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THE PROMISE OF EUTECTICS FOR AIRCRAFT TURBINES

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ABSTRACT

A key to advanced-turbine engine performance lies in the development of advanced materials. Directionally solidified eutectics show promise of becoming the next generation of turbine blade materials, with projected increases in use-temperature capability of from 40° to 110° C (70° to 200° F). The current status of the first generation eutectics, $\gamma/\gamma' - \delta$ and NiTaC-13, is described in detail. Several second generation systems, such as $\gamma/\gamma' - \alpha$, NiTaC 3-116A, $\gamma - \beta$, and COTAC 74 are also reviewed with particular emphasis on their critical physical and mechanical properties, future research directions, and potential applications. Results of recent cost-benefit analyses of eutectic turbine blades are discussed.

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SUMMARY

Directionally solidified eutectics, a relatively new class of blade and vane materials, show promise of being used in advanced gas turbine engines. Their potential increase in use temperature capability of from 40° to 110° C (70° to 200° F) over currently available alloys offers the engine designer opportunities to improve engine performance, increase component life and reduce fuel consumption.

The current status of the first generation eutectics, $\gamma/\gamma' - \delta$ and NiTaC-13, is described in detail. Their composition, structure, critical mechanical and physical properties are reviewed. NiTaC-13 has been successfully engine tested as an uncooled low pressure turbine blade in a J101 engine. $\gamma/\gamma' - \delta$ is currently undergoing extensive evaluation for use as a small solid turbine blade in a helicopter and business jet turbine engine.

Several second generation eutectic systems, $\gamma/\gamma' - \alpha$, NiTaC 3-116A, $\gamma - \beta$, and COTAC 74, are also reviewed to the extent that their early development status permits. Particular attention is given to critical mechanical properties, current and future research directions, and potential applications. NiTaC 3-116A and $\gamma/\gamma' - \alpha$ have about 17-35° C (30-60° F) greater use temperature capability than the first generation eutectics and appear to have promise for advanced turbine blade applications. COTAC 74 and $\gamma - \beta$ appear to have promise for turbine vane applications.

Results of recent cost-benefit analyses of eutectic turbine blades for commercial engines are discussed. Fuel savings of up to 400×10^9 liters (104 million gal) per year have been projected from the increased metal temperature capability of eutectic turbine blades. One of the biggest challenges to the promise of eutectics for aircraft turbines is the projected unfavorable economics. Eutectics are directionally solidified at low rates of less than 2.5 centimeters per hour (1 in./hr), often with low yields and resultant projected high prices. Additional development effort is required in automation, cluster casting, mold and core materials in order to fulfill the promise of eutectics for advanced aircraft turbine engines.

INTRODUCTION

A key to advanced turbine engine performance lies in the development of advanced materials. In particular turbine airfoil (blade and vane) materials with higher use temperature capabilities are vital to the energy efficient, high work gas turbines desired for the 1980's. Directionally solidified eutectics (dse), a relatively new class of materials, show promise of becoming the next generation of turbine blade materials. The potential increase of from 40° to 110° C (70° to 200° F) in use temperature capability predicted for eutectics is a larger increment over currently available alloys than previously obtained in any new turbine blade alloy. The historical and the author's projected use temperature capabilities of blade materials at a stress level of 150 MPa (22 ksi) for 1000 hours of life are shown in figure 1. These projected advances in blade materials rely not only on new alloy compositions and/or strengthening mechanisms but also on radical changes in processing technology.

Most current turbine blade alloys are conventionally cast with a controlled grain size, but with random grain orientations, see figure 2. Enlargements of portions of the blades illustrate the differences between the equiaxed, randomly oriented grains typical of conventionally cast blades and the elongated, unidirectional grains that are produced by directionally solidifying a blade from the root toward the tip.

Directional structures have optimum properties along the length of the blade, parallel to the main stress axis of the blade. Hence, the creep strength and use temperature capability of such directional structures are markedly increased as a result of this unique processing technique. For example, the nickel-base superalloy MAR-M 200 + hafnium (Hf) can be used at about 940° C (1725° F) in its conventionally cast form, while the directionally solidified (d.s.) version of the same alloy can be used to about 960° C (1760° F).

As shown in figure 1 still greater use temperature potential is predicted by the author for d.s. single crystal alloys, d.s. eutectics, oxide dispersion strengthened (ODS) superalloys, and tungsten fiber reinforced superalloys. Development of a new turbine blade material requires a considerable time period. Approximately eight years of research and development effort has gone into the evaluation of the first generation eutectics ($\gamma/\gamma' - \delta$ and NiTaC-13) since their initial potential based on stress rupture strength was recognized. In recent years several promising second generation eutectics have been identified, the potential of single crystal alloys has been recognized, and major advances have been achieved in the processing of ODS superalloys and fiber reinforced superalloys. Some of these latter two materials may ultimately have greater potential for turbine applications, but they must still undergo a long term, detailed evaluation of their properties prior to their use in turbines. Thus, it is possible that eutectics may actually be used in gas turbine engines before these other advanced blade materials are used.

Eutectics have received extensive support in the past few years under sponsorship of the National Aeronautics and Space Adminstration, Air Force Materials Lab and Aero Propulsion Lab, Naval Air Systems Command and Naval Air Propulsion Test Center. The potential payoffs from eutectics justify this widespread support. Cost-benefit studies have recently been performed which quantify the economic benefits of advanced turbine blade materials (1 and 2). These studies were performed for a fleet of four engine, subsonic commercial transport aircraft utilizing advanced technology and materials representative of the mid-1980's. The basic characteristics of these studies were a 3700 km (2000 n. mi.) average range aircraft and a load factor of 55 percent of the total passenger capacity of 200.

Turbine cooling airflow requirements in hollow blades can be substantially reduced because of the increased temperature capability of eutectics, or any other advanced blade material, thus resulting in increased engine efficiency, decreased fuel consumption and decreased engine weight. The magnitude of these economic benefits is dependent upon the increase in blade metal temperature. For example, the cost-benefit studies indicated that a d.s. eutectic with a 56° C (100° F) increase in use temperature over d.s. MAR-M 200 + Hf (at equivalent casting cost) would result in an increased return on investment (ΔROI) of 0.29 points (14.60 to 14.89%). This is equivalent to a decrease of 1.2 percent in direct operating costs (ΔDOC) or a decrease of $1,080,000 per aircraft in life cycle costs (ΔLCC). Increases of 83° and 110° C (150° F and 200° F) in blade metal temperature would result in even more substantial economic payoffs. Fuel savings range from 1.9 to 2.9 percent in thrust specific fuel consumption (TSFC) for material use temperature increases of 56° to 110° C (100° to 200° F), respectively. Such savings are equivalent to 257 and 400×10^9 liters (68 and 104×10^9 gal) of fuel per year for a fleet of 500 aircraft.

