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MATERIALS FOR ADVANCED TURBINE ENGINES

PROJECT COMPLETION REPORT
PROJECT 1

LOW-COST DIRECTIONALLY-SOLIDIFIED TURBINE BLADES

VOLUME I

by

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FOREWORD

This Project Completion Report was prepared for the National Aeronautics and Space Administration, Lewis Research Center. It presents the results of a program conducted to establish exothermic heated casting technology for the manufacture of low-cost, directionally-solidified, uncooled turbine blades for gas turbine engines. The program was conducted as part of the Materials for Advanced Turbine Engines (MATE) Program under Contract NAS3-20073.

The authors wish to acknowledge the assistance and guidance of N. L. Saunders, C. P. Blankenship, and R. L. Dreshfield of the Materials and Structures Division of NASA-Lewis Research Center. Major contributions to the success of the program were made by C. M. Phipps and R. J. Quigg of Jetshapes, Inc.

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INTRODUCTION

The NASA Materials for Advanced Turbine Engines (MATE) Program is a cooperative effort with industry to accelerate introduction of new materials into aircraft turbine engines. As part of this effort, AiResearch was authorized under NASA Contract NAS3-20073 to develop a new technology for manufacturing low-cost directionally-solidified uncooled cast turbine blades to reduce cost and fuel consumption in the TFE731-3 Turbofan Engine. The process development performed included those efforts required to carry the technology from the previously demonstrated feasibility stage through component demonstration by engine test. Portions of the overall effort included process scale-up, alloy evaluations, mechanical property generation, hardware procurement, and full-scale engine testing to evaluate potential benefits.

This report constitutes Volume 1 of a two-volume Project Completion Report presenting the results of the investigations and tests performed under MATE Project 1, Low-cost Directionally-Solidified Turbine Blades. This volume covers all Project 1 tasks with the exceptions of full-scale engine testing and post-test analysis, which are the subjects of Volume 2 of this report.

The intent of Project 1 was to develop a process to produce directionally-solidified, solid, uncooled turbine blades and to design and substitute this blade for the hollow, air-cooled, conventionally-cast turbine blade utilized in the high-pressure turbine of the Garrett AiResearch TFE731-3 Turbofan Engine. The project goals associated with this substitution were:

(1) A reduction in engine specific fuel consumption (SFC) of at least 1.7 percent;

(2) A reduction in engine manufacturing costs of at least 3.2 percent;

(3) A reduction in engine weight of at least 1 percent;

(4) A reduction in engine maintenance costs of at least 6.2 percent.

Project 1 was subdivided into the following seven tasks:

Task I - Casting Technology
Task II - Alloy/Process Selection
Task III - Property Characterization
Task IV - Blade Design
Task V - Component Manufacture
Task VI - Engine Test
Task VII - Post-Test Analysis

In Task I, the exothermic directional-solidification (DS) process was adapted to economically cast solid high-pressure turbine blades of MAR-M 247 for the TFE731-3 Turbofan Engine, and establish the levels of mechanical properties attainable. During Task II, four candidate alloys (MAR-M 247, MAR-M 200+Hf, IN 792+Hf, and NASA-TRW-R) were evaluated as exothermically cast DS blades, and all except IN 792+Hf were selected for subsequent test comparison. An improved heat treatment for MAR-M 247 incorporating a higher solution heat-treatment temperature was also developed. In Task III, mechanical and physical properties of DS castings of the three selected alloys were further evaluated to provide allowable stress levels for a redesigned turbine blade. Mechanical properties determined included creep-rupture strengths, tensile strengths, and high- and low-cycle-fatigue strengths. Concurrently, Task IV was accomplished to adapt the disk, and design the blade airfoil and blade root to best accommodate the stress-rupture, tensile strength, and other properties of the chosen alloys to the test engine. During Task V, manufacture of the hardware required to support the Task VI engine testing was accomplished. NASA-TRW-R, one of the three alloys, demonstrated a castability problem in Task V and was therefore dropped from the project. Turbine blades manufactured from the remaining two alloys, MAR-M 247 and MAR-M 200+Hf, were engine tested.

The engine testing, performance, and post-engine-test evaluations of the turbine blades are described in Volume 2 of this report.

SUMMARY

The project accomplishments included the development of the exothermically-heated, directional-solidification casting process into a viable process for producing solid TFE731-3 high-pressure turbine blades. High quality directionally-solidified blades of the new design were cast in the MAR-M 247 and MAR-M 200+Hf alloys. These blades were finish processed through heat treatment, machining, and coating operations for the engine test described in Volume 2 of this report. The blade cost portion of the engine manufacturing cost goal of this project was achieved with projected volume production costs for the solid DS blade being 58-percent of the cost of the cooled equiaxed IN100 blade. The engine weight reduction goal can be achieved in a turbine redesign by eliminating the retainer plate used to deliver the blade cooling air and redesigning the disk. These changes were not incorporated in the engine test configuration since reduced cooling air was required to utilize a production Waspaloy disk thus avoiding a new disk design and/or material. The long-term maintenance cost goal is expected to be realized by the substitution of a more rugged, solid airfoil for the thin walled, cooled blade currently used. This design provides more resistance to foreign object damage (FOD) and more capability for being recoated. The elimination of cooling air and the cooling air circuit also avoids many operational problems over the life of an engine.

Task I of the project established a directional-solidification casting process for solid MAR-M 247 high-pressure turbine blades employing an exothermically heated ceramic mold. Key process elements established were the mold design, a furnace ignition technique for the exothermically-heated molds, and improved quality requirements for the exothermic material. Baseline tensile and stress-rupture strengths for DS MAR-M 247 turbine blades were determined. Good reproducibility was shown for

the results of tests on 0.178-cm (0.070-inch) gauge diameter minibars machined from the DS blades (MFB). This MFB minibar was thus used for all subsequent tensile and stress-rupture testing in this project.

Utilizing the DS casting process developed in Task I, turbine blades and test slabs of four nickel-base alloys (MAR-M 247, MAR-M 200+Hf, IN 792+Hf, and NASA-TRW-R) were successfully cast in Task II. Casting process yields and selected mechanical and physical properties were determined for castings of the four alloys, and a heat-treatment optimization study was conducted. During the course of Task II, the IN 792+Hf alloy was dropped from the project, as its stress-rupture strength was substantially lower than those of the other three alloys. A solution heat-treatment temperature of 1505°K (2250°F) was found to produce more uniform and higher stress-rupture lives in MAR-M 247 DS castings than did the 1494°K (2230°F) treatment previously used.

Task III characterized, in greater detail, the mechanical and physical properties of MAR-M 247, MAR-M 200+Hf, and NASA-TRW-R DS cast turbine blades and bars. Tensile and stress-rupture tests were performed in both longitudinal and transverse blade directions.

An uncooled turbine blade design tailored to the mechanical properties of the strong DS cast alloys was developed in Task IV. A preliminary design was developed early in the project, and a final design, more thoroughly analyzed for the engine test conditions, was developed later utilizing material property data from Task III. To accommodate the uncooled final design blades, modifications were made to the turbine disk, nozzle, and other turbine section components of the TFE731-3 Engine.

In Task V, the DS turbine blades and other unique components for the engine test were manufactured. During the casting of these blades, a "hot tear" castability problem with the NASA-TRW-R alloy was encountered. The NASA-TRW-R alloy was thus eliminated from further consideration, and only MAR-M 247 and MAR-M 200+Hf blades were processed into engine test parts. Approximately three-fourths of the finish-processed blades were MAR-M 247.

Task VI subjected the DS-cast turbine blades to engine testing in a modified TFE731-3 Turbofan Engine. Post-test evaluations of the engine-tested turbine blades were performed in Task VII. The engine testing and the post-test evaluations are reported separately in Volume 2 of this Project Completion Report.

TASK I - CASTING TECHNOLOGY

Exothermically-Heated Casting System

The objective of Task I was to develop the capability to produce controlled directionally-solidified grain structure in the uncooled high-pressure turbine blade for the test engine. The low-cost, exothermically-heated casting system was selected to produce the turbine blade. This process was selected based on the success achieved in prior contract work performed by Detroit Diesel Allison for the Air Force Materials Laboratory.[(1)] A schematic of this process is shown in Figure 1.

With this casting process, a lost-wax ceramic mold is manufactured that is open at the top for receiving the molten metal, and is also open (in a flat plane) on the bottom. After dewax and firing this mold is fitted inside a preformed refractory sleeve and surrounded with a suitable high-firing temperature exothermic material. The exothermic material is packed around and over the tops of the airfoil mold and gating, leaving the top and bottom openings of the mold exposed. The mold assembly is then heated by the heat released from ignition of the exothermic material to a temperature above the melting point of the alloy to be cast.

Prior to pouring, the hot mold assembly is placed on a water-cooled copper chill that provides a bottom closure for the mold. This chill establishes a very steep temperature gradient in the mold cavity. Since the bottom closure of the mold cavity is formed by the chill, very rapid nucleation will occur in the molten metal that directly contacts the chill as the metal is poured. Nucleation is prevented in portions of the mold at greater distances away from the chill since heat released by the exothermic material maintains the local mold temperature above

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[(1)] Kanaby et al, "Directional Solidifcation of Superalloys"; AFML-TR-77-126, September 1977.

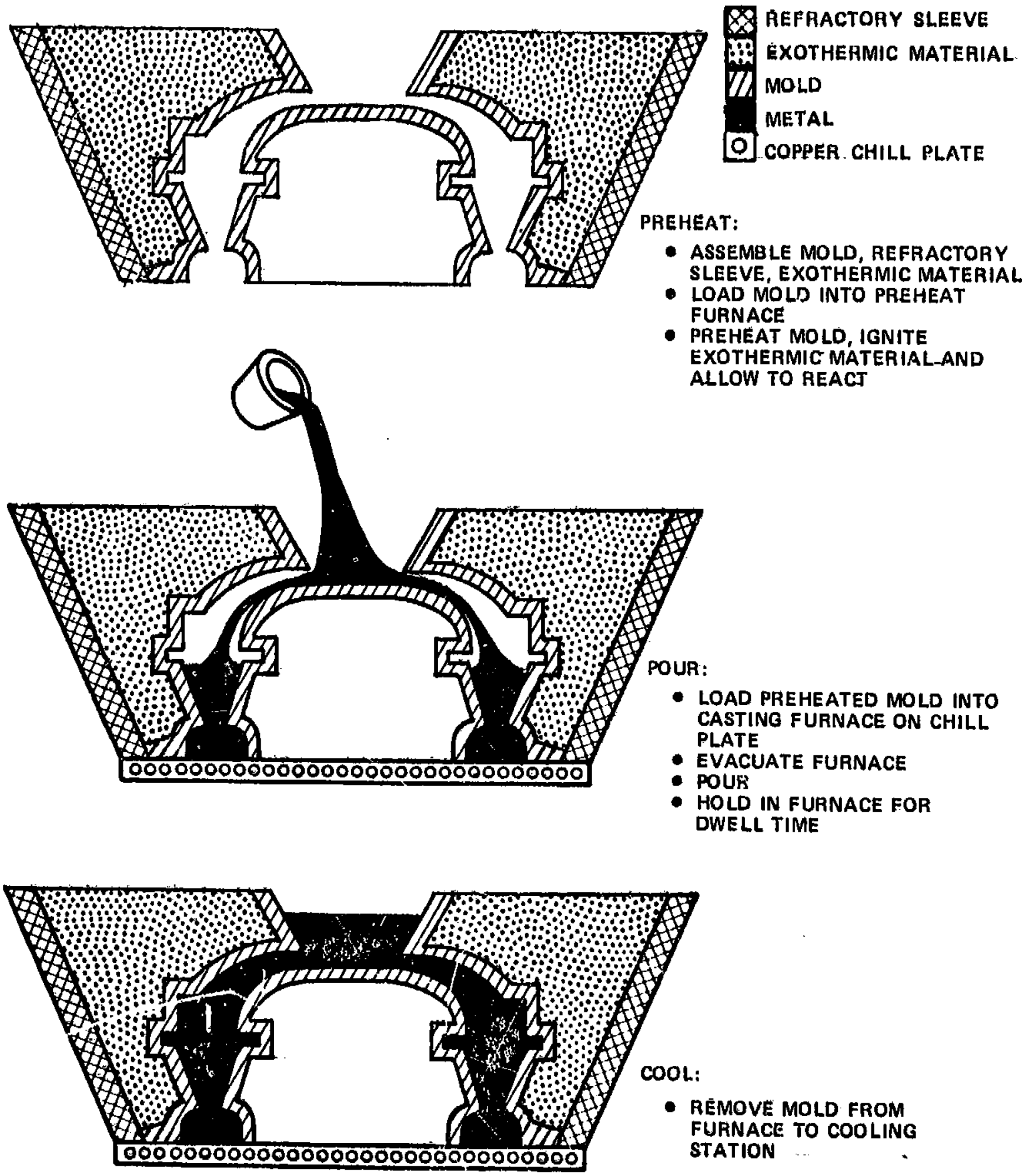


Figure 1. Simplified Schematic of Exothermically-Heated Directional-Solidification Casting Process

the melting point of the alloy. Therefore, those grains nucleated at the chill plate that have a crystallographic orientation favorable for rapid grain growth in the direction of the mold temperature gradient quickly develop a columnar grain structure that is perpendicular to the chill. In the case of a turbine blade casting, parallel grains [of (100) crystalline direction] grow in the spanwise direction of the blade.

This columnar growth continues as long as the vertical temperature gradient is steep enough to preclude nucleation of new grains ahead of the advancing solidification front. The extent of growth of these columnar-oriented grains is limited only by the relationship of the rate of heat extraction through the solidified metal behind the advancing solidification front to the rate of heat loss from the molten metal ahead of the solidification front. The grain growth pattern in the casting will revert to an equiaxed structure at some distance away from the chill after the rate of heat extraction downward through the casting is not significantly larger than that in some other direction (for instance, horizontally through the mold wall).

Turbine blades can be cast with controlled solidification that produces a completely columnar structure with grain boundaries parallel to the major stress axis in the root and airfoil. This provides increased operational blade-temperature capability due to the absence of grain boundaries normal to the direction of highest stress that would ordinarily provide a preferred stress-rupture fracture path.

Process Development

One of the conclusions resulting from the Cost/Benefit Analysis[2] performed by AiResearch as part of the MATE Program was that solid DS cast turbine blades offer superior cost and fuel economy relative to cooled turbine blades for small engines. Achievement of these advantages is dependent upon the development of a low-cost manufacturing process that provides effective control over desired blade characteristics. A major objective of Task I was to demonstrate the technical and economic advantages of the exothermic casting process. The demonstration was performed under subcontract to AiResearch in a commercial foundry--Jetshapes, Inc., Rockleigh, N. J. (Jetshapes). The goal of the Task I activity performed by Jetshapes, was to evaluate casting process variables for the establishment of a controlled process for use in subsequent tasks. This was accomplished by manufacturing trial castings followed by evaluation of their quality and mechanical properties, and then developing preliminary process controls.

Casting trials and results. The Task I casting trials utilized the nickel-base alloy MAR-M 247 for the casting of 15 molds of blades and test bars. Each mold provided a minimum of 15 blade castings and 4 test bars. Among the process variables evaluated were mold temperatures, metal temperatures, shell thickness, exothermic material weight, exothermic material distribution, and processing time.

Wax patterns for the existing TFE731-2 equiaxed uncooled blade designs were utilized in the first 12 molds because of pattern availability and presumed similarity to the airfoil design

(2) Comey, D, "Cost/Benefit Analysis, Advanced Material Technologies, Small Aircraft Gas Turbine Engines; NASA CR135265 (AiResearch 21-2391), September 1977.

that would ultimately be engine tested. The final 3 molds of castings were produced from injected wax patterns utilizing the initial TFE731-3 blade design established under Task IV.

The baseline mold system utilized throughout this program was the Colal-P* alumina-flour binder developed by Detroit Diesel-Allison[3]. This binder minimizes metal-mold reactions in the prime (first) coat that contacts the molten metal during the pouring process. The back-up coats, which give the mold its basic strength and heat conductivity characteristics, were Jetshapes conventional silica-bonded alumina-silicate mold system.

Evaluations of a more conventional silica-bonded zirconium-silicate prime coat, in conjunction with standard back-up coats, were conducted during the program because of the relatively short useful shelf life of the Colal-P binder. However, a measurable decrease in the surface quality of castings, as evidenced by fluorescent-penetrant inspection, was always noted with the zirconium-silicate prime coat as a result of reactions between the molten metal and this prime coat in the DS casting process. The Colal-P binder shelf life problem has been reduced to an acceptable level by using plastic liners in all mixing and storage containers. The "gelling" of this binder is accelerated by contact with ferrous materials used for containers.

1. Molds 1 and 2. The initial mold was cast with the existing "best practice" casting procedure based on previous AiResearch-funded development work. The mold design, as adapted to the TFE731-2 high-pressure turbine blade design, had 5 radial spokes with a central downsprue and pouring cup as shown in Figure 2. Four blades, with the airfoil chords parallel, were on

*Registered trademark of E.I. DuPont de Nemours and Company

[3] Kanaby et al, "Automated Directional Solidification of Superalloys," AFML-TR-75-150, 1975)

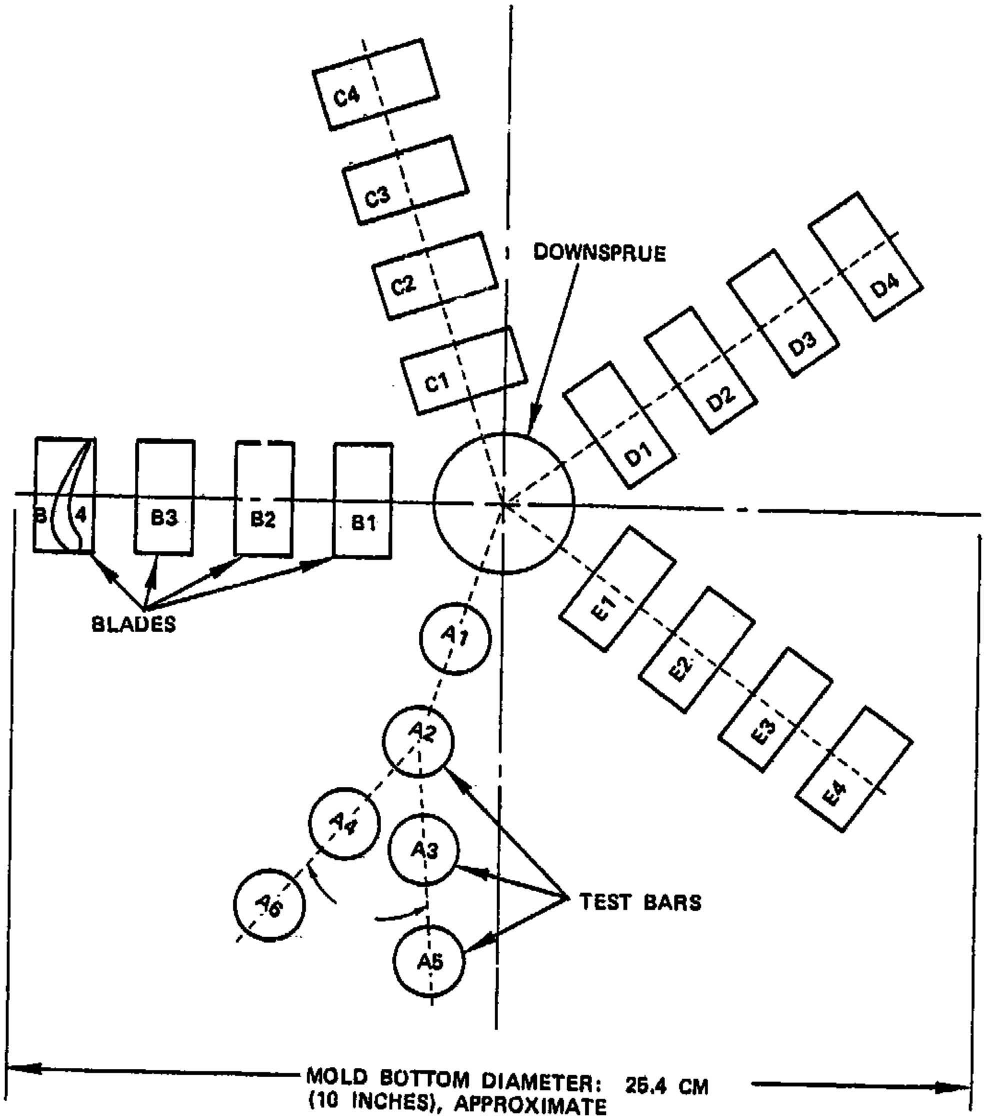


Figure 2. Task I Straight Spoke Mold Configuration

each of 4 spokes, with the fifth spoke having six 1.587-cm (0.625-inch) diameter test bars. This test-bar spoke was "Y" shaped to accommodate the two additional parts. The mold was cast with the blades in a root-down orientation.

Mold No. 2 was configured to evaluate the effect of an in-line airfoil chord arrangement to provide contact of the exothermic material against a larger surface area on the blade root and airfoil as compared to the parallel-chord arrangement. Due to the limiting diameter of the insulating sleeve used during exothermic firing, This chord-in-line arrangement required that each of the 5 spokes be wound in a spiral shape as shown in Figure 3.

Molds 1 and 2 were packed with standard-size [2.5 x 1.9 x 1.3 cm (1 x 0.75 x 0.5 inch)] Exomet Isogard* briquets inside an insulation sleeve. The assembled mold with the exothermic material was then preheated in a gas-fired furnace to 1144°K (1600°F) for 30 minutes to attain a uniform elevated temperature for the entire assembly, and to lessen possible thermal shock during ignition. The molds were removed from the furnace and the exothermic material was torch-ignited at the top. The entire assembly was covered with an insulated "can" and the exothermic process allowed to continue. Based on visual observation, the "burn" was complete in approximately 8 minutes for each mold. The mold was placed on a water-cooled copper chill in the vacuum-mold interlock 15 minutes after ignition of the exothermic, and the metal was poured after a 3-minute chamber pump-down time.

The copper chill for these two molds had been newly resurfaced with a shallow-groove, diamond-shaped 0.317-cm (0.125-inch) grid pattern for increased contact area with the casting. This grid pattern did not incorporate draft in the grooves, and consequently, the solidified castings were tightly locked into the

*Registered trademark of Exomet, Inc.

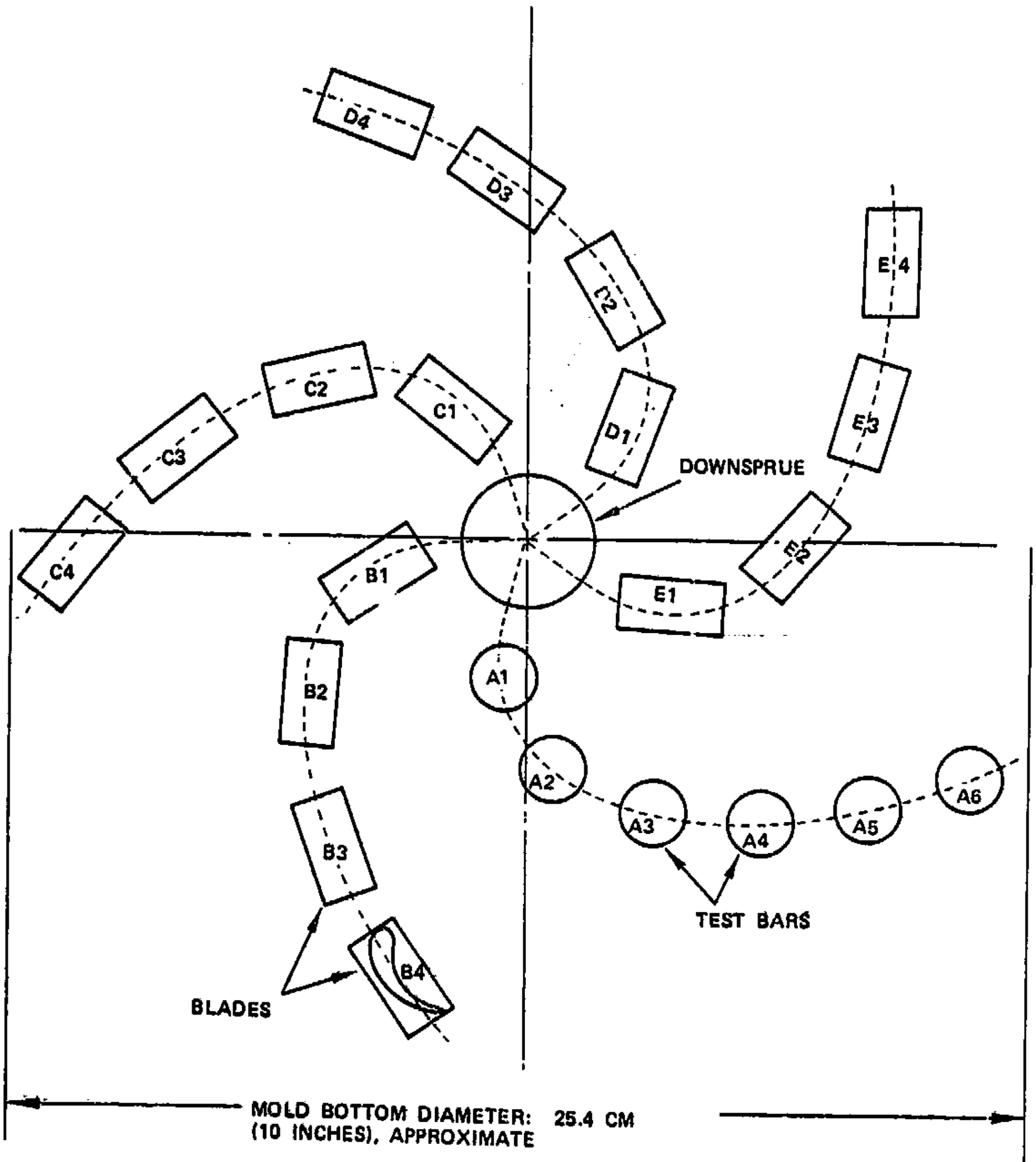


Figure 3. Task I Spiral Spoke Mold Configuration

chill. The mold material and exothermic cinder had to be broken off to remove the individual castings from the chill. The chill was subsequently reworked to provide adequate draft in the machined grooves.

All individual castings from Molds 1 and 2 were macroetched for grain structure evaluation. None of the blades from Mold 1 had an acceptable grain structure. This was due to nucleation of grains in the root at a considerable distance above the chill and from the airfoil trailing edge. However, the grain structure of the test bars was considered acceptable. Six of the 16 blades from Mold 2 had a reasonably controlled columnar grain structure, and all the test bars were acceptable. Four of the blades cast in Mold I are shown in Figure 4. It was evident that the temperatures employed during the casting process were too low, especially at the blade cavities next to the mold center.

2. Molds 3 and 4. For Mold 3 (straight spoke) and Mold 4 (spiral spoke), the hold time after exothermic material ignition was decreased, and the pour temperature was increased to increase the casting yield. In addition, based on observations of the exothermic cinder from Mold 2, small pieces [1.9-cm (0.75-inch) maximum dimensions] of exothermic briquets were used to fill mold 4 to above the top of the blade to improve the packing density, particularly for the innermost blades. Standard size briquets were used to fill the remainder of the mold to 7.5 to 10 cm (3 to 4 inches) above the top of the test bars. Mold 3 was filled with standard size briquets in the same manner as Mold 1.

Each mold was preheated and ignited using the same procedure as was used with Molds 1 and 2. However, as soon as visible flames stopped coming from the bottom of the pack, the mold was placed in the vacuum mold interlock and the metal was poured after pump-down. This reduced the ambient air temperature exposure time

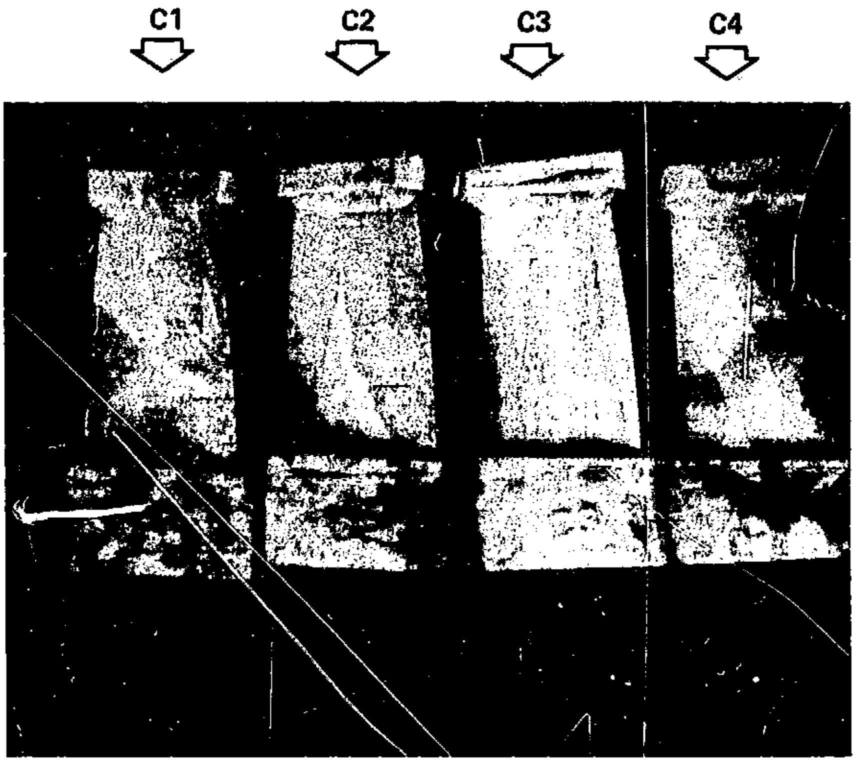


Figure 4. Task I, Mold 2 Blades Showing Good Grain Structure in Blade "C3" with Undesirable Grain Structure in the Other Three Blade Castings

after ignition by 7 to 8 minutes. The molds were also poured with the metal temperature approximately 28°K (50°F) higher than the pouring temperature for Molds 1 and 2.

The grain evaluation of these castings showed that the increased mold and metal temperature resulted in improved columnar structure, but further process modification was considered necessary to improve the grain structure to an acceptable level. A photograph of castings from Mold 4 is presented in Figure 5.

3. Molds 5 and 6. Based on the results of the first four molds cast, it was felt that, with the exothermic material and shell system utilized, the mold had not reached a sufficiently high temperature for completely satisfactory directional solidification. The 30-minute preheat period at 1144°K (1600°F) may have caused a gradual degradation of the exothermic material by partial oxidation of metallic constituents, resulting in a decrease in available heat energy.

Molds 5 (straight spoke) and 6 (radial spoke) were then cast utilizing direct-furnace ignition at 1366°K (2000°F). This procedure was evaluated as a means of ensuring maximum thermal energy distribution in the mold. Mold 5 was the first to be cast with this method. Eight and one-half minutes were required at 1366°K (2000°F) for exothermic igntion to be detected. The mold was left in the furnace for an additional 3 minutes and then removed. Six more minutes elapsed before the visible flames terminated, and the mold was placed in the vacuum chamber for metal pouring. Mold 6 was then cast following the same procedure. Seven and one-half minutes were required in the furnace for ignition, the mold burned for 5 minutes in the furnace, then was removed and burned an additional 5 minutes before being placed in the vacuum chamber for pouring.

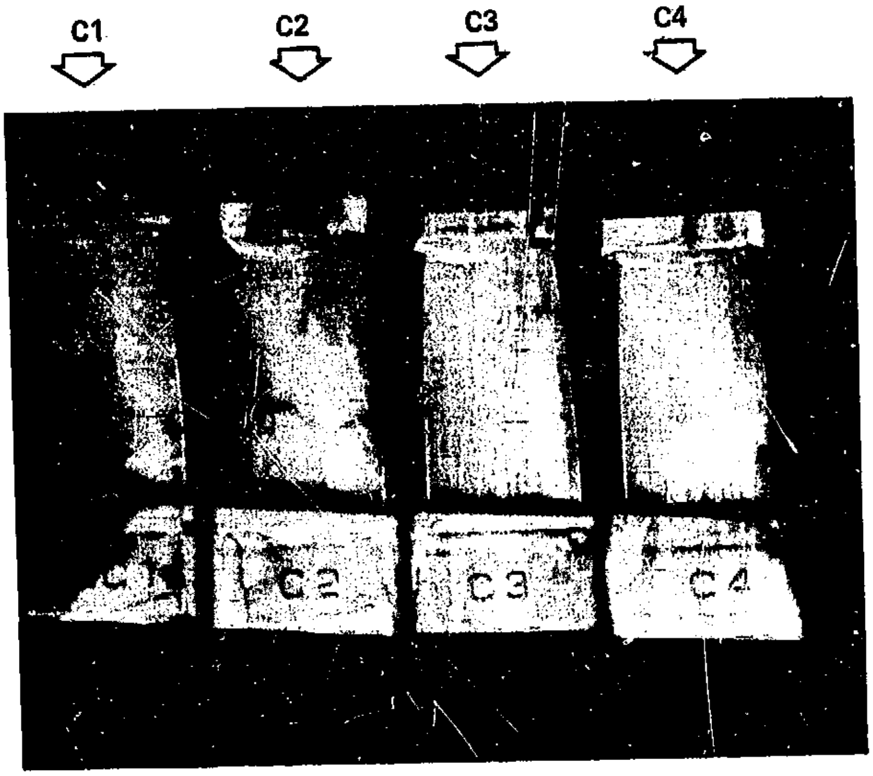


Figure 5. Task I, Mold 4 Blades Showing Straight Columnar Grains in Castings "C3" and "C4"

Evaluation of the grain structures of castings from these two molds confirmed that the 1366°K (2000°F) furnace ignition aided in obtaining better columnar grain control as shown in Figure 6. Results also indicated that it was of benefit to retain the mold in the furnace for a longer time after ignition.

Evaluation of the burned exothermic material indicated that a much higher temperature had been obtained as compared to the previous molds preheated at 1144°K (1600°F). Evidence in support of this conclusion was the nearly total fusing of the individual briquets into a monolithic mass in the outer radial regions of the mold. However, nearer the center of the mold cluster, temperatures attained during the burn appeared considerably lower. This was evidenced by briquets near the center downsprue and in contact with the center blade cavities. These briquets had sagged somewhat from their original shape and sintered to adjacent briquets, rather than fusing into one continuous mass. It was felt that these physical indications of maximum temperature correlated well with the quality of columnar grains obtained on the individual castings from the central to outer locations.

The ratio of the mass of exothermic material to the local mass of heat-absorbing mold material was believed to be a major factor in producing these temperature differences. It was therefore decided that the ceramic mold material in the bottom half of the downsprue decreased the potentially available space for exothermic material at the center of the cluster, and also acted as a large heat sink.

In addition, there were indications from the fillout and grain structure in the individual blade castings that the rate of fill for the airfoil cavities varied along individual spokes, as well as from spoke-to-spoke in a given mold. The slowest fill was at the center of the cluster on the spokes with the highest runner

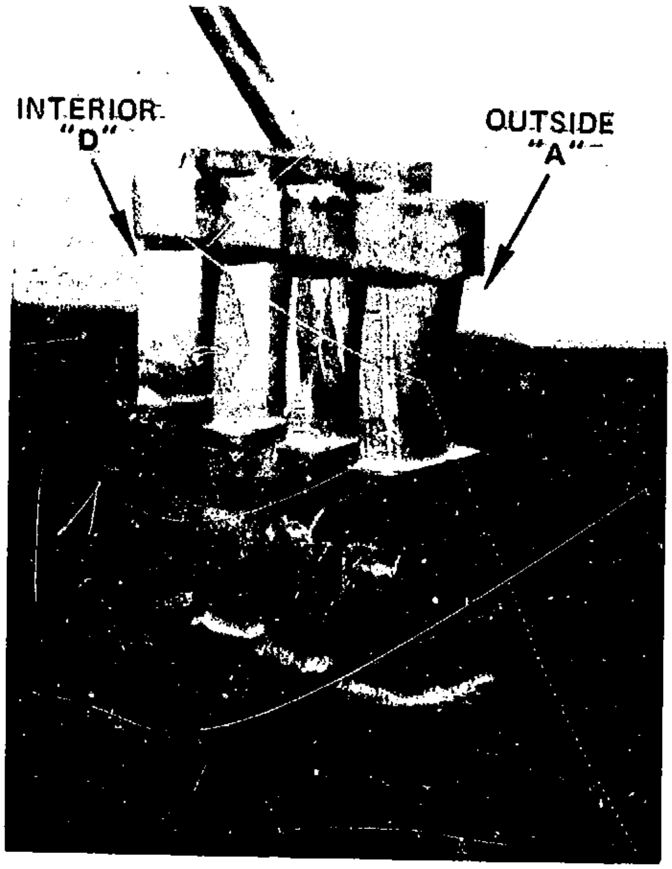


Figure 6. Task I, Mold 5 Blade Castings Showing Desirable Grain Structure Near the Outside "A" Casting of the Mold Cluster with Trailing-Edge Nucleation in the Interior "D" Castings

connection on the downsprue. The blades cast with the apparent slower fill rate gave the largest angular deviation of columnar grain orientations. This indicated that a better control of grain growth could be obtained if a ~~faster fill~~ could be achieved.

4. Molds 7 and 8. To correct the problems observed with the Molds 5 and 6 castings, the mold assembly was redesigned to eliminate the center downsprue below the pour-cup level, and to provide an increased cross-sectional area of runners and in-gates for faster filling of each mold cavity. Mold 7 (straight spoke) and Mold 8 (spiral spoke) were fabricated in this fashion, and both of these molds were packed with exothermic material and furnace-ignited at 1366°K (2000°F) (the same technique as used with Molds 5 and 6). Molds 7 and 8 both required 8 minutes to ignite, and were left in the 1366°K (2000°F) furnace for the first 5 minutes of the exothermic burn. An additional 7 minutes were required for the flaming to cease and for transfer to the copper chill in the vacuum chamber before pouring.

Evaluation of the grain structures of castings in Molds 7 and 8 indicated the changes made in mold design had allowed the mold to reach a sufficiently high temperature to produce good columnar grain structure in all but two blades. However, castings from both molds had indications of gas evolution due to a manufacturing problem associated with mold firing in a gas-fired furnace that inadvertenly had a reducing atmosphere. This eventually produced silicon-monoxide (SiO) on the inside of the mold. The SiO subsequently was evolved as a gas when the metal was poured in vacuum; this apparently restricted the fill in some mold cavities.

5. Mold 9. Mold 9 (straight spoke) was cast to evaluate the feasibility of using the Jetshapes-produced zircon face coat in place of the previously used higher thermal-conductivity alumina system. This mold was poured using the same design and

casting procedures used for Mold 7. An evaluation of the grain structure of the castings from this mold indicated that very good columnar growth was obtained, but a degradation in casting surface quality was visually detected.

6. Mold 10. Mold 10 (straight spoke) was prepared and poured in essentially the same manner as Mold 7. Representative examples of the grain orientation produced in Mold 10 are presented in Figure 7. The grain structure of these castings have the desired longitudinal directional orientation. Surface shrinkage on the blade platforms was observed. This was characteristic of prior molds cast with the blade-root down.

7. Molds 11 and 12. Molds 11 and 12 were the last molds produced using the TFE731-2 blade waxes. To eliminate the platform surface shrinkage characteristics of prior molds cast with the blade-root down, these molds were cast with the blade-root up, and as anticipated, this change eliminated the platform shrinkage.

Erratic ignition behavior of the exothermic material was observed on Molds 11 and 12. These molds failed to ignite after the usual time in the 1366°K (2000°F) furnace. To obtain satisfactory castings, the exothermic material in these molds was torch ignited. Subsequent testing of this exothermic material indicated substantially different ignition characteristics from the material used on the prior 10 molds.

