been achieved primarily by the magnetic materials industry and by the manufacturers of tool bits and dies. This has been accomplished by utilizing ferrite magnets and development of cobalt-free cutting tools.

The increased usage of cobalt in superalloys can be attributed largely to the increased orders of aircraft engines which is the predominate superalloy market. Airlines have announced orders for new planes to supplement their current fleets, and the new engines will require large amounts of the strategic metal cobalt. Since the aircraft industry is a major factor on the positive side of the U.S. balance-of-payments,[13] a healthy aircraft industry is of utmost importance to the United States. Because of this, the NASA COSAM Program, industry efforts, and other activities underway are essential to assure that if the cobalt supply is disrupted, viable substitutes and alternatives are available to aircraft engine designers and producers.

METALLURGICAL CONSIDERATIONS

Cobalt is used in a variety of both cobalt-base and nickel-base superalloys. The largest usage in terms of pounds consumed, however, is in nickel-base alloys. Several nickel-base and cobalt-base superalloys are listed in figure 6 which shows the range of cobalt content in these alloys. Figure 6 also shows that cobalt is found in cast, wrought, and powder metallurgy alloys. One of the largest consumers of cobalt is Waspaloy, a wrought alloy used in aircraft engine turbine and compressor disks. These components are heavy (thus consuming significant quantities of cobalt) but are vital to today's high-temperature aircraft turbine engines.

In a recent publication by Tien, et al.,[14] a review of the existing literature on the role of cobalt in superalloys was presented. In addition an empirical model of the role of cobalt in superalloys was discussed at some length. A summary of the various roles of cobalt on mechanical and physical properties of superalloys observed by a number of investigators is presented in figure 7. Based on a high-temperature torsion test, cobalt additions in the advanced Nimonic series of alloys was reported to improve hot-workability. Figure 8, from the paper by Heslop[15] (test temperature not stated), illustrates that there is a linear dependence of the number of twists to failure and the cobalt content of the Nimonic alloy.

Cobalt has been reported by Habraken and Coutsouradis[16] to improve oxidation/corrosion resistance of high temperature alloys. This conclusion was based in part on the work on simple composition cobalt-chromium binary alloys compared to similar composition iron or nickel-base alloys.

The primary role of cobalt in nickel-base superalloys of interest to aircraft engine producers is its beneficial effect on high-temperature strength properties. Figure 7 shows that cobalt's beneficial effect on stress-rupture strength has been noted by Urbain[17] for Nimonic and Inconel alloys. More recently similar results have been noted by Maurer[18] (Waspaloy), Nathal[19] (MAR-M247), and Tien[20] (Udimet 700) where cobalt was systematically removed in incremental steps from these three complex composition superalloys. The latter two research efforts are part of the NASA COSAM Program and will be presented during this Cobalt Session of the Workshop.

A summary of Urbain's observations is presented in figure 9. Stress-rupture strength against temperature is shown for Nimonic 80A and Nimonic 90 (an alloy of similar composition to that of Nimonic 80A but with 17 percent cobalt added). An improvement in stress-rupture strength of these wrought alloys is noted as a result of the cobalt addition. A similar effect is noted in figure 9 for the cast alloys Inconel 713C (no cobalt) and Inconel 717C (similar compositon, but with 8 percent cobalt added).

Creep curves for reduced cobalt Waspaloy-type alloys, based on the work of Maurer, are shown in figure 10. It should be noted that cobalt increases rupture life, decreases minimum creep rate, and (negatively) reduces creep ductility in Waspaloy at 730° C.

The effect of cobalt on microstructure of nickel-base superalloys is summarized in figure 11. It should be noted that most of this research has been reported by Heslop on simple composition nickel-chromium-cobalt (60:20:20) ternary alloys. With the exception of the work by Lund,[21] et al., very little work has been reported on complex composition superalloys. For example, stacking faults were observed in the nickel-chromium-cobalt alloys, while for a binary Ni-Cr alloy (80:20) stacking faults were not observed. This lead to the conclusion that cobalt reduces the stacking fault energy in nickel-base alloys. The effect of cobalt on aluminum and titanium solubility in the nickel-chromium-cobalt system is shown in figure 12. The microstructural influences of cobalt listed in figure 11 are interrelated to the changes in mechanical and physical properties of the nickel-base superalloys. However, the specifics of this interrelationship have not been elucidated at this point in time.