Directional solidification technology and equipment required to produce fully aligned eutectic microstructures are more sophisticated than those used for current d.s. superalloys. A typical directional solidification rig for eutectics is shown in figure 3. Such rigs are capable of producing a thermal gradient of several hundred °C per centimeter at the liquid/solid interface. As solidification occurs the location of the interface remains essentially fixed with respect to the furnace when the crucible is withdrawn through the furnace bottom. For eutectic alloys the liquid/solid interface must be planar in order to suppress constitutional supercooling so as to promote fully coupled growth of the eutectic phases. There is a critical G/R (thermal gradient/growth rate) which is characteristic of each eutectic system and is a measure of the degree of difficulty of achieving fully aligned microstructures. Some advanced d.s. rigs utilize radiation baffles and/or a liquid tin bath to achieve higher temperature gradients, thus permitting solidification at somewhat faster rates than previously achieved (3). Additional research and development effort is required in automation, cluster casting, mold and core materials in order to produce eutectic blades more economically. If mold and core reactions could be minimized with improved ceramics, melt superheat temperatures could be increased, thereby achieving higher thermal gradients and permitting faster solidification rates. A novel method of achieving very high thermal gradients is currently under development (private communication: M. Flemings, et al., Massachusetts Institute of Technology, NSG 3046, 1977), see figure 4. The essential concept of this design is the close coupling of the high thermal induction input just above the liquid/solid interface and an extremely efficient heat sink just below the interface. Molten eutectic alloy is continuously fed in from the surrounding pool. Thus, high thermal gradients (850° C/cm (3900° F/in.)) may be obtainable across the interface without the excessive superheating of a large volume of liquid (and resultant mold reaction problems) associated with conventional d.s. furnaces, as in figure 3.

It should be noted that the economic benefits discussed above resulted from utilizing the full increment in material use temperature capability to reduce cooling air requirements, thereby reducing fuel consumption of advanced turbine engines. It is also possible for the turbine designer to elect to use eutectic blades in other ways with resulting payoffs of up to 10-fold greater service life, or up to 10 percent increase in engine thrust for a constant flow size engine, or a higher design stress for a given blade at the same design temperature. Thus, the engine designer may extract the benefit offered by an advanced eutectic in a number of ways; e.g., improved performance, improved fuel economy, or longer component life.

FIRST GENERATION SYSTEMS FOR BLADE APPLICATIONS

Although numerous eutectic systems have been investigated during the past two decades, only two are currently receiving extensive evaluation in the United States for near-term engine applications - gamma/gamma prime-delta ($\gamma/\gamma' - \delta$) and NiTaC-13. The properties of these eutectics that relate to their use as gas-turbine blade materials have been determined by numerous investigators (3 to 10). Some of the most pertinent ones will be presented along with discussions of macro- and micro-studies that relate to these properties.

$\gamma/\gamma' - \delta$

Composition, structure and processing. The chemical composition of the recently optimized (4) $\gamma/\gamma' - \delta$ eutectic is Ni-20.1Cb-6Cr-2.5Al-0.06C (in weight percent), see table I. The alloy microstructure, shown in figure 5, consists of a ductile Ni-Cr matrix (γ phase) containing fine strengthening Ni_3Al precipitates (γ' phase), and reinforced with about 40 volume percent of aligned, intermetallic Ni_3Cb lamellae (δ phase). This structure forms during plane front solidification at a rate (R) of about 2 centimeters per hour (0.8 in./hr) with a thermal gradient (G) at the liquid/solid interface of 300° C per centimeter (1400° F/in.). The critical G/R for $\gamma/\gamma' - \delta$ is 150° C hr/cm^2 (1740° F hr/in.^{2}). These physical properties of $\gamma/\gamma' - \delta$ together with those of the other eutectics to be discussed in this paper are listed in table I.

Critical mechanical properties. Detailed evaluation (4) of the stress rupture properties of $\gamma/\gamma' - \delta$ has demonstrated that the eutectic has a 40° C (70° F) use temperature advantage over d.s. MAR-M 200 + Hf at a stress level of 150 MPa (22 ksi) for 1000 hours, see figure 6 and table II. D.S. MAR-M 200 + Hf will be used throughout this paper as the comparative baseline alloy since it is the most advanced turbine blade alloy currently in use in commercial engines.

The long-term isothermal and cyclic stability of the $\gamma/\gamma' - \delta$ eutectic are excellent. For example, specimens given long-term (1000 to 3600 hr) isothermal creep exposures to 1 percent elongation followed by stress rupture testing had rupture lives equivalent to short-term (100 to 300 hr) rupture tests of as-directionally solidified specimens, see figure 7. In addition 3000 thermal cycles between 425° and 1100° C (800° and 2010° F) had no degrading effect on subsequent stress rupture properties (4). Although gamma prime coarsening and some minor phase precipitation were observed during these exposures, no degradation of the lamellar structure or interfaces was observed.

The oxidation resistance of $\gamma/\gamma' - \delta$ is about equivalent to that of d.s. MAR-M 200 + Hf at 980° C (1800° F) but is substantially poorer around 760° C (1400° F) where the intermetallic δ phase preferentially oxidizes. Electron beam deposited NiCrAlY coatings have been demonstrated as providing adequate oxidation and hot corrosion protection for airfoil regions, while either NiCrAlY or platinum modified diffusion aluminide coatings were found to be adequate for the cooler surfaces of the blade root (6).