Examination of the castings made in Molds 11 and 12 indicated that uniform directional solidification of the grains was not achieved from blade root to tip. The "sort-out" zone between the randomly-oriented grains nucleated at the chill and the desired DS grains extended into the upper portion of these airfoils. This was primarily the result of two factors: (1) inadequate mold temperature due to erratic performance of the exothermic material,

PRESSURE SIDES

SUCTION SIDES

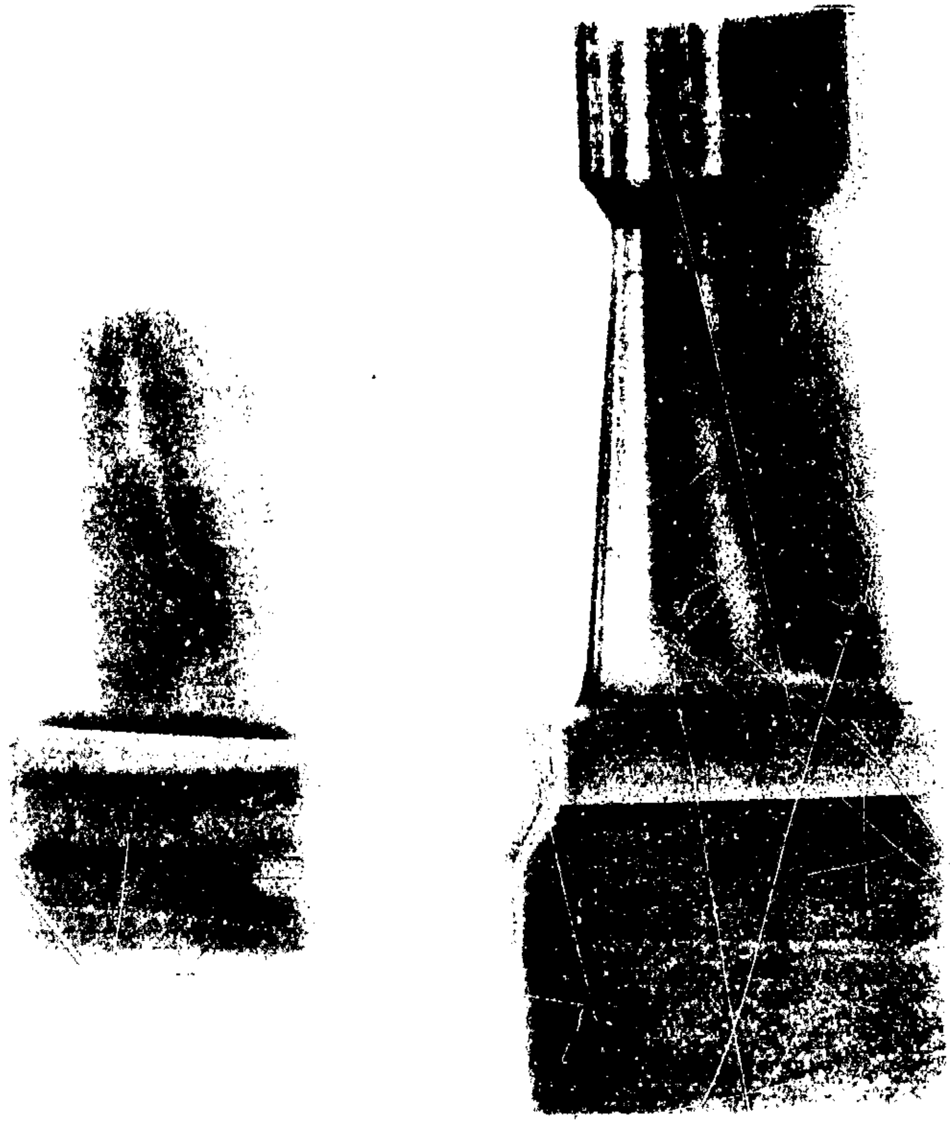
Figure 7. Task I, Mold 10, Spoke "B" Macroetched Blades Showing Consistent Directional Grain Orientations

and (2) slow pouring of the molten metal into the molds resulting in some loss of the needed superheat. Despite these problems, sufficient satisfactory directionally-solidified grain structures were obtained in blades from Molds 11 and 12 to permit machining and testing of sound test specimens.

8. Molds 13, 14 and 15. These molds were made from new waxes of the preliminary uncooled blade design established in Task IV. The waxes were designed with smoothly-transitioned extensions of both root and tip to permit the casting of blades in either root-down or root-up positions. Figure 8 shows injected waxes for the conventional TFE731-2 blade and the wax for the preliminary uncooled TFE731-3 blade design.

The casting problems experienced with Molds 11 and 12 resulted in process adjustments prior to casting the last 3 molds. New exothermic material from Exomet and a rapid pour rate were used to ensure adequate mold preheat and molten metal superheat on all molds. On Mold 13, each spoke of 4 airfoils had a different starter block and/or in-gate configuration as shown in Figure 9. Spoke 1 had 2.54 x 12.7 x 3.81-cm high (1.0 x 0.5 x 1.5-inch high) rectangular starter blocks to fit the airfoil tip extensions. Spoke 3 had 1.50-cm (0.625-inch) diameter by 3.81-cm (1.5-inch) high round starter blocks for tip extensions. Spoke 4 had paired airfoils cast from large rectangular starter blocks and twin in-gates.

The process changes resulted in good DS grain patterns that were uniform on all of the castings of Mold 13. The airfoils produced on Spokes 1, 2, and 3 were to blueprint contour, but residual stresses induced in the paired airfoil castings of Spoke 4 caused them to twist out of limits after knockout from the chillplate and cut-off from the runners. A hairline crack in the Mold 13 shell resulted in some metal leakage and a lack of complete fill in a few castings.



TFE731-2 CASTING WAX
TASK I — MOLDS 1 THROUGH 12

TFE731-3 CASTING WAX
TASK I — MOLDS 13, 14, AND 15

Figure 8. Suction Sides of the Injected Casting Waxes for Task I Turbine Blades (Mag.: 1.5X)

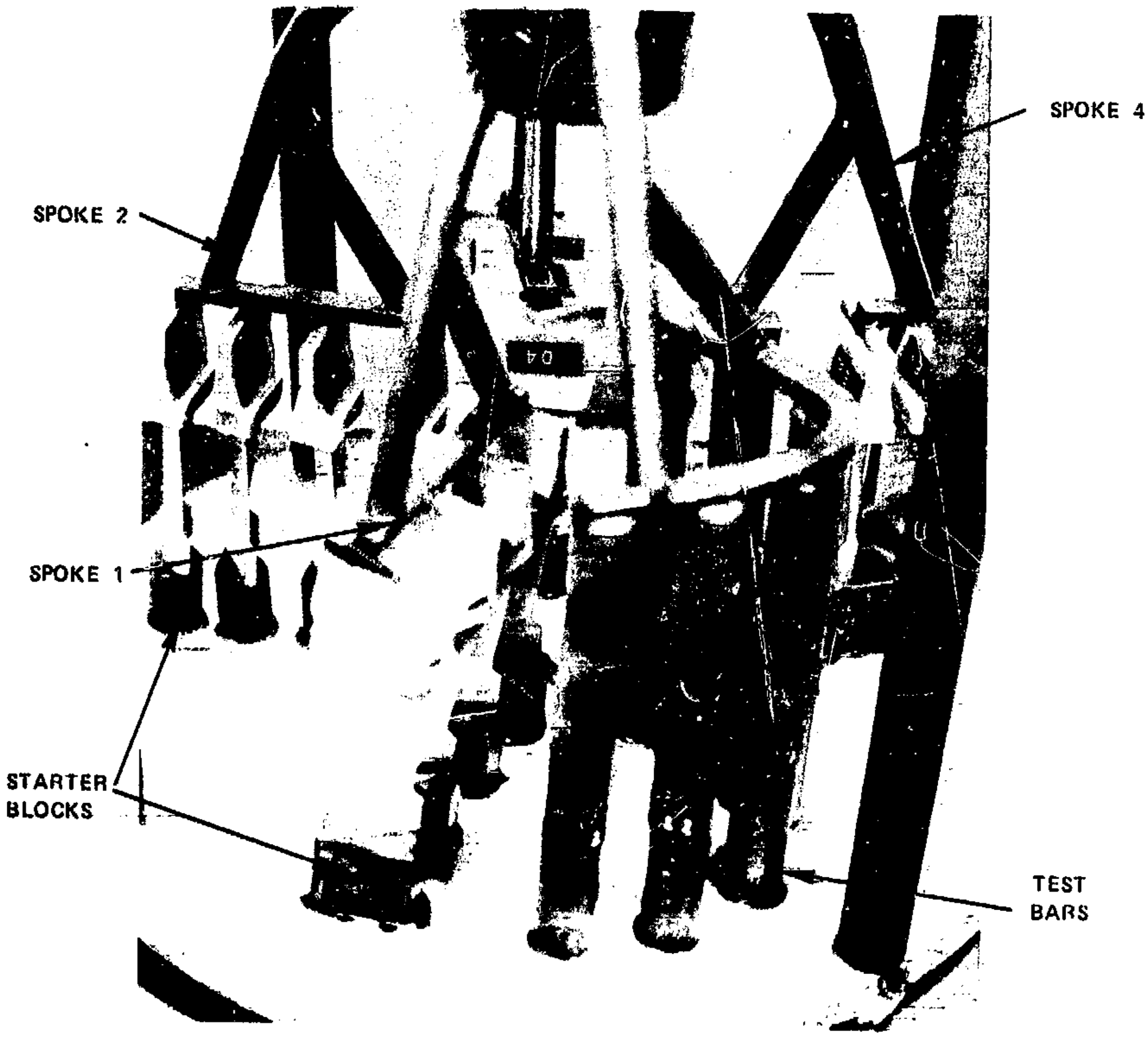


Figure 9. Task I, Mold 13 Wax Assembly for the Preliminary Design of the Uncooled TFE731-3 Blade in the Root-Up Position.

Molds 14 and 15 had the same design as Mold 13, including the starter blocks. These molds were poured to establish the reproducibility of the Mold 13 processing, and to evaluate a lower silica-content binder for the casting shell. The introduction of this new binder was imposed upon Jetshapes because the supplier of the previous binder material discontinued its production. The new binder produced a thinner shell than the previous binder, and after pouring, it was discovered that a small amount of zinc-oxide impurity in the new exothermic material had reacted with the thinner shell and caused localized mold deterioration. This thinner shell mold also exhibited localized cracking at sharp corners on the square starter blocks and along airfoil trailing edges. The thinner shell also slightly upset the good thermal balance achieved in Mold 13.

The grain structure of castings produced in Molds 14 and 15 had satisfactory directional orientation in the turbine blade airfoils and roots. A few stray grains nucleated and grew in the risers attaching the blade roots to the in-gate system.

Exothermic behavior. The exothermic material utilized during Task I was "Isogard Nuggets". This briquet-shaped material is a special blend of iron oxide taken from mill scale and iron ore, with aluminum-metal particles and silicate binders. When the briquets are heated to a sufficiently high temperature in air, molten aluminum-metal particles start reducing the iron-oxide particles to a lower oxide state or to metallic iron, accompanied by a considerable release of heat energy. A free flow of an oxidizing atmosphere through the porous exothermic pack is necessary for the reaction to proceed to completion. With heat losses external to the mold minimized, the reaction is capable of producing temperatures of 2033°K (3200°F) in the briquet pack. The actual temperatures achieved during Task I were slightly lower as a result of the heat sink capability of the mold system. As a minimum, sufficient heat energy must be supplied by the preheat atmosphere and the exothermic reaction to raise the mold face-coat to a temperature above the melting point of the alloy to be cast. This requires a reasonably uniform distribution of the exothermic material within the mold. The gating system was designed to ensure that the local distribution of exothermic material was adequate to preheat the mass of the adjacent mold material to maintain the required local vertical temperature gradients during casting solidification.

Several problems encountered during Task I were associated either directly or indirectly with the exothermic material. An early objective was to develop a preheat cycle using a gas-fired furnace to supply part of the required heat energy. This would permit an increase in the total packing density of blade and test bar molds to a maximum in the available space as a result of the need for a smaller quantity of exothermic material. It was found that long preheat times at moderate temperatures [e.g. 1144°K (1600°F)] prior to ignition of the exothermic material actually reduced the amount of available exothermic heat due to a gradual degradation of the exothermic material by partial oxidation of metallic constituents and a slowed reaction of the aluminum with the preheat atmosphere. The use of higher preheat temperatures tended to promote very rapid self-ignition at the surface of the exothermic material before adequate time had elapsed for the preheat temperature to penetrate deeply into the mold assembly.

The best process evolved included a 1366°K (2000°F) gas-fired preheat furnace, with an oxidizing atmosphere. This preheat level resulted in self-ignition at the top of the exothermic pack in 5 to 7 minutes. The entire exothermic reaction was then allowed to proceed to completion within the 1366°K (2000°F) furnace prior to transfer of the mold to the vacuum casting furnace.

An additional problem manifested--an occasional appearance of yellow particles on the mold surface caused by a metal-mold reaction in local areas, and penetration of the mold by the molten alloy. Through chemical analysis, this problem was traced to a zinc-oxide impurity in the iron ore used in manufacture of the exothermic material. The supplier was able to eliminate this problem by use of ore that did not contain zinc oxide.

Mechanical-property evaluations. With the exception of Mold 1, which did not yield satisfactory blade castings, individual blade castings and separately cast test bars were selected from each mold for machining into test specimens for use in mechanical-property evaluation. Prior to machining into test specimens, all of the blade castings and separately cast test bars were solution treated at 1494°K (2230°F) for 2 hours, and subsequently aged at 1144°K (1600°F) for 20 hours. The machined-from-blade (MFB) ("mini-bar") test specimens had a 0.178-cm (0.070-inch) gage diameter and a 0.762-cm (0.300-inch) gage length configured as shown in Figure 10. The location, with respect to the complete blade casting, of the material slug removed for machining the mini-bar test specimen is presented in Figure 11. Test specimens machined from separately cast test bars (SCTB) had a standard 0.625-cm (0.250-inch) gage diameter and 3.18-cm (1.25-inch) gage length as shown in Figure 12. These specimens were machined from the as-cast 1.587-cm (0.625-inch) diameter test bars.

The MFB mini-bar and SCTB test specimens were subjected to the following tests:

- Room-temperature tensile
- 1033°K (1400°F) tensile
- 1033°K (1400°F) stress-rupture at 724 and 758 MPa (105 and 110 ksi)

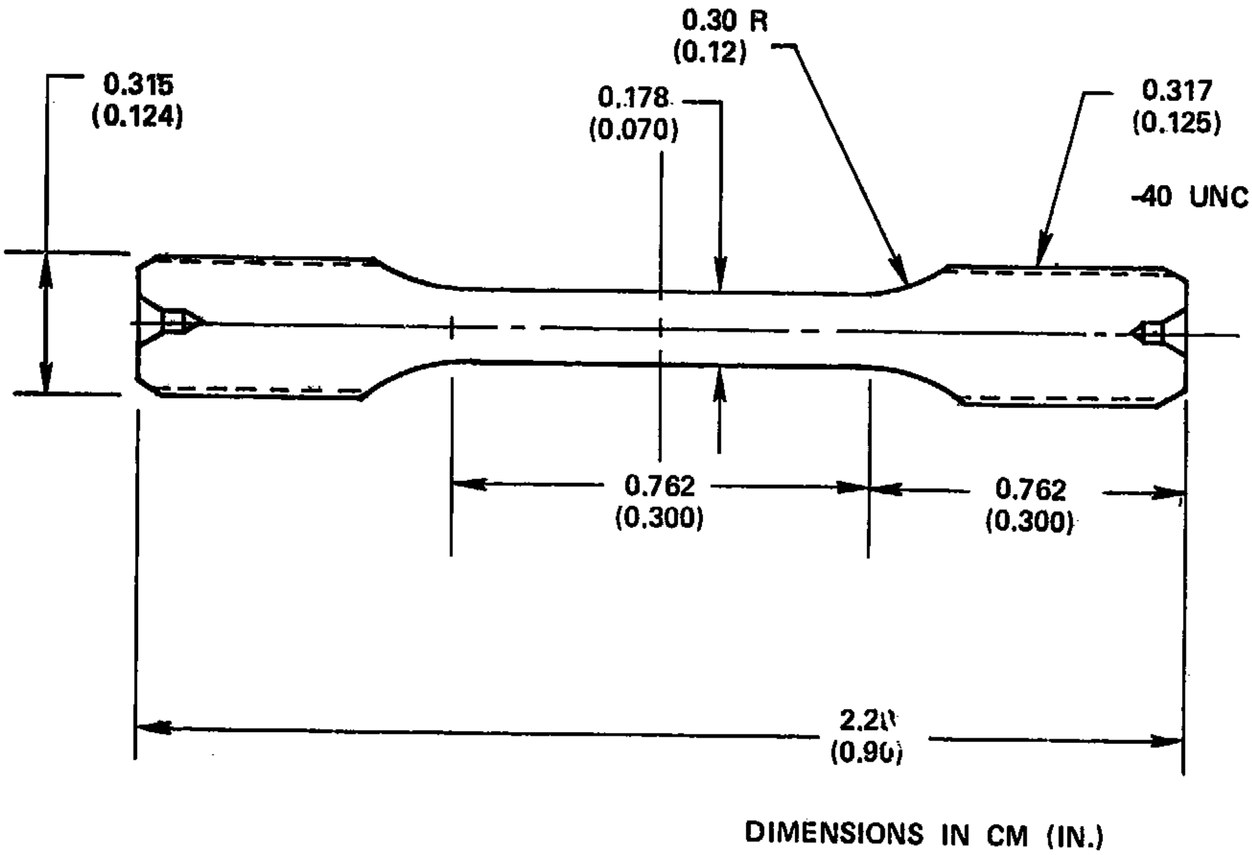


Figure 10. Mini-Bar Test Specimen

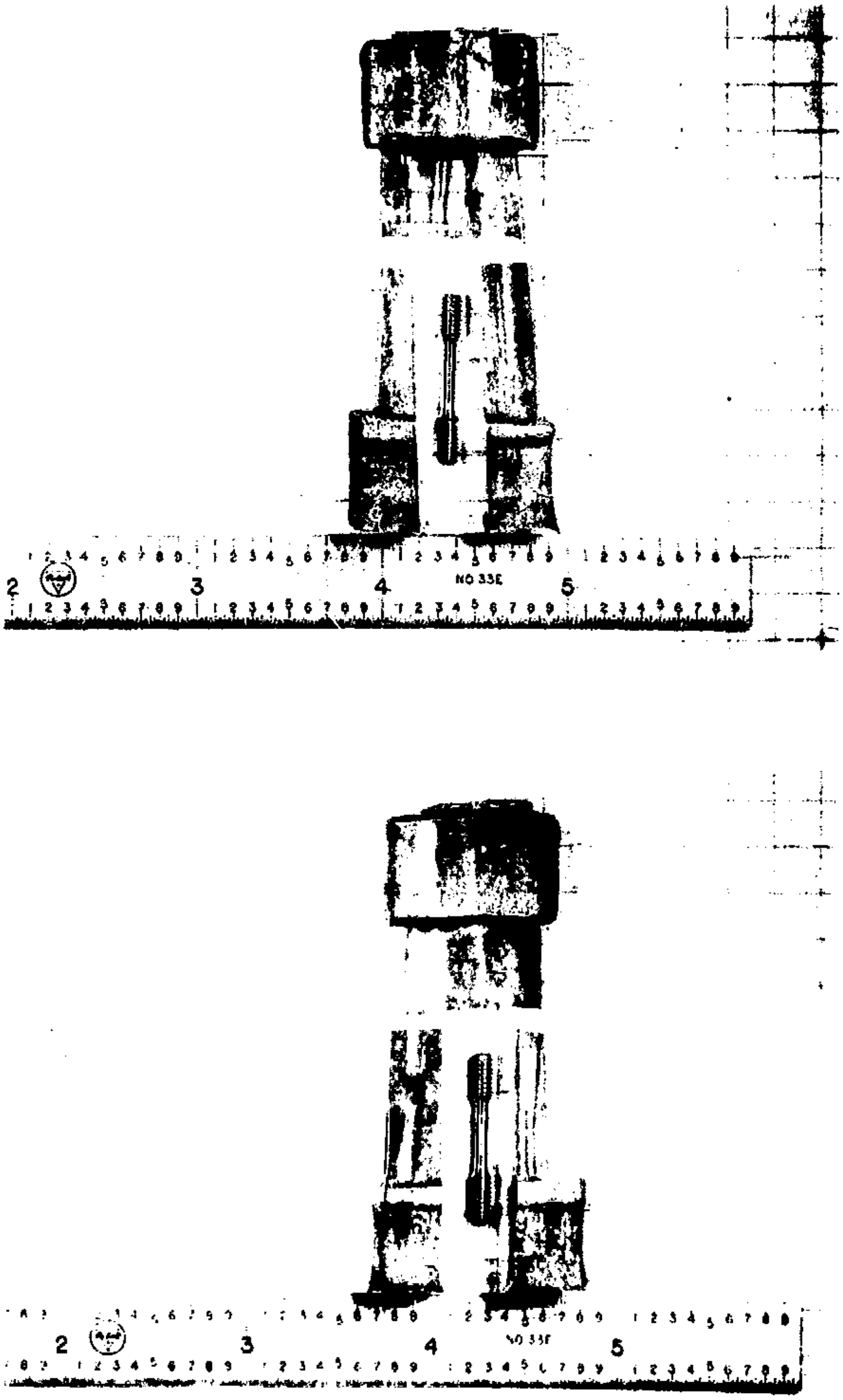


Figure 11. Longitudinal Orientation of Machined Mini-Bar Test Specimen with Respect to Exothermically-Cast DS TFE731-2 Turbine Blade

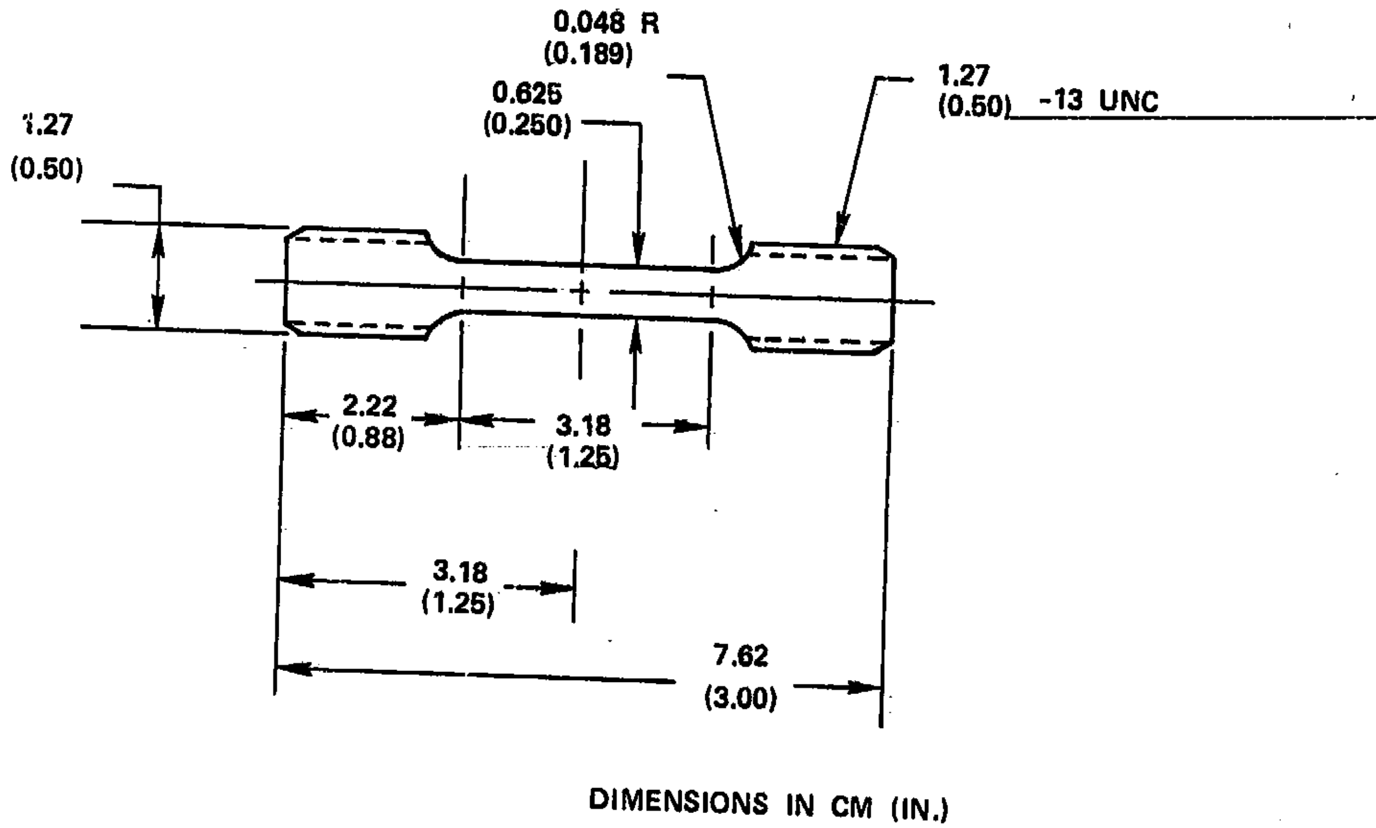


Figure 12. Standard Tensile Test Specimen

- 1255°K (1800°F) stress-rupture at 207 and 221 MPa (30 and 32 ksi)

Mechanical test results generated in Task I are summarized in Tables I through V.

Table I lists the stress-rupture test results of the MFB mini-bar specimens. Stresses were selected to produce failure in approximately 100 hours. The 221 MPa (32 ksi) stress level shown in Table I(c) for the 1255°K (1800°F) tests on MFB mini-bar test specimens from Molds 7, 8 and 9 were inadvertently used in lieu of the intended 207 MPa (30 ksi) stress level. Stress-rupture lives were determined for mini-bars machined from the remaining molds at 1255°K/207 MPa (1800°F/30 ksi) as listed in Table I(b) and for mini-bars machined from all molds at 1033°K/724 MPa (1400°F/105 ksi) as listed in Table I(a).

Table II lists the test results of stress-rupture tests on specimens machined from separately cast test bars. The combined data shows excellent consistency in rupture lives, and exceptionally high ductility at the two test conditions. The data also shows good correlation between the MFB mini-bar tests and the SCTB tests at the 1255°K (1800°F) temperature level. Lives here at 221 MPa (32 ksi) averaged 50.1 hours for minibars and 52.4 hours for SCTBs.

Table III presents comparative test data obtained on standard test specimens machined from separately cast test bars of conventionally-cast equiaxed MAR-M 247. These conventional castings were made from one of the heats used to produce the DS castings. Lower rupture lives and ductility are evident at 1255°K (1800°F) when compared to the DS casting test data shown in Tables I and II.

TABLE I. TASK I STRESS-RUPTURE TEST RESULTS ON DS CAST MACHINED-FROM-BLADE TEST SPECIMENS

[Test specimens machined from exothermically cast DS MAR-M 247 blades after heat treatment at 1494°K (2230°F) for 2 hours and 1144°K (1600°F) for 20 hours.]

Mold	Specimen	Rupture time, hours	Elongation, percent	Reduction of area, percent
(a) Tests at 1033°K/724 MPa (1400°F/105 ksi)				
2	A	12.8	19.5	32.1
2	B	46.7	18.1	23.5
3	A	147.0	9.3	14.6
3	B	205.1	19.1	22.9
4	A	52.5	5.0	12.6
4	B	100.1	19.0	25.6
5	A	197.4	19.8	22.5
5	B	269.9	27.6	31.2
6	A	202.0	14.1	18.5
6	B	192.3	20.5	25.3
7	A	76.1	13.3	20.5
7	B	64.0	12.3	18.8
8	A	95.2	10.9	22.9
8	B	25.7	10.6	24.1
9	A	87.4	12.4	19.0
9	B	184.8	18.8	28.5
10	A	150.1	12.0	15.2
11	A	29.6	16.3	25.0
11	B	24.1	10.8	12.8
12	A	160.3	9.3	18.4
12	B	15.9	11.7	17.5
13	A	133.9	13.8	19.0
13	B	179.3	16.8	18.6
14	A	137.3	17.4	24.1
14	B	130.7	15.2	28.9
15	A	125.5	15.6	22.7
15	B	134.0	17.5	27.6

TABLE I. (CONCLUDED)

Mold	Specimen	Rupture time, hours	Elongation, percent	Reduction of area, percent
(b) Tests at 1255°K/ 207 MPa (1800°F/30 ksi)				
2	A	99.2	25.7	52.6
2	B	72.1	26.6	48.4
3	A	91.1	27.9	44.6
3	B	71.4	21.3	40.0
4	A	80.9	28.4	52.6
4	B	81.3	34.8	43.6
5	A	97.6	39.7	56.5
5	B	84.7	26.4	51.0
6	A	79.2	19.3	48.9
6	B	91.7	32.8	46.7
10	A	79.1	36.5	48.4
10	B	95.4	45.3	56.7
11	A	86.6	31.0	47.1
11	B	74.0	29.1	45.8
12	A	68.1	28.2	39.0
12	B	74.8	29.7	47.0
13	A	73.6	24.8	47.0
13	B	69.4	15.2	34.1
14	A	68.6	32.6	57.4
14	B	69.1	22.0	41.0
15	A	74.1	23.5	42.8
15	B	68.7	21.4	47.0
(c) Tests at 1255°K/ 221 MPa (1800°F/32 ksi)				
7	A	56.4	18.3	50.6
7	B	46.4	17.9	47.0
8	A	52.7	16.1	46.8
8	B	49.5	17.6	51.0
9	A	47.0	19.4	48.2
9	B	48.6	17.3	46.8

TABLE II. TASK I STRESS-RUPTURE TEST RESULTS ON DS CAST SEPARATELY CAST TEST SPECIMENS

[Test specimens machined from exothermically cast DS MAR-M 247 separately cast test bars after heat treatment at 1494°K (2230°F) for 2 hours and 1144°K (1600°F) for 20 hours.]

Mold	Rupture time, hours	Elongation, percent	Reduction of area, percent
(a) Tests at 1033°K/758 MPa (1400°F/110 ksi)			
1	85.5	12.7	17.8
2	83.9	13.6	20.0
3	85.2	16.5	23.4
4	106.6	14.2	19.1
5	148.6	13.7	19.1
6	107.8	15.4	24.0
7	95.0	18.2	24.7
8	109.1	20.6	24.3
9	95.7	20.6	24.3
10	140.0	19.7	23.0
11	91.1	16.9	21.6
12	86.9	15.0	19.9
13	133.0	17.4	22.8
14	111.9	18.7	26.0
15	123.8	17.7	23.1
(b) Tests at 1255°K/221 MPa (1800°F/32 ksi)			
1	57.2	37.2	61.7
2	44.3	33.1	53.9
3	55.8	35.0	60.0
4	53.4	35.0	59.1
5	40.5	28.0	59.3
6	47.8	30.8	55.4
7	69.2	32.3	60.5
8	48.7	31.8	57.9
9	44.7	31.8	59.4
10	54.9	34.4	55.7
11	53.1	43.1	61.9
12	52.7	34.7	59.7
13	61.3	41.9	63.5
14	50.8	49.7	65.2
15	51.7	33.4	59.0

TABLE III. TASK I STRESS-RUPTURE TEST RESULTS ON CONVENTIONALLY CAST EQUIAXED MAR-M 247 TEST SPECIMENS

[Test specimens machined from separately cast test bars of conventionally cast equiaxed MAR-M 247 made from one of the heats used to produce the DS castings.]

Bar no.	Rupture time, hours	Elongation, percent	Reduction of area, percent
(a) Tests at 1033°K/758 MPa (1400°F/110 ksi)			
1	64.8	4.5	7.6
2	75.1	5.0	6.8
(b) Tests at 1255°K/221 MPa (1800°F/32 ksi)			
1	20.3	10.5	15.3
2	20.8	10.1	18.9

TABLE IV. TASK I TENSILE TEST RESULTS ON DS CAST MACHINED-FROM-BLADE TEST SPECIMENS

[Test specimens machined from exothermically cast DS MAR-M 247 blades after heat treatment at 1494°K (2230°F) for 2 hours and 1144°K (1600°F) for 20 hours.]

Mold	Specimen	Ultimate tensile strength, MPa (ksi)		0.2-Percent yield strength, MPa (ksi)		Elongation, percent	Reduction of area, percent
(a) Tests at Room Temperature							
3	A	1136	(165)	914	(133)	12.2	14.4
4	A	1163	(169)	891	(129)	11.9	14.8
5	A	1036	(150)	834	(121)	11.4	17.7
5	B	991	(144)	822	(119)	12.8	15.9
6	A	1093	(159)	871	(126)	11.6	17.2
6	B	1067	(155)	849	(123)	10.5	15.5
7	A	1160	(168)	878	(127)	3.1	8.5
7	B	1149	(162)	820	(119)	9.1	13.8
7	C	980	(142)	726	(105)	14.2	30.1
8	A	1078	(156)	843	(122)	11.4	17.0
9	A	1070	(155)	821	(119)	14.9	26.1
9	B	1109	(161)	826	(120)	9.6	18.3
9	C	1025	(149)	846	(123)	9.0	17.2
10	A	1179	(171)	934	(136)	13.0	15.7
10	B	1049	(152)	876	(127)	11.6	13.3
11	A	Failed in threads on loading					--
11	B	950	(138)	829	(120)	9.1	13.1
12	A	1016	(147)	881	(128)	10.4	13.2
12	B	823	(119)	814	(118)	2.2	9.5
13	A	1005	(146)	894	(130)	8.2	10.9
13	B	1034	(150)	940	(136)	5.0	10.0
14	A	1118	(162)	880	(128)	11.7	13.2
14	B	1000	(145)	841	(122)	12.6	17.5
15	A	1082	(157)	874	(127)	13.4	14.8
15	B	989	(143)	820	(119)	13.5	19.3

TABLE IV. (CONCLUDED)

Mold	Specimen	Ultimate tensile strength, MPa (ksi)		0.2-Percent yield strength, MPa (ksi)		Elongation, percent	Reduction of area, percent
(b) Tests at 1033°K (1400°F)							
3	B	1202	(174)	949	(138)	10.2	17.5
3	C	1153	(167)	907	(132)	7.6	15.7
4	B	1117	(162)	833	(121)	6.3	15.5
4	C	1070	(155)	847	(123)	9.0	13.9
5	C	1181	(171)	915	(133)	7.3	16.6
5	D	1026	(149)	790	(115)	6.4	14.8
6	C	1090	(158)	870	(126)	7.3	21.2
6	D	1093	(159	868	(126)	8.5	15.0
7	D	1104	(160)	828	(120)	14.1	21.4
7	E	1121	(163)	860	(125)	9.3	14.8
8	B	1076	(156)	869	(126)	6.8	10.9
8	C	1034	(150)	846	(123)	7.6	15.5
8	D	1010	(147)	798	(116)	8.2	13.2
9	D	1116	(162)	891	(129)	6.9	11.7
10	C	1209	(175)	1019	(148)	11.5	15.6
10	D	1172	(170)	991	(144)	8.6	8.8
11	C	1050	(152)	854	(124)	6.8	11.2
11	D	Failed in threads on loading					--
12	C	1145	(166)	978	(142)	8.0	11.9
12	D	1170	(170)	994	(144)	9.0	11.5
13	A	1260	(183)	878	(127)	12.3	13.9
13	B	1105	(160)	932	(135)	8.8	17.0
14	A	1072	(156)	939	(136)	9.7	11.2
14	B	1141	(166)	963	(140)	9.2	10.5
15	A	991	(144)	824	(120)	3.7	13.4
15	B	1145	(166)	956	(139)	10.5	15.5

TABLE V. TASK I TENSILE TEST RESULTS ON DS CAST SEPARATELY CAST TEST SPECIMENS

[Test specimens machined from exothermically cast DS MAR-M 247 separately cast test bars after heat treatment at 1494°K (2230°F) for 2 hours and 1144°K (1600°F) for 20 hours.]

Mold	Ultimate tensile strength, MPa (ksi)		0.2-Percent yield strength, MPa (ksi)		Elongation, percent	Reduction of area, percent
(a) Tests at Room Temperature						
1	1147	(166)	856	(124)	12.8	14.8
2	1171	(170)	864	(125)	11.7	11.7
3	1218	(177)	854	(124)	12.1	12.2
4	1196	(173)	863	(125)	12.8	16.0
5	1254	(182)	872	(126)	13.3	14.2
6	1154	(167)	854	(124)	13.4	16.5
7	1172	(170)	832	(121)	12.5	16.0
8	1182	(172)	845	(123)	15.0	16.5
9	1131	(164)	849	(123)	12.0	16.1
10	1231	(179)	896	(130)	13.1	14.4
11	1153	(167)	887	(129)	12.9	16.5
12	1232	(179)	914	(133)	12.3	13.8
13	1170	(170)	903	(131)	10.9	15.7
14,15			Not tested			
(b) Tests at 1033°K (1400°F)						
1	1172	(170)	973	(141)	8.3	12.4
2	1121	(163)	880	(128)	7.0	14.2
3	1173	(170)	956	(139)	13.3	20.8
4	1176	(171)	947	(137)	13.5	20.7
5	1082	(157)	845	(123)	16.4	26.4
6	1176	(171)	976	(142)	10.9	16.2
7	1150	(167)	931	(135)	16.2	23.7
8	1131	(164)	896	(130)	12.7	17.8
9	1123	(163)	925	(134)	2.9	4.6
10	1188	(172)	951	(138)	13.5	19.5
11	1180	(171)	962	(140)	11.5	15.1
12	1189	(173)	972	(141)	12.4	16.6
13	1207	(175)	965	(140)	11.1	13.3
14,15			Not tested			

Tables IV and V list the room temperature and 1033°K (1400°F) tensile tests results for the MFB mini-bar and SCTB test specimens, respectively. With the exception of several low-ductility specimens, the results appear to have normal scatter. The only planned tensile data not collected were the tests on separately cast test bars from Molds 14 and 15. Due to metal leakage from cracks in these molds, some of the test bars did not fill completely and the available bars were used for the stress-rupture tests.

Of the mechanical test data listed in Tables I through V, the results from Molds 13, 14 and 15 best represent the capability of the process developed in Task I.

Chemical Analyses. Chemical analyses of all blades cast were performed to determine: (1) the overall chemistry in the root section of the blade, and (2) the hafnium content of the blades in the root and airfoil tip sections.

Table VI lists the results of the bulk chemical analysis, the analysis of each of the two MAR-M 247 master heats employed, and the material specification limits. Table VI also presents the results of hafnium analysis at the blade roots and airfoil tips. With the exception of Mold 11, where a spurious root analysis was obtained, the reversal of the hafnium gradient for the blades cast root-up is apparent.

Recommended Casting Practice

A basic set of process control guidelines evolved from the MAR-M 247 process experiments of Task I that were considered satisfactory for casting all four program alloys in Task II.

TABLE VI. RESULTS OF BULK CHEMICAL ANALYSES OF TASK 1 EXOTHERMICALLY CAST DS MAR-M 247 BLADES

(Certified heat analyses and specification ranges shown for comparison)

Mold[a] No.	Hf[b] Root	Hf[b] Tip	Composition, percent by weight: C	Cr	Mo	Ta	Al	Ti	Hf	B	Zr	Co	Mn	S	Si	W	P	Cb	Cu	Fe	Ni
			Root section bulk chemical analysis																		
1	1.47	1.47	0.13	8.12	0.65	3.02	5.42	1.09	1.34	0.013	0.055	10.59	<0.10	0.003	<0.10	10.28	--	--	--	0.23	Bal
2	1.49	1.48	0.17	8.36	0.63	3.09	5.40	1.12	1.52	0.016	0.095	10.60	<0.10	<0.001	<0.10	10.20	--	--	--	0.26	Bal
3	1.38	1.32	0.13	8.16	0.65	3.10	5.38	1.03	1.39	0.015	0.065	10.21	<0.10	<0.001	<0.10	10.11	--	--	--	0.19	Bal
4	1.45	1.34	0.13	8.15	0.62	3.03	5.60	1.07	1.34	0.014	0.070	10.34	<0.10	<0.001	<0.10	10.07	--	--	--	0.25	Bal
5	1.28	1.32	0.16	8.14	0.59	3.07	5.34	1.11	1.48	0.017	0.085	10.42	<0.10	0.004	<0.10	10.21	--	--	--	0.26	Bal
6	1.39	1.39	0.15	8.15	0.60	3.00	5.44	1.12	1.46	0.014	0.090	10.60	<0.10	0.005	<0.10	10.20	--	--	--	0.33	Bal
7	1.31	1.31	0.095	8.08	0.62	3.00	5.43	1.06	1.34	0.013	0.055	10.40	<0.10	0.002	<0.10	10.11	--	--	--	0.25	Bal
8	1.27	1.12	0.11	8.14	0.64	3.09	5.36	1.03	1.33	0.014	0.075	10.42	<0.10	0.003	<0.10	10.15	--	--	--	0.23	Bal
9	1.28	1.20	0.13	8.22	0.64	3.02	5.45	1.07	1.35	0.013	0.090	10.46	<0.10	0.001	<0.10	10.26	--	--	--	0.25	Bal
10	1.30	1.25	0.16	7.51	0.70	3.08	5.52	1.04	1.27	0.014	0.095	10.49	<0.10	0.001	<0.10	10.11	--	--	--	0.19	Bal
11	1.77	1.40	0.14	8.45	0.61	2.99	5.46	1.08	1.48	0.014	0.072	10.63	<0.10	<0.001	<0.10	10.11	--	--	--	0.23	Bal
12	1.39	1.40	0.14	8.40	0.71	2.94	5.44	1.07	1.48	0.014	0.076	10.70	<0.10	0.004	<0.10	10.14	--	--	--	0.17	Bal
13	1.29	1.33	0.13	7.61	0.66	2.93	5.54	1.03	1.26	0.014	0.069	10.61	<0.10	<0.001	<0.10	10.07	--	--	--	0.21	Bal
14	1.21	1.34	0.09	8.43	0.66	3.10	5.44	1.09	1.28	0.018	0.057	10.70	<0.10	0.004	<0.10	10.23	--	--	--	0.16	Bal
15	1.23	1.42	0.11	8.32	0.64	3.08	5.51	1.12	1.30	0.017	0.060	10.61	<0.10	0.004	<0.10	10.25	--	--	--	0.25	Bal
			Cannon-Muskegon Heat B596																		
			0.16	8.00	0.52	3.20	5.50	1.10	1.46	0.019	0.06	10.60	--	0.006	--	9.70	--	--	--	--	Bal
			Special Metals Heat B654																		
			0.14	7.75	0.59	3.16	5.56	1.02	1.40	0.018	0.053	10.56	0.032	0.006	0.115	9.83	--	--	--	0.12	Bal
			Specification Range, AiResearch EMS55447																		
		Min	0.13	8.00	0.50	2.80	5.30	0.90	1.20	0.01	0.05	9.00	0.20	0.15	0.20	9.50	--	--	--	0.50	Bal
		Max	0.17	8.80	0.80	3.30	5.70	1.20	1.60	0.02	0.10	11.00	Max	Max	Max	10.50	--	--	--	Max	Bal

a Molds 1-6 were cast from the Cannon-Muskegon heat. Molds 7-15 were cast from the Special Metals heat. Molds 1-10 were cast from blade-root down. Molds 11-15 were cast with blade-root up.

b Separate hafnium analyses at blade roots and airfoil tips.