SUPERALLOY FUNDAMENTAL RESEARCH

As was brought out in the preceding section of this paper, much of the research aimed at determining the role of cobalt in nickel-base superalloys has been conducted on simple binary and ternary alloys. As part of the NASA COSAM Program, the determination of the role of cobalt in today's more complex nickel-base superalloys has been undertaken.

Five (four nickel-base and one cobalt-base) superalloys have been selected for the COSAM investigation. The five alloys are listed in figure 13 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, turbine blades, and combustors. A variety of product forms are represented by the applications of the five alloys, as noted in figure 13. The selection of the five alloys was based primarily upon the considerations given in this figure. Waspaloy* was selected because it represents the highest tonnage of cobalt in commercial aircraft engines. Selection of Udimet-700* was based on the fact that this alloy is used in the as-cast, as-wrought ingot, as-wrought powder, and as-HIP powder-metallurgy fabricated conditions. The potential for determining the impact of cobalt on both conventionally-cast as well as on single crystal turbine blades was the reason for selecting MAR-M247*. Rene' 150* was chosen because it is one of the most advanced directionally-solidified turbine blade alloys. The wrought, sheet alloy HA-188* was selected because it represents one of the largest uses of a cobalt-base alloy in aircraft engines.

The primary purpose of the cobalt strategic element substitution research is to determine the fundamental role of cobalt in a wide variety of nickel-base superalloys and in a high-use cobalt-base superalloy. A secondary purpose is to develop the methodology to explore the roles of other strategic elements in similarly chosen alloys so as to have maximum impact on a wide range of users.

Figure 14 shows the current participants in the COSAM activities on cobalt strategic element substitution. These initial research efforts are planned for a three-year period and consist of cooperative programs involving universities, industry, and NASA Lewis Research Center. Nominal compositions of the five alloys given in figure 14 indicate that cobalt content ranges from 10 percent in MAR-M247 to 39 percent in HA-188. In addition the γ' phase ranges from 20 percent in Waspaloy to 65 percent in

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*Trademarks

Waspaloy	United Technologies Corporation
Udimet	Special Metals Corporation
MAR-M	Martin Marietta Corporation
Rene'	General Electric Corporation
HA	Cabot Corporation

Rene' 150. The first phase in each research effort will involve substituting the less-strategic-element nickel for cobalt in incremental steps to a zero cobalt content. The effects of this substitution on properties and phases present, such as γ', will make-up the major portion of the research effort in the first year of each program element. Efforts in subsequent years will be directed at identifying and optimizing alloying elements as substitutes for cobalt in the five alloys so as to maintain the key properties of these alloys.

The cooperative nature (government-industry-academia) of the research being conducted on Waspaloy and Udimet-700 is illustrated in figure 15. The role of industry, as represented by Special Metals Corporation, is outlined. Their primary role is to characterize and optimize fabrication and heat treating procedures for the reduced cobalt Waspaloy and Udimet-700 alloys. The university role in this effort is also shown in figure 15. Columbia University will be involved with mechanical property characterization, structural stability, microstructural features, and theoretical formulations to identify future alloy modifications if required for the second phase of the project. Purdue University will be primarily responsible for microstructural and microchemistry characterization of the reduced cobalt content alloys. To round out the program, NASA Lewis Research Center will be involved in further mechanical and physical metallurgy characterization of the alloys as shown in figure 15. The output of this cooperative effort is expected to be a clearer understanding of the role of cobalt in nickel-base superalloys to help point the directions for future development of new/modified superalloys.

The research efforts on MAR-M247 and Rene' 150 parallel the previously described efforts on Waspaloy and Udimet-700. It is anticipated that these projects will lead to an understanding of the fundamental role of cobalt in a variety of conventional and directional nickel-base superalloys. These results should provide an improved technical base to guide the identification of high potential modified superalloys in the planned COSAM Program.

CONCLUDING REMARKS

From the literature survey of the information on world cobalt producers and the United States dependence on imports for over 90 percent of the cobalt consumed in this country, it is clear that cobalt is truly a strategic metal. Furthermore, the increase in the use of cobalt for superalloys, which are used primarily for aircraft gas turbine engines, indicates the vital nature of cobalt to this industry. Of particular concern is the impact that would result to the aerospace industry if cobalt supplies were cut off for an extended length of time.