Although the longitudinal rupture properties of $\gamma/\gamma' - \delta$ have been optimized by directional solidification, some other properties are marginal. For instance, in a simulated turbine blade service cycle with imposed strain-temperature cycling, the thermomechanical fatigue resistance of $\gamma/\gamma' - \delta$ has been shown to be substantially poorer than that of d.s. MAR-M 200 + Hf (8). This poor thermomechanical fatigue behavior of the eutectic has been attributed to its high modulus of elasticity (220 GPa (32×10^6 psi)) in the longitudinal direction and its relatively low transverse ductility, shown in figure 8. Specifically, at 760° C (1400° F), a temperature region where airfoils experience maximum strain during thermal cycling, the $\gamma/\gamma' - \delta$ eutectic has only about 0.5 percent transverse ductility. As evident from this figure, this level of ductility is substantially less than that of d.s. MAR-M 200 + Hf and NiTaC-13. In addition a turbine blade material must have good shear rupture strength to withstand root shear stress loading. Laboratory evaluation of this eutectic has demonstrated that its shear rupture strength is substantially less than that of a conventionally cast nickel-base superalloy (4), see figure 9. For example, at 760° C (1400° F) the 100 hour shear rupture stress of $\gamma/\gamma' - \delta$ is 170 MPa (25 ksi) whereas that of B-1900 is about 450 MPa (65 ksi).

Prognosis. Based on the results of several detailed investigations (3, 4, 6, and 8), it appears that the $\gamma/\gamma' - \delta$ eutectic will not provide adequate service for thermal fatigue limited components - such as vanes and first-stage hollow blades for advanced commercial turbine engines. Since the shear rupture strength falls short of root attachment requirements of some advanced, high work turbine engines, lower stress root designs and/or superalloy bonded roots would be required for such applications (8). In addition further optimization of protective coatings is desirable to minimize fatigue crack initiation and thermal expansion mismatch between coatings and the $\gamma/\gamma' - \delta$ eutectic substrate.

Since the operating conditions of many existing and advanced turbine engines are not as severe as those of the advanced commercial engine evaluated in the program of reference 8, it is quite possible that the $\gamma/\gamma' - \delta$ eutectic does have adequate properties for and would perform reliably in these less demanding applications. For example, the $\gamma/\gamma' - \delta$ eutectic is currently being evaluated (9) for use as a small, solid turbine blade in the PT-6 engine which powers many current helicopters and business jet aircraft. The alloy may be used as a direct substitution for the currently used d.s. superalloy in the PT-6 engine in order to achieve increased engine thrust, fuel savings, and blade life without resorting to cooled turbine blades. Engine testing of $\gamma/\gamma' - \delta$ for this application is planned for the end of this year.

NiTaC-13

Composition, structure and processing. The chemical composition of NiTaC-13 is Ni-3.3Co-4.4Cr-3.1W-6.2Re-5.4Al-5.6V-8.1Ta-0.48C (in weight percent), also listed in table I (5). The alloy microstructure, shown in figure 10, consists of a ductile γ/γ' nickel-base matrix, reinforced with about 3 volume percent of tantalum carbide (TaC) whisker-like rods. This structure was produced at a growth rate of 0.6 centimeter per hour (0.25 in./hr) in a d.s. rig with a thermal gradient of approximately 65° C per centimeter (300° F/in.) (critical G/R = 100° C hr/cm^2 (1160° F hr/in.^{2})).

Critical mechanical properties. Detailed evaluation of the NiTaC-13 eutectic (5) has demonstrated an average stress rupture temperature advantage of 45° C (80° F) over d.s. MAR-M 200 + Hf (see fig. 6). Specifically, material 5.0 centimeters (2 in.) from the bottom (first to freeze) of d.s. bars exhibits a stress rupture capability of 1015° C (1860° F) for 1000 hours at 150 MPa (22 ksi), while material from nearer the top (12.6 cm (5 in.) from the bottom) of bars has a temperature capability of only 980° C (1800° F), see figure 11. These results are directly attributable to the segregation of alloying elements along the length of a d.s. casting. For example, the volume percent of reinforcing TaC rods decreases from about 3.4 to 1.9 percent as solidification progresses from the bottom to the top of the d.s. bars discussed above, and the turbine blade shown in figure 10(a). In addition to variations in mechanical properties this effect results in a density decrease of 8.9 to 8.5 gm/cm^3 (0.319 to 0.308 lb/in.^{3}) from the bottom to the top of d.s. castings.

Both the low cycle fatigue and thermal fatigue resistance of NiTaC-13 are superior to those of several conventional nickel-base superalloys. The transverse tensile ductility of the eutectic at 650° C (1200° F) is 3 percent which is substantially greater than that of $\gamma/\gamma' - \delta$, see figure 8. However, the low transverse elongation at 1040° C (1900° F) of about 1 percent may result in some casting problems (e.g., hot tearing) with intricate hollow blade designs.

Although some indications of microstructural instabilities (e.g., precipitation of new phases) have been observed, their influence on mechanical properties has not yet been determined. A NiCrAlY coating evaluated in this program (5) was determined to be inadequate for eventual service applications. Although it provided excellent protection against oxidation and hot corrosion under mildly corrosive conditions, it was deficient under severe corrosion conditions and it substantially degraded high cycle fatigue strength.

Blade life analyses, based on test bar mechanical and physical properties, predicted that the low cycle fatigue life of NiTaC-13 greatly exceeded the goal of 5000 cycles, the high cycle fatigue life was within 5 percent of the goal, and that the stress rupture capability was about 43 percent below the predicted life of the cooled superalloy blade. Bench and rig tests of full size blades confirmed the LCF and HCF predictions, indicated that the root shear properties were adequate, and indicated that NiTaC-13 would meet the stress rupture life goal. Long-term engine testing would be required to confirm these bench test results.

Prognosis. The overall objective of this program (5) was the development of materials, design and fabrication technologies required for the application of eutectics as aircraft turbine blades. The specific goal of producing an uncooled NiTaC-13 low pressure turbine blade for the J101 engine which could be substituted for the currently cooled superalloy blade was successfully demonstrated. This goal represents an increase in blade pitch line bulk metal temperature of from 890° C (1635° F) for the current superalloy to 977° C (1790° F) for NiTaC-13.

In an extension to the program of reference 5, six instrumented, uncoated, solid NiTaC-13 blades, together with 76 cooled superalloy blades, were successfully tested in a J101 engine for 13 hours. Although both laboratory and engine test results indicate that NiTaC-13 has some potential as a turbine blade material, this was a demonstration program only and it does not appear at this time that NiTaC-13 will be used in commercial applications, primarily because of microstructural instability and poor uncoated and coated oxidation resistance. However, this eutectic system can be considered the forerunner of subsequent NiTaC-type eutectics.