Wax assembly manufacture. The wax assembly selected for the casting of uncooled TFE731-3 turbine blades consisted of an approximately 25-cm (10-inch) diameter cluster of 20 blade waxes, arranged in 5 equally-spaced radial spokes, with 4 blades in each spoke, and assembled to a central pouring cup. Each blade was placed on top of a 2.54-cm high by 1.50-cm diameter (1-inch by 0.625 inch) cylindrical starter extension, blade-root up. The starter extensions were vertically oriented on a wax-covered aluminum plate. The plate initially served as a frame in mold dipping operations, and subsequently as a base plate to form the flat-plane bottom surface and the base flange of the open-bottom final DS mold. The blades in each spoke were oriented with their roots parallel to each other and perpendicular to the mold spoke axis. A short "riser" extension on top of each blade root was attached to a common 1.27-cm by 1.27-cm (0.5-inch by 0.5-inch) cross-section horizontal runner for each spoke. Each runner was connected to the central pour cup by an inverted-"Y"-shaped downgate. An approximate 3.8-cm (1.5-inch) unobstructed space was left in the center of the assembly under the pour cup, as well as, the space surrounding each 4-blade spoke, to provide open areas for packing of exothermic briquets.

Mold manufacture. The wax assembly was then dipped with the Colal-P alumina-flour prime coat, followed by sufficient silicon-bonded alumina-silicate back-up dips to produce a 0.635- to 0.825-cm (0.250- to 0.325-inch) shell thickness. After autoclave dewaxing, the mold was fired in a gas furnace to produce the completed open-bottom DS mold as shown in Figure 13.

Casting process. As an initial step in the DS casting process, the mold was placed upright on a metal support plate. A preformed ceramic-fiber insulating sleeve was placed around the mold with the base of the sleeve resting on top of the mold base flange. An optical sight tube made of dipped shell material was placed

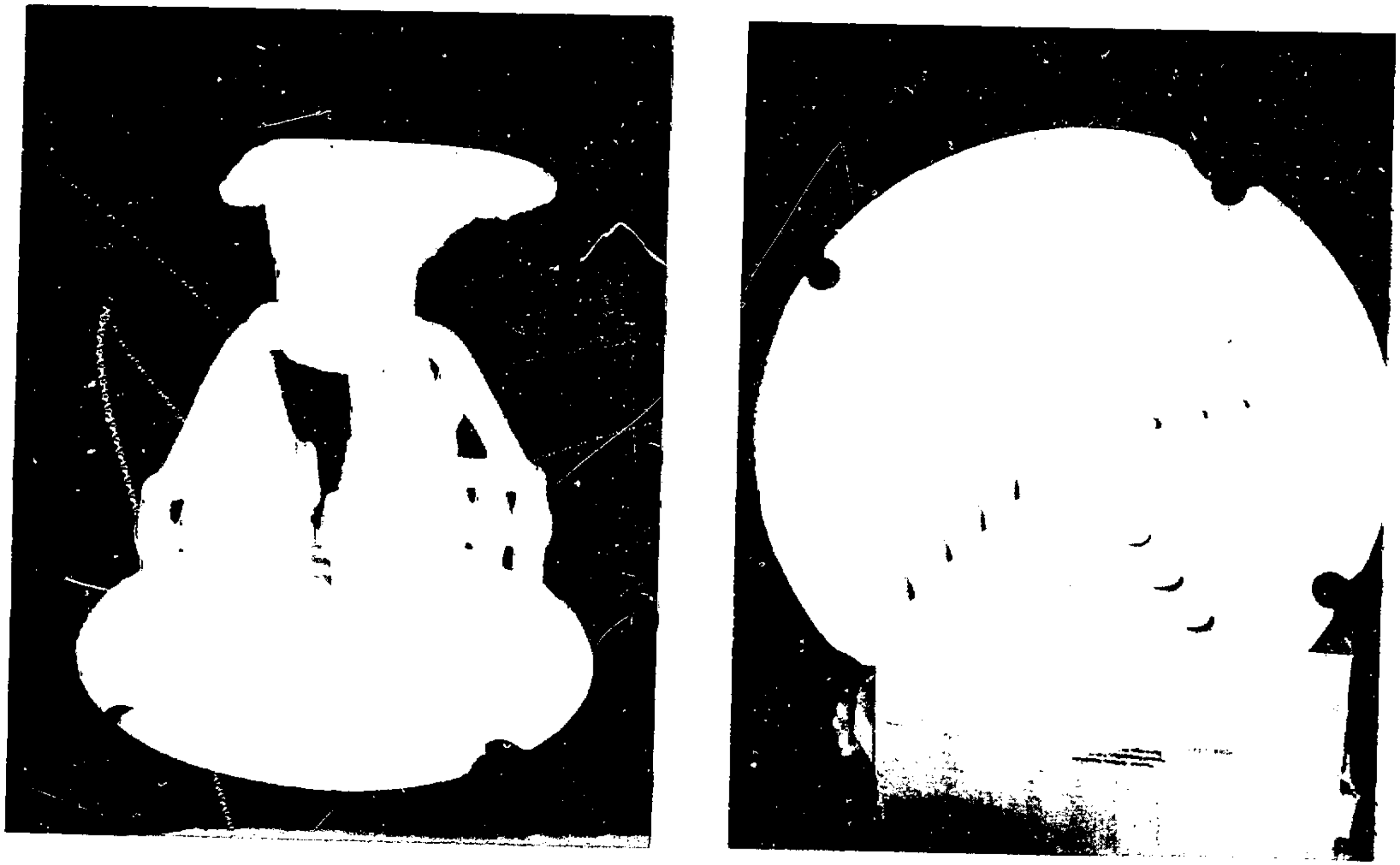


Figure 13. Completed Task I Final Configuration Open-Bottom Mold, After Dewaxing, Prepared for Exothermic Casting the Preliminary Design Uncooled TFE731-3 Turbine Blades

through the wall of the sleeve to provide a reference surface for optical temperature measurements after firing. Sufficient exothermic briquets were poured into the insulating sleeve around the central open area of the mold and around all the blade clusters to at least 10-cm (4-inches) above the top runner of the gating system. Approximately 23 kg (50 pounds) of briquets were required.

The mold assembly was placed into a gas-fired oxidizing-atmosphere furnace stabilized at 1366°K (2000°F). This furnace preheat temperature ignited the exothermic briquets after 5 to 7 minutes exposure. The mold was left in the furnace for a total time of 15 minutes to permit completion of the exothermic "burn".

The preheated mold assembly was removed from the furnace and the support plate was removed. After checking the temperature, the mold was transferred into the casting furnace and placed on a grooved, water-cooled copper chill, which had previously been covered with a single layer of nickel foil.

The melting cycle of the casting alloy was performed in an isolated induction-heated vacuum-melt chamber. The timing of this melting cycle was coordinated with the mold heating cycle so that the molten charge could be stabilized at the proper pouring temperature while the mold chamber was being pumped down.

The valve between the two chambers was opened, and the mold was poured at a molten metal temperature of 195° to 220°K (350° to 400°F) above the liquidus temperature of the alloy. The pouring took place approximately 25 minutes after the start of the preheat cycle. The metal cast was held in place under vacuum on the chill for 5 minutes, after which it was removed from the chamber for air cooling prior to shakeout.

TASK II - ALLOY/PROCESS SELECTION

Scope

The major objectives of Task II were to evaluate four alloys in exothermically cast DS form, establish a heat treatment for these alloys, evaluate their metallurgical characteristics, and select the two alloys showing the greatest potential for use as solid high-pressure turbine blades for the TFE731-3 engine. The four nickel-base alloys selected for evaluation were:

(a) MAR-M 247

(b) NASA-TRW-R

(c) IN 792+Hf

(d) MAR-M 200+Hf

As was the case with Task I, the Task II activity was accomplished with the aid of Jetshapes, Inc.

Test Material Production

The four alloys were used in producing a total of 16 molds of blade castings and 8 molds of slab castings for Task II evaluations. These castings were produced in groups of four molds, one alloy being used for each group. Similar exothermic material and process controls were employed for each group of molds, consistent with the Task I recommended casting practice.

Initially, four molds designed to yield 20 DS blade castings per mold were cast, one for each of the four alloys. The blade molds were of a radial-spoke design, having 5 equally-spaced spokes with provision for 4 turbine blade castings in each spoke. Figure 14 presents a typical blade mold wax assembly, and Figure 13 shows two views of a blade mold fabricated from this wax assembly. These first four molds were cast to evaluate the

Figure 14. Wax Pattern Assembly for Exothermic DS Casting Twenty Task II Preliminary Design TFE731-3 Turbine Blades

response of the several alloys to the gating and process control procedures developed with MAR-M 247 during Task I. Prior to pouring the initial casting, the freezing temperature (cooling curve plateau) was checked for each master heat of the four alloys. All of the alloys exhibited a freezing plateau within a range of 17°K (30°F). This range is less than the reproducibility capability of the optical pyrometer and recorder used in the casting process. Therefore, a single target pouring temperature of 1755°K (2700°F) (uncorrected for emissivity and instalation errors) was used for all four alloys in the initial and subsequent Task II castings.

The first four molds were packed with exothermic, and sequentially furnace-ignited at 1366°K (2000°F) using the procedures developed in Task I. Ignition times of the exothermic material in the gas-fired furnace varied from 4.5 to 7 minutes. All of the molds remained in the furance for a total of 15 minutes. They were then removed and held in air until visible flaming from the exothermic burn ceased. This additional burn time varied from approximately 1 minute to 6 minutes, with the longer times directly related to a larger percentage of smaller pieces of exothermic material in the exothermic pack. Pumpdown, pour, cooling under vacuum, and removal from the chill plate were all well within the prescribed limits. Generally satisfactory grain orientation was observed on castings of all four alloys.

A second group of four molds, one for each alloy, was cast using the same process controls and a second lot of exothermic material. Grain etching of the castings made in this group revealed significantly poorer grain orientation on all four alloys, the probable cause being inadequate heat input from the exothermic material. All remaining exothermic material from the suspect batch was returned to the supplier and exothermic material of improved quality was procured for use in subsequent castings. The improved material had a minimum burn temperature of

3050°F, as required by the Detroit Diesel Allison EMS 197A Specification.

The final eight blade molds were then cast in groups of four, one mold per alloy in each group. In addition, eight slab molds were also cast, two molds per alloy, to provide test bars for use in mechanical testing. Figure 15 shows a typical slab mold wax assembly. A new lot of more uniform quality exothermic material was utilized for casting these 16 molds. The new lot of exothermic material consistently ignited in the 1366°K (2000°F) air furnace within 4 to 5 minutes. The total furnace ignition time plus exothermic burn time was 15 minutes in all cases, consistent with the process control plan developed during Task I. The new lot of exothermic material was found to have a lower heat output than the lot used on the first four molds. Blades of generally satisfactory growth were, however, cast in all alloys with the exception of IN 792+Hf.

A summary of the mold identification for the four casting groups for blades and the two casting groups for slabs is presented in Table VII.

Heat Treatment Studies

Six different heat treatments were employed during Task II as shown in Table VIII. The heat treatments were applied to the casting prior to machining mechanical test specimens. Tabulated results of the tensile and stress-rupture testing are included herein under Task II "Mechanical Tests" in Tables XV through XXVIII.

Evaluation of the Task II mechanical property test data resulted in the following observations and conclusions, all

Figure 15. Wax Pattern Assembly for Exothermic DS Casting Six Task II Test Slabs

TABLE VII. SUMMARY OF TASK II MOLD IDENTIFICATIONS

Casting group	Mold serial number for alloys				Remarks
	MAR-M 247	NASA-TRW-R	MAR-M 200+Hf	IN 792+Hf	
Blades					
1	62	66	65	64	Lot 1 exothermic material
2	70	71	73	72	Inadequate exothermic material - Lot 2
3	101	74	90	89	Improved exothermic material - Lot 3
4	113	102	104	103	Improved exothermic material - Lot 3
Slabs					
5	82	83	85	84	Improved exothermic material - Lot 3
6	106	86	109	107	Improved exothermic material - Lot 3

TABLE VIII. TASK II HEAT-TREATMENT PROCESS SUMMARY

Heat treatment process	Step 1		Step 2		Step 3	
	Solution treatment [a]		Simulated coating cycle		Aging cycle	
	Temperature, °K (°F)	Duration, hours	Temperature, °K (°F)	Duration, hours	Temperature, °K (°F)	Duration, hours
A	1494 (2230)	2	--	-	1144 (1600)	20
B	1494 (2230)	2	1255 (1800)	5	1144 (1600)	20
C	1483 (2210)	2	1255 (1800)	5	1144 (1600)	20
D	1505 (2250)	2	1255 (1800)	5	1144 (1600)	20
E [b]	1519 (2275)	2	1255 (1800)	5	1144 (1600)	20
F [b]	1533 (2300)	2	1255 (1800)	5	1144 (1600)	20

a All solution treatments were performed in vacuum and followed by argon gas quenching.

b Applied to MAR-M 247 only

referenced to the original nominal 1494°K (2230°F) solution treatment temperature:

<u>MAR-M 247</u> - Room-temperature tensile and yield strengths appear to be maximized by the 1505°K (2250°F) solution treatment, while similar properties at 1033°K (1400°F) were lowered by the same solution treatment. Both 1033°K (1400°F) and 1255°K (1800°F) stress-rupture strengths were maximized by the 1505°K (2250°F) solution treatment. The 1483°K (2210°F) solution treatment produced no improvement in mechanical properties.

<u>MAR-M 200+Hf</u> - Tensile properties at room temperature appeared to be insensitive to heat treatment, but at the 1033°K (1400°F) test temperature the tensile properties were maximized by the 1494°K (2230°F) solution treatment. Rupture lives decreased with the 1483°K (2210°F) solution treatment at both test temperatures. The 1494°K (2230°F) and 1505°K (2250°F) solution treatments produced equivalent stress-rupture lives.

<u>NASA-TRW-R</u> - The 1505°K (2250°F) solution treatment lowered room-temperature tensile strengths and maximized the 1033°K (1400°F) tensile strengths. This was an unexpected trend. The 1505°K (2250°F) solution temperature also moderately increased rupture lives at the two test temperatures.

<u>IN 792+Hf</u> - The 1505°K (2250°F) solution treatment yielded slightly higher tensile and rupture strengths than the 1494°K (2230°F). The alloy was, however, substantially weaker than the other three in stress-rupture.

Based on apparent superior results achieved with MAR-M 247 at the 1505°K (2250°F) solution temperature, blades were later solution treated at 1519°K (2275°F) and 1533°K (2300°F), with the objective of determining the tolerance of this alloy to solution treatment at these higher temperatures. Figures 16 and 17 show typical microstructures of DS MAR-M 247 solution treated at temperatures in the range 1483° to 1533°K (2210° to 2300°F). The lowest temperature is obviously inadequate to solution treat primary gamma prime, while at the highest temperature, a small amount of incipient melting occurs. Tabulated results of 1255°K (1800°F) stress-rupture tests on specimens treated at these higher temperatures are presented herein under "Mechanical Tests". A summary of all Task I and Task II stress-rupture test results on DS MAR-M 247 specimens at 1255°K (1800°F) after various solution-treatment temperatures is presented in Table IX.

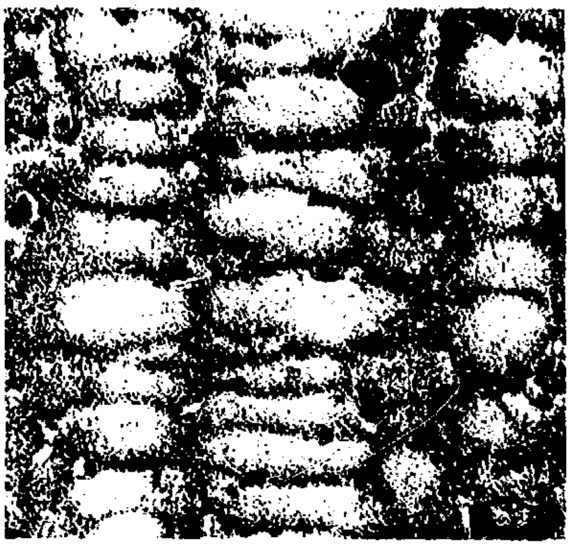
Based on review of the overall results of the heat-treatment study, the solution temperature of 1505°K (2250°F) was selected for application to the alloys cast in Task III.

Metallurgical Evaluation

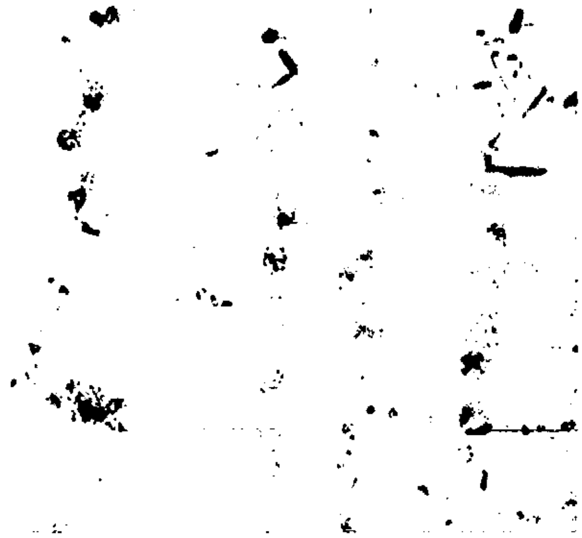
Castings from each of the molds cast during Task II were subjected to nondestructive evaluation, chemical analysis, mechanical tests, and metallurgical tests, including grain etch.

<u>Nondestructive Evalution (NDE)</u>. All Task II blade castings were macroetched to show grain orientation, X-rayed, and fluorescent-penetrant inspected.

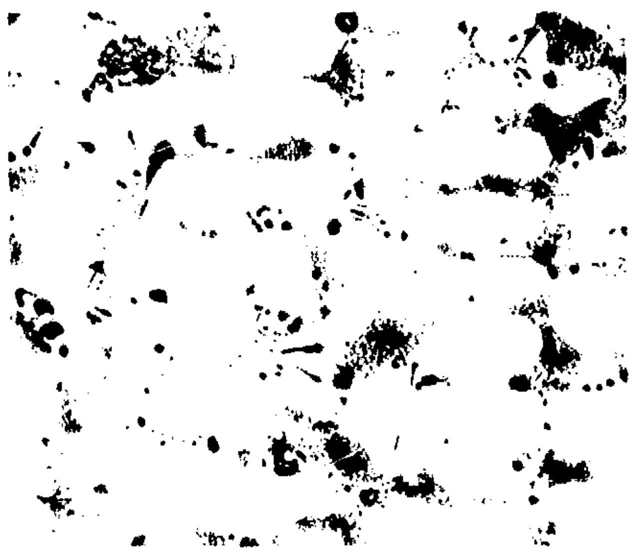
Grain etch of the blade castings from the first group of four molds, revealed that all four alloys responded well to the selected process control procedures. The MAR-M 247 and the NASA-TRW-R produced the finest and straightest columnar grain patterns. The IN 792+Hf grain structure was somewhat coarser but was still acceptable. The four innermost (center) blades in the



(a) $1483^{\circ}K$ ($2210^{\circ}F$)

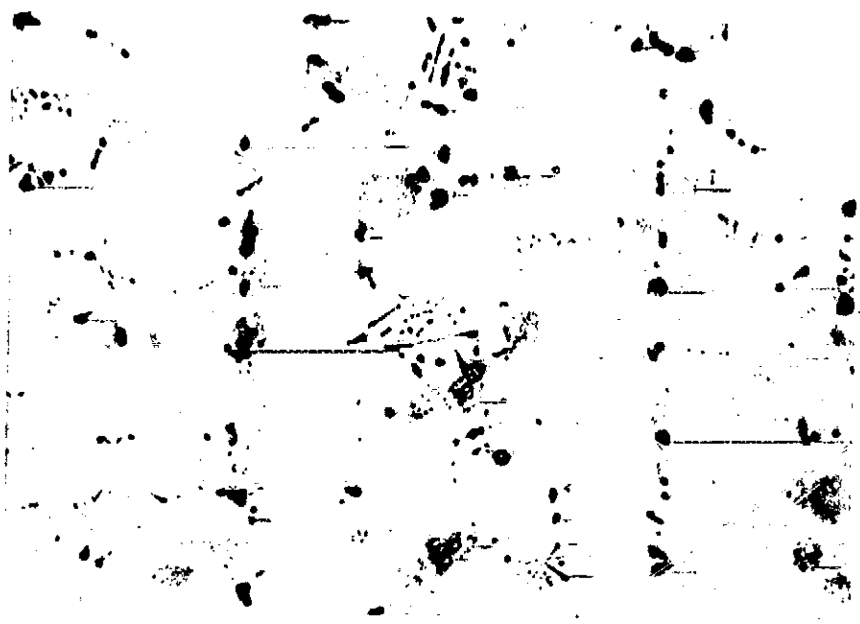


(b) $1494^{\circ}K$ ($2230^{\circ}F$)

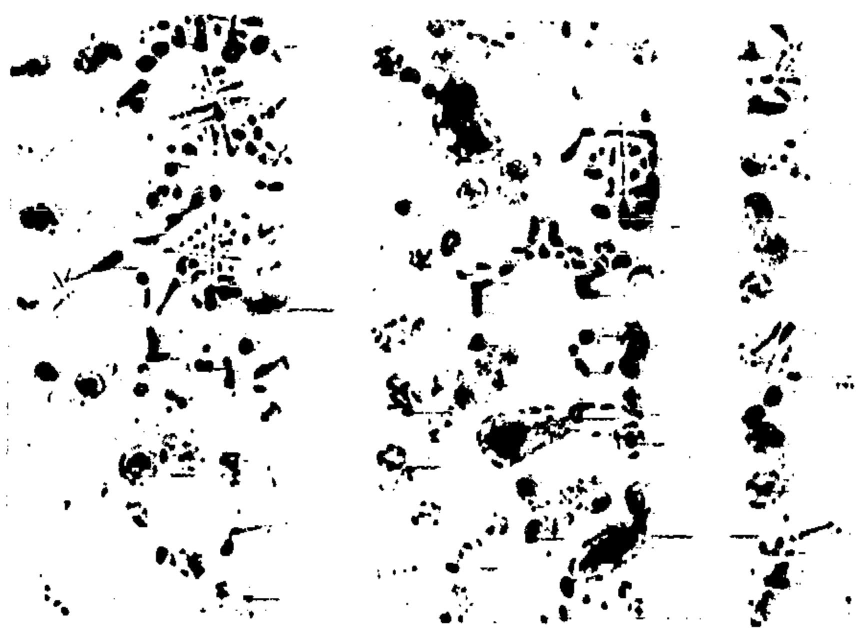


(c) $1505^{\circ}K$ ($2250^{\circ}F$)

Figure 16. Typical Microstructures of DS MAR-M 247 Turbine Blades Solution Treated for Two Hours at the Indicated Temperatures. Grain Growth Direction is Vertical. Kallings Etch. (Mag.:100X)



(a) 1519°K (2275°F)



(b) 1533°K (2300°F)

Figure 17. Typical Microstructures of DS MAR-M 247 Turbine Blades Solution Treated for Two Hours at the Indicated Temperatures. Grain Growth Direction is Vertical. Kallings Etch (Mag.:100X)

TABLE IX. SUMMARY OF TASK II 1255°K (1800°F) STRESS-RUPTURE TEST RESULTS

[Test specimens machined from Task II exothermically cast DS MAR-M 247 turbine blades having various solution treatments. All were inert gas quenched after 2 hours at the solution temperatures, then exposed to 1255°K (1800°F) for 5 hours, air cooled, and aged for 20 hours at 1144°K (1600°F)]

Solution treatment temperature, °K (°F)	Hours to rupture	Number of tests
Longitudinal grain orientation tests at 207 MPa (30 ksi)		
1483 (2210)	53.7 - 75.1	2
1494 (2230)	51.0 - 99.2	29
1505 (2250)	85.2 - 98.5	2
1519 (2275)	79.9 - 125.0	4
1533 (2300)	79.7 - 126.8	4
Transverse grain orientation tests at 186 MPa (27 ksi)		
1494 (2230)	101.3 - 136.7	4
1519 (2275)	97.3 - 173.0	4
1533 (2300)	147.5 - 202.3	4

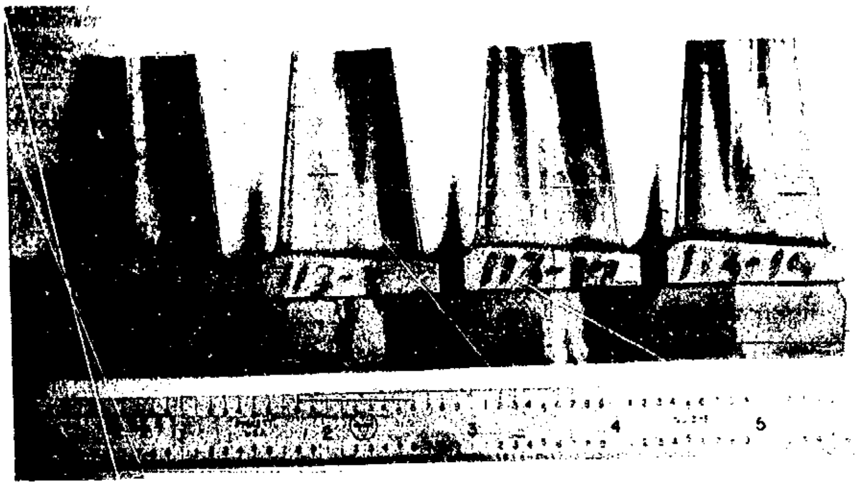
MAR-M 200+Hf mold exhibited some misoriented grains. This uncontrolled nucleation in flash from a hairline mold crack indicated that the local mold temperature was slightly low in the center of the mold cluster.

Grain etching of the castings made in the second group of four molds revealed significantly poorer grain orientation on all four alloys. This was caused by inadequate heat input from the exothermic material. This inadequate heat input disturbed the thermal balance required to produce good DS castings. Despite the relatively poor yield of this group of castings, most of the blades had sufficiently sound, well-oriented grain areas to permit subsequent machining of test specimens for mechanical testing.

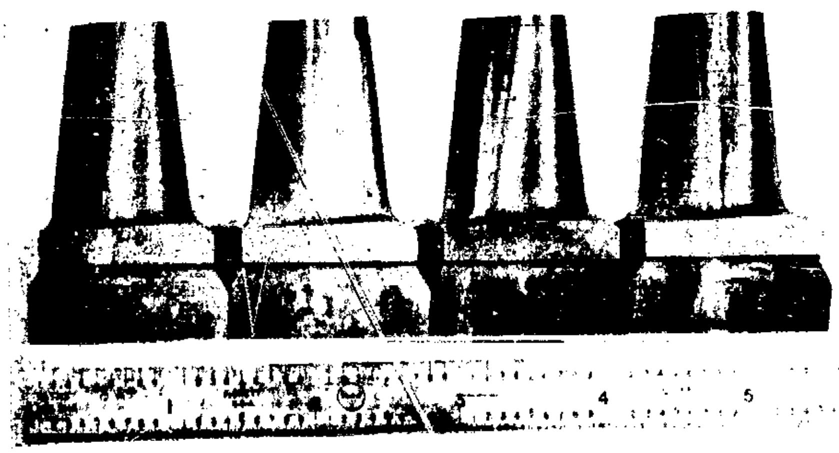
Figures 18 through 21 show typical macroetched blade castings selected from the last two molds cast from each of the alloys. All of the alloys cast showed a good response to the casting process with the exception of IN 792+Hf. All of the blades of this alloy reverted from DS to equiaxed grains in the root sections in the last two molds cast (Molds 89 and 103), which used the third lot of exothermic material.

In addition to grain etch, all Task II blade castings were X-rayed and fluorescent-penetrant inspected (FPI). The accept/reject standards used were those employed for solid IN100 TFE731-2 high-pressure turbine blades, the inspections being performed by AiResearch production Quality Assurance inspectors.

A summary of X-ray, FPI, and DS grain inspection results is presented in Table X. The yields are presented for each mold of each alloy, as well as overall yields for individual inspections and for all inspections combined. Combined inspection results rank the alloys as follows:

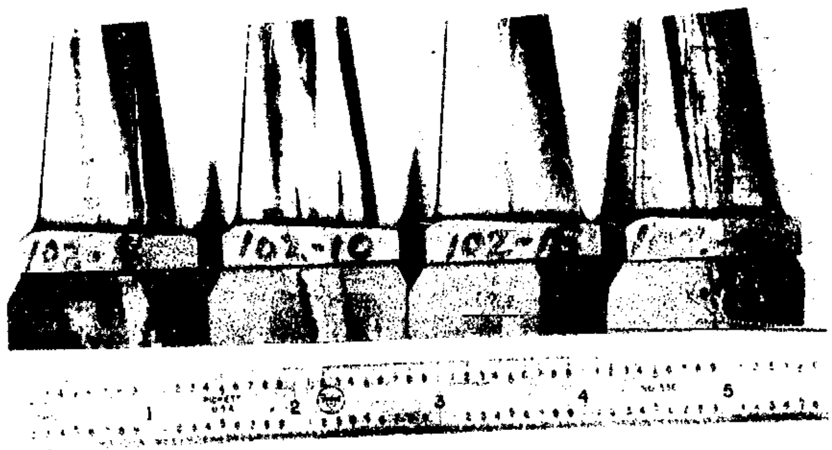


PRESSURE SIDE

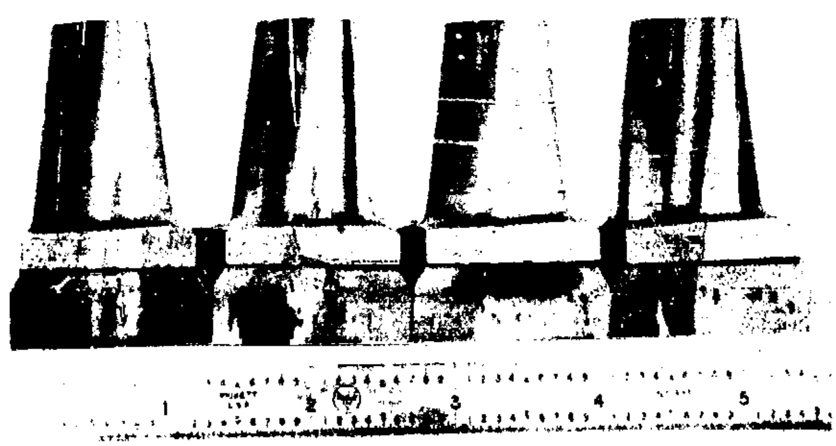


SUCTION SIDE

Figure 18. Typical MAR-M 247 Task II Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades

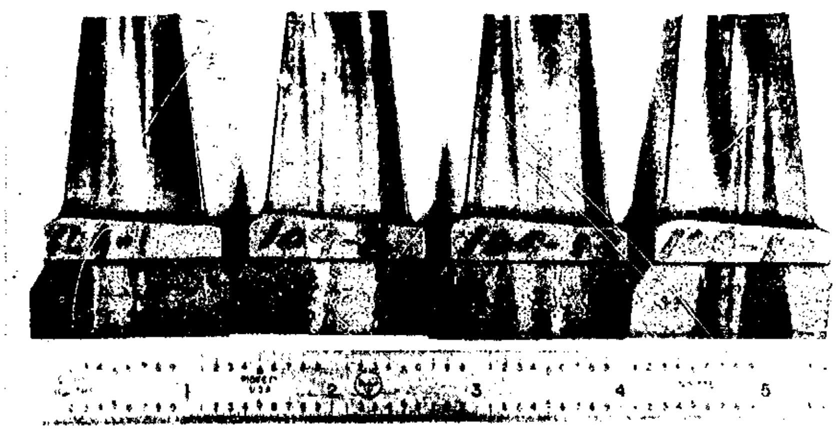


PRESSURE SIDE

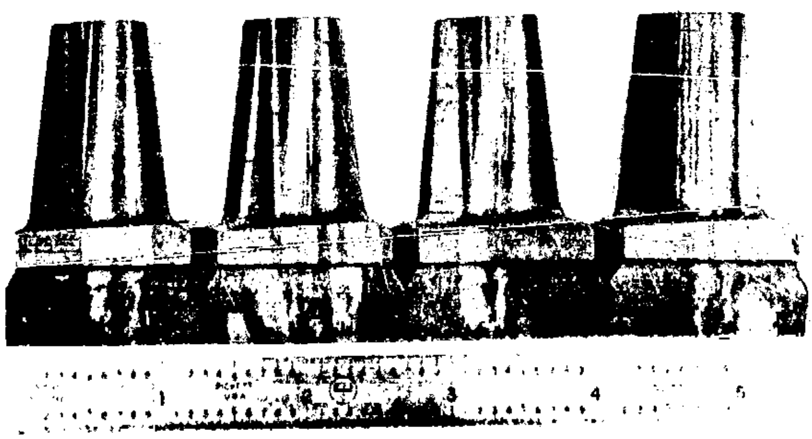


SUCTION SIDE

Figure 19. Typical NASA-TRW-R Task II Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades

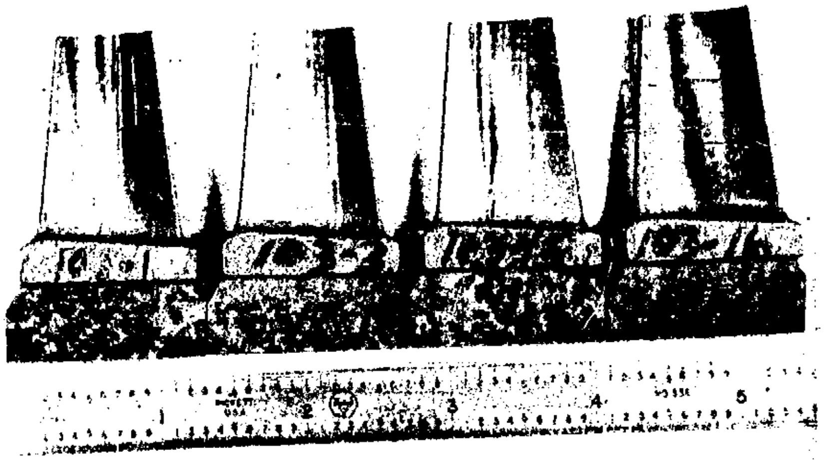


PRESSURE SIDE

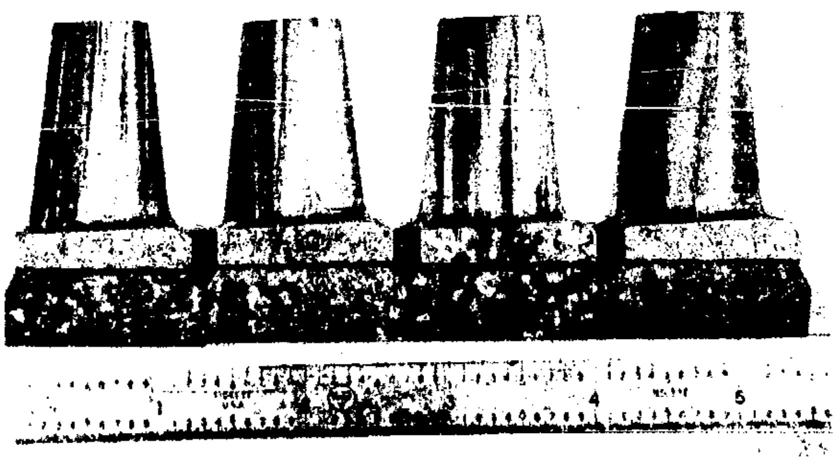


SUCTION SIDE

Figure 20. Typical MAR-M 200+Hf Task II Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades



PRESSURE SIDE



SUCTION SIDE

Figure 21. Typical IN 792+Hf Task II Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades

TABLE X. INSPECTION RESULTS OF TASK II EXOTHERMICALLY CAST DS PRELIMINARY DESIGN TFE731-3 TURBINE BLADES

Alloy	Mold serial number	Percent Acceptable							
		X-ray		FPI		DS grain		Combined	
		Mold	Alloy	Mold	Alloy	Mold	Alloy	Mold	Alloy
MAR-M 247	62	70	60	55	71	85	73	45	40
	70	60		65		55		35	
	101	45		65		70		25	
	113	65		100		80		55	
NASA-TRW-R	66	90	81	70	60	95	70	65	38
	71	80		35		65		20	
	74	90		75		65		40	
	102	65		60		55		25	
MAR-M 200+Hf	65	65	54	40	59	80	61	20	33
	73	40		60		35		15	
	90	30		50		50		25	
	104	80		85		80		70	
IN 792+Hf	64	80	76	85	74	95	40	80	30
	72	75		80		65		40	
	89	55		45		0		0	
	103	95		85		0		0	

(a) MAR-M 247 (best)

(b) NASA-TRW-R

(c) MAR-M 200+Hf

(d) IN 792+Hf (poorest)

Of the three evaluations, the X-ray results would be the most difficult to improve. The blades were generally rejected during X-ray due to high-density inclusions--presumably hafnium oxides. Of the four alloys, the poorest X-ray yield was from MAR-M 200+Hf--the alloy with the highest hafnium content. FPI results must be considered conservative since no attempt was made to blend out any surface defects, and thus improve yields. The last two molds of each alloy were cast with exothermic material with a lower heat output than the initial molds, but only the IN 792+Hf alloy DS grain structure was affected. The other three alloys exhibited a greater tolerance for variability in the heat output of the exothermic material.

Chemical analyses. Chemical analyses were made of castings from all molds. The results of these analyses are shown in Tables XI through XIV. These tables also show the material source master heat identification and certified chemical analyses of the master heats.

No significant deviations were found in the chemistries of the parts versus the chemistries of the master heats, except that the parts tended to have lower hafnium contents than the master heats. This was true of all the alloys except IN 792+Hf, which makes the original certified hafnium content of this alloy suspect. Tables XI through XIV also include hafnium analyses of the root and tip of one blade from each blade mold cast in Task II. The hafnium gradients apparently were lower than the sensitivity of the analytical technique, since the consistently higher hafnium level expected at the tips of these blades (cast root up) was not demonstrated.