A review of the literature indicates that the role of cobalt in nickel-base superalloys is not clearly defined and the minimum amount required has not been established. These factors give rise to the need for research to determine the roles of cobalt in superalloys and to identify effective alloying substitutes for cobalt. From these basic research studies, alloys may be identified that minimize or eliminate the need for cobalt in nickel-base superalloys, thus providing non-strategic element alternatives to aircraft engine producers in the event of a cobalt crisis. The initial efforts now underway in the NASA COSAM Program should help meet this national need.

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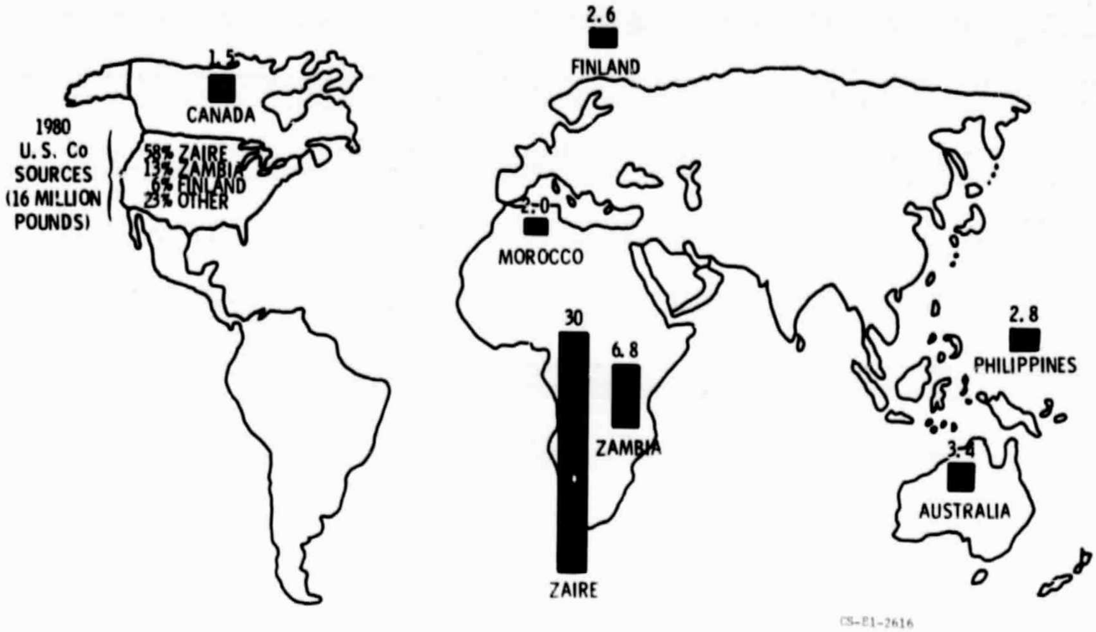

Figure 1. - Leading cobalt producers (million pounds).

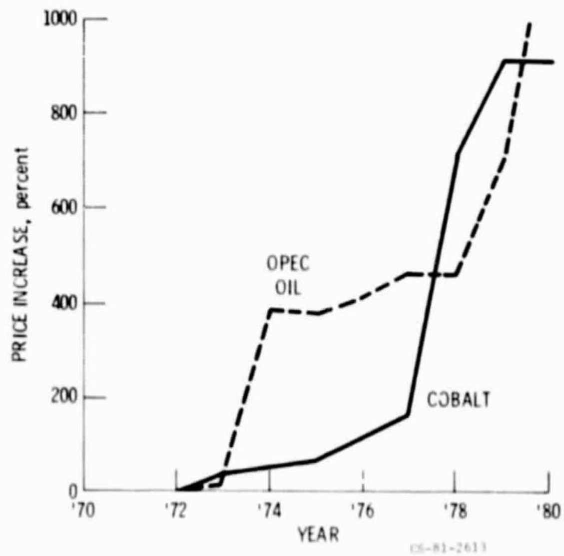

Figure 2. - Price trend comparison of cobalt and OPEC oil 1972 - 1980.