SECOND GENERATION SYSTEMS FOR BLADE APPLICATIONS

$\gamma/\gamma' - \alpha$

Research on the gamma/gamma prime-alpha eutectic has made significant progress in the past year, and it now appears that this system may have potential as a turbine blade material. The eutectic consists of a gamma matrix strengthened by gamma prime precipitates (7), or the converse (11), and is reinforced with approximately 23 volume percent of molybdenum rods, see table I and figure 12. Limited data available to date indicate that the simple ternary eutectic Ni-32Mo-6Al solidified at 3 centimeters per hour (1.2 in./hr) has about 55° C (100° F) stress rupture advantage over d.s. MAR-M 200 + Hf at a stress of 150 MPa (22 ksi) for 1000 hours, see table II. Substantial research effort is currently underway in order to more fully characterize this eutectic system and to increase its use temperature capability still further. Major compositional modifications are being evaluated in order to strengthen both the matrix and the reinforcing rods.

Preliminary data indicate that the $\gamma/\gamma' - \alpha$ eutectic has good transverse ductility (2% or greater at all temperatures), good oxidation resistance (particularly when alloyed with small amounts of chromium), and good tensile shear strength. However, available data also indicate that the shear rupture strength of the eutectic is almost as low as that of $\gamma/\gamma' - \delta$, and that the thermal fatigue resistance and thermal cycling stability of the $\gamma/\gamma' - \alpha$ eutectic need improvement (11). Additional research is required to improve these properties, to evaluate root joining or forming techniques, and to develop an oxidation and hot-corrosion resistant coating with a coefficient of thermal expansion closely matched to the $\gamma/\gamma' - \alpha$ substrate.

NiTaC 3-116A

An extensive effort has recently been completed on developing an improved NiTaC eutectic for use as an advanced high pressure turbine blade (12). Goals of this program were improved stress rupture capability, thermal stability, and oxidation resistance relative to NiTaC-13. The eutectic most closely meeting the program goals has been termed NiTaC 3-116A, with a composition of Ni-8.2Ta-0.24C-6.3Re-6.5Al-4.2V-3.7Co-1.9Cr (table I). It has a gamma/gamma prime matrix reinforced with about 3 volume percent of TaC rods, and has a density of approximately 8.6 g/cm^3 (0.31 $lb/in.^3$). Limited data available when this paper was written indicated that the stress rupture capability of this eutectic was 70° C (130° F) greater than MAR-M 200 + Hf (table II). Detailed evaluation of other mechanical properties, such as tensile, fatigue, impact, hot-corrosion, were underway as of this writing. Assuming that no "show stoppers" are uncovered during subsequent development of this eutectic, its very high use temperature capability offers great promise for use as an advanced hollow blade material.

SECOND GENERATION SYSTEMS FOR VANE APPLICATIONS

Turbine vane materials have somewhat different physical and mechanical property requirements than do candidate turbine blade materials. For example, operating stress levels for vanes are substantially lower than blade stress levels. Typical vane stresses range from 35 to 75 MPa (5 to 11 ksi) and for comparison purposes in this paper a stress of 69 MPa (10 ksi) will be used, see table II. Vane materials must also have good thermal fatigue, oxidation and corrosion resistance. A high melting point is also desirable in order to minimize the effects of occasional over-temperature operating conditions. Two recently identified eutectics appear to have potential as vane materials for turbine engines. The properties of these two eutectics will be described in this section to the extent that their very early development status permits.

$\gamma - \beta$

Preliminary evaluations indicate that the gamma-beta eutectic has potential as an advanced vane material (7). A matrix of γ solid solution strengthened nickel can be reinforced with β NiAl lamellae in the Ni-11Al-8W-10Co alloy or reinforced with β rods (and TaC rods) in the Ni-10Al-3W-10Co (-6Ta-C) alloy (table I). Nominal densities of eutectics in the $\gamma - \beta$ system are 8 g/cm^3 (0.29 $lb/in.^3$), growth rates range from 2 to 5 centimeters per hour (0.8-2 in./hr), and solid vanes have been readily produced. The stress rupture strength of this eutectic is superior to currently used vane alloys, such as X-40 and MAR-M 509, figure 13. Thermal cycling to 1150° C (2100° F) had virtually no effect on mechanical properties. The oxidation resistance is superior to that of the first generation eutectics, and in fact, one lamellar version of this eutectic had cyclic oxidation resistance better than Hastelloy X. Additional research is required to evaluate the thermal fatigue resistance and to develop hot-corrosion and oxidation resistant coatings.

COTAC 74

Another eutectic for potential vane applications has been termed COTAC 74, although it is a gamma/gamma prime nickel-base eutectic, reinforced with CbC rods, with the composition, Ni-20Co-10Cr-10W-4Al-4.9Cb-0.6C (table I and ref. 13). This eutectic appears to have good thermal stability, transverse ductility and shear rupture strength. The stress rupture capability of this eutectic is less than conventional superalloys at low to intermediate temperatures, but is superior to the eutectics discussed previously at temperatures above 1000° C (1830° F), see figure 13.. If the thermal fatigue resistance is shown to be adequate and protective coatings are developed, this eutectic will have promise for vane or possibly for low pressure turbine blade applications.

CONCLUDING REMARKS

The economic benefits of eutectics are, of course, directly dependent upon the cost of the blade casting. For example, as shown in figure 14 and discussed previously, the cost-benefit studies of references 1 and 2 indicated that substantial economic benefits could be realized if eutectic blades could be produced for the same cost as d.s. MAR-M 200 + Hf blades. However, although fuel savings would still result, the other economic benefits (ROI and LCC) would all but vanish if eutectic blades were to cost twice as much as the MAR-M 200 + Hf blades. These studies illustrate one of the most critical aspects affecting the promise of eutectics - low solidification rates (<2.5 cm/hr (<1 in./hr)), low yields and projected high prices for eutectic blades.

It has not been the intent of this paper to review and discuss all of the eutectic systems identified to date. Rather, the purpose was to review in some detail the first generation eutectics, $\gamma/\gamma' - \delta$ and NiTaC-13, which have been or will shortly be evaluated through engine testing, and to briefly review a few of the more promising second generation eutectics. Particular attention has been paid to mechanical properties, such as transverse ductility and shear strength, that can be inherently critical in a directional structure like that of eutectics. Further research and development requirements in the fields of properties, coatings and lower cost processing technology have been identified. It is anticipated that the first use of a eutectic airfoil may be as solid blades or vanes for military engine applications, with the ultimate use as an advanced hollow turbine blade possibly occurring by the mid 1980's.