TABLE XI. TASK II CHEMICAL ANALYSIS OF MAR-M 247

Mold No.	Hf Root	Hf Tip	C	Cr	Mo	Ta	Al	Ti	Hf	B	Zr	Co	Mn	S	Si	W	P	Cb	Cu	Fe	Ni
	Composition, percent by weight																				
(a) Root section bulk chemical analysis																					
62	-	-	0.11	8.18	0.68	2.98	5.44	1.05	1.27	0.016	0.062	10.78	<0.10	0.001	<0.10	10.03	-	-	-	0.11	Bal
62	1.32	1.31																			
70	-	-	0.11	8.12	0.63	3.09	5.49	1.07	1.25	0.016	0.064	10.69	<0.10	<0.001	<0.10	10.10	-	-	-	0.12	Bal
70	1.30	1.26																			
101	-	-	0.11	8.28	0.69	3.05	5.46	1.07	1.39	0.017	0.069	10.65	<0.10	0.001	<0.10	9.98	-	-	-	0.13	Bal
101	1.40	1.41																			
113	-	-	0.13	8.52	0.67	3.10	5.41	1.05	1.28	0.016	0.064	10.73	<0.10	<0.001	<0.10	10.11	-	-	-	0.15	Bal
(b) Slab (near chill) bulk chemical analysis																					
82	(Not Analyzed)			-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
106	-	-	0.13	8.85	0.72	2.99	5.43	1.07	1.36	0.017	0.065	10.70	<0.10	<0.001	<0.10	10.06	-	-	-	0.15	Bal
(c) Special Metals Heat No. 7-10187																					
			0.14	8.4	0.74	2.99	5.46	1.01	1.54	0.014	0.05	10.3	-	-	-	10.1	-	-	-	-	Bal
(d) Specification range, AiResearch EMS55447																					
		MIN	0.13	8.00	0.50	2.80	5.30	0.90	1.20	0.010	0.03	9.0	0.20	0.015	0.20	9.50	-	-	-	0.50	Bal
		MAX	0.17	8.80	0.80	3.30	5.70	1.20	1.60	0.020	0.08	11.00	MAX	MAX	MAX	10.50	-	-	-	MAX	

TABLE XII. TASK II CHEMICAL ANALYSIS OF NASA-TRW-R

Mold No.	Hf		Composition, percent by weight																		
	Root	Tip	C	Cr	Mo	Ta	Al	Ti	Hf	B	Zr	Co	Mn	S	Si	W	P	Cb	Cu	Fe	Ni
(a) Blade root section bulk chemical analysis																					
65	-	-	0.073	7.95	3.02	7.00	5.42	1.02	0.81	0.019	0.16	7.65	<0.05	<0.001	<0.05	3.96	<0.001	0.52	<0.05	0.19	Bal
66	0.89	0.82																			
71	-	-	0.063	7.44	3.00	7.20	5.38	1.03	0.84	0.020	0.17	7.72	<0.05	<0.001	<0.05	4.00	<0.001	0.54	<0.05	0.22	Bal
71	0.89	0.84																			
74	-	-	0.076	8.15	3.06	7.02	5.36	1.01	0.82	0.021	0.17	7.66	<0.05	<0.001	<0.05	3.97	<0.001	0.56	<0.05	0.21	Bal
74	0.86	0.81																			
102	-	-	0.071	7.81	3.10	7.21	5.39	1.01	0.78	0.021	0.18	7.57	<0.05	<0.001	<0.05	4.00	<0.001	0.55	<0.05	0.19	Bal
102	0.80	0.76																			
(b) Slab (near chill) bulk chemical analysis																					
83	-	-	0.085	8.17	3.07	7.24	5.37	1.03	0.80	0.019	0.15	7.58	<0.05	<0.001	<0.05	3.98	<0.001	0.55	<0.05	0.21	Bal
84	-	-	0.081	8.24	3.02	7.25	5.35	1.03	0.83	0.022	0.16	7.65	<0.05	<0.001	<0.05	3.96	<0.001	0.56	<0.05	0.20	Bal
(c) Cannon-Muskegon Co. Heat No. VE-889																					
			0.08	8.1	3.04	6.70	5.47	0.92	1.07	0.015	0.12	7.75	-	-	-	4.15	-	0.40	-	-	Bal

TABLE XIII. TASK II CHEMICAL ANALYSIS OF MAR-M 200+Hf

Mold No.	Composition, percent by weight																				
	Hf		C	Cr	Mo	Ta	Al	Ti	Hf	B	Zr	Co	Mn	S	Si	W	P	Cb	Cu	Fe	Ni
	Root	Tip																			
(a) Blade root section bulk chemical analysis																					
65	-	-	0.14	8.12	-	-	4.96	2.01	1.90	0.018	<0.10	9.78	<0.10	<0.001	<0.10	11.78	<0.001	0.99	<0.05	<0.10	Bal
65	1.90	1.83																			
73	-	-	0.14	8.14	-	-	4.99	2.05	1.91	0.019	<0.10	9.84	<0.10	<0.001	<0.10	11.88	<0.001	0.97	<0.05	<0.10	Bal
73	1.92	1.81																			
90	-	-	0.14	8.31	-	-	4.98	2.03	1.75	0.017	<0.10	9.90	<0.10	<0.001	<0.10	11.90	<0.001	1.02	<0.05	0.19	Bal
90	1.75	1.83																			
104	-	-	0.15	8.50	-	-	5.04	2.13	2.00	0.018	<0.10	9.95	<0.10	<0.001	<0.10	11.82	<0.001	1.03	<0.05	0.12	Bal
104	1.86	1.80																			
(b) Slab (near chill) bulk chemical analysis																					
85	-	-	0.20	8.44	-	-	5.06	2.10	1.89	0.016	<0.10	9.78	<0.10	<0.001	<0.10	11.75	<0.001	1.00	<0.05	0.11	Bal
109	-	-	0.14	8.48	-	-	4.98	2.09	1.76	0.016	<0.10	9.78	<0.10	<0.001	<0.10	11.82	<0.001	0.96	<0.05	0.15	Bal
(c) Howmet Alloy Division Heat No. 132B5335																					
			0.15	8.53	-	-	4.95	1.90	1.98	0.014	0.06	9.60	-	-	-	11.50	-	0.89	-	-	Bal

TABLE XIV. TASK II CHEMICAL ANALYSIS OF IN 792+Hf

Mold No.	Hf Root	Hf Tip	C	Cr	Mo	Ta	Al	Ti	Hf	B	Zr	Co	Mn	S	Si	W	P	Cb	Cu	Fe	Ni
			Composition, percent by weight																		
(a) Blade root section bulk chemical analysis																					
64	-	-	0.040	11.65	2.00	3.88	3.46	4.07	0.93	0.014	0.092	9.49	<0.05	0.001	<0.05	4.01	<0.001	-	-	0.12	Bal
64	1.00	0.93																			
72	-	-	0.070	11.24	1.94	3.97	3.48	4.15	1.13	0.014	0.10	9.25	<0.05	0.001	<0.05	4.00	<0.001	-	-	0.13	Bal
72	1.09	1.05																			
89	-	-	0.068	11.68	1.88	3.91	3.44	4.05	0.92	0.014	0.096	9.25	<0.05	0.001	<0.05	4.02	<0.001	-	-	0.14	Bal
89	0.89	1.01																			
103	-	-	0.081	12.25	1.89	3.90	3.40	4.05	0.90	0.014	0.089	9.38	<0.05	0.001	<0.05	4.03	<0.001	-	-	0.15	Bal
103	0.86	0.93																			
(b) Slab (near chill) bulk chemical analysis																					
84	-	-	0.089	12.15	1.91	3.90	3.36	3.97	1.06	0.013	0.10	9.32	<0.05	0.001	<0.05	4.03	<0.001	-	-	0.13	Bal
107	-	-	0.088	12.06	1.91	3.91	3.41	3.92	1.01	0.015	0.10	9.13	<0.05	0.001	<0.05	3.98	<0.001	-	-	0.13	Bal
(c) Certified Alloy Products Heat No. V3802																					
			0.09	12.40	1.79	3.99	3.27	3.99	0.96	0.013	0.05	9.0	-	-	-	4.03	-	-	-	-	Bal

Mechanical tests

1. Tests on Specimens Machined from Blades. A number of blades were selected from the first eight Task II molds and divided into two groups for heat treatment. The heat treatments (summarized in Table VIII) used were as follows:

Heat Treatment A: Solution treated at 1494°K (2230°F) for 2 hours, followed by aging at 1144°K (1600°F) for 20 hours.

Heat Treatment B: Solution treated at 1494°K (2230°F) for 2 hours, followed by a simulated aluminide coating thermal cycle of 5 hours at 1255°K (1800°F), and aging at 1144°K (1600°F) for 20 hours.

Test specimens conforming to the mini-bar configuration used in Task I, as shown in Figure 11, were machined from blades from both heat treatment groups. Bars were machined to provide separate specimens with longitudinal (grain-growth direction) and transverse orientation in all cases. The longitudinal specimens were machined from airfoil sections of the castings and the transverse specimens from the root sections. Tensile tests were conducted on specimens at room temperature and at 1033°K (1400°F). Stress-rupture tests were conducted at 1033°K (1400°F) and 1255°K (1800°F). The results are presented in Tables XV through XX.

The room-temperature tensile test results are presented in Table XV. As anticipated, the transverse-orientation strengths were significantly lower than the longitudinal values. The coating cycle did not significantly affect the strengths of any of the alloys except IN 792+Hf. The coating cycle was generally

TABLE XV. TASK II ROOM-TEMPERATURE TENSILE TEST RESULTS

(Test specimens machined from exothermically cast DS preliminary design TFE731-3 turbine blades, Task II blade casting Groups 1 and 2.)

Specimen number	Grain orientation [a]	Heat treatment [b]	Ultimate tensile strength, MPa (ksi)	0.2-Percent yield strength, MPa (ksi)	Elongation, percent	Reduction of area, percent
(a) MAR-M 247						
62-4	L	A	984 (143)	853 (124)	6.4	16.4
62-9	L	A	944 (131)	872 (126)	6.2	12.3
62-4	T	A	756 (100)	747 (108)	4.5	16.1
62-9	T	A	767 (111)	756 (110)	9.3	16.4
62-14	L	B	974 (141)	714 (118)	6.7	14.6
62-16	L	B	972 (141)	830 (120)	6.0	13.5
62-14	T	B	716 (104)	712 (103)	8.6	18.8
62-16	T	B	790 (115)	738 (107)	8.9	37.9
(b) NASA-TRW-R						
66-2	L	A	994 (144)	860 (124)	5.6	13.1
66-8	L	A	970 (141)	834 (121)	6.9	11.8
66-2	T	A	763 (111)	756 (110)	1.8	4.0
66-8	T	A	783 (114)	763 (111)	1.4	7.1
66-9	L	B	972 (141)	829 (120)	6.3	9.7
66-18	L	B	973 (141)	828 (120)	6.8	10.9
66-9	T	B	749 (109)	712 (103)	6.7	18.2
66-18	T	B	727 (106)	711 (103)	3.9	10.2
(c) MAR-M 200+Hf						
65-3	L	A	772 (112)	771 (112)	5.8	15.9
65-6	L	A	988 (143)	855 (124)	7.8	17.2
65-3	T	A	772 (112)	770 (112)	9.1	14.0
65-6	T	A	856 (124)	822 (119)	2.9	11.8
65-13	L	B	923 (134)	812 (118)	8.7	16.4
65-16	L	B	968 (140)	822 (119)	7.3	15.7
65-13	T	B	781 (113)	779 (113)	9.0	19.0
65-16	T	B	828 (120)	757 (110)	11.7	26.5
(d) IN 792+Hf						
64-7	L	A	1109 (161)	918 (133)	7.0	19.5
64-11	L	A	1107 (161)	919 (133)	5.6	11.0
64-7	T	A	822 (119)	781 (113)	5.2	12.3
64-11	T	A	798 (116)	778 (112)	3.5	6.5
64-17	L	B	1056 (153)	853 (124)	6.7	13.8
72-19	L	B	1019 (148)	828 (120)	4.6	13.5
64-17	T	B	767 (111)	741 (108)	4.3	13.7
72-19	T	B	866 (126)	735 (107)	10.4	21.0

[a] L = Longitudinal T = Transverse

[b] A = 1494°K (2230°F) for 2 hours and 1144°K (1600°F) for 20 hours
B = 1494°K (2230°F) for 2 hours, 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours

TABLE XVI. TASK II 1033°K (1400°F) TENSILE TEST RESULTS

(Test specimens machined from exothermically cast DS preliminary design TFE731-3 turbine blades, Task II blade casting Groups 1 and 2.)

Specimen No.	Grain orientation [a]	Heat treatment [b]	Ultimate tensile strength, MPa (ksi)		0.2-Percent yield strength, MPa (ksi)		Elongation, percent	Reduction of area, percent
(a) MAR-M 247								
62-8	L	A	997	(145)	814	(118)	8.3	15.5
62-2	T	A	818	(119)	713	(103)	5.5	22.2
62-8	T	A	732	(106)	676	(98)	6.7	14.8
62-13	L	B	1091	(158)	886	(129)	4.4	15.3
62-15	L	B	952	(138)	773	(112)	7.0	27.3
62-13	T	B	758	(110)	683	(99)	10.7	26.1
62-15	T	B	741	(108)	663	(96)	3.8	16.6
(b) NASA-TRW-R								
66-5	L	A	1042	(151)	832	(121)	4.6	21.4
71-11	L	A	1109	(161)	880	(128)	12.5	22.8
66-5	T	A	745	(108)	684	(99)	5.5	15.7
71-11	T	A	945	(137)	832	(121)	2.9	13.9
66-16	L	B	1085	(157)	914	(133)	4.1	11.1
71-20	L	B	1071	(155)	894	(130)	9.5	26.7
66-16	T	B	765	(111)	722	(105)	6.4	9.3
71-20	T	B	796	(115)	738	(107)	9.6	17.3
(c) MAR-M 200+Hf								
65-4	L	A	1123	(163)	872	(127)	5.4	14.0
73-10	L	A	1136	(165)	901	(131)	7.3	16.4
65-4	T	A	936	(136)	790	(115)	2.9	8.3
73-10	T	A	761	(110)	709	(103)	12.9	20.0
65-15	L	B	1117	(162)	909	(132)	5.2	13.8
73-17	L	B	1120	(163)	898	(130)	6.9	20.9
65-15	T	B	809	(117)	702	(102)	12.6	20.9
73-17	T	B	882	(128)	760	(110)	6.8	18.7
(d) IN 792+Hf								
64-8	L	A	1111	(161)	840	(122)	11.0	33.5
72-7	L	A	1067	(155)	779	(113)	14.4	28.0
64-8	T	A	897	(130)	683	(99)	8.0	14.9
72-7	T	A	871	(127)	621	(90)	9.8	15.5
64-15	L	B	1096	(159)	800	(116)	13.0	28.5
72-12	L	B	1089	(158)	778	(113)	7.7	18.3
64-15	T	B	740	(109)	644	(93)	4.7	11.9
72-12	T	B	960	(139)	687	(100)	5.1	14.0

[a] L = Longitudinal T = Transverse

[b] A = 1494°K (2230°F) for 2 hours and 1144°K (1600°F) for 20 hours
B = 1494°K (2230°F) for 2 hours, 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours

TABLE XVII. TASK II 1033°K (1400°F) STRESS-RUPTURE TEST RESULTS - LONGITUDINAL GRAIN ORIENTATION

(Test specimens machined from exothermically cast DS preliminary design TFE731-3 turbine blades, Task II blade casting Groups 1 and 2.)

Specimen no.	Heat treatment[a]	Hours to rupture	Elongation, percent	Reduction of area, percent
1033°K/ 724 MPa (1400°F/105 ksi) Tests				
MAR-M 247				
62-1	A	79.9	10.6	18.1
62-7	A	12.4	14.0	19.0
62-12	B	55.7	11.7	20.2
70-12	B	53.2	10.0	28.9
NASA-TRW-R				
66-4	A	79.1	9.2	34.7
71-6	A	29.2	12.1	36.9
66-14	B	34.8	9.6	26.1
71-14	B	36.4	11.2	29.4
MAR-M 200+Hf				
65-2	A	18.2	6.7	18.1
73-8	A	77.1	12.1	23.9
65-12	B	87.3	8.8	21.2
73-13	B	59.4	11.6	31.2
1033°K/ 689 MPa (1400°F/100 ksi) Tests				
IN 792+Hf				
64-5	A	23.7	9.3	31.7
72-4	A	31.6	11.1	25.0
64-14	B	17.8	13.4	40.0
72-10	B	14.5	10.8	33.5

[a] A = 1494°K (2230°F) for 2 hours, and 1144°K (1600°F) for 20 hours

B = 1494°K (2230°F) for 2 hours, 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours

TABLE XVIII. TASK II 1033°K (1400°F) STRESS-RUPTURE TEST RESULTS - TRANSVERSE GRAIN ORIENTATION

(Test specimens machined from exothermically cast DS preliminary design TFE731-3 turbine blades, Task II blade casting Groups 1 and 2.)

Specimen no.	Heat[a] treatment	Stress, MPa (ksi)	Hours to rupture	Elongation, percent	Reduction of area, percent
MAR-M 247					
62-1	A	689 (100)	3.7	3.9	15.1
62-7	A	621 (90)	70.0	4.4	10.9
62-12	B	689 (100)	6.0	4.4	25.9
70-12	B	621 (90)	229.1	13.1	23.9
NASA-TRW-R					
66-4	A	689 (100)	9.9	4.4	22.9
71-6	A	621 (90)	10.2	11.1	38.2
66-14	B	689 (100)	3.8	4.3	23.1
71-14	B	621 (90)	21.1	8.0	21.4
MAR-M 200+Hf					
65-2	A	689 (100)	5.0	4.6	14.4
73-8	A	621 (90)	579.1	6.7	18.7
65-12	B	689 (100)	2.6	9.0	24.3
73-13	B	621 (90)	83.3	10.0	18.7
IN 792+Hf					
64-5	A	655 (95)	12.4	6.3	26.5
72-4	A	621 (90)	23.4	6.0	9.7
64-14	B	655 (95)	10.3	4.3	10.9
72-10	B	621 (90)	28.1	4.3	13.5

[a] A = 1494°K (2230°F) for 2 hours and 1144°K (1600°F) for 20 hours

B = 1494°K (2230°F) for 2 hours, 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours

TABLE XIX. TASK II 1255°K (1800°F) STRESS-RUPTURE TEST RESULTS - LONGITUDINAL GRAIN ORIENTATION

(Test specimens machined from exothermically cast DS preliminary design TFE731-3 turbine blades, Task II blade casting Groups 1 and 2.)

Specimen no.	Heat treatment [a]	Hours to rupture	Elongation, percent	Reduction of area, percent
1255°K/207 MPa (1800°F/30 ksi) Tests				
MAR-M 247				
62-6	A	63.7	20.1	49.7
70-19	A	69.7	18.2	44.0
62-10	B	61.8	14.1	34.9
70-10	B	68.1	7.8	21.6
NASA-TRW-R				
66-3	A	49.1	17.1	44.5
71-1	A	53.6	17.9	45.2
66-10	B	39.4	14.8	35.9
71-13	B	39.0	13.0	37.4
MAR-M 200+Hf				
65-1	A	58.9	14.5	47.0
73-1	A	59.7	15.5	43.1
65-9	B	46.9	19.6	49.3
73-11	B	73.5	18.8	37.4
1255°K/193 MPa (1800°F/28 ksi) Tests				
IN 792+Hf				
64-1	A	14.7	16.4	33.6
72-1	A	36.3	17.6	48.6
64-13	B	27.3	15.8	38.2
72-9	B	29.0	15.5	42.7

[a] A = 1494°K (2230°F) for 2 hours and 1144°K (1600°F) for 20 hours
B = 1494°K (2230°F) for 2 hours, 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours

TABLE XX. TASK II 1255°K (1800°F) STRESS-RUPTURE TEST RESULTS - TRANSVERSE GRAIN ORIENTATION

(Test specimens machined from exothermically cast DS preliminary design TFE731-3 turbine blades, Task II blade casting Groups 1 and 2)

Specimen no.	Heat treatment[a]	Stress MPa (ksi)	Hours to rupture	Elongation, percent	Reduction of area, percent
MAR-M 247					
62-6	A	186 (27)	104.8	9.4	18.3
70-19	A	186 (27)	136.7	7.2	21.6
62-10	B	186 (27)	118.2	14.1	34.9
70-10	B	186 (27)	101.3	7.8	21.6
NASA-TRW-R					
66-3	A	186 (27)	61.3	1.8	8.3
71-1	A	186 (27)	56.0	8.7	16.2
66-10	B	186 (27)	76.6	5.4	13.1
71-13	B	186 (27)	104.3	9.0	13.3
MAR-M 200+Hf					
65-1	A	186 (27)	98.6	4.4	15.5
73-1	A	186 (27)	95.7	16.4	25.5
65-9	B	186 (27)	111.6	13.6	15.9
73-11	B	186 (27)	103.6	3.5	12.0
IN 792+Hf					
64-1	A	172 (25)	44.7	6.4	13.8
72-1	A	138 (20)	105.3	5.8	12.0
64-13	B	172 (25)	7.9	7.0	15.1
72-9	B	138 (20)	95.0	4.3	10.7

[a] A = 1494°K (2230°F) for 2 hours and 1144°K (1600°F) for 20 hours

B = 1494°K (2230°F) for 2 hours, 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours

beneficial to ductility, particularly in the transverse direction. Originally there seemed to be an identification problem with specimen 65-3 of MAR-M 200+Hf--the results of the testing appeared to be for a transverse orientation specimen rather than a longitudinal one. Macroetching and inspection of the specimen indicated that the identification, as presented, is correct.

Table XVI presents the 1033°K (1400°F) tensile test results. All of the alloys appeared to have a peak tensile strength at this temperature, and the transverse properties were again significantly lower than the longitudinal. The simulated coating cycle apparently had no effect on tensile strength or ductility at this temperature.

Results of the 1033°K (1400°F) stress-rupture tests are presented in Tables XVII and XVIII. The longitudinal orientation results of Table XVII indicate that IN 792+Hf was significantly weaker than the other three alloys. MAR-M 247, NASA-TRW-R, and MAR-M 200+Hf were essentially of the same strength level. The simulated coating cycle apparently caused a reduction in the scatter of results for the strong alloys and weakened IN 792+Hf. The transverse-orientation test results given in Table XVIII show a wide distribution of rupture lives due to changes in stress levels for this testing. The main reason for this was the problem in selecting initial stress levels to yield 100-hour failures in the absence of prior test data. The data illustrates that MAR-M 247 and MAR-M 200+Hf are the strongest of the four alloys in the transverse direction.

The 1255°K (1800°F) stress-rupture test results are reported in Tables XIX and XX. Once again, IN 792+Hf was the weakest of the four alloys, and the other three were very close in strength. Review of the grain structure, heat treatment, and mechanical properties data available at this point in the program resulted in a decision to reduce the level of evaluation of IN 792+Hf for the remainder of Task II and eliminate this alloy from consideration in subsequent tasks.

Blades of the three strongest alloys chosen for further evaluation were selected from the various Task II molds. These blades were divided into three groups for heat treatment--one group subjected to solution treatment at 1494°K (2230°F) (Heat Treatment B as summarized in Table VIII), a second group at 1483°K (2210°F) (Heat Treatment C), and the third of 1505°K (2250°F) (Heat Treatment D). Following solution treatment, each of the groups were subjected to a simulated coating cycle of 1255°K (1800°F) for 5 hours followed by an aging cycle of 1144°K (1600°F) for 20 hours.

Mini-bar test specimens were machined from the airfoil section of blades of each heat-treatment group, with all specimens having longitudinal grain orientation. The specimens were subjected to tensile tests at room temperature and 1033°K (1400°F), and stress-rupture tests at 1033°K (1400°F) and 1255°K (1800°F). Specimens of IN 792+Hf, were selected for test only from Heat Treatment D, [1505°K (2250°F) solution treatment followed by the simulated coating cycle and aging].

Results of the tensile and stress-rupture tests are presented in Tables XXI through XXIV. To facilitate evaluation of these results, the tables include selected longitudinal data previously reported in Tables XV through XX for specimens from the first two groups of Task II molds. A discussion of the results of these Task II tests is presented herein under "Heat Treatment Studies" (see page 48).

Results of stress-rupture tests at 1255°K (1800°F) on MAR-M 247 specimens machined from blades solution treated at 1519°K (2375°F) and 1533°K (2300°F) are presented in Table XXV.

TABLE XXI. TASK II ROOM-TEMPERATURE TENSILE TEST RESULTS

(Test specimens machined from Task II exothermically cast DS turbine blades having heat treatment noted below.)

Specimen no.	Grain orientation [a]	Heat treatment [b]	Ultimate tensile strength, MPa (ksi)		0.2-percent yield strength, MPa (ksi)		Elongation, percent	Reduction in area, percent
MAR-M 247								
70-3	L	C	1068	(155)	866	(126)	5.7	17.0
70-16	↓	C	874	(127)	784	(114)	13.4	24.3
70-8	↓	B	974	(141)	800	(116)	15.9	29.2
62-11	↓	B	1002	(145)	847	(123)	13.1	15.3
62-14c	↓	B	974	(141)	814	(118)	6.7	14.6
62-16c	↓	B	972	(141)	830	(120)	6.0	13.5
113-12	↓	D	1017	(148)	890	(129)	8.7	15.7
62-17	↓	D	1005	(146)	878	(127)	8.2	14.4
MAR-M-200+Hf								
73-3	L	C	989	(144)	809	(117)	8.9	11.5
73-6	↓	C	1134	(162)	885	(128)	10.0	16.2
73-5	↓	B	1062	(154)	880	(128)	10.4	19.8
73-7	↓	B	966	(140)	851	(123)	10.6	21.6
65-13c	↓	B	923	(134)	812	(118)	8.7	16.4
65-16c	↓	B	968	(140)	822	(119)	7.3	15.7
73-2	↓	D	999	(145)	872	(127)	13.1	15.5
104-7	↓	D	1014	(147)	899	(130)	11.8	15.9
NASA-TRW-R								
66-12	L	C	792	(115)	763	(111)	5.2	14.6
102-13	↓	C	1006	(146)	809	(117)	9.3	21.0
66-7	↓	B	972	(141)	825	(120)	6.4	14.3
66-19	↓	B	1110	(161)	927	(135)	6.8	12.2
66-9 c	↓	B	972	(141)	829	(120)	6.3	9.7
66-18c	↓	B	973	(141)	828	(120)	6.8	10.9
66-1	↓	D	851	(123)	778	(113)	8.9	14.3
66-6	↓	D	872	(127)	785	(114)	8.0	23.0
IN 792+Hf								
64-7 c	L	B	1109	(161)	918	(133)	7.0	19.5
64-11c	↓	B	1107	(161)	919	(133)	5.6	11.0
64-6	↓	D	1118	(162)	918	(133)	5.9	15.5
103-8	↓	D	1181	(171)	913	(132)	6.5	13.9

a L = Longitudinal
  T = Transverse

b B = 1494 °K (2230 °F) for 2 hours, plus 1255 °K (1800 °F) for 5 hours, and 1144 °K (1600 °F) for 20 hours.
  C = 1483 °K (2210 °F) for 2 hours, plus 1255 °K (1800 °F) for 5 hours, and 1144 °K (1600 °F) for 20 hours.
  D = 1505 °K (2250 °F) for 2 hours, plus 1255 °K (1800 °F) for 5 hours, and 1144 °K (1600 °F) for 20 hours

c Data previously reported in Tables XV through XX

TABLE XXII. TASK II 1033°K (1400°F) TENSILE TEST RESULTS

(Test specimens machined from Task II exothermically cast DS turbine blades having heat treatment noted below.)

Specimen no.	Grain orientation [a]	Heat treatment [b]	Ultimate tensile strength, MPa (ksi)		0.2-percent yield strength, MPa (ksi)		Elongation, percent	Reduction in area, percent
MAR-M 247								
113-13	L	C	1011	(147)	837	(121)	6.7	17.9
113-20		C	1043	(151)	826	(120)	7.3	19.8
113-1		B	1074	(156)	869	(126)	6.7	16.8
113-14		B	878	(127)	755	(110)	5.9	12.2
62-13 c		B	1091	(158)	886	(129)	4.4	15.3
62-15 c		B	952	(138)	773	(112)	7.0	27.3
70-18		D	858	(125)	745	(108)	11.9	29.7
113-5		D	931	(135)	779	(113)	7.3	13.2
MAR-M 200+Hf								
104-5	L	C	1111	(161)	894	(130)	6.0	14.7
104-15		C	1105	(160)	902	(131)	6.1	17.6
65-14		B	1159	(168)	959	(139)	5.2	11.0
104-6		B	(Specimen broken prior to testing)					
65-15 c		B	1117	(163)	909	(132)	5.2	13.8
73-17 c		B	1120	(163)	898	(130)	6.9	20.9
65-17		D	933	(135)	795	(115)	8.9	17.0
65-19		D	1115	(162)	878	(127)	9.6	17.9
NASA-TRW-R								
102-5	L	C	1118	(162)	909	(132)	6.2	10.7
102-12		C	1121	(163)	887	(129)	5.2	12.2
71-4		B	1144	(166)	934	(135)	8.1	21.6
102-7		B	1017	(148)	856	(124)	4.8	12.2
66-16 c		B	1085	(157)	914	(133)	4.1	11.1
71-20 c		B	1057	(155)	894	(130)	9.5	26.7
71-3		D	1193	(173)	911	(132)	6.5	15.1
102-9		D	1160	(168)	937	(136)	4.4	10.9
IN 792+Hf								
64-17 c	L	B	1056	(153)	853	(124)	6.7	13.8
72-19 c		B	1019	(148)	828	(120)	4.6	13.5
64-16		D	1131	(164)	814	(118)	14.7	35.9
103-1		D	1126	(163)	767	(111)	10.8	25.5

a L = Longitudinal
T = Transverse

b B = 1494°K (2230°F) for 2 hours, plus 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours.
C = 1483°K (2210°F) for 2 hours, plus 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours.

c Data previously reported in Tables XV through XX.

TABLE XXIII. TASK II 1033°K (1400°F) STRESS-RUPTURE TEST RESULTS

(Longitudinal grain orientation test specimens machined from Task II exothermically cast DS turbine blades having heat treatment noted below.)

Specimen no.	Heat treatment [a]	Hours to rupture	Elongation, percent	Reduction of area, percent
1033°K/724 MPa (1400°F/105 ksi) Tests				
MAR-M 247				
113-17	C	86.1	10.5	24.5
113-19	C	72.6	7.8	25.0
113-6	B	75.6	12.1	24.8
62-18	B	11.1	14.4	28.9
62-12 b	B	55.7	11.7	20.2
70-12 b	B	53.2	10.0	28.9
113-15	D	127.1	9.4	24.3
62-20	D	80.6	10.2	21.8
MAR-M 200+Hf				
104-4	C	67.8	23.4	36.9
104-8	C	61.3	9.8	24.8
104-3	B	107.7	9.6	21.0
104-14	B	140.2	9.4	22.3
65-12 b	B	87.3	8.8	21.2
73-13 b	B	59.4	11.6	31.2
104-2	D	171.2	13.5	24.1
104-17	D	86.1	10.5	24.5
NASA-TRW-R				
71-15	C	37.5	11.5	31.3
102-8	C	87.6	8.7	29.6
66-11	B	38.3	9.9	26.1
71-5	B	42.1	11.5	29.1
66-14 b	B	34.8	9.6	26.1
71-14 b	B	36.4	11.2	29.4
66-13	D	58.5	9.2	25.2
102-11	D	86.2	9.7	25.3
1033°K/689 MPa (1400°F/100 ksi) Tests				
IN 792+Hf				
64-14 b	B	17.8	13.4	40.0
72-10 b	B	14.5	10.8	33.5
64-10	D	81.6	10.0	21.9
103-15	D	17.2	7.3	25.4

[a] B = 1494°K (2230°F) for 2 hours, plus 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours
C = 1483°K (2210°F) for 2 hours, plus 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours
D = 1505°K (2250°F) for 2 hours, plus 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours

[b] Data previously reported in Tables XV through XX.

TABLE XXIV. TASK II 1255°K (1800°F) STRESS-RUPTURE TEST RESULTS

(Longitudinal grain orientation test specimens machined from Task II exothermically cast DS turbine blades having heat treatment noted below.)

Specimen no.	Heat treatment [a]	Hours to rupture	Elongation, percent	Reduction of area, percent
1255°K/207 MPa (1800°F/30 ksi) Tests				
MAR-M 247				
113-3	C	75.1	35.5	42.1
113-7	C	53.7	22.3	41.6
113-11	B	56.0	15.5	39.9
113-18	B	68.8	9.9	26.8
62-6 b	B	61.8	14.1	34.9
70-19 b	B	68.1	7.8	21.6
113-2	D	85.2	22.8	30.3
113-4	D	98.5	40.0	53.2
MAR-M 200+Hf				
104-9	C	51.0	18.5	40.3
104-13	C	51.0	21.8	39.4
104-1	B	76.5	20.5	26.8
104-11	B	53.5	21.3	46.6
65-9 b	B	46.9	19.6	49.3
73-11 b	B	73.5	18.8	37.4
104-10	D	82.0	15.5	41.6
104-12	D	59.0	17.8	37.8
NASA-TRW-R				
102-15	C	64.5	20.9	42.1
102-19	C	40.7	16.1	41.5
102-10	B	63.8	21.1	47.4
104-14	B	58.1	16.7	43.7
66-10 b	B	39.4	14.8	35.9
71-13 b	B	39.0	13.0	37.4
102-1	D	65.3	22.0	35.1
102-18	D	63.7	18.7	42.8
1255°K/193 MPa (1800°F/28 ksi) Tests				
IN 792+Hf				
64-13 b	B	27.3	15.8	38.2
72-9 b	B	29.0	15.5	42.7
64-2	D	36.5	18.3	42.4
103-18	D	38.6	16.8	41.6

[a] B = 1494°K (2230°F) for 2 hours, plus 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours
C = 1483°K (2210°F) for 2 hours, plus 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours
D = 1505°K (2250°F) for 2 hours, plus 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours

[b] Data previously reported in Tables XV through XX.

a-2

TABLE XXV. TASK II 1255°K (1800°F) STRESS-RUPTURE TEST RESULTS (Test specimens machined from Task II exothermically cast DS Mar-M 247 turbine blades solution-treated at 2 temperatures. Solution treatment for 2 hours, followed by inert gas quenching, then 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours.)

Specimen no.	Grain Orientation[a]	Stress MPa (ksi)	Hours to rupture	Elongation, percent	Reduction of area, percent
1519°K (2275°F) solution treatment					
70-2	L	207 (30)	125.0	28.5	57.4
70-9	L	207 (30)	105.7	27.7	49.7
70-14	L	207 (30)	79.9	24.6	44.6
70-20	L	207 (30)	116.0	26.9	50.9
70-2T	T	186 (27)	173.0	21.0	37.9
70-9T	T	186 (27)	135.7	5.9	11.3
70-14T	T	186 (27)	97.3	6.8	12.5
70-20T	T	186 (27)	162.3	9.6	15.4
1533°K (2300°F) solution treatment					
70-6	L	207 (30)	79.7	4.9	9.0
70-7	L	207 (30)	106.7	24.2	55.8
70-11	L	207 (30)	126.8	23.4	44.9
70-17	L	207 (30)	83.5	24.6	45.2
70-6T	T	186 (27)	202.3	14.5	34.2
70-7T	T	186 (27)	173.3	13.9	29.5
70-11T	T	186 (27)	147.5	6.5	13.9
70-17T	T	186 (27)	158.5	5.9	10.5

[a] L = Longitudinal
T = Transverse

2. Tests on Specimens Machined from Slabs. The eight slab molds cast for Task II cyclic-rupture testing provided for 6 rectangular slabs per mold, with 2 molds cast per alloy. These slabs were 15.24-cm high, 7.62-cm wide and 1.27-cm thick (6 inches by 3 inches by 0.5 inch), and were heat treated using a solution temperature of 1494°K (2230°F) for 2 hours followed by inert gas quenching, a simulated coating cycle at 1255°K (1800°F) for 5 hours and aging at 1146°K (1600°F) for 20 hours.

Both smooth and notched test specimens were machined from the slabs with separate specimens having longitudinal, transverse and 45-degree grain orientations. The smooth test specimens had a standard 0.625-cm (0.25-inch) gage diameter and 3.175-cm (1.25-inch) gage length as shown in Figure 13). The notched specimens had a nominal notch diameter of 0.452 cm (0.178-inch) and were otherwise configured as shown in Figure 22.

Initial cyclic-rupture tests at 1033°K (1400°F) on smooth, longitudinal-grain specimens machined from slabs indicated that cyclic testing did not degrade the stress-rupture life of the alloys. Using a 10-second load, 90-second hold, and 10-second unload cycle, smooth test specimens were tested at progresively higher stresses as shown in Table XXVI. Based on these results, three tests were run on similar specimens at peak stresses of 723.9 MPa (105 ksi). Results of these tests, as shown in Table XXVII, indicated that the stresses were not sufficiently high to produce the desired 100-hour failure. Therefore, the balance of the cyclic rupture testing was accomplished at 758 MPa (110 ksi) maximum stress for the longitudinal-grain specimens and 724 MPa (105 ksi) for the 45-degree-grain-oriented specimens.

The results of the cyclic-rupture testing at 1033°K (1400°F) on specimens machined from slabs are tabulated in Table XXVIII and graphically compared in Figure 23. The bulk of the testing

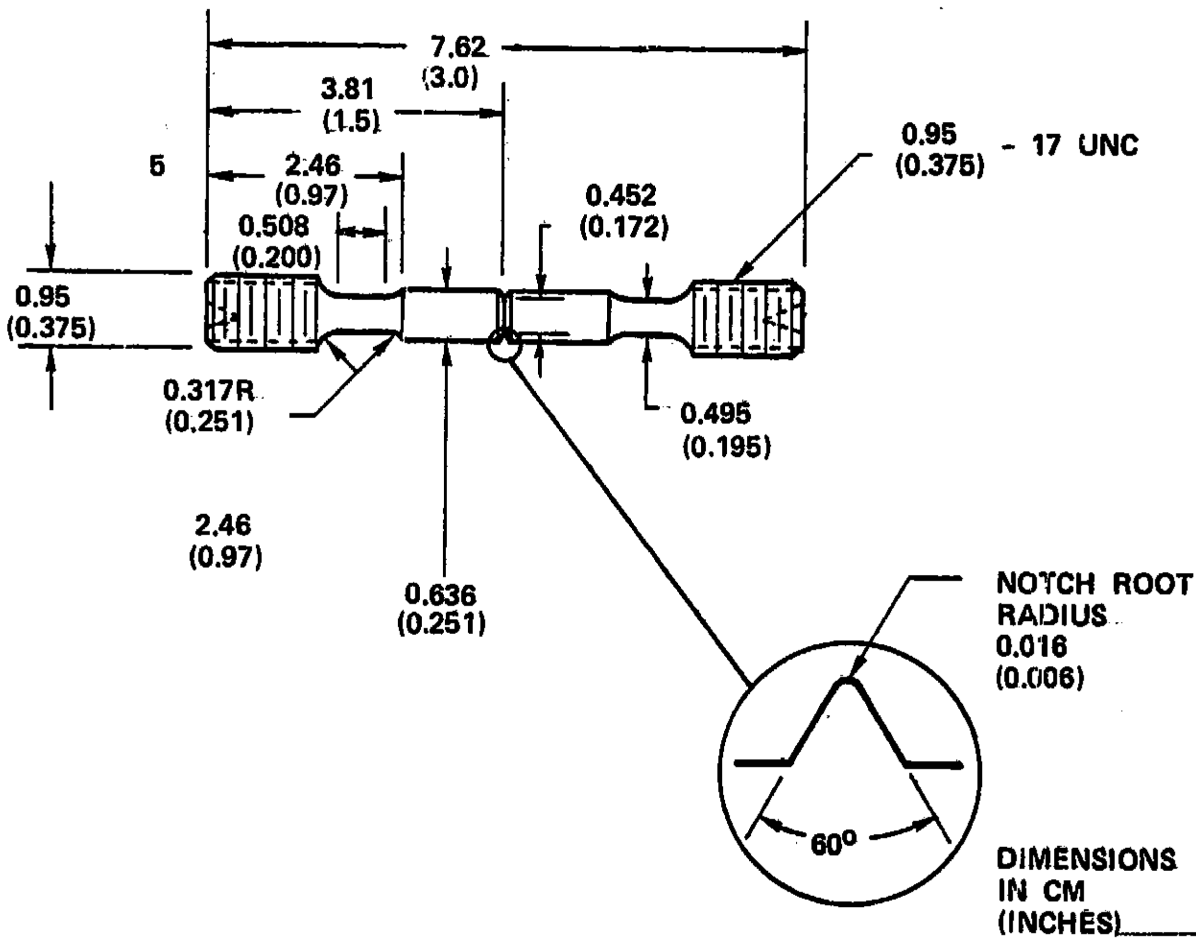


Figure 22. Cyclic Rupture Specimen

TABLE XXVI. TASK II 1033°K (1400°F) CYCLIC-RUPTURE TEST RESULTS AT PROGRESSIVELY HIGHER STRESSES.