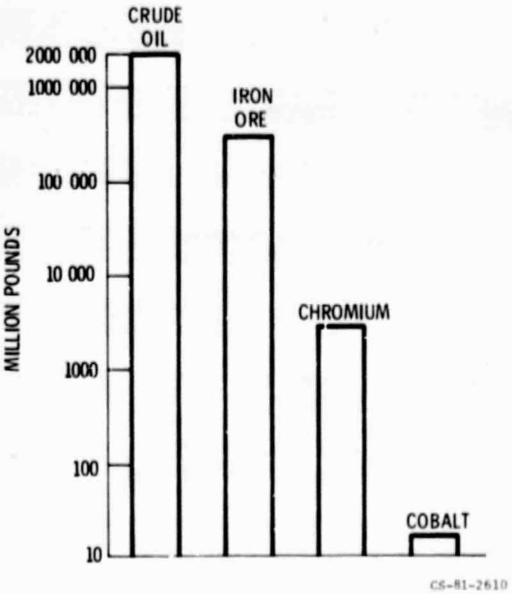

Figure 3. - 1980 United States consumption of selected commodities.

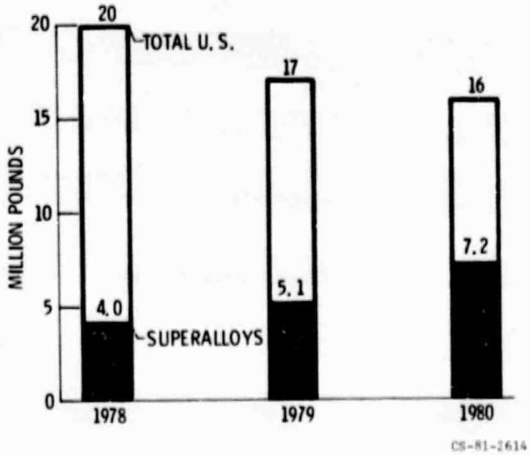

Figure 4. - Recent trends in U. S. and aerospace cobalt usage.

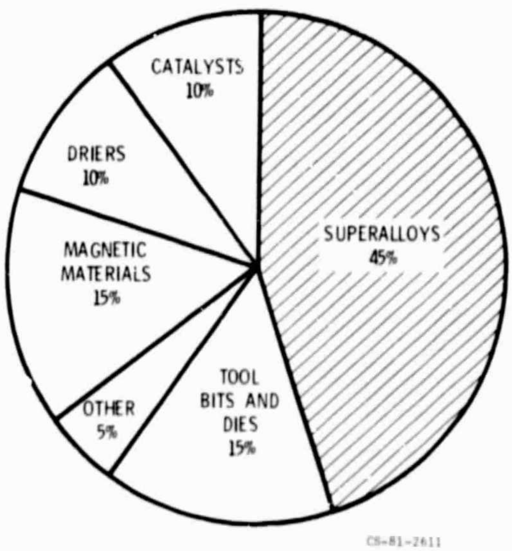

Figure 5. - Distribution of 1980 U. S. cobalt consumption (16 million pounds).

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

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Figure 6. - Cobalt content of typical superalloys.

COBALT

APPARENT EFFECT	ALLOY SYSTEM	AUTHOR
IMPROVES HOT WORKABILITY	NIMONIC SERIES	HESLOP
INCREASE OXIDATION/CORROSION RESISTANCE	COBALT - BASE	HABRAKEN & COUTSOURADIS
INCREASE STRESS-RUPTURE LIFE	NIMONIC SERIES	URBAIN
	INCONEL SERIES	URBAIN
	WASPALOY	MAURER
	MAR-M247	NATHAL
	UDIMET 700	TIEN

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Figure 7. - Cobalt's role in superalloys mechanical/physical properties.