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Table I. Composition, Structure and Processing Conditions of Several Directionally Solidified Eutectics

System / Property	First generation eutectic systems for blades		Second generation eutectic systems			
			Blades		Vanes	
	$\gamma/\gamma' - \delta$	NiTaC-13	$\gamma/\gamma' - \alpha$	NiTaC 3-116A	$\gamma - \beta$	COTAC 74
Composition, w/o						
Ni	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.
Co	---	3.3	-	3.7	10	20
Cr	6.0	4.4	-	1.9	--	10
Al	2.5	5.4	6	6.5	11	4
Cb	20.1	---	-	---	--	4.9
Ta	---	8.1	-	8.2	--	--
C	0.06	.48	-	.24	--	0.6
W	---	3.1	-	---	8	10
Re	---	6.2	-	6.3	--	--
V	---	5.6	-	4.2	--	--
Mo	---	---	32	---	--	--
Matrix phase(s)	γ/γ'	γ/γ'	γ/γ'	γ/γ'	γ	γ/γ'
Reinforcing phase	Ni_3Cb	TaC	Mo	TaC	NiAl(TaC)	CbC
Reinforcing form	Lamellae	rods	rods	rods	lam/rods	rods
Reinforcing v/o	40	3	23	3	7-15	6
Density,						
g/cm^3	8.6	8.7	8.5	8.6	8.0	8.6
$lb/in.^3$	0.310	0.315	0.307	0.31	0.29	0.31
Melting temp.,						
°C	1270	1350	1310	----	1370	1330
°F	2320	2460	2390	----	2500	2425
Critical G/R,						
$°C\text{-}hr/cm^2$	150	100	50	----	----	----
$°F\text{-}hr/in.^2$	1740	1160	580	----	----	----
Growth rate,						
cm/hr	2	0.6	3	0.6	2-5	1
in./hr	0.8	0.25	1.2	0.25	0.8-2	0.4

Table II. Mechanical Properties of Several Directionally Solidified Eutectics

System / Property	First generation eutectic systems for blades		Second generation eutectic systems			
			Blades		Vanes	
	$\gamma/\gamma' - \delta$	NiTaC-13	$\gamma/\gamma' - \alpha$	NiTaC 3-116A	$\gamma - \beta$	COTAC 74
Potential use temp., °C* [150 MPa (22 ksi), 1000 hr], °F	1000 1830	1005 1840	1015 1860	1030 1890	---- ----	---- ----
[69 MPa (10 ksi), 1000 hr], °C °F	---- ----	---- ----	---- ----	---- ----	1010 1850	1095 2000
Shear rupture strength, MPa [760° C (1400° F), 100 hr], ksi	170 25	---- ----	220 32	---- ----	<170 <25	~340 ~50
Transverse tensile elongation at 760° C (1400° F), %	0.5	3	5	----	<1	2
Oxidation/hot corrosion resistance	Poor	Poor	Good	Good	Exc.	Good

*Baseline 960° C (1760° F) for d.s. MAR-M 200 + Hf.

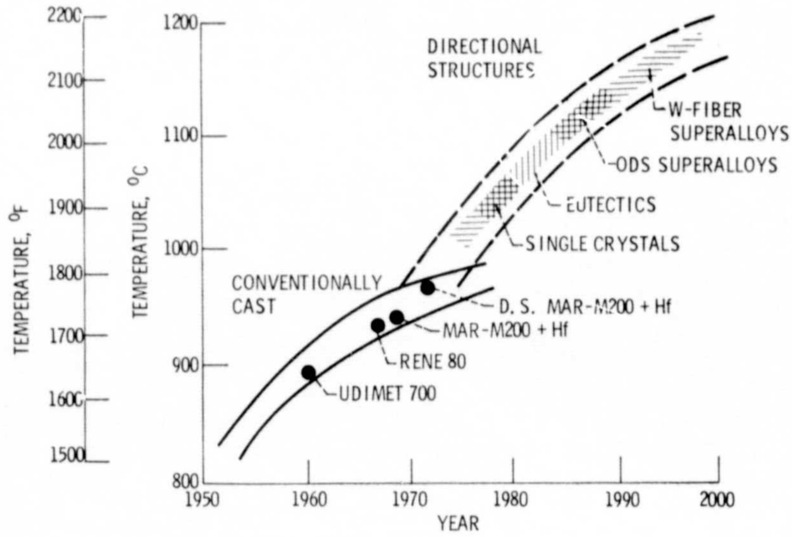

Fig. 1. Use temperature capabilities of currently available conventionally cast turbine blade alloys and projected capabilities of advanced blade materials at 150 MPa (22 ksi) for 1000 hours.

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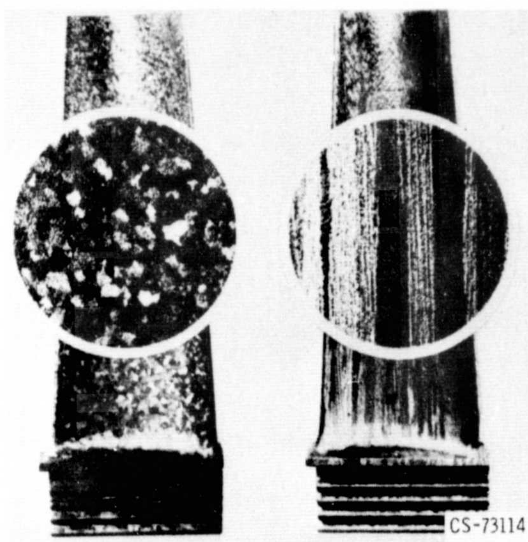

CONVENTIONALLY CAST DIRECTIONALLY SOLIDIFIED

Fig. 2. - Random and controlled grain structures in cast blades. (Courtesy of Pratt and Whitney Aircraft.)