[Smooth, longitudinal grain orientation test specimens machined from exothermically cast DS slabs. Prior to machining, slabs were solution-treated at 1494°K (2230°F) for 2 hours followed by inert gas quenching, 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours.]

Alloy	Hours at the indicated test stresses			
	655 MPa (95 ksi)	690 MPa (100 ksi)	726 MPa (105 ksi)	Total hours
Mar-M 247 (Specimen 105)	300	100	67.4	467.4
Mar-M 200+Hf (Specimen 97)	300	100	73.2	473.2
NASA-TRW-R (Specimen 101)	300	100	Failed on loading	400.0

TABLE XXVII. TASK II 1033°K (1400°F), 724 MPa (105 ksi) CYCLIC-RUPTURE TEST RESULTS

[Smooth, longitudinal grain orientation test specimens machined from exothermically cast DS slabs. Prior to machining, slabs were solution-treated at 1494°K (2230°F) for 2 hours followed by inert gas quenching, 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours.]

Alloy	Hours	Cycles
MAR-M 247 (Specimen 106)	182.8	5678
MAR-M 200+Hf (Specimen 98)	185.0	6046
NASA-TRW-R (Specimen 102)	158.2	5285

TABLE XXVIII. TASK II, 1033°K (1400°F) CYCLIC-RUPTURE TEST RESULTS FOR THREE GRAIN ORIENTATIONS

[Test specimens machined from exothermically cast DS slabs. Prior to machining, slabs were solution-treated at 1494°K (2230°F) for 2 hours followed by inert gas quenching, 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours.]

Specimen	Orientation[a]	Type of specimen	Maximum stress, MPa (ksi)	Hours to failure	Cycles to failure	Elongation, percent	Reduction of area, percent
49	L	Smooth	758 (110)	122.7	3919	8.7	11.5
50	L	Smooth	758 (110)	89.9	2989	7.3	11.6
53	L	Smooth	758 (110)	89.8	2979	11.0	12.9
54	L	Smooth	758 (110)	97.6	3227	9.2	11.4
107	L	Smooth	758 (110)	236.7	7592	6.0	10.1
51	L	Notched (K_t=1.8)	758 (110)	187.0	6217	-	-
52	L	Notched (K_t=1.8)	758 (110)	249.2	8351	-	-
55	L	Notched (K_t=1.8)	758 (110)	234.0	7621	-	-
56	L	Notched (K_t=1.8)	758 (110)	207.9	6967	-	-
65	T	Smooth	724 (105)	93.1	3045	4.0	8.1
66	T	Smooth	724 (105)	57.2	1891	4.6	8.5
67	T	Notched (K_t=1.8)	724 (105)	225.9	7333	-	-
68	T	Notched (K_t=1.8)	724 (105)	231.8	7514	-	-
57	45°	Smooth	724 (105)	62.4	2023	5.5	13.5
58	45°	Smooth	724 (105)	110.0	3496	3.4	11.7
59	45°	Notched (K_t=1.8)	724 (105)	87.3	2792	-	-
60	45°	Notched (K_t=1.8)	724 (105)	112.1	3633	-	-
MAR-M 200+Hf							
1	L	Smooth	758 (110)	180.3	5865	8.0	10.6
2	L	Smooth	758 (110)	266.3	8726	6.6	9.1
5	L	Smooth	758 (110)	187.1	6249	7.0	8.7
6	L	Smooth	758 (110)	185.4	6074	7.1	9.2
10	45°	Smooth	724 (105)	86.4	2900	4.3	8.5
13	45°	Smooth	724 (105)	105.8	3487	2.9	7.2
11	45°	Notched (K_t=1.8)	724 (105)	108.0	3327	-	-
12	45°	Notched (K_t=1.8)	724 (105)	217.7	7051	-	-

[a] L = Longitudinal
T = Transverse

TABLE XXVIII. (CONCLUDED)

Prior to machining, slabs were solution-treated at 1494°K (2230°F) for 2 hours followed by inert gas quenching, 1255°K (1800°F) for 5 hours, and 1144°K (1600°F) for 20 hours.

Specimen	Orientation[a]	Type of specimen	Maximum stress, MPa (ksi)	Hours to failure	Cycles to failure	Elongation, percent	Reduction of area, percent
25	L	Smooth	758 (110)	85.6	2795	4.7	8.0
26	L	Smooth	758 (110)	261.0	8435	3.8	8.0
29	L	Smooth	758 (110)	131.2	4430	4.4	7.5
30	L	Smooth	758 (110)	220.2	7240	4.1	8.0
103	L	Smooth	758 (110)	86.2	2863	5.1	7.7
27	L	Notched (K_t=1.8)	758 (110)	57.0	1851	-	-
28	L	Notched (K_t=1.8)	758 (110)	169.0	5469	-	-
41	T	Smooth	724 (105)	156.8	5187	3.0	5.4
42	T	Smooth	724 (105)	55.3	1847	2.7	6.3
43	T	Notched (K_t=1.8)	724 (105)	61.9	1984	-	-
44	T	Notched (K_t=1.8)	724 (105)	42.2	1363	-	-
33	45°	Smooth	724 (105)	37.0	1198	5.1	13.3
34 b	45°	Smooth	724 (105)	0.6	21	5.6	7.7
37	45°	Smooth	724 (105)	32.6	1080	5.8	16.2
35	45°	Notched (K_t=1.8)	724 (105)	84.3	2713	-	-
36	45°	Notched (K_t=1.8)	724 (105)	119.3	3868	-	-

a L = Longitudinal
T = Transverse

b Invalid test - defect found on fracture surface.

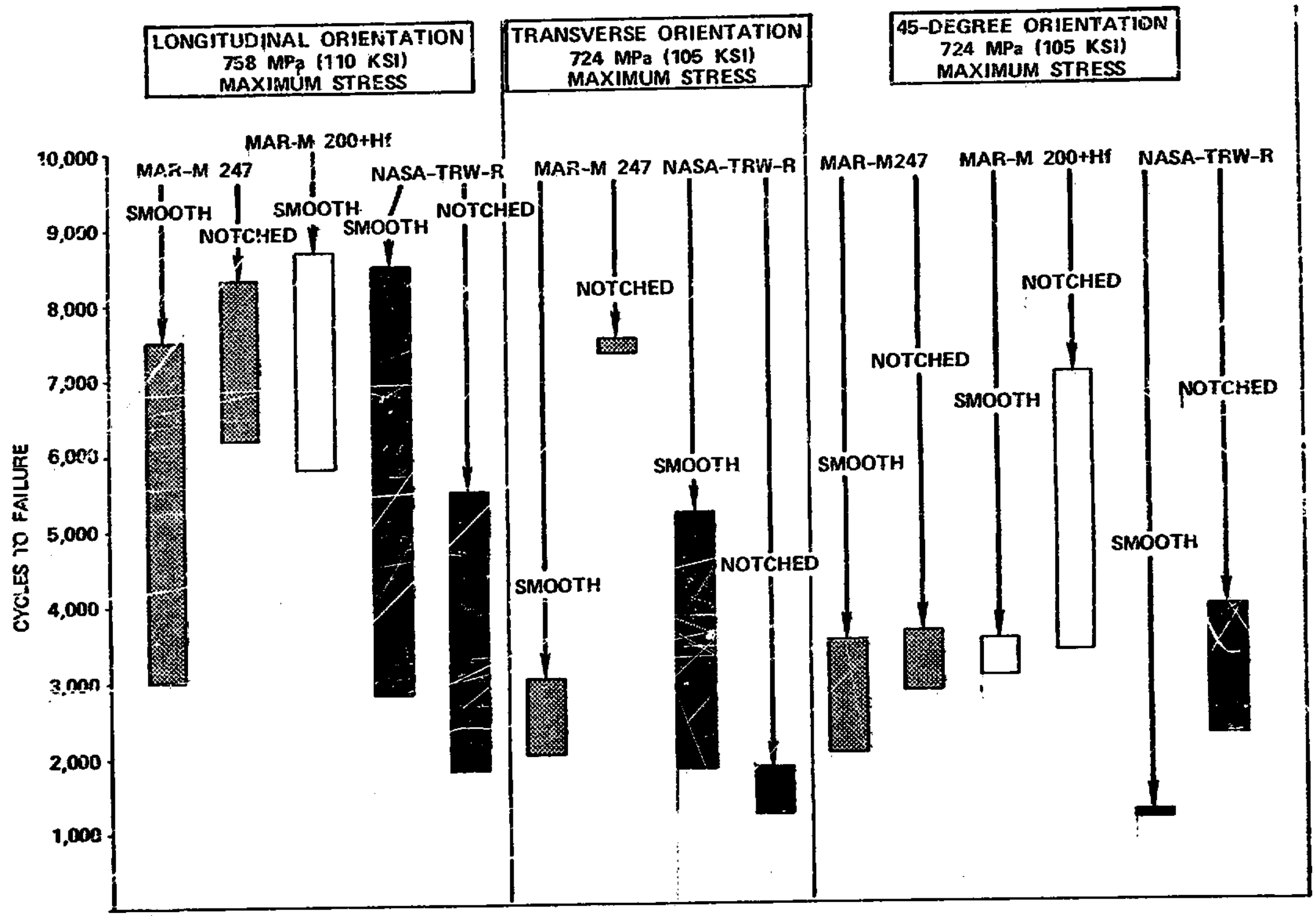


Figure 23. Summary of Task II 1033°K (1400°F) Cyclic-Rupture Test Results on Test Specimens Machined from Exothermically DS Cast Slabs of Three Alloys

was done on the MAR-M 247 and NASA-TRW-R alloys, as an extensive production background exists for the DS cast MAR-M 200+Hf alloy, and previous program data resulted in elimination of IN 792+Hf as a candidate material. A basic purpose of the cyclic-rupture testing was to provide data useful in design of the firtree-attachment region of the turbine blade where high stresses are present at various orientations where stress-concentrations exist.

The major conclusions drawn from the cyclic testing were:

(a) MAR-M 247 was notch-strengthened in all three orientations.

(b) NASA-TRW-R was notch-weakened in the longitudinal and transverse orientations.

(c) The limited testing of the MAR-M 200+Hf revealed no problems with this alloy.

(d) All three alloys were notch strengthened in the 45-degree orientation.

Thermal fatigue tests. Eight blades of each alloy were selected from the final eight Task II molds for use in conducting thermal-fatigue tests. Following solution treatment at 1494°K (2230°F), four blades of each alloy were coated with RT-21* aluminide coating at 1255°K (1800°F) for 5 hours, then aged at 1144°K (1600°F) for 20 hours. The remaining four blades were left uncoated (bare), but were subjected to a heat-treatment process equivalent to that used for the coated blades. In addition, a

*A proprietary aluminide coating applied by the Chromalloy Corporation; Orangeburg, New York.

mold of equiaxed cast MAR-M 247 blades was cast to provide a baseline for comparison of thermal-fatigue characteristics with the DS castings.

An initial 1000-cycle thermal-fatigue test was conducted by the Illinois Institute of Technology Research Institute (IITRI) on bare and coated blades of all four alloys. The test was conducted in fluidized beds which permitted cycling the blades between 308°K (95°F) and 1228°K (1750°F). The blades were alternately held for 3 minutes in each of the hot and cold beds.

Only one crack was found after completion of the 1000-cycle test. A second 1000-cycle test was then performed on the same blades with cycle temperatures of 308°K (95°F) and 1283°K (1850°F), which was the highest temperature attainable on the test equipment. A summary of the results of this higher temperature test is as follows:

(a) MAR-M 247

Bare - First crack was observed after 500 cycles. The crack had grown to 0.076 cm (0.030 inch) at test completion.

Coated - No cracks were observed.

(b) MAR-M 200+Hf

Bare - First crack was observed after 200 cycles. The crack had grown to 0.076 cm (0.030 inch) at test completion.

Coated - The first crack had been observed on the blade pressure side after 1000 cycles of the earlier 308°K (95°F) and 1228°K (1750°F) test. This crack had grown to 0.508 cm (0.200 inch) after 300 cycles of the second test [1283°K (1850°F)]. A second coating crack was observed, on the blade suction side, after 500 cycles of the second test. This crack had grown to 0.076 cm (0.03 inch) at test completion.

(c) NASA-TRW-R

Bare - One very tight crack was observed at test completion.

Coated - No cracks were observed.

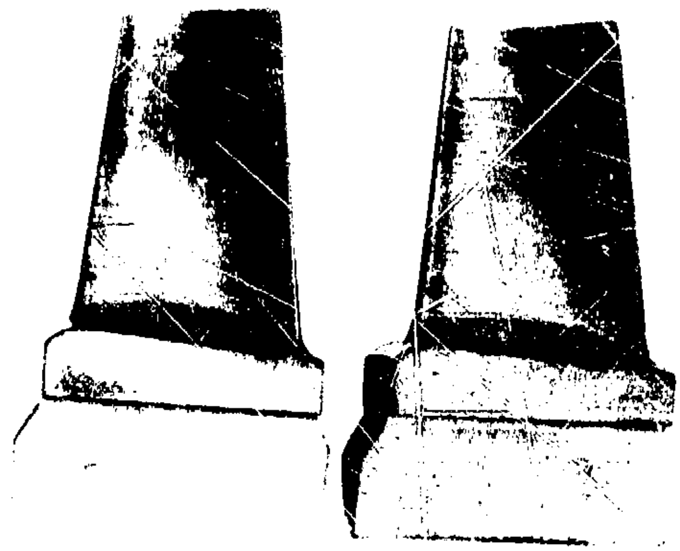
(d) IN 792+Hf

Bare - A crack was observed after 50 cycles. The crack had grown to 0.178 cm (0.070 inch) at test completion.

Coated - No cracks were observed

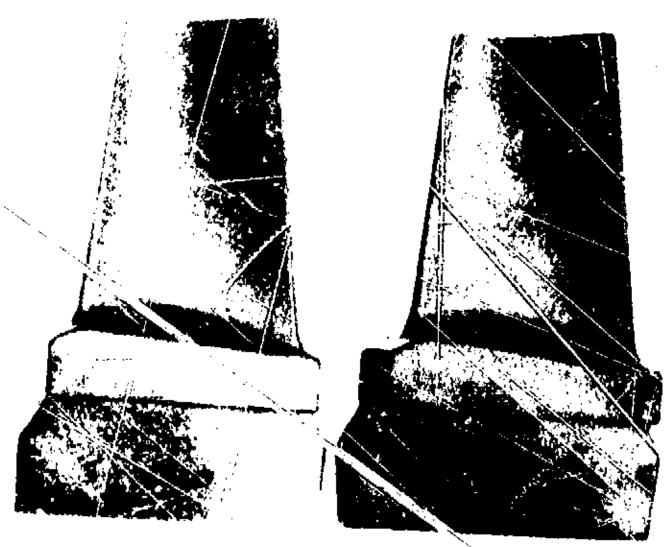
Except for one blade, all of the coating cracks were located at the trailing-edge platform intersection, which is a sharp transition of thin-to-thick section that should generate maximum thermal stresses. The sole exception was the coated MAR-M 200+Hf blade that developed airfoil cracks. Figure 24 presents a typical photograph of bare and coated MAR-M 247 blades before and after testing.

As indicated by the summary above, the thermal cycling results show little to discriminate between the four alloys. To further evaluate the thermal-fatigue characteristics of MAR-M 247, two additional tests were conducted at IITRI. Each test used two equiaxed and two DS cast MAR-M 247 blades of identical design. Testing consisted of 1000 cycles between 1228°K (1750°F) and 311°K (100°F), followed by another 1000 cycles between 1283°K (1850°F) and 311°K (100°F). The blades were alternately held in the hot and cold beds three minutes each to stabilize temperatures.



COATED UNCOATED

(a) AS RECEIVED



COATED UNCOATED

(b) THERMALLY CYCLED

Figure 24. Surface Appearance of DS MAR-M 247 Preliminary Design TFE731-3 Turbine Blades As-Received and After 1000 Thermal Cycles Between 308°K and 1228°K (95°F and 1751°F), and 1000 Thermal Cycles Between 308°K and 1283°K (95°F and 1850°F). (Mag.: 1X)

No cracking was observed on any blade after the first 1000 cycles. The two equiaxed blades cracked during the second 1000 cycles, while the DS cast blades did not. A crack was observed in one equiaxed blade after 25 cycles of the 1283°K (1850°F) and 311°K (100°F) thermal cycling, and a crack was observed in the other after 300 cycles. Crack propagation in the equiaxed grain blades was as shown in Table XXIX:

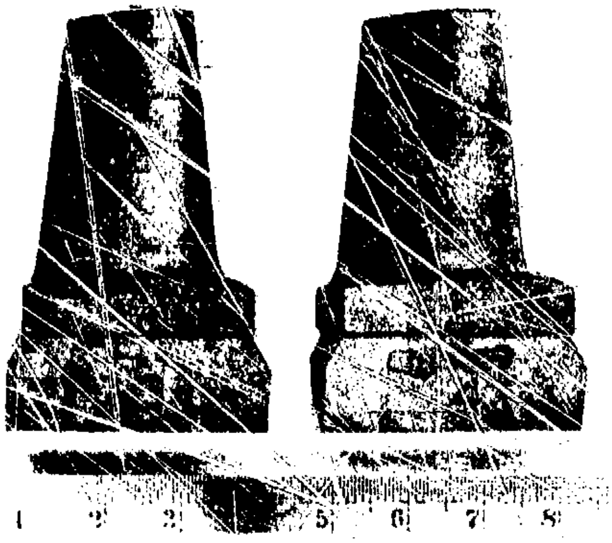
TABLE XXIX. CRACK PROPAGATION IN THE EQUIAXED GRAIN BLADES

Number of Cycles	Average crack length, cm (inch)			
	Blade No. 14		Blade No. 16	
25	-	-	0.05	(0.02)
50	-	-	0.05	(0.02)
75	-	-	0.08	(0.03)
100	-	-	0.08	(0.05)
200	-	-	0.18	(0.07)
300	0.08	(0.03)	0.20	(0.08)
400	0.10	(0.04)	0.20	(0.08)
500	0.10	(0.04)	0.20	(0.08)
700	0.18	(0.07)	0.20	(0.08)
1000	0.20	(0.08)	0.20	(0.08)

Figure 25 presents the four tested blades after completion of the 2000 cycles of testing, and Figure 26 shows the cracks in the equiaxed blades.

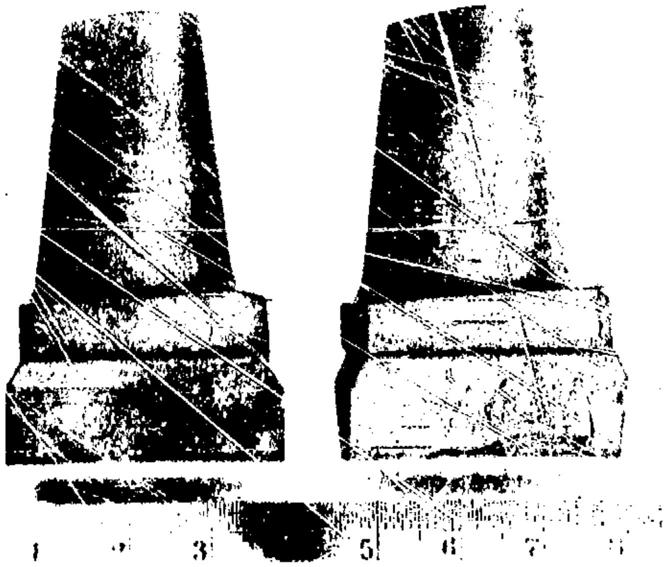
Due to the fact that crack location is a function of blade geometry, only a crude qualitative conclusion can be reached--that based on this testing the DS cast blades were more thermal-fatigue resistant than the equiaxed blades.

Dynamic modulus testing. Dynamic modulus of elasticity tests were performed in triplicate on test specimens machined



BLADE 140-14 BLADE 138-19

EQUIAXED BLADES (MAG.: 2X)

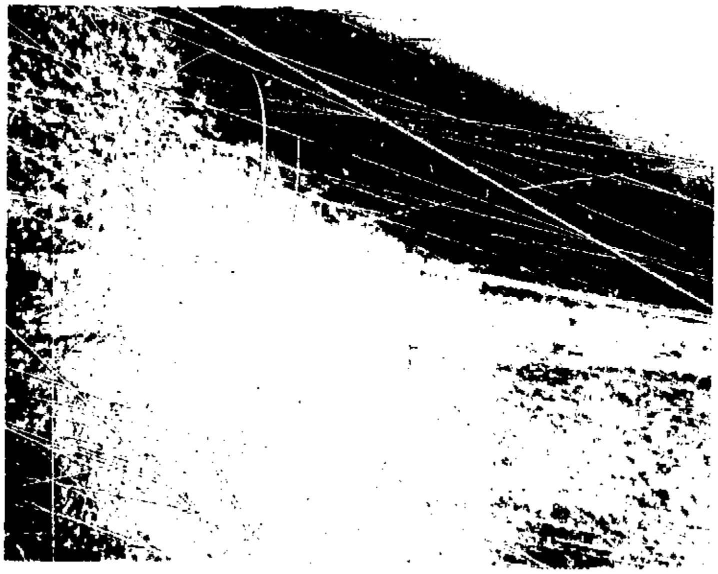


BLADE 14 BLADE 16

DS BLADES (MAG.: 2X)

Figure 25. Appearance of Equiaxed and DS MAR-M 247 TFE731 Turbine Blades after 1000 Thermal Cycles between 311°K and 1228°K (100°F and 1750°F) and 1000 Thermal Cycles Between 311°K and 1283°K (100°F and 1850°F)

(a) BLADE 14 (MAG.: 25X)



(b) BLADE 16 (MAG.: 25X)

Figure 26. Appearance of Thermal-Fatigue Cracks at Trailing Edge Near Root of Equiaxed MAR-M 247 Blade Nos. 14 and 16 after 1000 Cycles at 1283°K (1850°F)

from Task II DS slab castings for each of the four alloys. The test specimen configuration for these tests was rectangular plates 10-cm long, 1.3-cm wide, and 0.13-cm thick (4 by 0.5 by 0.05 inches). Tests were conducted at room temperature and at 111°K (200°F) temperature increments from 811°K (1000°F) to 1255°K (1800°F). Averaged results of these tests are tabulated in Table XXX. The maximum variation of individual test results from the averages shown was 4 percent.

Metallographic examination. Representative Task II DS castings (blades root-up) from the four alloys were metallographically examined in the root and blade-tip areas before and after heat treatment. Figures 27 through 30 illustrate the results of this evaluation. The grain-growth direction as shown on these figures is vertical in all cases.

MAR-M 247 microstructures are presented in Figure 27. Script carbides are evident in all four photos, and grain boundaries can be seen in the as-cast structures. The structure is generally coarser at the root, since the thermal gradient during the casting process was greater at the blade tip, which was near the chill plate.

Figure 28 presents photomicrographs of MAR-M 200+Hf blade castings. The script carbides were also evident in this precursor alloy of MAR-M 247. Larger amounts of gamma/gamma prime eutectic were present in both the as-cast and heat-treated conditions than were observed in MAR-M 247.

Figure 29 presents the microstructures of the NASA-TRW-R alloy. This photomicrograph shows fewer script carbides than the two MAR-M alloys. The amount of incipient melting observed in the root area after treatment may indicate that 1494°K (2230°F) is the upper limit for solution treatment of this alloy.

TABLE XXX. AVERAGE DYNAMIC MODULUS OF ELASTICITY OF TASK II DS CAST ALLOYS

(Longitudinal grain orientation test specimens machined from exothermically DS cast slabs. Heat treatment consisted of 1494°K (2230°F) for 2 hours and 1144°K (1600°F) for 20 hours.

Alloy	Modulus of Elasticity E [GPa (10^6 psi)]					
	Room Temperature	811°K (1000°F)	922°K (1200°F)	1033°K (1400°F)	1144°K (1600°F)	1255°K (1800°F)
MAR-M 247	143 (21)	121 (18)	116 (17)	118 (16)	106 (15)	93.1 (14)
MAR-M 200+Hf	138 (19)	117 (17)	112 (16)	104 (15)	101 (15)	88.9 (13)
NASA-TRW-R	135 (20)	121 (18)	117 (17)	114 (17)	104 (15)	93.1 (14)
IN 792+Hf	134 (20)	121 (18)	118 (16)	108 (16)	103 (15)	91.7 (13)

NOTES:

a. Testing performed at Southern Research Institute, Birmingham, Alabama.

b. Values are an average of three readings.

c. Specimen configuration: 10 by 1.3 by 1.3 cm
(4 by 0.5 by 0.050 inch)

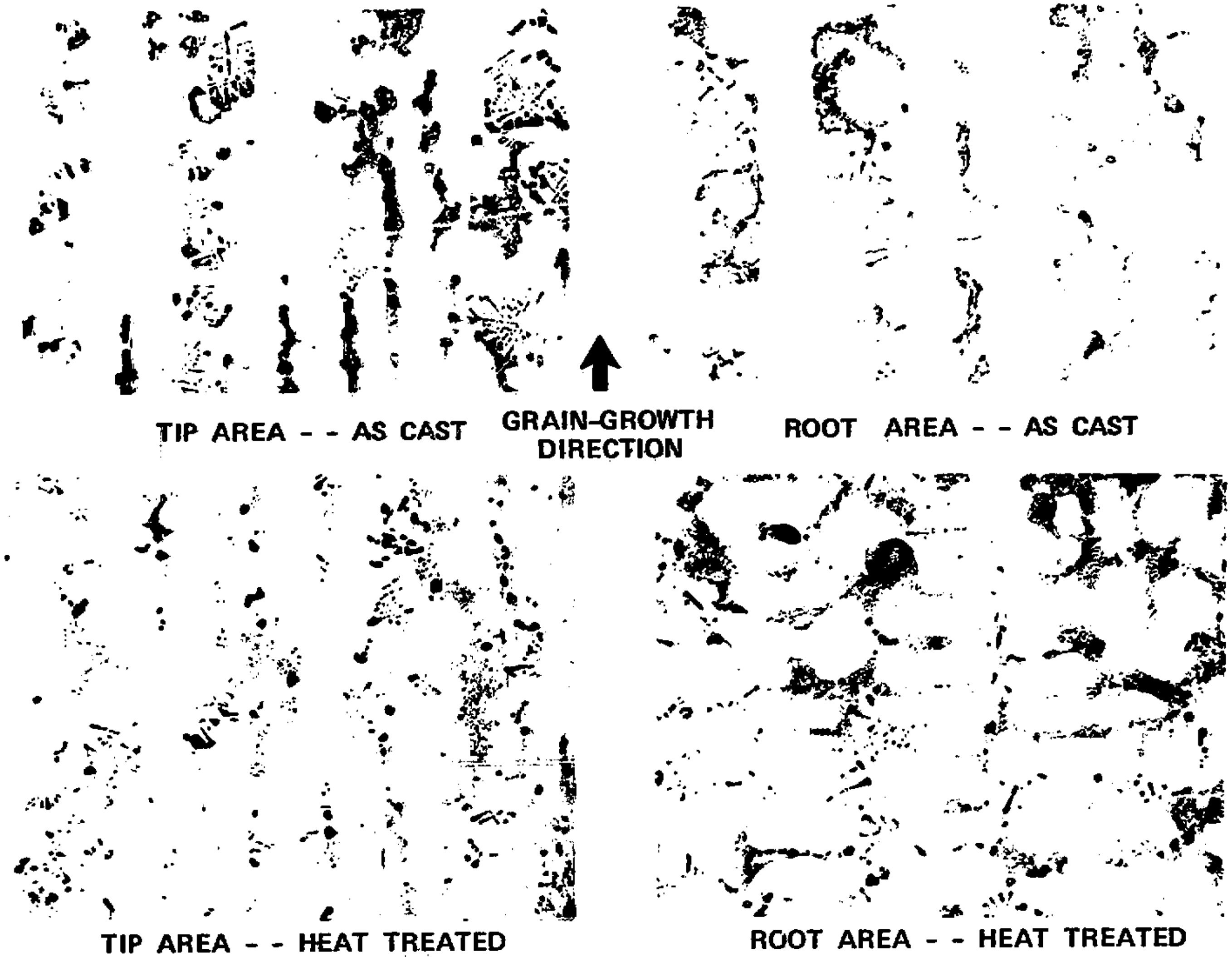


Figure 27. Typical Microstructures of Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades of MAR-M 247. Kallings Etch. (Mag.: 100X)

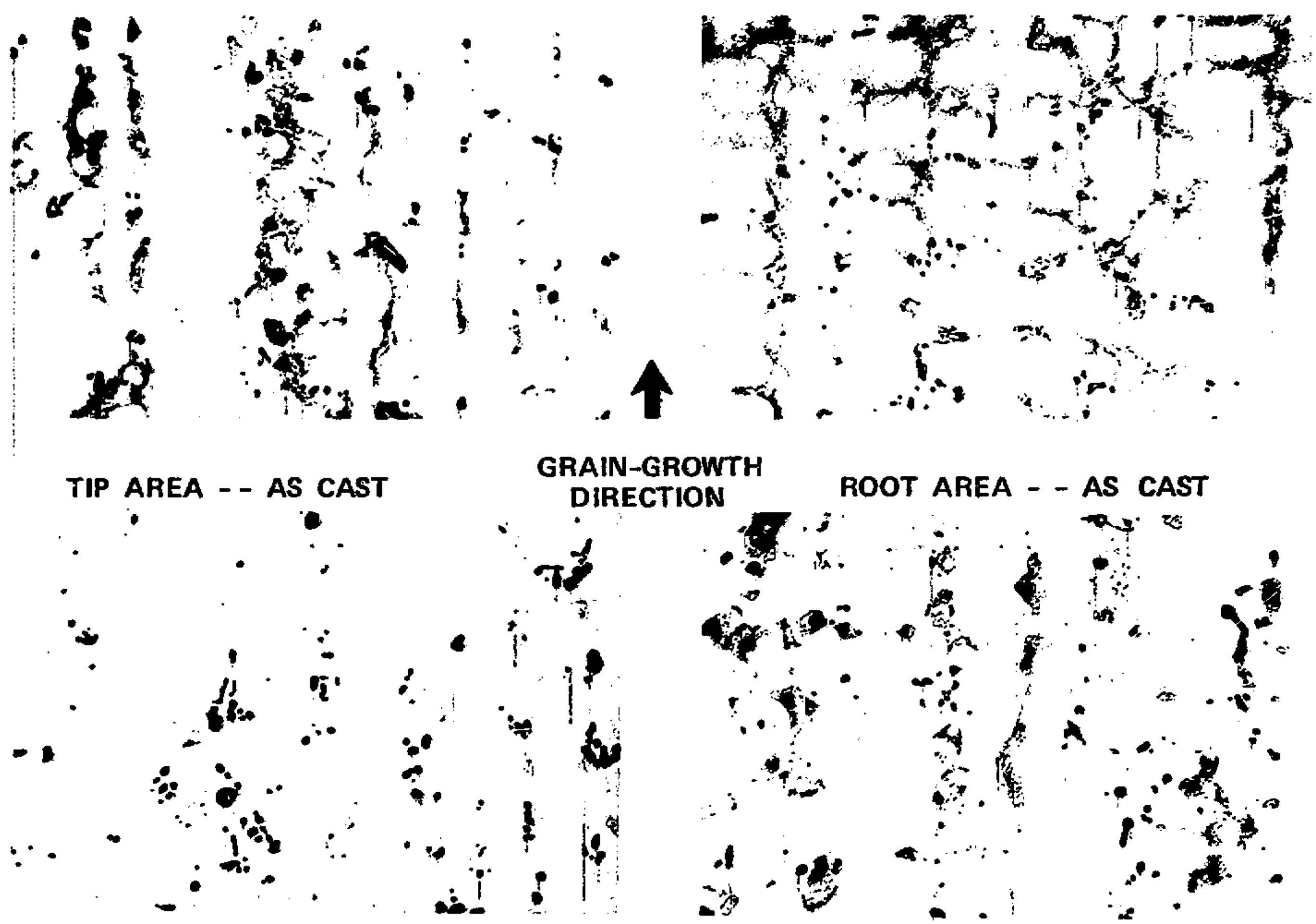


Figure 28. Typical Microstructures of Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades of MAR-M 200+Hf. Kallings Etch. (Mag.: 100X)

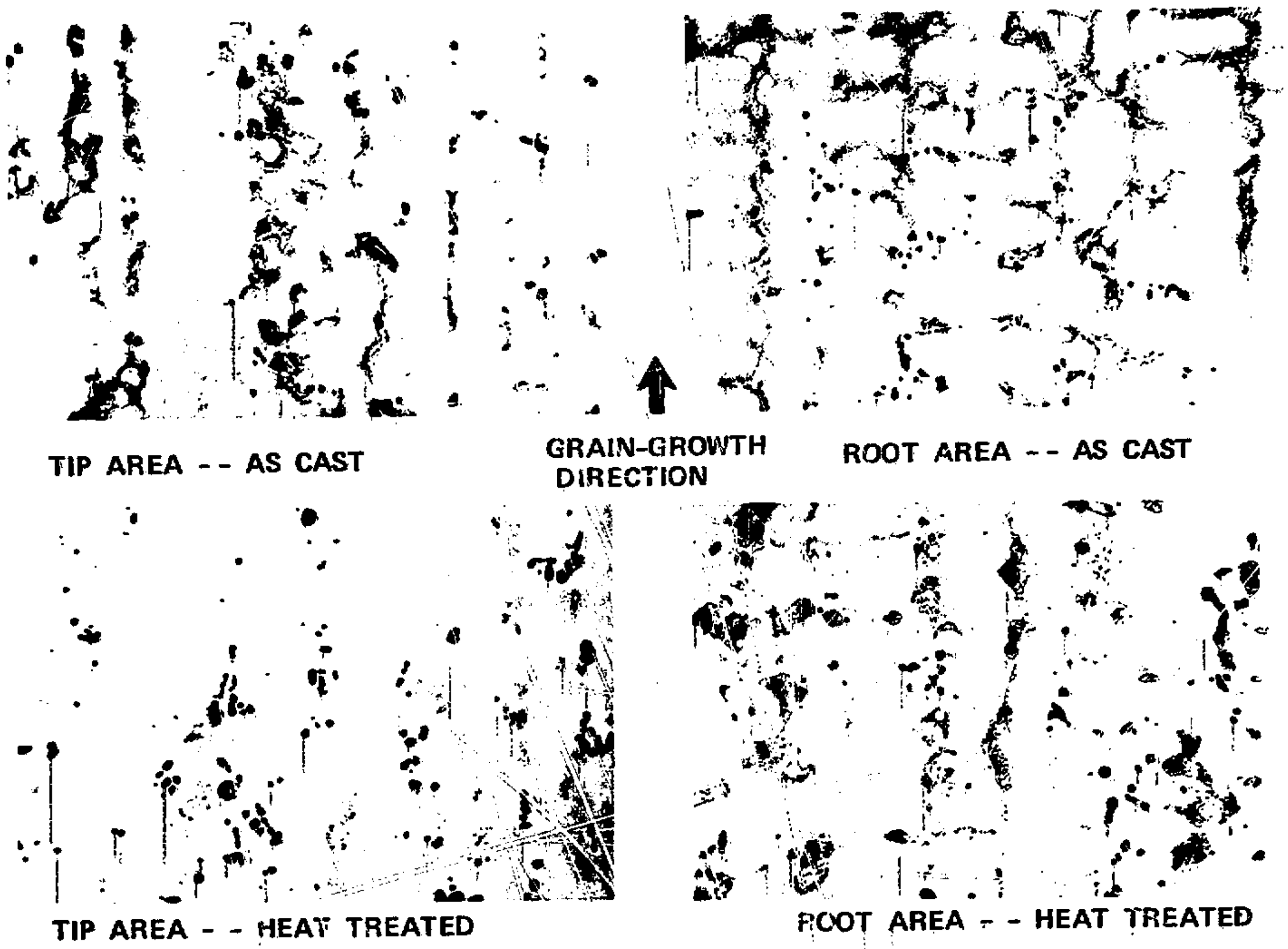


Figure 29. Typical Microstructures of Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades of NASA-TRW-R. Kallings Etch. (Mag.: 100X)

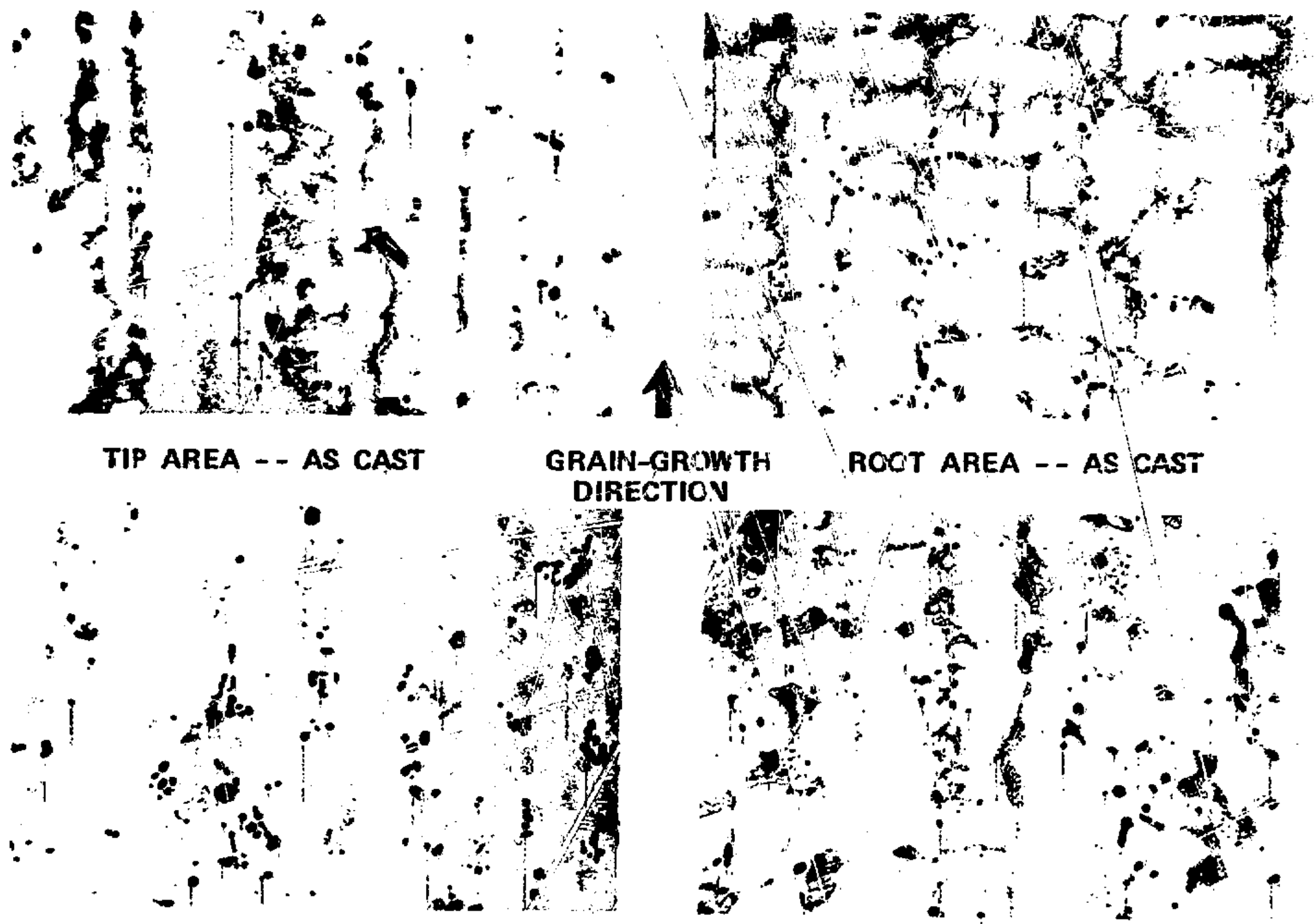


Figure 30. Typical Microstructures of Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades of IN 792+Hf. Kallings Etch. (Mag.: 100X)

The IN 792+Hf microstructures are depicted in Figure 30. Script carbides were absent and incipient melting occurred in the root section of the blade.

Alloy Selection

As a result of the Task II tests and evalutions of the four alloys, MAR-M 247, MAR-M 200+Hf, and NASA-TRW-R alloys were selected for further evaluations in Task III. The IN 792+Hf alloy was eliminated from the Task III effort due to its lower stress-rupture strength.