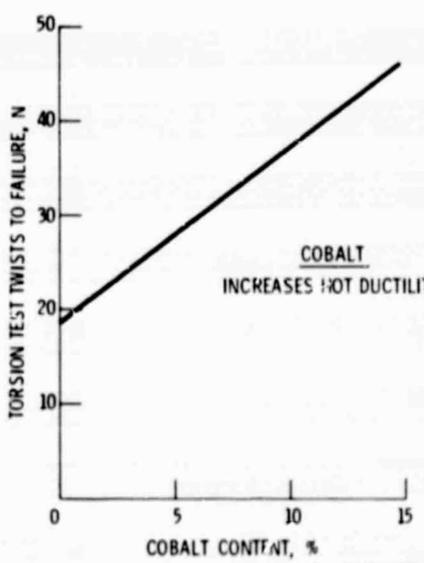

Figure 8. - Cobalt effect on hot-workability (advanced nimonic alloy)

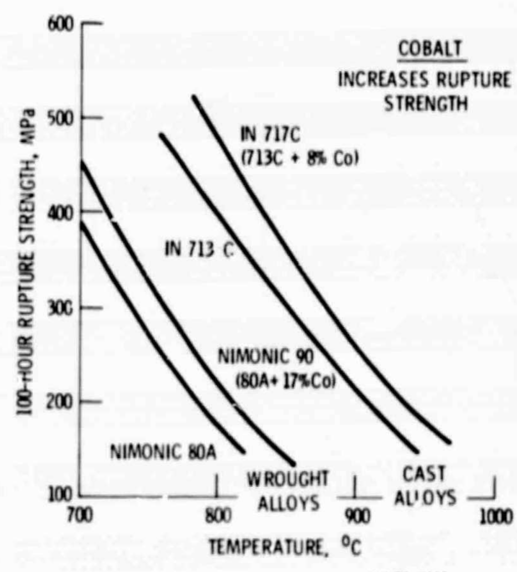

Figure 9. - Cobalt effect on rupture strength.

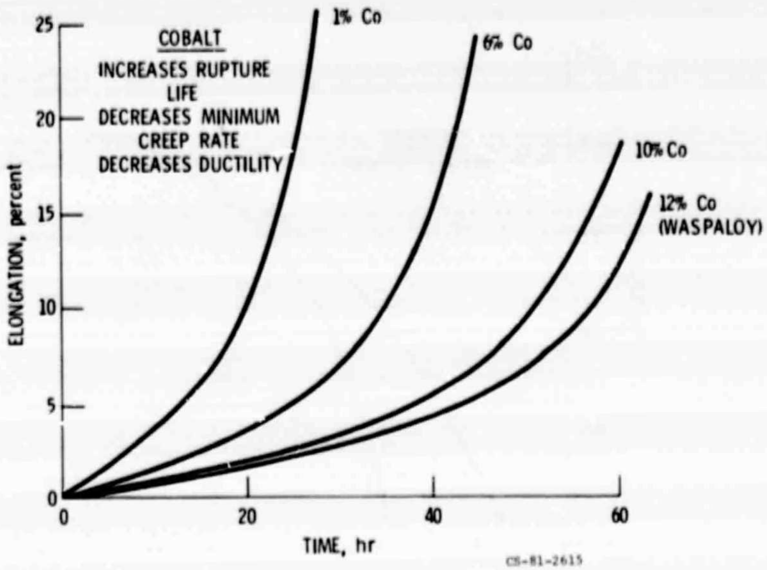

Figure 10. - Waspaloy creep curves 730° C - 550 MPa.

COBALT APPARENT EFFECT	ALLOY SYSTEM	AUTHOR
DECREASE STACKING FAULT ENERGY	Ni - Cr - Co	HESLOP
REDUCE Al & Ti SOLUBILITY	Ni - Cr - Co, NIMONIC SERIES	HESLOP
INCREASE γ' v/o	Ni - Cr - Co	HESLOP
INCREASE γ' SOLUTIONING TEMPERATURE	Ni - Cr - Co	HESLOP
INCREASE CARBON SOLUBILITY	Ni - Cr - Co	HESLOP
SUBSTITUTE FOR Ni IN M_6C	Ni - BASE SUPERALLOYS	SABAL & STICKLER
INCREASE ALLOY STABILITY (σ)	MAR - M421	LUND, ET. AL.

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Figure 11. - Cobalt's role in superalloys microstructure.