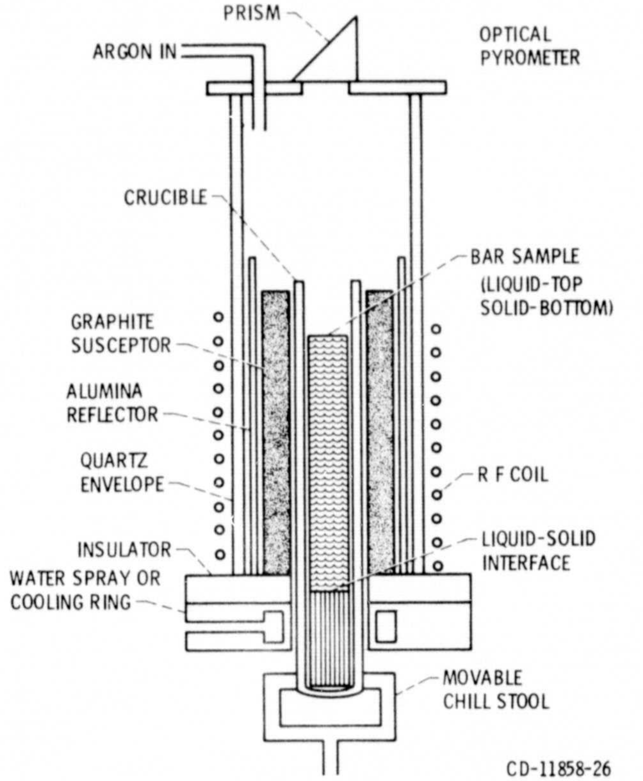

Fig. 3. Directional solidification apparatus.

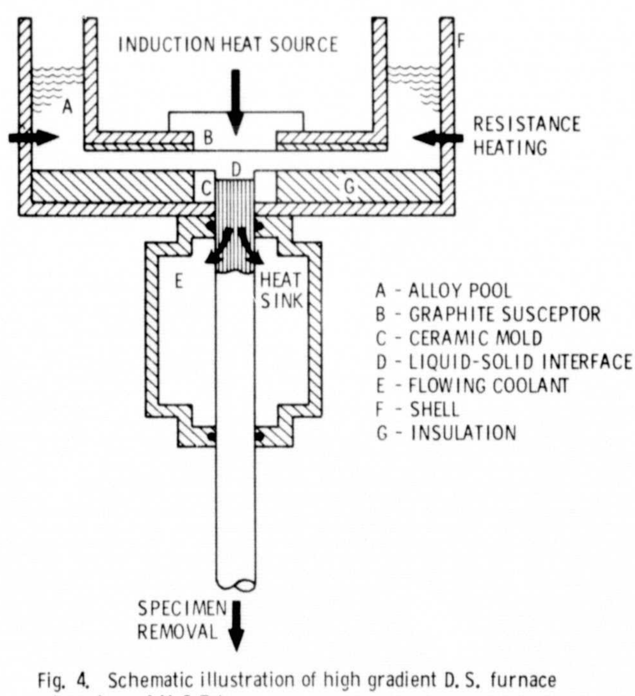

Fig. 4. Schematic illustration of high gradient D. S. furnace (courtesy of M. I. T.).

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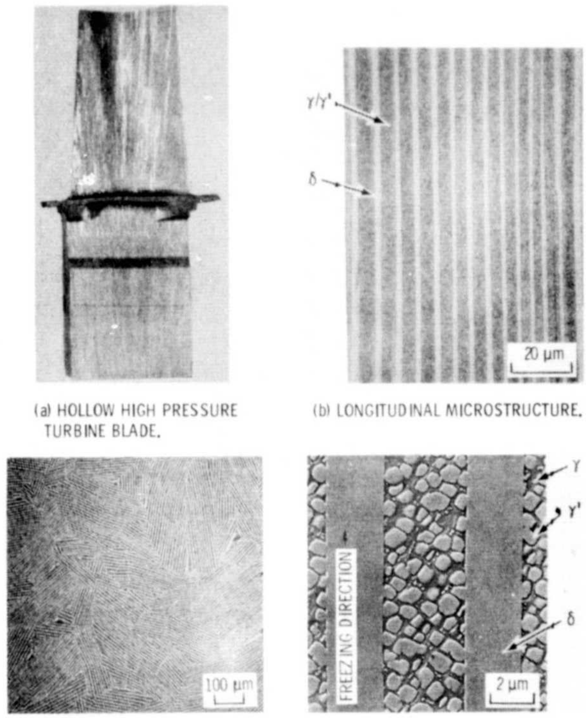

(a) HOLLOW HIGH PRESSURE TURBINE BLADE.

(b) LONGITUDINAL MICROSTRUCTURE.

(c) TRANSVERSE MICROSTRUCTURE.

(d) LONGITUDINAL MICROSTRUCTURE.

Fig. 5. - Turbine blade and microstructure of γ/γ'-δ (ref. 3 and 4). (Photographs courtesy of Pratt and Whitney Aircraft.)

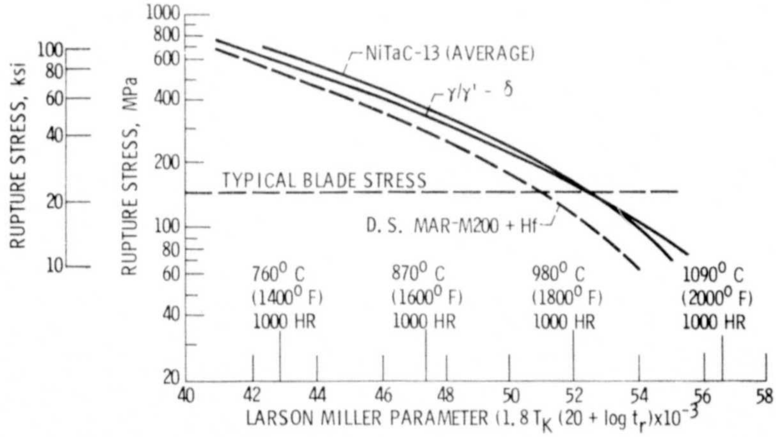

Fig. 6. A comparison of stress-rupture properties of first generation directionally solidified eutectics with those of D. S. MAR-M200 + Hf (refs. 4 and 5).