TASK III - ALLOY PROPERTY CHARACTERIZATION

Scope

During Task III, the three selected alloys, MAR-M 247, NASA-TRW-R, and MAR-M 200+Hf, were further evaluated in DS cast form to determine and document mechanical and physical properties to validate the final design for the turbine blades. This was accomplished by the manufacture of additional turbine blade and test bar castings by Jetshapes using process controls developed during Tasks I and II, followed by comprehensive testing of castings and test specimens by AiResearch and independent laboratories.

Test Material Production. Turbine blade and separatly cast test bar molds were exothermically DS cast with all three alloys to provide material for Task III evaluations. A new 7000-pound heat of low-gas content MAR-M 247 was used for pouring all castings with this alloy. Oxygen content of this heat was 8 ppm; nitrogen was 4 ppm. Typical gas contents for normal remelt heats of vacuum cast nickel-base superalloys are 10- to 30-ppm oxygen and 15- to 25-ppm nitrogen. Heats of the other alloys were the ones procured for Task II.

The blade molds were of the same design as those used in Task II--five straight spokes with provisions for four root-up blades in each spoke. The standard test bar mold had five spiral spokes with six 1.590-cm (0.625-inch) test bars per spoke. In addition, one test bar mold was made to provide both tapered erosion-test bars and large-diameter thermal-conductivity test bars for Task III evaluations. In this special mold, one spiral spoke of six standard bars was replaced with a spoke having provisions for two 3.8-cm (1.5-inch) test bars, and another spiral spoke was replaced with a spoke providing six erosion-test bars.

In view of a reported possibility of discontinuance by the supplier of the Colal-P mold prime-coat material, one blade mold and one test bar mold were cast using the latest modification of the Jetshapes production prime coat for comparison with the Colal-P. While initial grain structure evaluation of parts from these two molds indicated that there were no apparent differences, nondestructive evaluation of the casting indicated the Colal-P mold had fewer fluorescent-penetrant indications than the newer Jetshapes mold. Based on these results, sufficient Colal-P was procured to meet remaining program requirements.

All Task III turbine blade castings were subjected to X-ray, fluorescent-penetrant, and DS grain evaluations. Results of this testing is presented in Table XXXI. The general level of fluorescent-penetrant indications on MAR-M 247 was lower than that observed on castings made for the preceding Tasks. This was attributed to the use of the low-gas content alloy for Task III castings.

Chemical analyses were performed on sample blade castings and separately cast test bars from all molds made in Task III. Results are reported in Tables XXXII through XXXIV. No significant anomalies were found in these analyses.

Property Testing.

1. Tensile testing. - Tensile tests on both longitudinal and transverse grain orientation MFB mini-bar test specimens (refer to Figure 11) of DS MAR-M 247 were conducted at various temperatures from room temperature to 1144°K (1600°F). Results of these tests are presented in tabulated form in Table XXXV, and in graphical form in Figures 31 and 32. As anticipated, the transverse strengths were lower than the longitudinal, although all strengths and ductilities were adequate for final blade design.

TABLE XXXI. INSPECTION RESULTS OF TASK III EXOTHERMICALLY CAST DS PRELIMINARY DESIGN TFE731-3 TURBINE BLADES

Alloy	Mold serial number	Percent acceptable							
		X-Ray		FPI		DS grain		Combined	
		Mold	Alloy	Mold	Alloy	Mold	Alloy	Mold	Alloy
MAR-M 247	130	90	91	75	76	65	64	55	53
	140	85		85		65		50	
	148	95		65		35		30	
	159	90		90		75		75	
	173	95		63		79		53	
MAR-M 200+Hf	168	100	98	43	64	43	59	14	40
	174	95		85		75		65	
NASA-TRW-R	186	79	86	93	93	64	57	43	47
	167	93		93		50		50	

TABLE XXXII. CHEMICAL ANALYSES OF TASK III EXOTHERMICALLY CAST DS MAR-M 247 CASTINGS

Mold No.	Hf Root	Hf Tip	C	Cr	Mo	Ta	Al	Ti	Hf	B	Zr	Co	Mn	S	Si	W	P	Cb	Cu	Fe	Ni
			Composition, percent by weight																		
(a) Blade root section bulk chemical analysis																					
138			0.11	8.31	0.68	3.10	5.49	1.17	1.44	0.017	0.081	10.32	<0.10	<0.001	<0.10	9.72	-	-	-	0.15	Bal
130	1.32	1.27																			
140			0.11	8.73	0.65	2.90	5.41	1.10	1.35	0.018	0.086	10.51	<0.10	<0.001	<0.10	9.97	-	-	-	0.17	Bal
140	1.30	1.27																			
140			0.14	8.45	0.70	2.97	5.40	1.10	1.23	0.016	0.071	10.38	<0.10	<0.001	<0.10	10.14	-	-	-	0.18	Bal
148	1.30	1.28																			
159			0.10	8.74	0.70	2.93	5.42	1.09	1.31	0.017	0.059	10.48	<0.10	<0.001	<0.10	10.23	-	-	-	0.16	Bal
159	1.27	1.24																			
173			0.13	8.32	0.57	3.06	5.53	1.00	1.27	0.016	0.054	10.28	<0.10	<0.001	<0.10	10.13	-	-	-	0.1[illegible]	Bal
173	1.23	1.27																			
(b) Separately cast test bar bulk chemical analysis																					
135	-	-	0.12	8.79	0.71	2.99	5.45	1.14	1.26	0.017	0.060	10.55	<0.10	<0.001	<0.10	10.21	-	-	-	0.15	Bal
136	-	-	0.13	8.53	0.71	3.10	5.40	1.11	1.26	0.014	0.058	10.34	<0.10	<0.001	<0.10	10.13	-	-	-	0.10	Bal
137	-	-	0.13	8.69	0.65	3.09	5.41	1.07	1.30	0.015	0.055	10.32	<0.10	<0.001	<0.10	10.24	-	-	-	0.16	Bal
145	-	-	0.13	8.59	0.70	3.00	5.44	1.12	1.26	0.016	0.053	10.45	<0.10	<0.001	<0.10	10.24	-	-	-	0.16	Bal
153	-	-	0.13	8.72	0.68	3.04	5.46	1.14	1.32	0.016	0.062	10.48	<0.10	<0.001	<0.10	10.30	-	-	-	0.16	Bal
171	-	-	0.13	8.44	0.57	3.01	5.51	1.01	1.27	0.017	0.052	10.47	<0.10	<0.001	<0.10	10.[illegible]	-	-	-	0.10	Bal
(c) Specification range, AiResearch EMS55447																					
		MIN	0.13	8.00	0.50	2.00	5.30	0.90	1.20	0.01	0.03	9.00	0.20	0.015	0.20	9.50	-	-	-	0.50	Bal
		MAX	0.17	8.80	0.80	3.30	5.70	1.20	1.60	0.02	0.08	11.00	Max.	Max.	Max.	10.50	-	-	-	Max.	
(d) Master Heat V-4984, Cannon-Muskegon Corporation																					
			0.15	8.3	0.61	3.13	5.56	1.0	1.34	0.012	0.03	10.0	-	-	-	9.8	-	-	-	-	Bal

TABLE XXXIII. CHEMICAL ANALYSES OF TASK III EXOTHERMICALLY CAST DS MAR-M 200+Hf CASTINGS

Mold No.	Hf		Composition, percent by weight																		
	Root	Tip	C	Cr	Mo	Ta	Al	Ti	Hf	B	Zr	Co	Mn	S	Si	W	P	Cb	Cu	Fe	Ni
(a) Blade root bulk chemical analysis																					
168	-	-	0.14	8.34	-	-	5.01	1.90	1.32	0.017	<0.05	9.96	<0.10	0.001	<0.10	12.13	<0.001	0.58	<0.10	0.13	Bal
168	1.40	1.67	0.14	8.45	-	-	5.06	1.95	1.35	0.016	<0.05	10.08	<0.10	<0.001	<0.10	12.03	<0.001	0.86	<0.10	0.15	Bal
174	-	-																			
174	1.43	1.61																			
(b) Separately cast test bar bulk chemical analysis																					
152			0.17	8.33	-	-	5.00	1.88	1.57	0.016	<0.05	9.35	<0.10	<0.001	<0.10	11.97	<0.001	0.84	<0.10	0.10	Bal
163			0.14	8.42	-	-	4.99	1.88	1.44	0.018	<0.05	9.91	<0.10	<0.001	<0.10	12.11	<0.001	0.91	<0.10	0.10	Bal
161			0.14	8.39	-	-	5.03	1.93	1.48	0.018	<0.05	9.97	<0.10	0.001	<0.10	12.00	<0.001	0.88	<0.10	<0.10	Bal
(c) Master Heat No. 132B5335, Howmet Alloy Division																					
			0.15	8.53	-	-		1.90	1.98	0.014	0.06	9.60	-	-	-	11.50	-	0.89	-	-	Bal

TABLE XXXIV. CHEMICAL ANALYSES OF TASK III EXOTHERMICALLY CAST DS NASA-TRW-R CASTINGS

Mold No.	Hf Root	Hf Tip	C	Cr	Mo	Ta	Al	Ti	Hf	B	Zr	Co	Mn	S	Si	W	P	Cb	Cu	Fe	Ni
			Composition, percent by weight																		
(a) Blade root section bulk chemical analysis																					
167	-	-	0.071	8.32	3.03	6.88	5.42	1.03	0.83	0.017	0.086	7.87	<0.10	<0.001	<0.10	4.04	0.001	0.60	<0.10	0.23	Bal
167	0.87	0.74																			
186	-	-	0.085	7.66	2.99	6.98	5.45	1.01	0.78	0.018	0.090	7.93	<0.10	<0.001	<0.10	4.16	0.001	0.55	<0.10	0.22	Bal
186	0.85	0.75																			
(b) Separately cast test bar bulk chemical analysis																					
146			0.083	7.90	3.02	6.90	5.46	1.03	0.84	0.017	0.082	7.81	<0.10	<0.001	<0.10	4.14	0.001	0.58	<0.10	0.21	Bal
147			0.081	7.88	3.00	6.82	5.44	1.02	0.88	0.017	0.082	7.72	<0.10	<0.001	<0.10	4.05	<0.001	0.57	<0.10	0.23	Bal
180			0.078	7.72	2.90	6.93	5.41	0.97	0.79	0.016	0.089	7.80	<0.10	0.001	<0.10	4.20	0.002	0.62	<0.10	0.20	Bal
(c) Master Heat VE-889, Cannon-Muskegon Corporation																					
			0.08	8.10	3.04	6.70	5.47	0.92	1.07	0.015	0.12	7.75	-	-	-	4.15	-	0.40	-	-	Bal

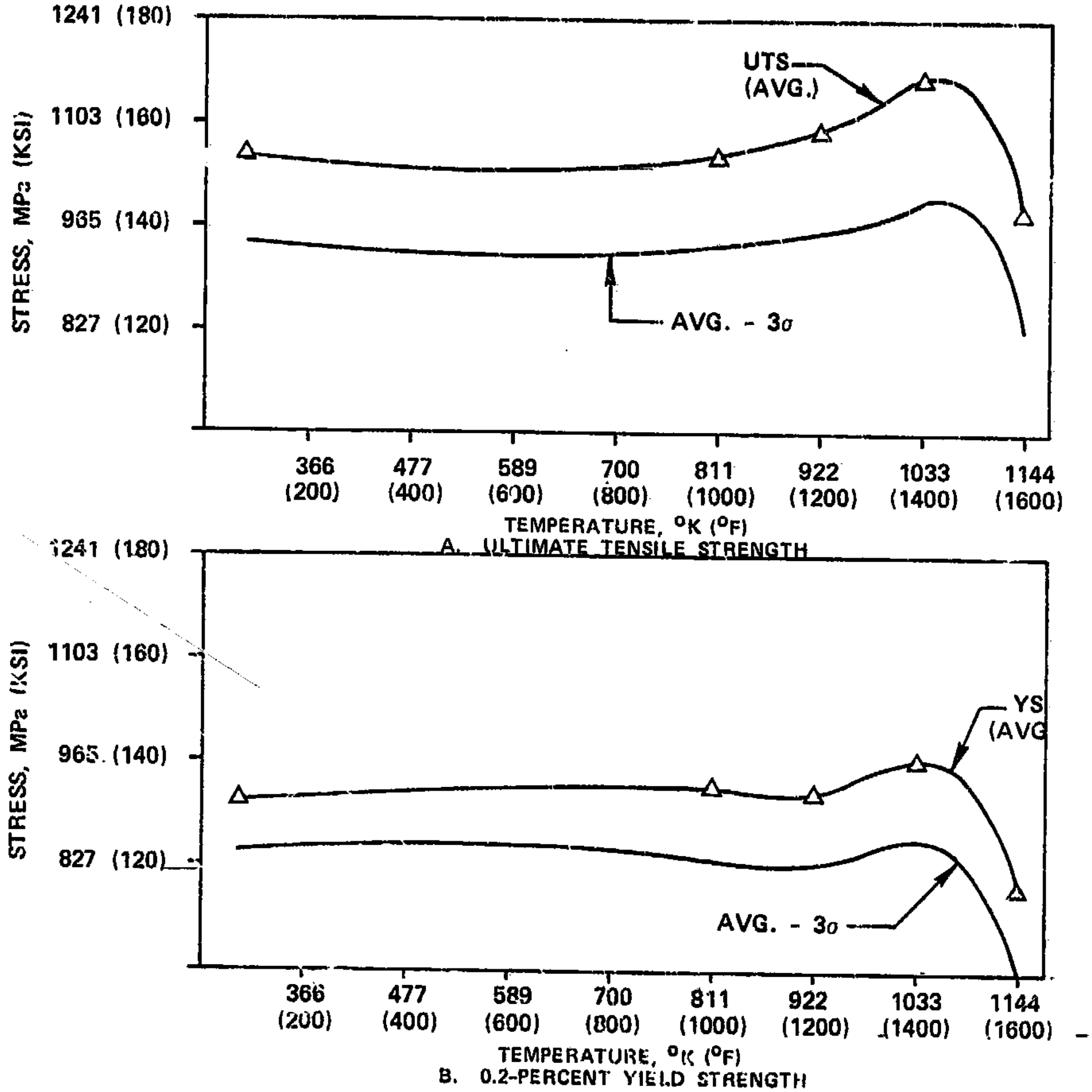
TABLE XXXV. TASK III TENSILE TEST RESULTS ON DS MAR-M 247 TURBINE BLADES

Heat treatment: 1505°K (2250°F) for 2 hours, plus
1255°K (1800°F) for 5 hours, plus
1144°K (1600°F) for 20 hours

(Test specimens machined from exothermically DS preliminary design TFE731-3 turbine blades.)

Specimen No.	Grain orientation [a]	Temperature, °K (°F)	Ultimate tensile strength, MPa (ksi)		0.2-percent yield strength, MPa (ksi)		Elongation, percent	Reduction in area, percent
138-8	L	Room Temperature	1100	(160)	885	(128)	5.9	12.5
148-8	L	↓	1052	(153)	928	(135)	6.5	13.8
159-9	L		1027	(149)	918	(133)	4.6	13.4
138-8T	T		843	(122)	825	(120)	5.6	15.9
148-8T	T		885	(128)	864	(125)	2.2	5.4
159-9T	T		660	(125)	853	(124)	2.9	11.2
138-7	L	811 (1000)	1016	(147)	892	(129)	7.1	13.3
140-7	L	↓	1088	(158)	954	(138)	4.6	10.9
159-19	L		1071	(156)	948	(136)	7.0	15.3
138-7T	T		873	(127)	837	(121)	3.8	9.0
140-7T	T		836	(121)	816	(118)	8.8	14.9
159-19T	T		858	(124)	852	(124)	9.8	11.1
138-1	L	922 (1200)	1014	(147)	873	(127)	7.5	12.5
148-14	L	↓	1135	(165)	968	(140)	6.2	10.9
159-10	L		1137	(165)	927	(134)	4.2	10.4
138-1T	T		830	(120)	764	(111)	9.5	14.6
148-14T	T		910	(132)	818	(119)	8.8	15.7
159-10T	T		816	(118)	785	(114)	9.8	14.6
138-10	L	1033 (1400)	1103	(160)	931	(135)	5.0	12.8
148-5	L	↓	1185	(172)	986	(143)	4.4	14.0
159-13	L		1209	(175)	992	(144)	5.2	14.9
138-10T	T		896	(130)	828	(120)	4.4	10.9
148-5T	T		965	(140)	841	(122)	7.8	14.6
159-13T	T		940	(136)	833	(121)	5.7	11.1
138-6	L	1144 (1600)	992	(144)	778	(113)	8.9	17.2
140-10	L	↓	1006	(146)	773	(112)	7.0	15.3
148-2	L		967	(140)	836	(121)	11.1	13.4
138-6T	T		839	(120)	738	(107)	12.8	21.2
140-10T	T		892	(129)	761	(110)	3.4	10.9
148-2T	T		829	(122)	745	(108)	7.3	14.4

a L = Longitudinal
T = Transverse



NOTE: ALL SPECIMENS HEAT TREATED FOR:
1505°K (2250°F) FOR 2 HOURS,
PLUS 1255°K (1800°F) FOR 5 HOURS,
PLUS 1140°K (1600°F) FOR 20 HOURS

Figure 31. Tensile Properties Versus Temperature of Longitudinal Specimens Machined from Task III MAR-M 247 Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades (Sheet 1 of 2)

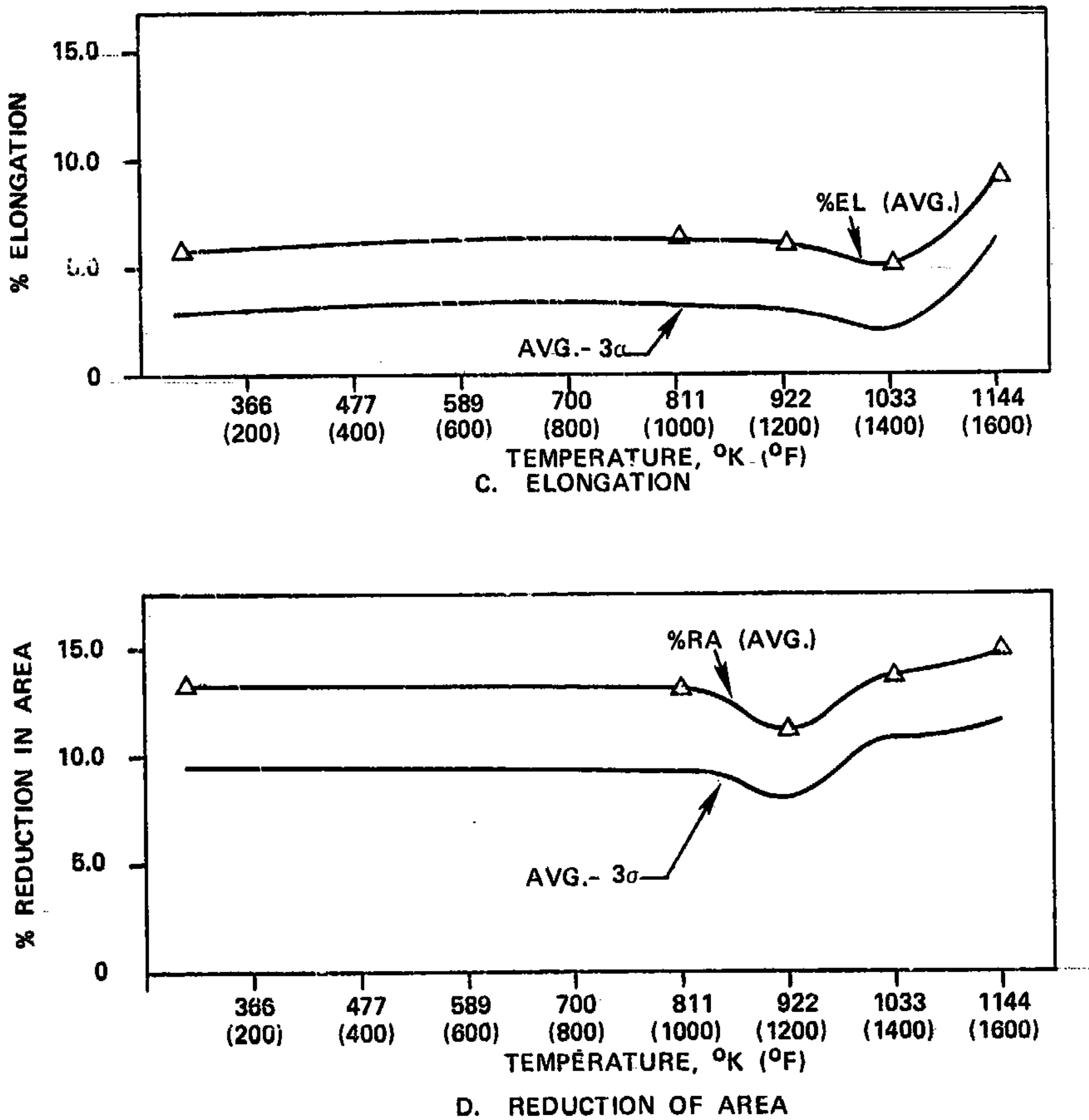
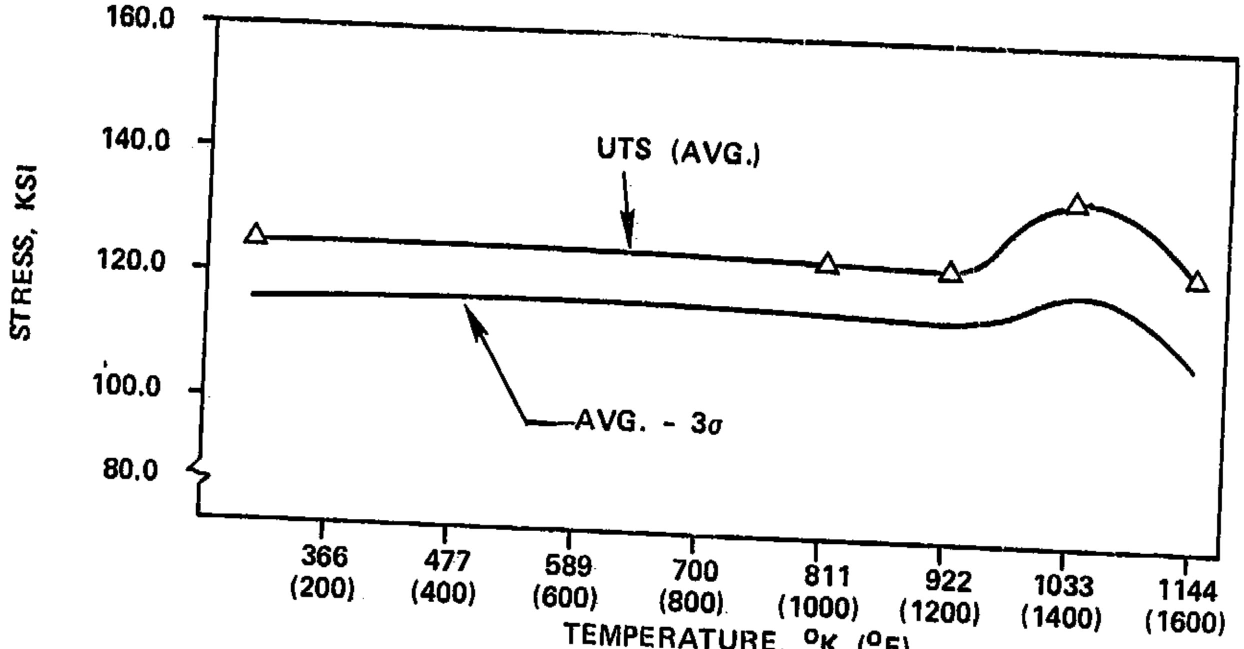
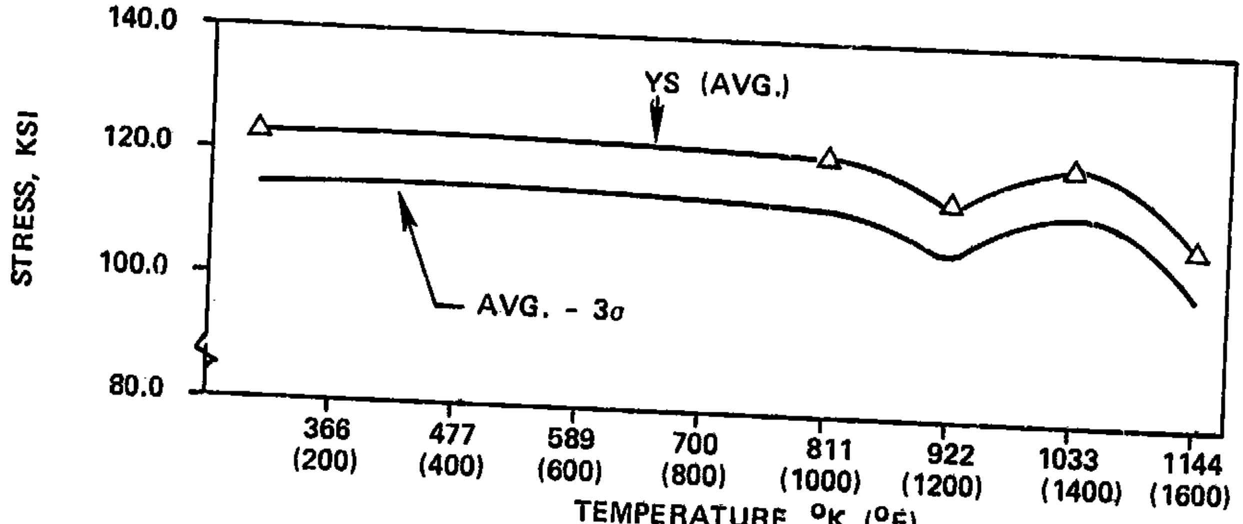


Figure 31. Tensile Properties Versus Temperature of Longitudinal Specimens Machined from Task III MAR-M 247 Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades (Sheet 2 of 2)



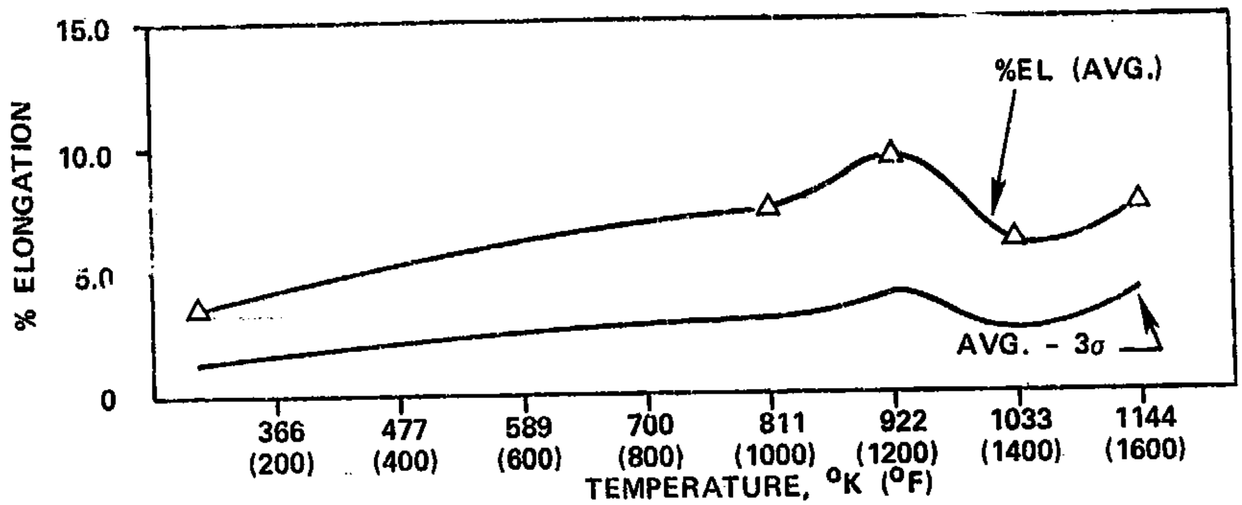
A. ULTIMATE TENSILE STRENGTH



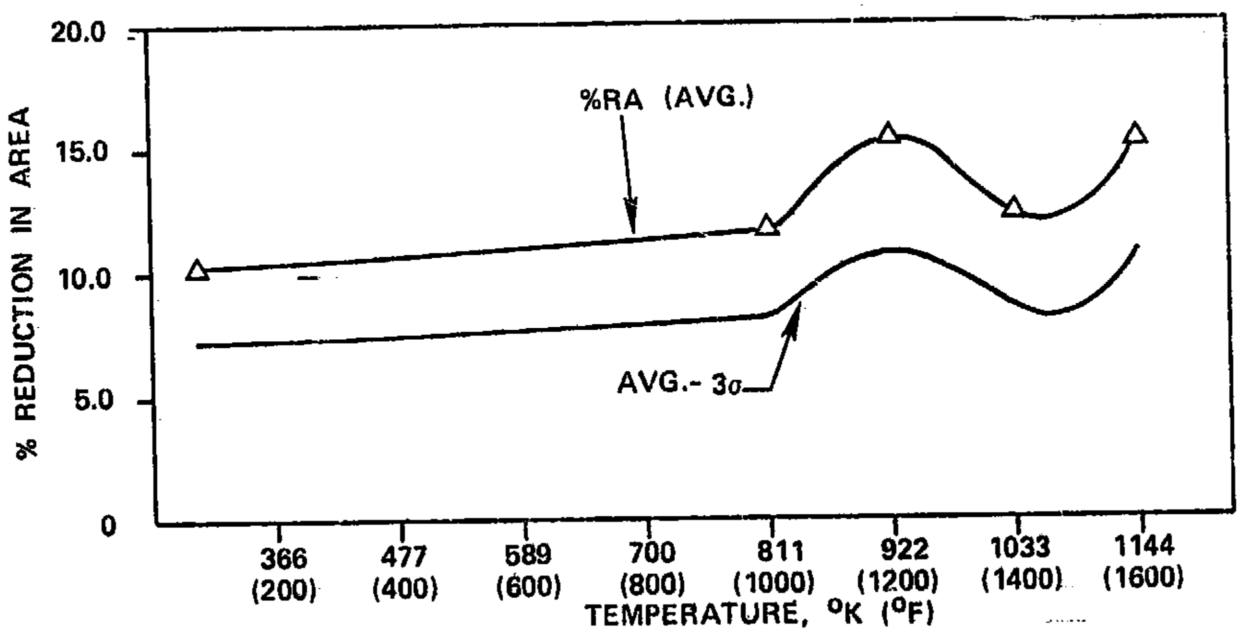
B. 0.2-PERCENT YIELD STRENGTH

NOTE: ALL SPECIMENS HEAT TREATED FOR:
1505°K (2250°F) FOR 2 HOURS,
PLUS 1255°K (1800°F) FOR 5 HOURS,
PLUS 1144°K (1600°F) FOR 20 HOURS

Figure 32. Tensile Properties Versus Temperature for Transverse Specimens Machined from Task III MAR-M 247 Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades (Sheet 1 of 2)



C. ELONGATION



D. REDUCTION OF AREA

Figure 32. Tensile Properties Versus Temperature for Transverse Speciemsn Machined from Task III MAR-M 247 Exothermically Cast DS Preliminary Design TFE731-3 Turbine Blades (Sheet 2 of 2)

Additional tensile testing on DS MAR-M 247 was conducted on 0.635-cm (0.250-inch) diameter test specimens machined from separately cast test bars (SCTB). Results of these tests are tabulated in Table XXXVI. Tensile and yield strengths of the SCTB specimens were 0- to 10-percent lower than results of the MFB mini-bar tests and the SCTB specimen results exhibited 40- to 100-percent higher ductility, probably as a result of specimen geometry.

Tensile test results of MFB mini-bar specimens and SCTB specimens of DS NASA-TRW-R and MAR-M 200+Hf are tabulated in Tables XXXVII and XXXVIII. The strength and ductility patterns for these alloys are similar to those observed on MAR-M 247.

2. <u>Stress-rupture testing</u>. - Stress-rupture testing was conducted at temperatures between 1033°K (1400°F), and 1311°K (1900°F) on MFB mini-bars with transverse and longitudinal grain orientations. Primary test emphasis was placed on MAR-M 247, the strongest of the three alloys. Stress-rupture properties of NASA-TRW-R were characterized at three temperatures, while the MAR-M 200+Hf alloy was tested only at two temperatures. The results of these tests are shown in tabulated form in Tables XXXIX and XL. As expected, the rupture-strength rankings were, in descending order of demonstrated strength--MAR-M 247, MAR-M 200+Hf, and NASA-TRW-R. The strengths of all three alloys were adequate for the final design turbine blades.

One of the major original goals of this Project was to obtain enough improvement in stress-rupture strength of DS MAR-M 247 (or another DS alloy) over equiaxed IN100, to permit the replacement of the current cooled IN100 high-pressure turbine blades in the TFE731-3 Engine with solid uncooled DS blades. Figure 33 presents data showing that this goal was achieved. The solid lines on this graph compare the average rupture strengths from mini-bar test specimens of equiaxed IN100 (AiResearch data) and DS MAR-M 247 from Tasks I and II of this contract. The solid circles are

TABLE XXXVI. TASK III TENSILE TEST RESULTS ON SEPARATELY CAST TEST BARS OF DS MAR-M 247

Heat treatment: 1505°K (2250°F) for 2 hours with argon quenching, plus 1255°K (1800°F) for 5 hours with air cooling, plus 1144°K (1600°F) for 20 hours with air cooling

(Longitudinal grain test specimens machined from exothermically cast bars)

Specimen No.	Test temperature °K (°F)	Ultimate tensile strength, MPa (ksi)	0.2-percent yield strength, MPa (ksi)	Elongation, percent	Reduction of area, percent	Modulus of elasticity [GPa(10^6 psi)]
196	Room temperature	1169 (170)	865 (126)	14.3	15.6	1441.0 (20.9)
205		1016 (147)	851 (123)	10.0	17.6	-
207		1054 (153)	849 (123)	12.1	12.9	-
	R.T. Avg.	1080 (157)	(124)	12.1	15.4	-
198	1033 (1400)	1165 (169)	959 (138)	9.1	19.1	95.2 (13.8)
206		1164 (169)	954 (138)	9.8	19.3	-
208	Average	1091 (158)	879 (128)	9.2	22.2	-
		1140 (165)	(135)	9.4	20.2	
177	1144 (1600)	954 (138)	713 (103)	10.6	13.4	75.2 (10.9)
209		938 (136)	706 (102)	12.7	17.7	-
210		965 (140)	721 (105)	15.6	23.9	-
		952 (138)	714 (104)	13.0	18.3	

TABLE XXXVII. TASK III TENSILE TEST RESULTS ON SEPARATELY CAST TEST BARS OF DS NASA-TRW-R

Heat treatment: 1505°K (2250°F) for 2 hours with argon quenching, plus
1255°K (1800°F) for 5 hours with air cooling, plus
1144°K (1600°F) for 20 hours with air cooling.

Specimen No.	Grain orientation[a]	Temperature, °K (°F)	Ultimate tensile strength, MPa	(ksi)	0.2-percent yield strength, MPa	(ksi)	Elongation, percent	Reduction in area, percent
Specimens machined from initial design TFE731-3 turbine blades								
160-5	L	RT	1011	(147)	950	(138)	7.2	9.8
174-3	L	↓	1016	(147)	927	(135)	6.9	9.5
168-5T	T	↓	858	(124)	839	(122)	4.0	8.6
174-3T	T	↓	837	(121)	832	(121)	3.2	7.3
168-6	L	1033 (1400)	1028	(149)	867	(126)	13.4	24.1
174-4	L	↓	1198	(174)	1000	(145)	10.9	20.8
168-6T	T	↓	847	(123)	819	(119)	4.3	8.7
174-4T	T	↓	838	(122)	783	(114)	3.7	11.1
168-7	L	1144 (1600)	978	(142)	792	(115)	10.7	20.0
174-8	L	↓	986	(143)	806	(117)	9.7	15.3
168-7T	T	↓	841	(122)	747	(108)	3.4	7.6
174-8T	T	↓	861	(125)	802	(116)	3.5	9.0
Specimens machined from separately cast test bars								
1117	L	RT	1043	(151)	847	(123)	13.9	17.8
1144	L	↓	1230	(163)	887	(129)	11.7	13.2
1174	L	↓	1101	(160)	874	(127)	13.7	19.2
1118	L	1033 (1400)	1134	(165)	908	(132)	12.1	24.2
1145	L	↓	1105	(168)	905	(131)	11.3	21.5
1146	L	1144 (1600)	957	(139)	710	(103)	19.5	24.4
1175	L	↓	969	(141)	721	(105)	16.7	24.2

a L = Longitudinal
T = Transverse

TABLE XXVIII. TASK III TENSILE TEST RESULTS ON SEPARATELY CAST TEST BARS OF DS MAR-M 200+Hf

Heat treatment: 1505°K (2250°F) for 2 hours with argon quenching, plus
1255°K (1800°F) for 5 hours with air cooling, plus
1144°K (1600°F) for 20 hours with air cooling.

Specimen No.	Grain Orientation[a]	Temperature °K (°F)	Ultimate tensile strength MPa (ksi)	0.2-percent yield strength, MPa (ksi)	Elongation, percent	Reduction in area, percent
Specimens machined from initial design TFE731-3 turbine blades						
167-1	L	RT	912 (132)	843 (122)	5.2	10.2
106-4	L		971 (141)	854 (124)	6.1	10.6
167-1T	T		804 (117)	789 (114)	2.8	7.9
186-4T	T		760 (110)	751 (109)	4.6	6.9
167-2	L	1033 (1400)	1211 (176)	1040 (151)	4.3	12.5
186-7	L		1105 (160)	1025 (149)	4.4	12.9
167-2T	T		843 (122)	761 (110)	3.4	6.9
186-7T	T		841 (122)	747 (108)	3.4	7.6
167-4	L	1144 (1600)	905 (131)	776 (113)	10.2	17.2
186-8	L		927 (135)	756 (110)	6.4	12.5
167-4T	T		812 (118)	718 (104)	7.2	9.7
186-8T	T		858 (124)	754 (109)	2.8	5.4
Specimens machined from separately cast test bars						
R25	L	RT	1187 (172)	871 (126)	11.2	11.5
R53	L		1098 (159)	836 (121)	9.2	10.8
R81	L		1088 (158)	854 (124)	9.9	11.9
R54	L	1033 (1400)	1204 (175)	985 (143)	7.5	13.0
R82	L		1224 (178)	973 (141)	9.7	16.3
R26	L	1144 (1600)	919 (133)	715 (104)	20.6	32.7
R83	L		908 (132)	716 (104)	16.9	29.4

a L = Longitudinal
T = Transverse

TABLE XXXIX. TASK III STRESS-RUPTURE TEST RESULTS ON MAR-M 247 TEST SPECIMENS

Heat treatment: 1505°K (2250°F) for 2 hours with argon quenching, plus
1255°K (1800°F) for 5 hours with air cooling, plus
1144°K (1600°F) for 20 hours with air cooling

(Test specimens machined from exothermically cast preliminary design TFE731-3 turbine blades.)