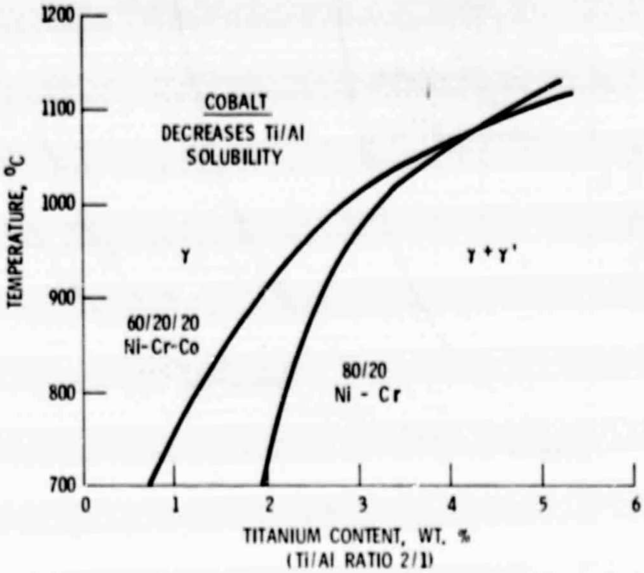

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Figure 12. - Cobalt effect on titanium-aluminum solubility.

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	CAST	CONVENTIONALLY-CAST, D.S. AND SINGLE CRYSTAL
RENÉ 150	TURBINE BLADES	DS-CAST	HIGHLY COMPLEX DIRECTIONALLY-CAST ALLOY
HA-188	COMBUSTORS	WROUGHT	HIGH USE COBALT-BASE SHEET ALLOY

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Figure 13. - Superalloys selected for pre-COSAM activities.

PARTICIPANTS	ALLOY	Ni	Cr	Co	Mo	W	Ta	Re	Al	Ti	Hf	γ'
		NOMINAL COMPOSITION										
COLUMBIA UNIV PURDUE UNIV SPECIAL METALS NASA-LEWIS	WASPALOY	58	20	13	4	--	--	--	1.3	3	--	20%
COLUMBIA UNIV PURDUE UNIV SPECIAL METALS NASA-LEWIS	UDIMET-700	53	15	19	5	--	--	--	4.3	3.5	--	40%
CASE-WESTERN RESERVE UNIV TELEDYNE NASA-LEWIS	MAR-M247	60	8	10	.6	10	3	--	5.5	1	1.4	55%
NASA-LEWIS	RENÉ 150	59	5	12	1	5	6	3	5.5	--	1.5	65%
(TBD)	HA-188	22	22	39	--	14	--	--	--	--	--	--

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Figure 14. - Elements of initial COSAM activities.

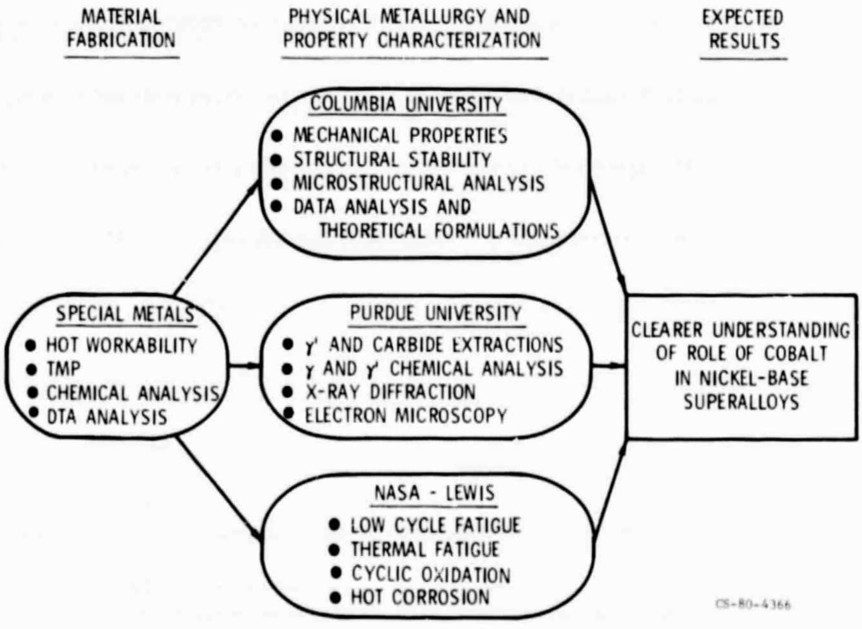

Figure 15. - Cooperative program to determine fundamental role of cobalt in WASPALOY and U-700.