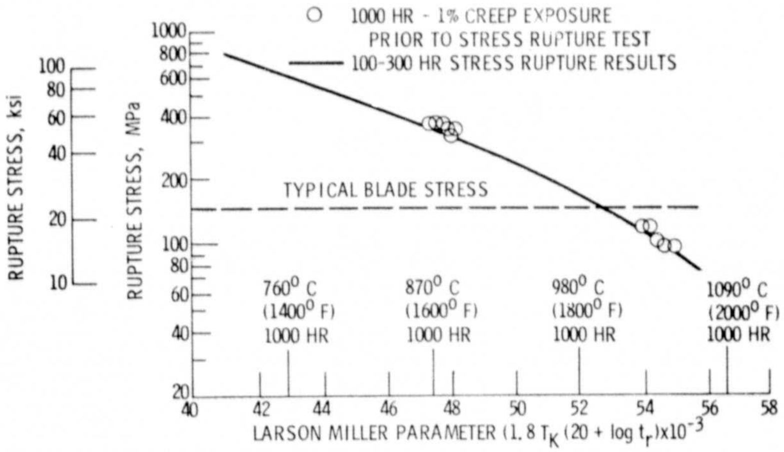

Fig. 7. Long-time creep exposure of γ/γ' - δ does not degrade subsequent stress rupture strength (ref. 4).

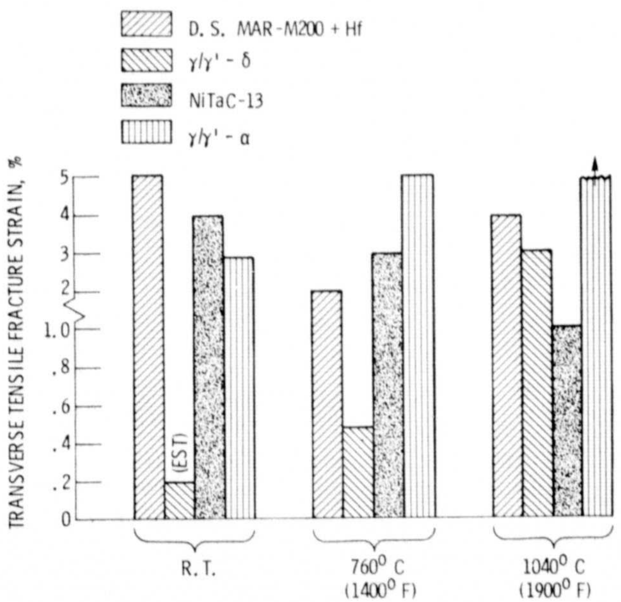

Fig. 8. Transverse tensile elongation of several eutectics and a d. s. superalloy (refs. 4, 5, 7, and 11).

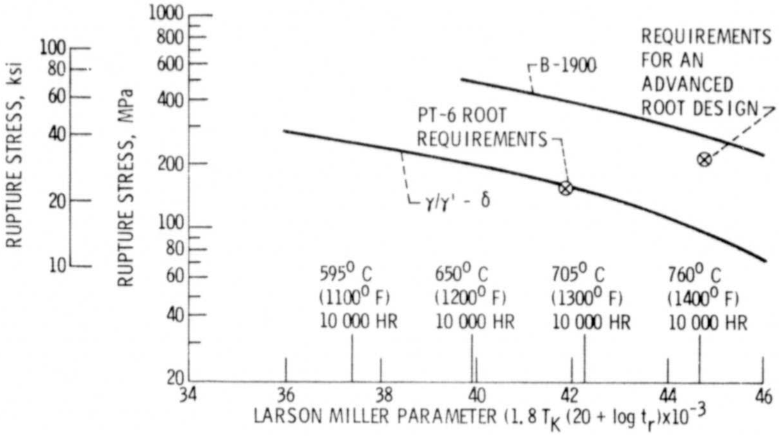

Fig. 9. Shear rupture capability of $\gamma/\gamma' - \delta$ and conventionally cast B-1900 nickel-base superalloy (refs. 4, 8, and 9).

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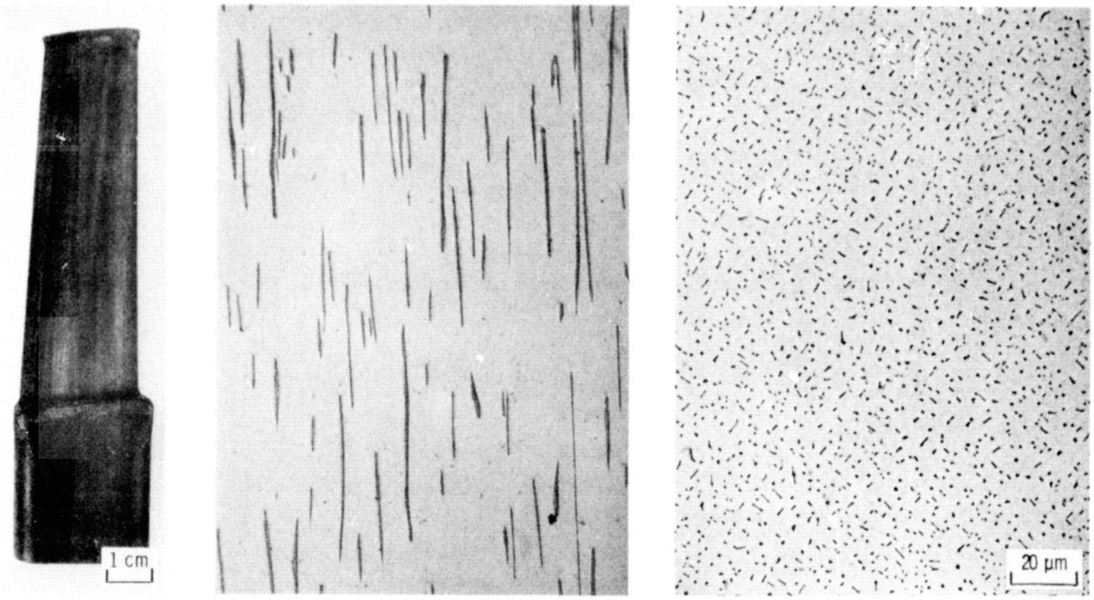


(a) SOLID LOW PRESSURE TURBINE BLADE. (b) LONGITUDINAL MICROSTRUCTURE. (c) TRANSVERSE MICROSTRUCTURE.

Fig. 10. - Turbine blade and microstructure of NiTaC-13 (ref. 5). (Photographs courtesy of General Electric Co.