Specimen No.	Grain orientation[a]	Temperature, °K (°F)	Stress, MPa (ksi)	Hours to rupture	Elongation, percent	Reduction of area, percent
140-9	L	1033 (1400)	724 (105)	309.1	14.2	16.8
148-6	L		669 (97)	1259.9	16.6	20.9
159-15	L		641 (93)	555.7	8.9	16.3
140-9T	T		669 (97)	0.5	1.9	5.0
159-15T	T		655 (95)	4.9	4.3	8.5
148-9T	T		641 (93)	8.0	1.1	1.6
138-18T	T		621 (90)	1155.2	13.5	17.9
148-6T	T		621 (90)	331.3	4.0	8.7
138-2	L	1144 (1600)	434 (63)	184.0	18.7	26.2
140-11	L		345 (50)	774.3	20.7	37.0
148-1	L		317 (46)	1270.0	30.8	41.4
140-11T	T		448 (65)	104.1	6.4	10.9
148-1T	T		434 (63)	136.3	9.3	10.9
138-2T	T		414 (60)	225.1	8.7	18.5
138-3	L	1200 (1700)	297 (43)	167.8	26.8	43.5
159-18	L		255 (37)	320.0	27.9	48.0
138-3T	T		276 (40)	169.3	8.8	11.7
159-18T	T		241 (35)	338.6	13.0	19.1
138-16	L	1255 (1800)	207 (30)	123.4	39.8	53.2
148-7	L		152 (22)	646.2	28.6	56.2
159-11	L		131 (19)	1678.3	25.2	48.2
148-7T	T		207 (30)	90.4	9.8	18.3
138-16T	T		186 (27)	124.3	12.3	17.4
159-11T	T		172 (25)	227.4	8.7	13.8
138-18	L	1311 (1900)	124 (18)	174.5	14.3	25.8
148-9	L	1311 (1900)	103 (15)	838.0	19.0	37.3

[a] L = Longitudinal
T = Transverse

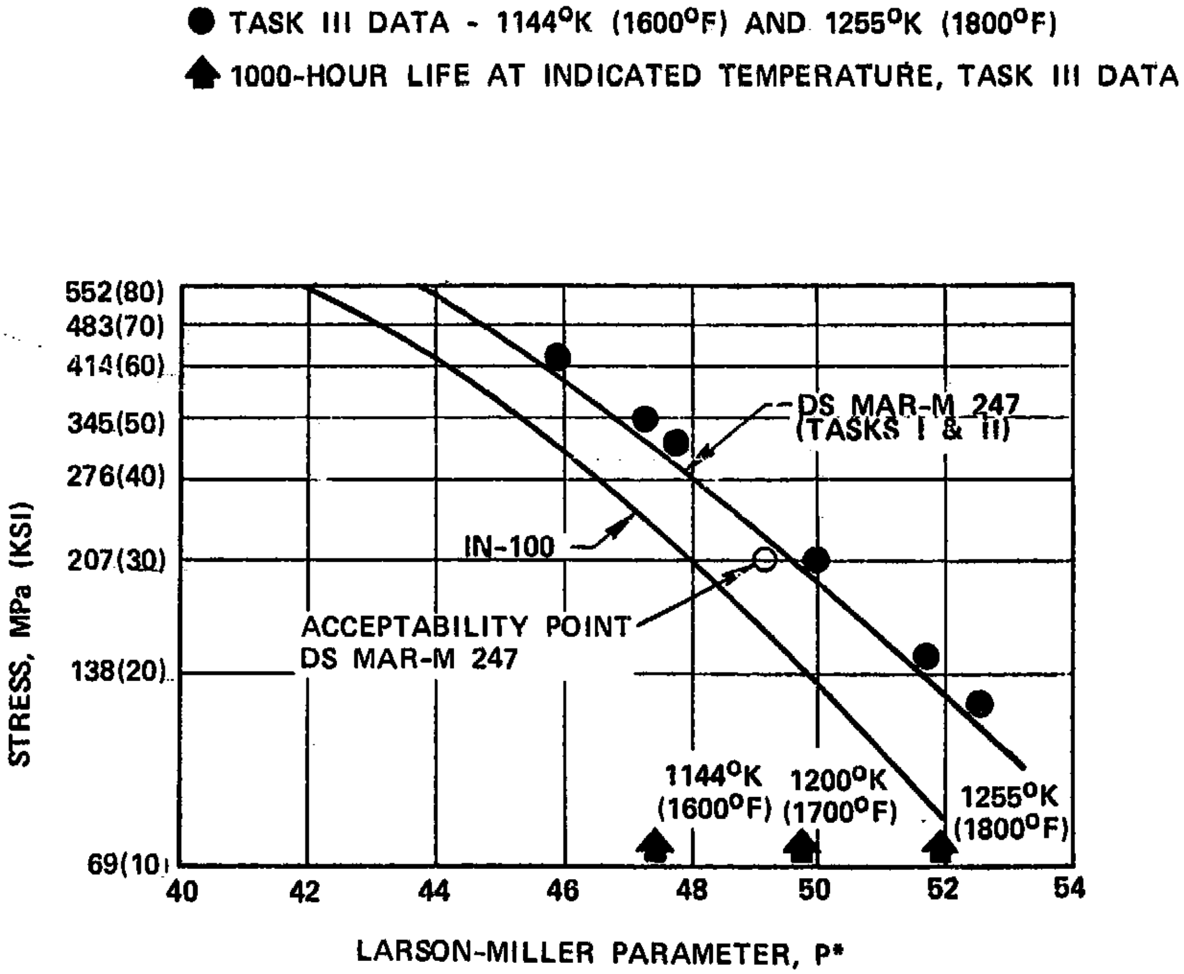
TABLE XL. TASK III STRESS-RUPTURE TEST RESULTS ON MAR-M 200+Hf AND NASA-TRW-R

Heat treatment: 1505°K (2250°F) for 2 hours with argon quenching, plus
1255°K (1800°F) for 5 hours with air cooling, plus
1144°K (1600°F) for 20 hours with air cooling.

(Test specimens machined from exothermically cast DS turbine blades)

Specimen Number	Grain orientation[a]	Temperature, °K (°F)	Stress, MPa (ksi)	Hours to rupture	Elongation, percent	Reduction of area, percent
MAR-M 200+Hf						
168-8	L	1144 (1600)	434 (63)	171.7	15.3	28.7
174-13	L		355 (50)	557.8	17.8	23.4
168-8T	T		414 (60)	168.1	6.7	10.2
174-13T	T		448 (65)	73.2	6.1	10.6
168-9	L	1255 (1800)	207 (30)	103.1	23.1	38.0
174-15	L		152 (22)	528.9	18.0	49.4
168-9T	T		186 (27)	0.3	2.2	4.1
174-15T	T		186 (27)	128.5	4.3	6.6
NASA-TRW-R						
167-7	L	1033 (1400)	724 (105)	85.0	6.2	14.9
186-9	L		641 (93)	455.9	10.8	19.0
167-7T	T		621 (90)	0.1	2.6	5.0
186-9T	T		586 (85)	511.0	6.5	12.4
167-8	L	1144 (1600)	436 (63)	68.8	17.8	24.5
186-11	L		317 (46)	619.3	29.6	35.0
167-8T	T		414 (60)	63.6	6.2	9.9
186-11T	T		379 (55)	19.3	1.9	4.0
167-10	L	1255 (1800)	207 (30)	50.5	18.5	39.4
186-12	L		131 (19)	832.8	22.0	51.9
167-10T	T		126 (27)	65.7	3.7	5.6
186-12T	T		172 (25)	122.9	7.8	14.4

[a] L = Longitudinal
T = Transverse



$$*P = T\ (20 + \text{LOG}\ t) \times 10^{-3}$$

WHERE: P = LARSON-MILLER PARAMETER

T = TEMPERATURE, °RANKINE

t = TEST TIME IN HOURS

Figure 33. Average Stress-Rupture Strength of DS MAR-M 247 Versus Equiaxed IN100, 0.178-cm (0.070-inch) MFB Test Specimens

the actual 1144°K (1600°F) and 1255°K (1800°F) Task III data points. The higher strength levels achieved in Task III are attributed to the increased solution temperature, 1505°K versus 1494°K (2250°F versus 2330°F), used on the Task III castings.

Using the Task III MAR-M 247 rupture and creep test data, a family of rupture and creep curves were prepared by regression analysis using a least squares method. The curves were plotted as average and minus three sigma curves. These curves are presented in Figures 34 through 37 for rupture, (0.5-, 1.0-, and 2.0-percent creep, respectively). These curves were utilized to validate the final blade design life predictions. The acceptability point for the DS MAR-M 247 specification is shown on Figure 34.

3. Low-Cycle Fatigue Testing. - Load-controlled low-cycle-fatigue (LCF) tests were conducted at room temperature and at 1033°K (1400°F) on smooth and notched test specimens machined from separately cast test bars of the three DS cast alloys. LCF tests were also conducted on smooth aluminide-coated (RT-21) test specimens of MAR-M 247. In addition, LCF tests were performed on equiaxed IN100 at room temperature and at 1033°K (1400°F) to provide a baseline for comparing the DS cast alloys with the equiaxed material currently being used for the TFE731-3 turbine blades. Results of this testing are presented in Tables XLI through XLIV.

Table XLV presents a comparison of the estimated maximum stresses, for the several materials, that would produce LCF failures in 5,000 and 10,000 cycles, based on Task III data. No advantage for any of the DS alloys is indicated at room temperature. At 1033°K (1400°F) all three DS alloys show greater LCF strength than equiaxed IN100, with MAR-M 200+Hf, and MAR-M 247 superior to NASA-TRW-R. All three DS alloys showed notch-strengthening at room temperature, and notch-weakening at 1033°K (1400°F).

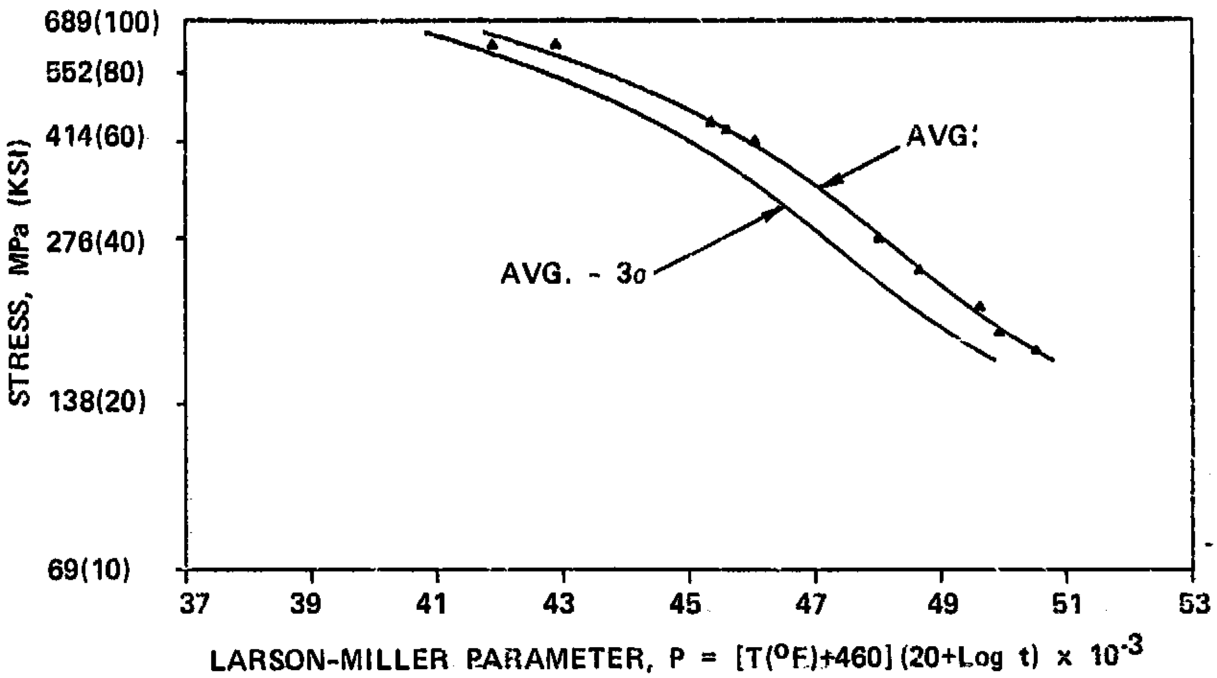


Figure 34. Larson-Miller Stress-Rupture Curve for DS MAR-M 247, Longitudinal Data, 0.178-cm (0.070-Inch) MFB Test Specimens

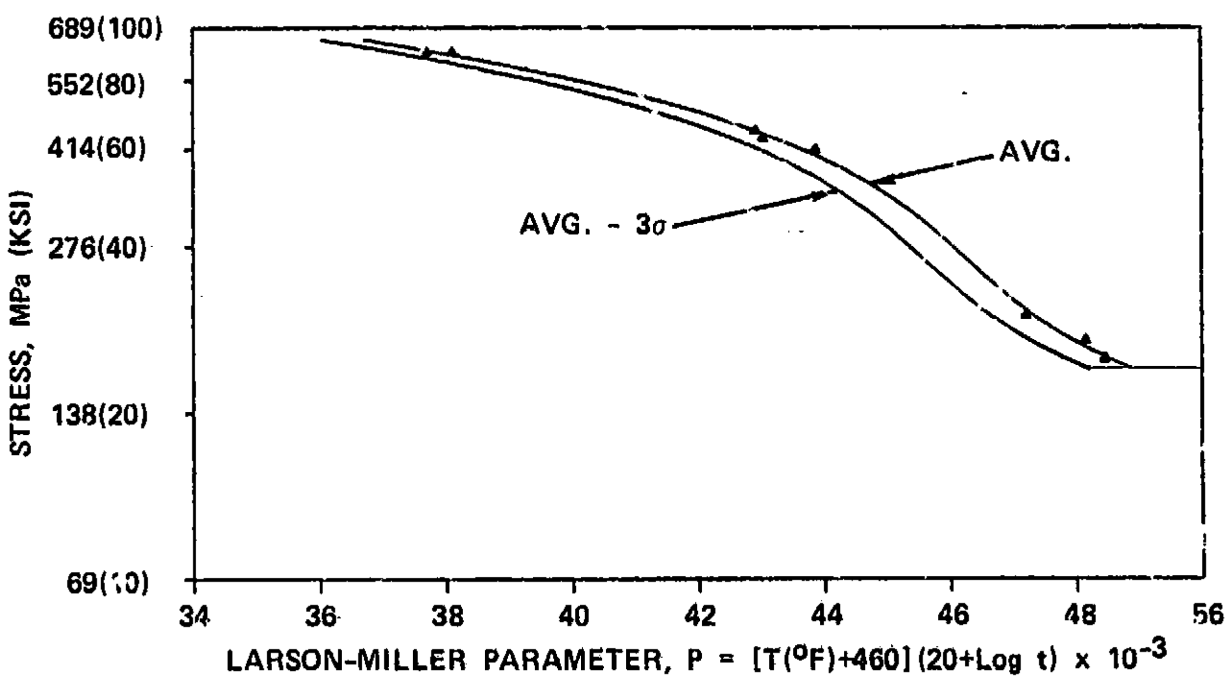


Figure 35. Larson-Miller 0.5-Percent Creep Curve for DS MAR-M 247, Longitudinal Data, 0.178-cm (0.070-Inch) MFB Test Specimens

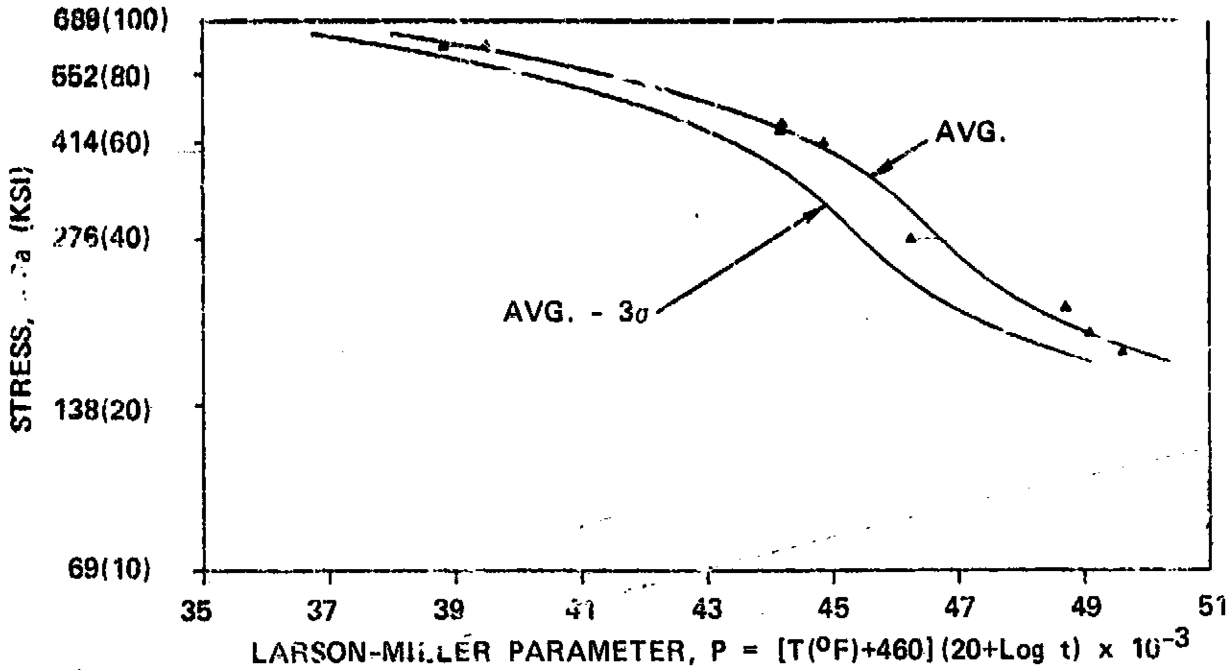


Figure 36. Larson-Miller 1.0-Percent Creep Curve for DS MAR-M 247, Longitudinal Data, 0.178-cm (0.070-Inch) MFB Test Specimens

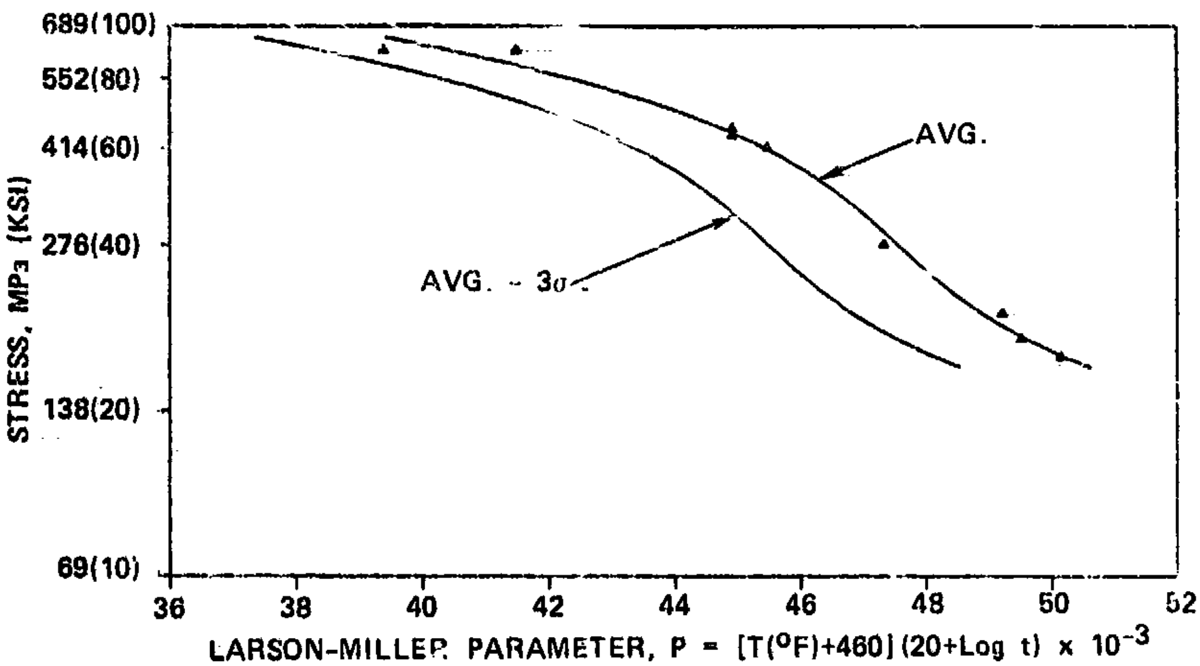


Figure 37. Larson-Miller 2.0-Percent Creep Curve for DS MAR-M 247, Longitudinal Data, 0.178-cm (0.070-Inch) MFB Test Specimens

TABLE XLI. LOW-CYCLE-FATIGUE TEST RESULTS ON DS MAR-M 247

Heat treatment: 1505°K (2250°F) for 2 hours, plus
1255°K (1800°F) for 5 hours, plus
1144°K (1600°F) for 20 hours

(Longitudinal grain orientation test specimens machined from separately cast test bars)

Specimen No.	Temperature, °K (°F)	Maximum stress, MPa (ksi)	Cycles to failure[a]	Remarks
(a) Uncoated smooth specimens				
232	RT	1138 (165)	620	
233		1138 (165)	830	
235		1104 (160)	2,550	
235		1103 (160)	2,780	
231		1069 (155)	4,450	
148		1034 (150)	5,300	
230		1034 (150)	6,580	
117		965 (140)	9,420	
115		931 (135)	11,660	
2		896 (130)	9,730	
1		896 (130)	12,930	
101		896 (130)	21,350	
239	1033 (1400)	1138 (165)	690	
243		1138 (165)	860	
238		1138 (165)	1,810	
106		1103 (160)	920	
104		1103 (160)	2,180	
4		1034 (150)	3,020	
3		1034 (150)	3,440	
242		1000 (145)	10,130	
240		965 (140)	7,730	
237		965 (140)	9,080	
236		965 (140)	9,320	
241		931 (135)	12,130	
(b) RT-21 coated smooth specimens				
114	1033 (1400)	965 (140)	960	
9		965 (140)	1,410	
162		965 (140)	1,060	
121		931 (135)	1,890	
120		896 (130)	2,690	
10		896 (130)	6,310	
149		896 (130)	2,800	
151		862 (125)	7,200	
158		862 (125)	31,590	
11		827 (120)	24,830	
122		827 (120)	29,240	Broke in threaded area

[a] Test parameters; Axial load control; sine wave form; 60 Hz frequency; "A" ratio = 1.0

TABLE XLII. LOW-CYCLE-FATIGUE TEST RESULTS ON DS MAR-M 247

Heat treatment: 1505°K (2250°F) for 2 hours, plus
1255°K (1800°F) for 5 hours, plus
1144°K (1600°F) for 20 hours

(Longitudinal grain orientation test specimens machined from separately cast test bars)

Specimen Number	Temperature, °K (°F)	Maximum stress, MPa (ksi)	Cycles[a] to failure	Remarks
Uncoated notched (K_t = 1.8) specimens				
251	RT	1241 (180)	1,630	
252	↓	1241 (180)	2,840	
249	↓	1172 (170)	4,260	
250	↓	1172 (170)	4,870	
6	↓	1138 (165)	5,070	
244	↓	1138 (165)	5,960	
245	↓	1103 (160)	6,530	
246	↓	1103 (160)	7,260	
5	↓	1034 (150)	4,210	
103	↓	1034 (150)	6,550	
247	↓	965 (140)	10,400	
248	↓	965 (140)	13,660	
7	1033 (1400)	1103 (160)	430	
125	↓	1103 (160)	920	
107	↓	1103 (160)	--	Overloaded
132	↓	1034 (150)	1,540	
253	↓	1034 (150)	1,890	
255	↓	965 (140)	2,800	
254	↓	965 (140)	2,860	
8	↓	827 (120)	4,840	
256	↓	827 (120)	6,760	
257	↓	758 (110)	9,120	
259	↓	758 (110)	9,280	
258	↓	758 (110)	16,500	

[a] Test parameters; Axial load control; sine wave form; 60 Hz frequency; "A" ratio = 1.0

TABLE XLIII. LOW-CYCLE-FATIGUE TEST RESULTS ON DS NASA-TRW-R AND EQUIAXED IN100

(Longitudinal grain orientation test specimens machined from separately cast test bars)

Specimen number	Temperature, °K (°F)	Maximum stress, MPa (ksi)	Cycles to failure[a]	Remarks
NASA-TRW-R uncoated smooth specimens[b]				
R1	RT	1138 (165)	140	
R58		1103 (160)	230	
R2		1034 (150)	3,750	
R29		1000 (145)	4,140	
R30		896 (130)	6,812	
R57		827 (120)	15,030	
R31	1033 (1400)	1034 (150)	380	
R59		965 (140)	1,520	
R32		965 (140)	2,460	
R60		931 (135)	7,930	
R3		896 (130)	13,600	
R4		827 (120)	17,530	
NASA-TRW-R uncoated notched (K_t = 1.8) specimens[b]				
R61	RT	1172 (170)	1,270	
R34		1138 (165)	1,920	
R33		1103 (160)	3,340	
R5		1034 (150)	7,010	
R62		1000 (145)	9,440	
R6		965 (140)	15,280	
R64	1033 (1400)	1069 (155)	1,120	
R7		1034 (150)	1,050	
R8		965 (140)	3,390	
R36		896 (130)	4,980	
R35		896 (130)	8,220	
R63		827 (120)	9,110	
Equiaxed IN-100 uncoated smooth specimens[c]				
I3	RT	1069 (155)	1,700	
I4		1034 (150)	5,970	
I2		931 (135)	19,450	
I1		931 (135)	20,340	
I5	1033 (1400)	1069 (155)	160	
I7		965 (140)	1,520	
I6		896 (130)	4,440	
I8		327 (120)	7,850	

a Test parameters: Axial load control; sine wave form; 60 Hz frequency; "A" ratio = 1.0

b Heat treatment: 1505°K (2250°F) for 2 hours, plus 1255°K (1800°F) for 5 hours, plus 1144°K (1600°F) for 20 hours.

c Heat treatment: 1255°K (1800°F) for 5 hours, plus 1144°K (1600°F) for 12 hours

TABLE XLIV. LOW-CYCLE-FATIGUE TEST RESULTS ON DS MAR-M 200+Hf

Heat treatment: 1505°K (2250°F) for 2 hours, plus
1255°K (1800°F) for 5 hours, plus
1144°K (1600°F) for 20 hours.

(Longitudinal grain orientation test specimens machined from separately cast test bars.)

Specimen number	Temperature, °K (°F)	Maximum stress, MPa (ksi)	Cycles to failure[a]	Remarks
(a) Uncoated smooth specimens				
M19	RT	1138 (165)	1,150	
M20	↓	1103 (160)	2,410	
M47	↓	1069 (155)	3,010	
M48	↓	1034 (150)	5,360	
M77	↓	1000 (145)	8,030	
M76	↓	965 (140)	14,290	
M21	1033 (1400)	1138 (165)	50	
M50	↓	1103 (160)	1,530	
M79	↓	1069 (155)	4,720	
M78	↓	1069 (155)	6,730	
M49	↓	1034 (150)	7,020	
M22	↓	1034 (150)	12,980	
(b) Uncoated Notched (K_t = 1.8) specimens				
M81	RT	1241 (180)	3,240	
M51	↓	1207 (175)	4,190	
M24	↓	1172 (170)	4,600	
M23	↓	1138 (165)	5,400	
M52	↓	1103 (160)	7,860	
M80	↓	1069 (155)	10,730	
M25	1033 (1400)	1103 (160)	1,570	
M54	↓	1103 (160)	1,990	
M53	↓	1103 (160)	3,150	
M26	↓	965 (140)	5,220	
M82	↓	896 (130)	11,240	Broke in threaded area.
M83	↓	896 (130)	27,110	

a Test parameters Axial load control; sine wave form; 60 Hz frequency; "A" ratio - 1.0

TABLE XLV. ESTIMATED MAXIMUM LOW-CYCLE-FATIGUE STRESS REQUIRED TO PRODUCE FAILURE IN EXOTHERMICALLY CAST DS ALLOYS AND EQUIAXED IN 100

Alloy	Condition	For 5,000 cycles life, MPa (ksi)	For 10,000 cycles life, MPa (ksi)
DS MAR-M 247	RT - Smooth Bars - Uncoated	1048 (152)	917 (133)
	RT - Notched Bars - Uncoated	1138 (165)	972 (141)
	1033°K (1400°F) - Smooth Bars - Uncoated	1014 (147)	958 (139)
	1033°K (1400°F) - Notched Bars - Uncoated	827 (120)	752 (109)
	1033°K (1400°F) - Smooth Bars - Coated	883 (128)	855 (124)
DS NASA-TRW-R	RT - Smooth Bars - Uncoated	931 (135)	862 (125)
	RT - Notched Bars - Uncoated	1055 (153)	993 (144)
	1033°K (1400°F) - Smooth Bars - Uncoated	945 (137)	910 (132)
	1033°K (1400°F) - Notched Bars - Uncoated	896 (130)	814 (118)
DS MAR-M 200+Hf	RT - Smooth Bars - Uncoated	1034 (150)	979 (142)
	RT - Notched Bars - Uncoated	1138 (165)	1069 (155)
	1033°K (1400°F) - Smooth Bars - Uncoated	1062 (154)	1020 (148)
	1033°K (1400°F) - Notched Bars - Uncoated	965 (140)	931 (135)
EQUIAXED IN100	RT - Smooth Bars - Uncoated	1034 (150)	965 (140)
	1033°K (1400°F) - Smooth Bars - Uncoated	862 (125)	827 (120)

The 1033°K (1400°F) LCF data on MAR-M 247 and IN100 is presented as least squares regression analysis curves in Figures 38 through 41. In all cases, the upper curve is the best fit of the data, and the lower curve is the best fit minus three sigma.

4. <u>High-cycle fatigue testing.</u> - Axial-axial high-cycle fatigue load-controlled tests of test specimens machined in the grain-growth direction from separately cast test bars were performed on the three alloys, with results as presented in Tables XLVI through L. MAR-M 247 tests were conducted on smooth and notched (K_t = 3.0) test specimens at room temperature and at 1144°K (1600°F), and at "A" ratios of infinity and 0.95. Testing of MAR-M 200+Hf was conducted on smooth and notched (K_t = 3.0) test specimens at room temperature and 1144°K (1600°F) at an "A" ratio of infinity. Due to the elimination of NASA-TRW-R as a program alloy in Task V, only room temperature tests on smooth test specimens were conducted on this material.

A number of test specimens failed in the threaded area, particularly at room temperature. In an attempt to avoid this kind of failure, several specimens were remachined to a minimum gage diameter of 0.51 cm (0.20-inch) and subjected to test. As can be seen from the results included in Table XLIX, the attempted corrective action did not succeed.

The room temperature and 1144°K (1600°F) fatigue strengths of both MAR-M 247 and MAR-M 200+Hf appear identical for smooth, uncoated specimens. At 1144°K (1600°F) both alloys are notch weakened with MAR-M 200+Hf less affected than MAR-M 247.

The estimated endurance limits for the specimens tested under Task III are given in Table LI. The degree of unexpected scatter in the test results obtained precluded the ability to make a meaningful statistical analysis of the results obtained.

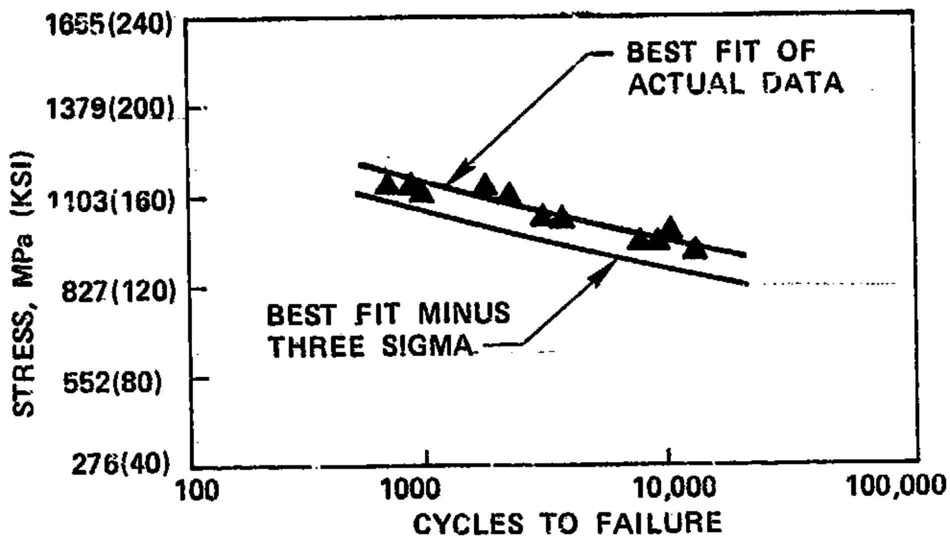


Figure 38. Low-Cycle Fatigue of Exothermically Cast DS MAR-M 247. [Longitudinal Data, 1035°K (1400°F), Load Controlled, $A = 1.0$, $K_t = 1.0$, Smooth Uncoated Test Specimens Machined from Separately Cast Test Bars]

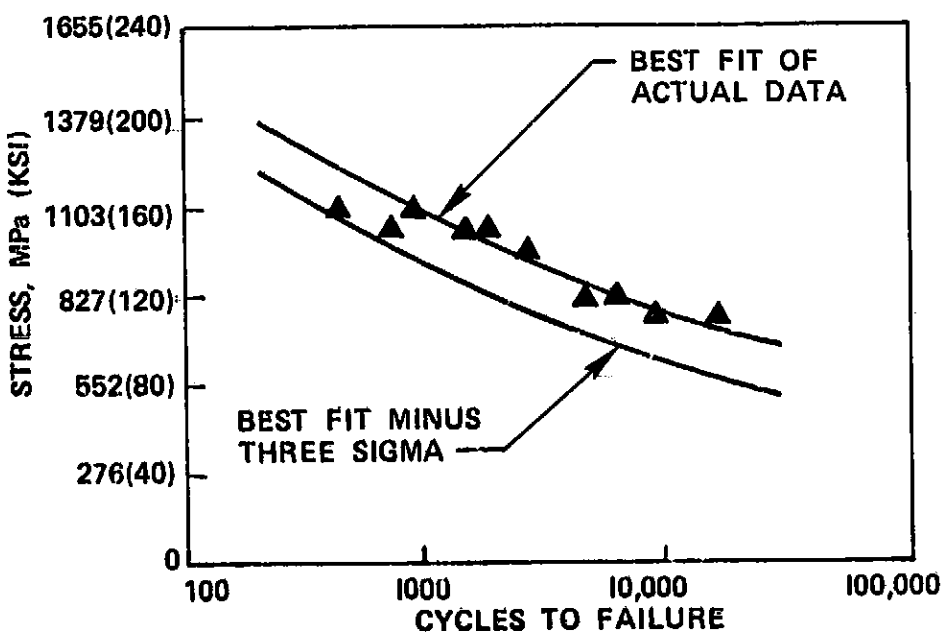


Figure 39. Low-Cycle Fatigue of Exothermically Cast DS MAR-M 247. [Longitudinal Data, 1033°K (1400°F), Load Controlled, $A = 1.0$, $K_t = 1.8$, Notched Uncoated Test Specimens Machined from Separately Cast Test Bars]

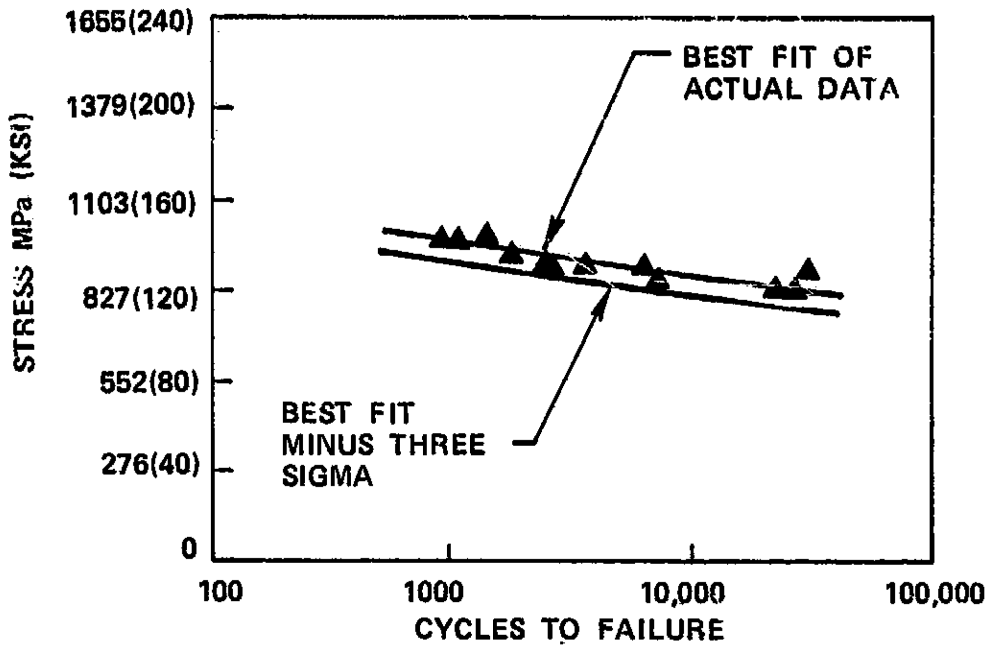


Figure 40. Low-Cycle Fatigue of Exothermically Cast DS MAR-M 247. [Longitudinal Data, 1033°K (1400°F), Load Controlled, A = 1.0, K_t = 1.0, Smooth RT-21 Coated Test Specimens Machined from Separately Cast Test Bars]

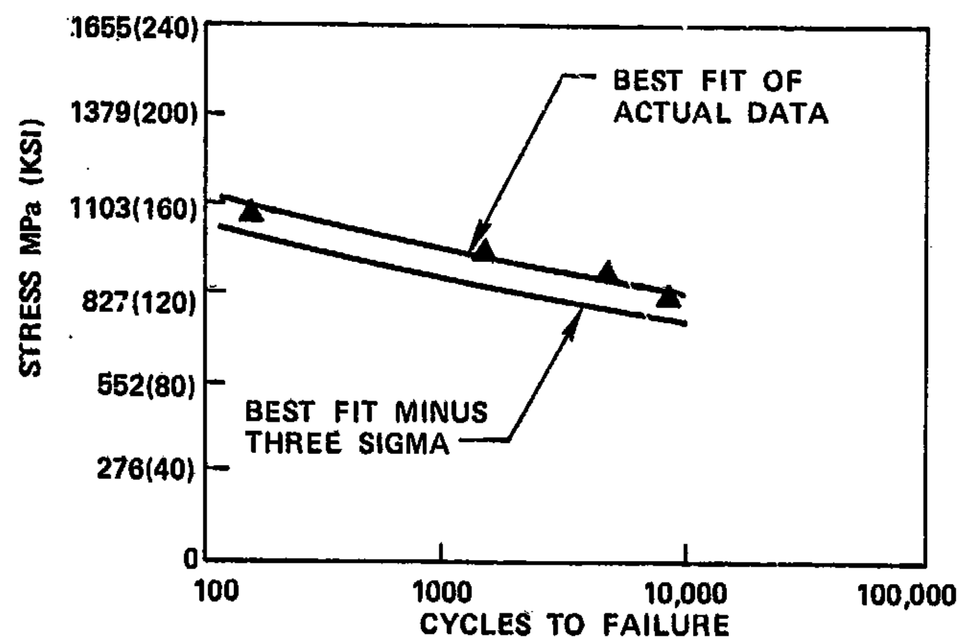


Figure 41. Low-Cycle Fatigue of Equiaxed IN100. [1033°K (1400°F), Load Controlled, A = 1.0, K_t = 1.0, Smooth Uncoated Test Specimens Machined from Separately Cast Test Bars]

TABLE XLVI. HIGH-CYCLE-FATIGUE TEST RESULTS ON DS MAR-M 247

Heat treatment: 1505°K (2250°F) for 2 hours, plus
1255°K (1800°F) for 5 hours, plus
1144°K (1600°F) for 20 hours

[0.64-cm (0.25-inch) test specimens machined from separately cast test bars.]

Specimen number	Configuration	A Ratio[a]	Temperature °K (°F)	Alternating stress, MPa (ksi)	Cycles to failure	Remarks
183-1	Smooth	∞	RT	689 (100)	5,000	
182-1				689 (100)	6,000	
102				621 (90)	16,000	
116				621 (90)	25,000	
160-1				552 (80)	23,000	
153-1				552 (80)	55,000	
119				517 (75)	42,000	Broke in threaded area
118				483 (70)	211,000	
124				414 (60)	806,000	
150				345 (50)	2,206,000	Broke in threaded area
153 b				345 (50)	734,000	
140-1	Smooth	∞	1144 (1600)	483 (70)	22,000	Broke in threaded area
105				483 (70)	70,000	
157-1				414 (60)	214,000	
135				414 (60)	389,000	
138				379 (55)	486,000	
140				345 (50)	504,000	
182				345 (50)	236,000	
134				276 (40)	867,000	
160				276 (40)	10,000,000+	Test terminated.
157				207 (30)	10,000,000+	Test terminated.
109	Notched (K_t = 3)	∞	RT	552 (80)	9,000	
188				552 (80)	13,000	
111				483 (70)	20,000	
113				414 (60)	29,000	
180				345 (50)	61,000	
145				345 (50)	72,000	
146				276 (40)	147,000	
173				276 (40)	188,000	
172				207 (30)	390,000	
147				207 (30)	519,000	
170				172 (25)	3,189,000	
152				138 (20)	10,000,000+	Test terminated.
165	Notched (K_t = 3)	∞	1144 (1600)	483 (70)	4,000	
204				483 (70)	3,000	
195				414 (60)	4,000	
174				414 (60)	5,000	
194				345 (50)	10,000	
176				345 (50)	15,000	
178				276 (40)	128,000	
193				276 (40)	188,000	
109				207 (30)	1,389,000	
192				207 (30)	2,543,000	
203				172 (25)	147,000	
190				138 (20)	10,000,000+	Test terminated.

a A Ratio = $\frac{\text{alternating stress}}{\text{mean stress}}$

b Test specimen remachined to 0.508-cm (0.200-inch) gage diameter

TABLE XLVII. HIGH-CYCLE-FATIGUE TEST RESULTS ON RT-21 COATED DS MAR-M 247

Heat treatment: 1505°K (2250°F) for 2 hours, plus
1255°K (1800°F) for 5 hours, plus
1144°K (1600°F) for 20 hours

[0.64-cm (0.25-inch) test specimens machined from separately cast test bars.]