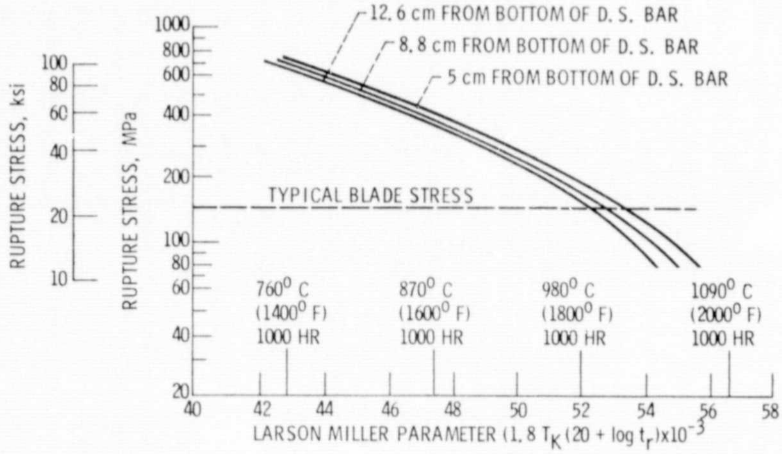
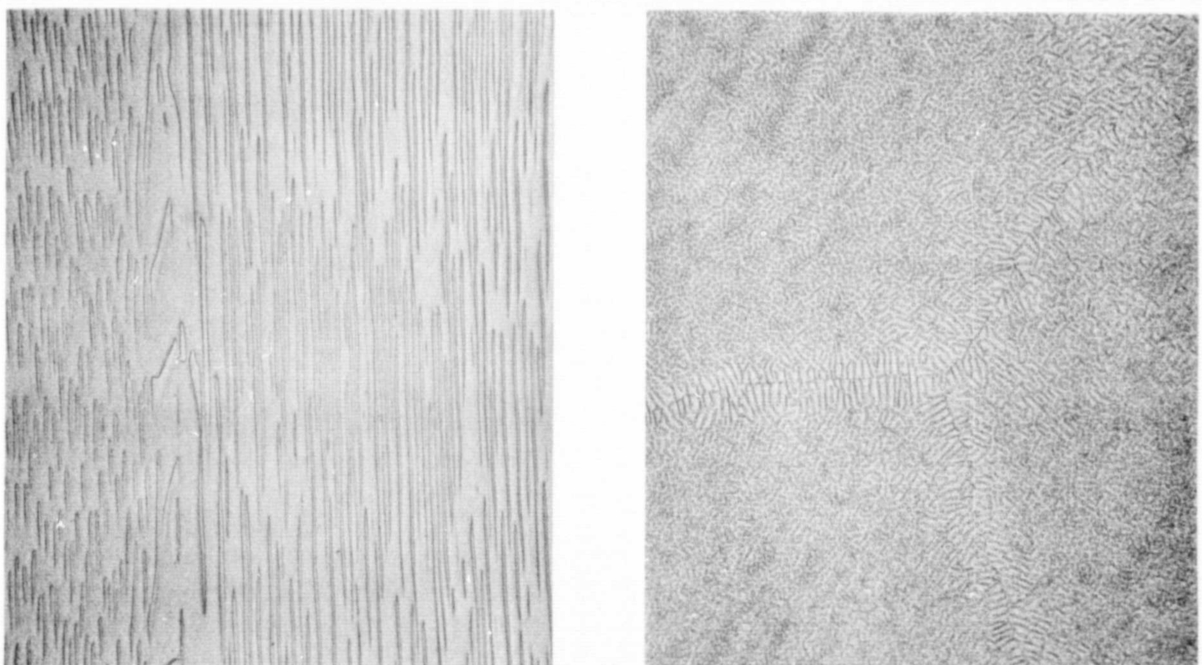


Fig. 11. Effect of alloy segregation during solidification on stress-rupture strength of NiTaC-13 (ref. 5).



(a) LONGITUDINAL.

(b) TRANSVERSE.

Fig. 12. - Typical microstructure of γ/γ'-α eutectic (ref. 7).

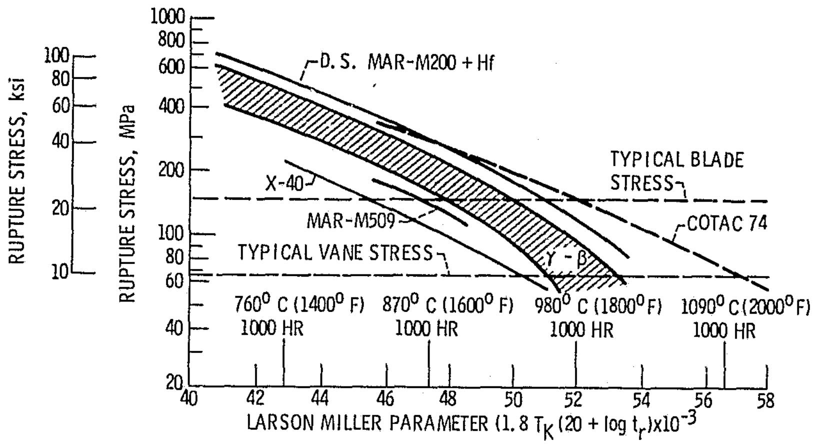


Fig. 13. Stress-rupture strength of D.S. eutectics for potential turbine vane applications compared with conventionally cast cobalt-base vane alloys and D.S. MAR-M200 + Hf (refs. 7 and 13).

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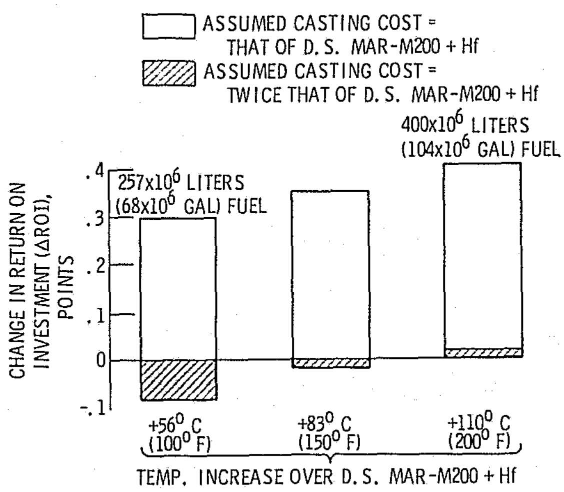

Fig. 14. Potential economic benefits and annual fuel savings for a fleet of 500 aircraft from using advanced turbine blades at various increases in use temperature capability (refs. 1 and 2).