Specimen number	Configuration	A Ratio[a]	Temperature °K (°F)	Alternating stress, MPa (ksi)	Cycles to failure	Remarks
131	Smooth	∞	RT	483 (70)	47,000	
127				414 (60)	97,000	
13				414 (60)	545,000	Broke in threaded area
110				379 (55)	629,000	Broke in threaded area
112				379 (55)	1,018,000	Broke in threaded area
123				345 (50)	1,316,000	Broke in threaded area
163				345 (50)	1,076,000	Broke in threaded area
167				276 (40)	7,320,000	Broke in threaded area
197				241 (35)	10,000,000+	Test terminated
202				241 (35)	10,000,000+	Test terminated
17	Smooth	∞	1144 (1600)	414 (60)	32,000	
16				414 (60)	293,000	Broke in threaded area
179				379 (55)	125,000	
18				345 (50)	1,435,000	
175				345 (50)	645,000	
171				310 (45)	235,000	
168				276 (40)	3,672,000	Broke in threaded area
136				276 (40)	10,000,000+	Test terminated
139				241 (35)	10,000,000+	Test terminated
137				207 (30)	10,000,000+	Test terminated

[a] $\text{A Ratio} = \frac{\text{alternating stress}}{\text{mean stress}}$

TABLE XLVIII. HIGH-CYCLE-FATIGUE TEST RESULTS ON DS MAR-M 247

Heat treatment: 1505°K (2250°F) for 2 hours, plus
1255°K (1800°F) for 5 hours, plus
1144°K (1600°F) for 20 hours

[0.64-cm (0.25-inch) test specimens machined from separately cast test bars.]

Specimen Number	Configuration	A Ratio[a]	Temperature °K (°F)	Alternating stress, MPa (ksi)	Cycles to failure	Remarks
130-1 b	Smooth	0.95	RT	689 (100)	121,000	
154 b	↓	↓	↓	689 (100)	176,000	
129-1 b				621 (90)	378,000	
133 b				621 (90)	432,000	
128-1 b				552 (80)	1,218,000	
130 b				552 (80)	6,087,000	Broke in threaded area
126-1 b				483 (70)	1,566,000	
129 b				483 (70)	2,884,000	
128 b				448 (65)	10,000,000+	Test terminated
155 b				448 (65)	10,000,000+	Test terminated
126 b				414 (60)	10,000,000+	Test terminated
156 b				414 (60)	10,000,000+	Test terminated
159-1	Smooth	0.95	1144 (1600)	621 (90)	73,000	
187	↓	↓	↓	586 (85)	646,000	
108				552 (80)	446,000	
186				512 (75)	10,000,000+	
141				483 (70)	3,741,000	
184				483 (70)	10,000,000+	Test terminated
161				448 (65)	245,000	
166				448 (65)	10,000,000+	
142				414 (60)	8,319,000	
169				414 (60)	10,000,000+	Test terminated
144				377 (55)	10,000,000+	Test terminated
143				345 (50)	446,000	

a A Ratio $= \dfrac{\text{alternating stress}}{\text{mean stress}}$

b Test specimen remachined to 0.508-cm (0.200-inch) gage diameter

TABLE XLIX. HIGH-CYCLE-FATIGUE TEST RESULTS ON DS MAR-M 200+Hf

Heat treatment: 1505°K (2250°F) for 2 hours, plus
1255°K (1800°F) for 5 hours, plus
1144°K (1600°F) for 20 hours

[0.64-cm (0.25-inch) test specimens machined from separately cast test bars.]

Specimen Number	Configuration	A Ratio [a]	Temperature °K (°F)	Alternating stress, MPa	(ksi)	Cycles to failure	Remarks
M1	Smooth	∞	RT	689	(100)	67,000	Broke in threaded area
M2				621	(90)	19,000	Broke in threaded area
M60 b				621	(90)	116,000	
M3				552	(80)	101,000	
M59 b				552	(80)	448,000	
M4				483	(70)	87,000	Broke in threaded area
M58 b				483	(70)	809,000	
M28				414	(60)	135,000	Broke in threaded area
M31 b				414	(60)	4,621,000	Broke in threaded area
M29				345	(50)	2,414,000	Broke in threaded area
M30				345	(50)	4,569,000	Broke in threaded area
M61 b				310	(45)		
M63	Smooth	∞	1144 (1600)	483	(70)	15,000	
M5				483	(70)	19,000	
M62				414	(60)	142,000	
M6				414	(60)	159,000	
M35				345	(50)	260,000	Broke in threaded area
M7				345	(50)	318,000	
M8				276	(40)	7,468,000	
M34				276	(40)	10,000,000+	
M33				241	(35)	10,000,000+	
M32				207	(30)	10,000,000+	
M64							
M65							
M38	Notched	∞	RT	552	(30)	8,000	
M37	(K_t = 3.0)			483	(70)	23,000	
M68				414	(60)	34,000	
M36				414	(60)	54,000	
M67				345	(50)	94,000	
M12				345	(50)	142,000	
M66				276	(40)	442,000	
M11				276	(40)	378,000	
M10				207	(30)	1,648,000	
M9				172	(25)	4,930,000	
M39				138	(20)	6,331,000	
M69				103	(15)		
M41	Notched	∞	1144 (1600)	483	(70)	1,000	
M40	(K_t = 3.0)			414	(60)	5,000	
M71				414	(60)	2,000	
M16				345	(50)	7,000	
M70				345	(50)	11,000	
M15				276	(40)	402,000	
M43				276	(40)	36,000	
M13				206	(30)	722,000	
M42				206	(30)	10,000,000+	
M14				172	(25)	10,000,000+	Test terminated.

a A Ratio = $\frac{\text{alternating stress}}{\text{mean stress}}$

b Test specimen remachined to 0.508-cm (0.200-inch) gage diameter

TABLE L. HIGH-CYCLE-FATIGUE TEST RESULTS ON DS NASA-TRW-R ALLOY

Heat treatment: 1505°K (2250°F) for 2 hours, plus
1255°K (1800°F) for 5 hours, plus
1144°K (1600°F) for 20 hours

[0.64-cm (0.25-inch) test specimens machined from separately cast test bars]

Specimen number[a]	Configuration	A Ratio[a]	Temperature	Alternating Stress, MPa (ksi)	Cycles to failure	Remarks
R9	Smooth	∞	RT	689 (100)	23,000	Broke in threaded area
R10	Smooth	∞	RT	621 (90)	71,000	Broke in threaded area
R11	Smooth	∞	RT	552 (80)	150,000	--
R12	Smooth	∞	RT	483 (70)	112,000	--
R37	Smooth	∞	RT	414 (60)	161,000	Broke in threaded area
R38	Smooth	∞	RT	345 (50)	755,000	Broke in threaded area

a A Ratio = $\frac{\text{alternating stress}}{\text{mean stress}}$

TABLE LI. ESTIMATED ENDURANCE LIMITS OF DS TEST SPECIMENS MACHINED FROM SEPARATELY CAST TEST BARS

Alloy	Temperature, °K (°F)	Notched specimen	Coated specimen	Estimated endurance limit at 10^7 Cycles, MPa (ksi)
Results at A = ∞				
MAR-M 247	Room	No	No	310 (45)
MAR-M 247	Room	Yes	No	138 (20)
MAR-M 247	Room	No	Yes	241 (35)
MAR-M 247	1144 (1600)	No	No	262 (38)
MAR-M 247	1144 (1600)	Yes	No	138 (20)
MAR-M 247	1144 (1600)	No	Yes	262 (38)
MAR-M 200+Hf	Room	No	No	310 (45)
MAR-M 200+Hf	Room	Yes	No	124 (18)
MAR-M 200+Hf	1144 (1600)	No	No	262 (38)
MAR-M 200+Hf	1144 (1600)	Yes	No	193 (28)
Results at A = 0.95				
MAR-M 247	Room	No	No	462 (67)
MAR-M 247	1144 (1600)	No	No	379 (55)

5. Physical properties. Tests were conducted by Southern Research Institute on the thermal expansion and conductivity of MAR-M 247 and NASA-TRW-R alloys in the fully heat-treated condition. Tests were made in triplicate and the thermal properties of the two alloys were virtually identical. The thermal expansion curves are presented in Figure 42 and the thermal conductivity curves in Figure 43.

Static modulus of elasticity was determined from the Task III tensile test data. The static moduli are presented in Table LII and compared to the dynamic moduli determined by Southern Research Institute in Task II on the same DS alloys. Results of the two methods of measurement generally agree at room temperature, but not at elevated temperatures.

6. Oxidation and hot-corrosion testing. - Oxidation and hot-corrosion tests were conducted in an AiResearch test rig on samples of coated and uncoated DS alloys.

The test rig design is described in the following paragraphs, and is shown schematically in Figure 44 and in the photos of Figure 45. The burner rig is a version of an oxidation/hot-corrosion burner rig that has been used extensively in industry to study hot corrosion of superalloys and coatings. The AiResearch burner rig has the following features:

- Automatic-temperature measurement and control with an Ircon radiation pyrometer system that can control temperature either by fuel flow or airflow to within ±10°F.

- Automatic burner cycling between two temperature set points, in addition to controlled automatic cycling to room temperature by airblast.

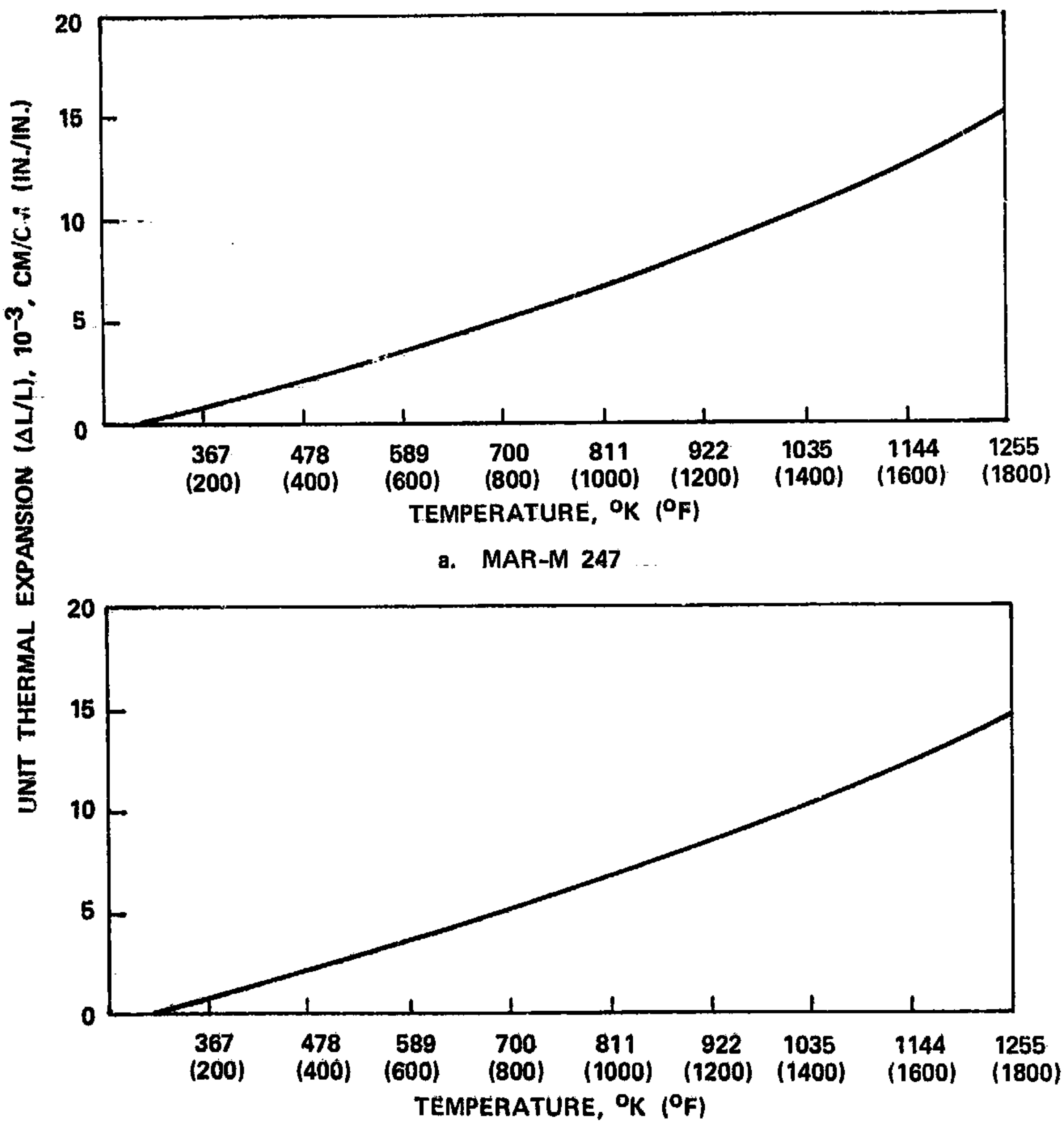
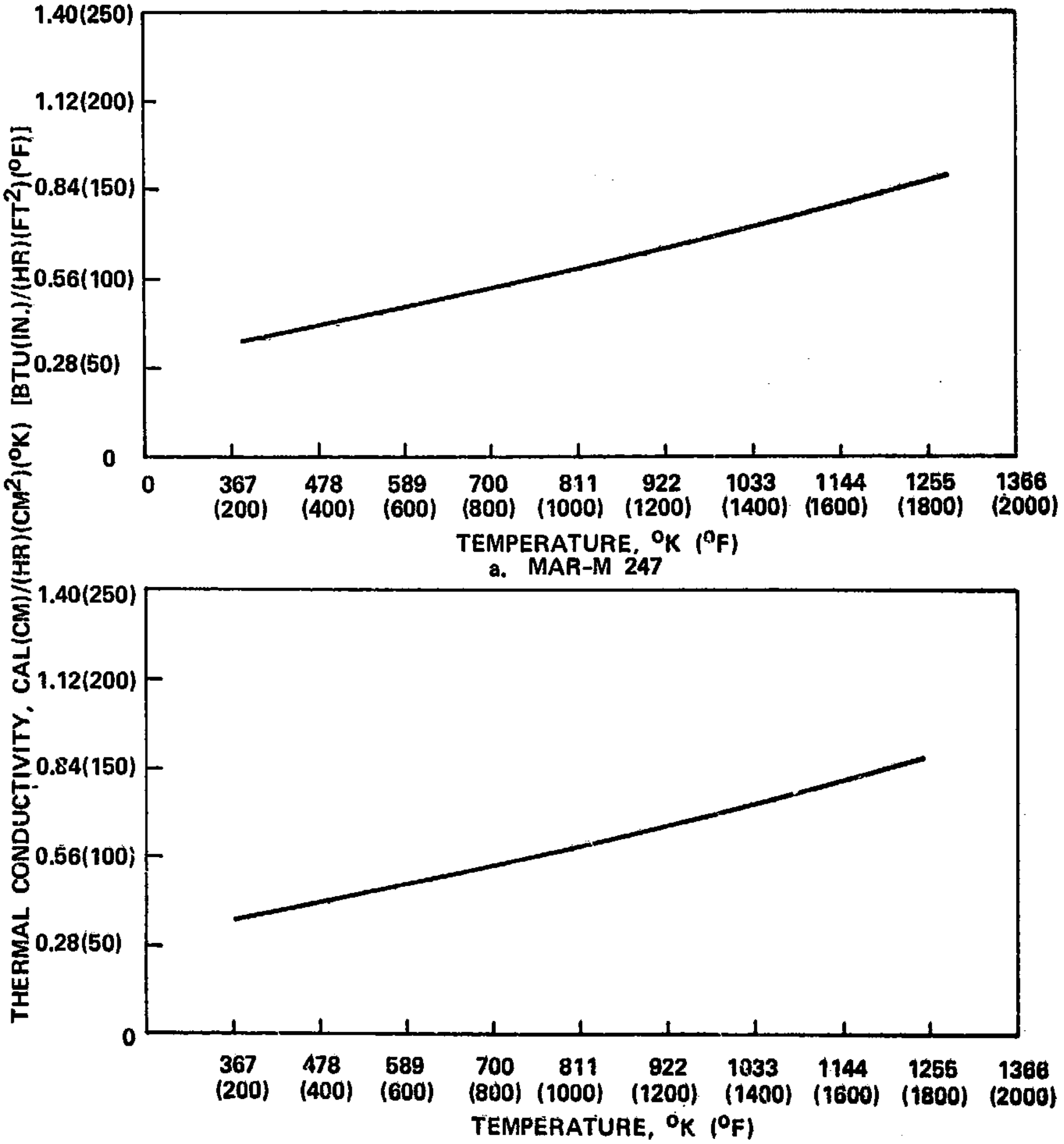


Figure 42. Thermal Expansion of Exothermically Cast DS MAR-M 247 and NASA-TRW-R



a. MAR-M 247

b. NASA-TRW-R

Figure 43. Thermal Conductivity Exothermically Cast DS MAR-M 247 and NASA-TRW-R

TABLE LII. MODULUS OF ELASTICITY

Alloy	Modulus of elasticity, [GPa (ksi)]					
	Room Temperature		1033°K (1400°F)		1144°K (1600°F)	
	Static[a]	Dynamic[b]	Static[a]	Dynamic[b]	Static[a]	Dynamic[b]
MAR-M 247	144 (21)	143 (21)	95 (14)	111 (16)	75 (11)	105 (15)
MAR-M 200+Hf	134 (19)	134 (19)	91 (13)	104 (15)	72 (11)	101 (15)
NASA-TRW-R	128 (19)	134 (20)	90 (13)	114 (17)	70 (10)	104 (15)

a Static values determined from Task III tensile tests of longitudinal grain orientation test specimens machined from exothermically cast DS separately cast test bars.

b Dynamic values determined by Task II dynamic modulus test of longtudinal grain orientation test specimens machined from exothermically cast DS test slabs (Ref. Table XXIX).

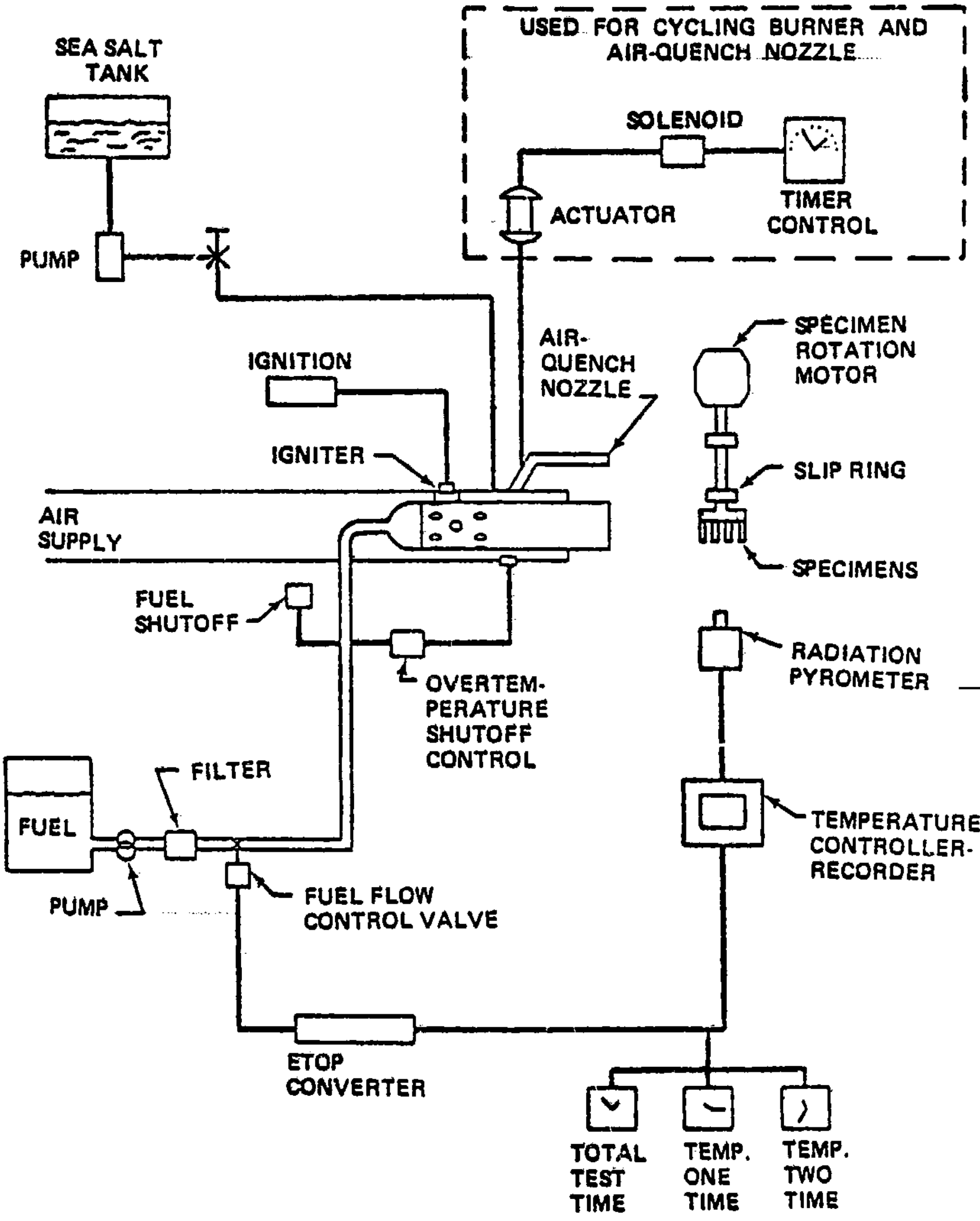
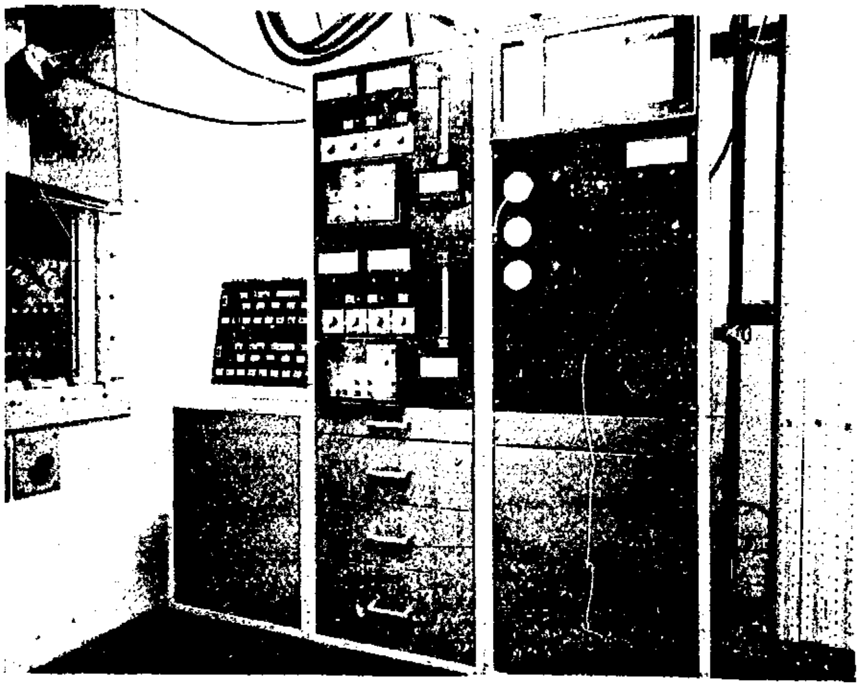
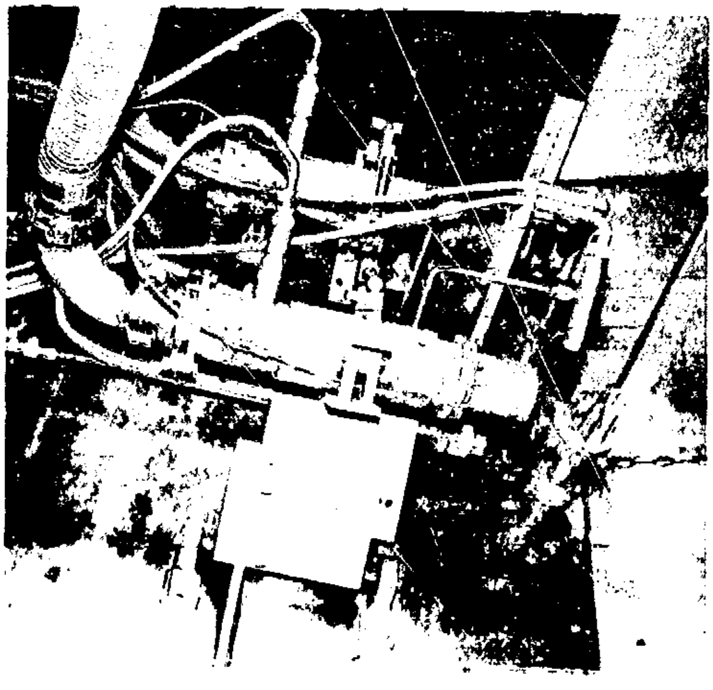


Figure 44. Schematic of AiResearch Oxidation Hot-Corrosion Burner Rig



TEST FACILITY CONTROLS



OXIDATION/HOT-CORROSION BURNER RIG

Figure 45. Oxidation/Hot-Corrosion Burner Rig

- Controlled addition of aqueous sea salt solutions, sulfur, or any other desired contaminant to the burner flame.

- Sophisticated control system to allow continuous, unattended cyclic testing with automatic shutoff if undesirable conditions develop during a test.

- Sample holders that normally hold eight test samples and can be rotated at up to 2000 rpm to ensure that all samples are exposed to the same burner conditions.

The oxidation/hot-corrosion burner rig test conditions and test results are presented in Tables LIII and LIV. No significant degradation was observed on the coated MAR-M 247 samples after 510-hours oxidation at 1311°K (1900°F) as shown in Table LIII. However, the uncoated MAR-M 247 sample was heavily attacked by hot corrosion after 310 hours at 1200°K (1700°F) as shown in Table LIV. Of the three coated alloys exposed in the same hot-corrosion test, MAR-M 247 showed very little attack, while the coatings failed at areas of lower temperature on the MAR-M 200+Hf and NASA-TRW-R alloys as shown in Figure 46.

7. Metallographic examination. - With the assistance of Micro-Met Laboratories of Lafayette, Indiana, metallographic examination was performed on three high-rupture-time MAR-M 247 stress-rupture specimens. The basic stress-rupture test history (refer to Table XXXIX) was as shown in Table LV:

TABLE LIII. TASK III 1311°K (1900°F) OXIDATION TEST RESULTS

Alloy	Weight change (in grams)[a] at indicated test time (in hours)[b]								
	25 hours	60	80	110	210	300	400	510	Remarks
MAR-M 247 (RT-21 coated)	+0.01	+0.01	+0.01	+0.01	-0.01	-0.01	-0.01	-0.01	No coating degradation
MAR-M 247 (Uncoated)	0	0	0	0	-0.02	-0.01	-0.01	-0.01	Slight oxidation
NASA-TRW-R (Uncoated)	+0.01	0	0	0	-0.02	-0.01	-0.01	-0.01	Slight oxidation

a Weight change is an average of 2 test specimens.

b Test parameters: Jet A fuel; 60 minutes hot; 3 minutes cold; 1500 rpm specimen rotation.

TABLE LIV. TASK III 1200°K (1700°F) HOT-CORROSION TEST RESULTS

Alloy	Weight change (in grams)[a] at indicated test time (in hours)[b]									Remarks
	20	40	60	80	100	160	210	260	310	
MAR-M 247 (Uncoated)	-0.06	-0.13	-0.24	-0.56	-1.09	-2.06	-5.14	-6.63	-9.83	Gross corrosion
MAR-M 247 (RT-21 coated)	0	0	0	0	0	0	+0.01	0	+0.01	Slight coating degradation
MAR-M 200+Hf (RT-21 coated)	0	0	0	0	0	+0.01	+0.01	0	-0.18	Coating degradation
NASA-TRW-R (RT-21 coated)	+0.01	+0.01	0	+0.01	+0.01	+0.01	+0.01	-0.05	-0.19	Coating degradation

a Weight change is an average of 2 test specimens

b Test parameters: Jet A fuel; 5 ppm synthetic sea salt (ASTM D1141-52) added to combustion products; 60 minutes hot; 3 minutes cold; 1500 rpm specimen rotation.

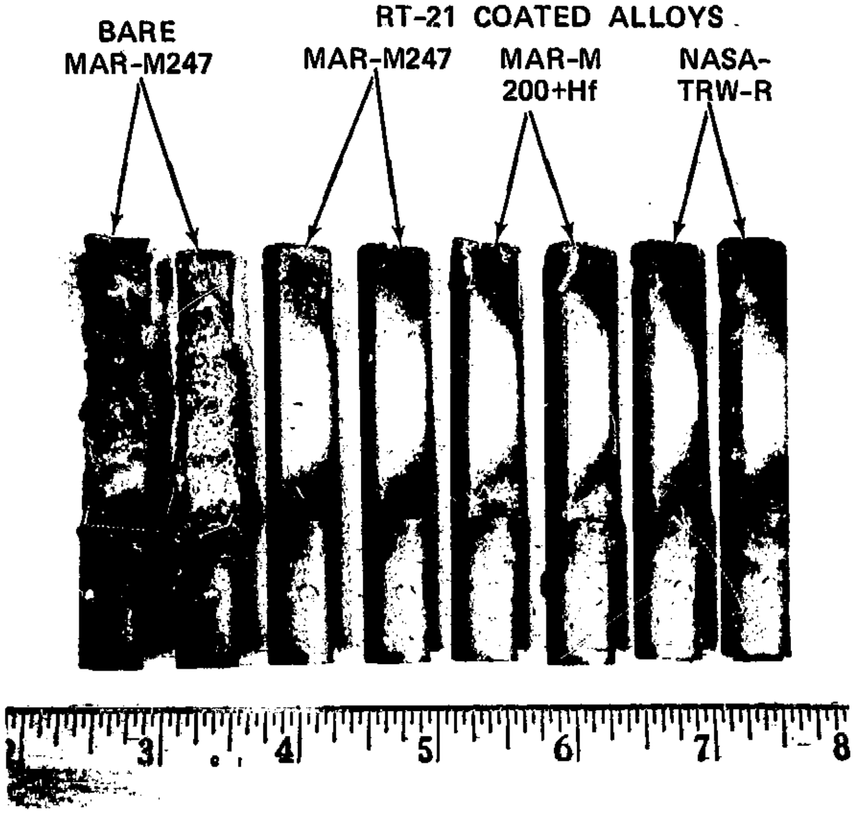


Figure 46. Task III, Hot-Corrosion Specimens after 310-Hours Exposure at 1200°K (1700°F) to 5 ppm Synthetic Sea Salt Added to the Combustion Products of Jet-A Fuel

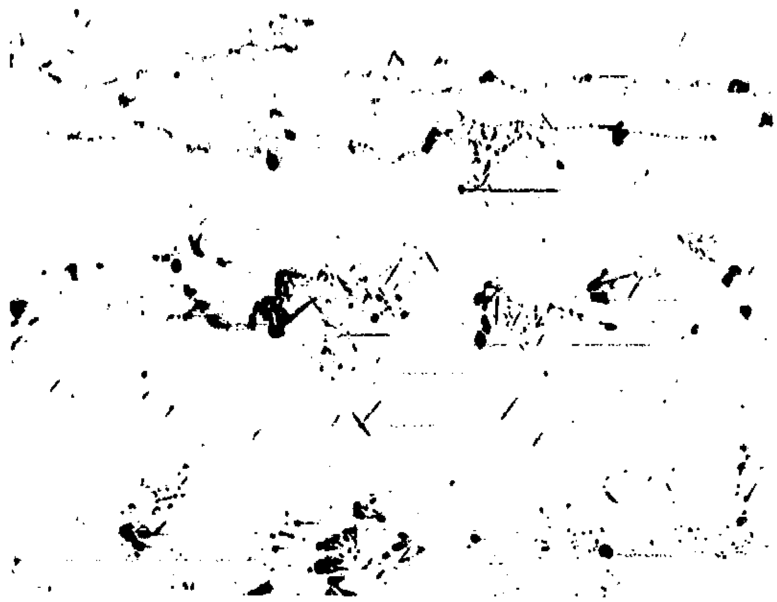
TABLE LV. BASIC STRESS-RUPTURE TEST HISTORY

Specimen number	Test temperature, °K (°F)	Stress, MPa (ksi)	Rupture time, hours
148-6	1033 (1400)	668 (97)	1259.9
148-1	1144 (1600)	317 (46)	1270.0
159-11	1255 (1800)	131 (19)	1678.3

Initial examination by AiResearch established that an acicular phase formed during stress-rupture testing at 1255°K (1800°F) as shown in Figure 47. The section examined was near the fracture in the gauge length of test specimen 159-11. Examination of another section in the thread area of the test specimen showed the same acicular structure, suggesting that thermal exposure rather than stress, was the primary driving force in the formation of this acicular phase. Stressed exposure of specimen 148-1 at 1144°K (1600°F) did not produce the acicular structure as indicated by Figure 48.

Figures 49 and 50 illustrate some of the results of the extensive metallographic work performed by Micro-Met Laboratories. These results confirmed the acicular phase formed at 1255°K (1800°F), and identified it as the M_6C carbide phase. This evaluation included a second 1255°K (1800°F) stress-rupture specimen (148-7, 646.2-hours rupture time) from a different mold but of the same heat as specimen 159-1. Both bars were further exposed to a condition of 1283°K (1850°F) such that the total combined exposure time at 1255°K (1800°F) and 1283°K (1850°F) was approximately 1600 hours.

The general structure and the morphology of the acicular phase is very similar in both 1255°K (1800°F) specimens, as shown in Figure 49. In contrast, Figure 50 shows the structure of



(MAG.: 100X)

(MAG.: 500X)

Figure 47. Microstructures of DS MAR-M 247 Stress-Rupture Specimen No. 159-11 Tested at 1255°K/131 MPa (1800°F/19 ksi) for 1678.3 Hours. Note Needles of Acicular Phase

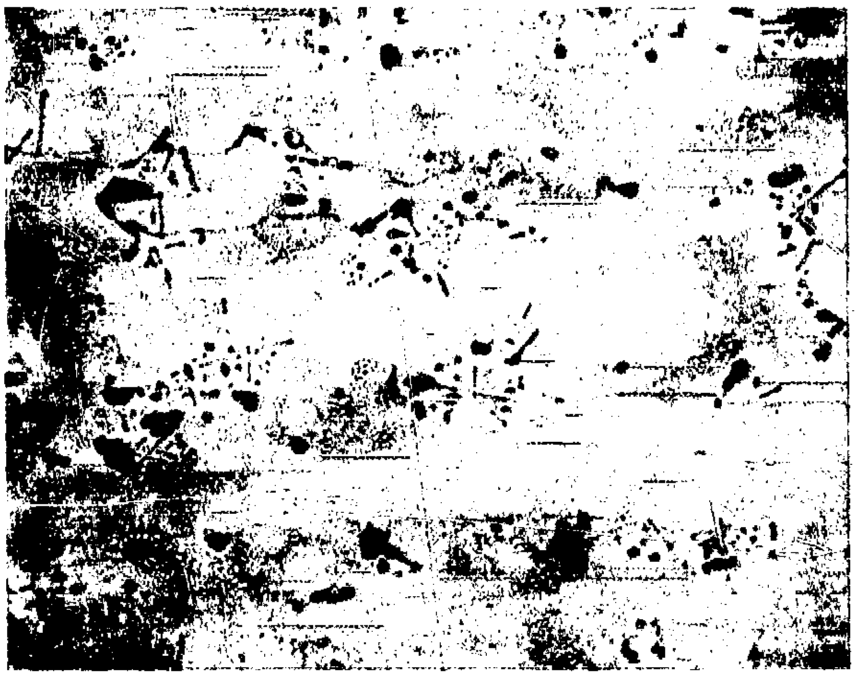


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Figure 48. Microstructure of DS MAR-M 247 Stress-Rupture Test Specimen No. 148-1 Tested at 1144°K/317 MPa (1600°F/46 ksi) for 1270 Hours. The Acicular Phase Formed at 1255°K (1800°F) is Absent

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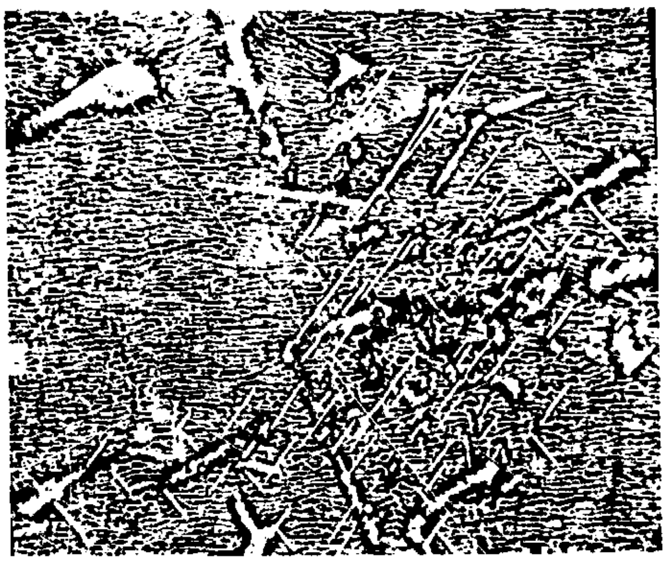

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Figure 49. Microstructures of DS MAR-M 247 Stress-Rupture Test Specimen Nos. 159-11 [Tested at 1255°K/131 MPa (1800°F/19 ksi) for 1678.3 Hours] and 148-7 [Tested at 1255°K/151.7 MPa (1800°F/22ksi) for 646.2 Hours]. Specimens were Subsequently Exposed at 1283°K (1850°F) for a Total Combined Time of Approximately 1600 Hours. The Acicular Phase is Evident in Both Specimens. Metallography by Micro-Met Laboratories, Inc.

(MAG.: 1000X)

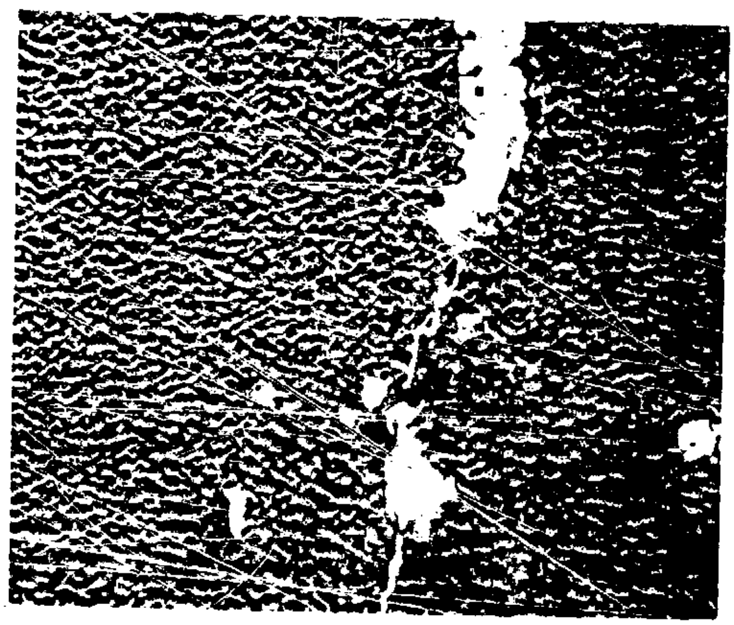

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Figure 50. Microstructures of DS MAR-M 247 Stress-Rupture Test Specimen No. 148-1. Specimen was Tested at 1144°K 317 MPa (1600°F/46 ksi) for 1270 Hours. No Acicular Phase was Present. Metallography by Micro-Met Laboratories, Inc.

stress-rupture specimen 148-1 tested at 1144°K (1600°F) for 1270 hours. No acicular phase was evident at either magnification (1000X or 3000X).

Probable identification of the occurance of the acicular phase after stress and temperature exposure of 1255°K (1800°F) was accomplished by extraction and identification of second phases from the matrix of a new DS MAR-M 247 blade (158-14) exposed to 1283°K (1850°F) for 1000 hours. The higher temperature was selected to accelerate the kinetics of the plate formation. The upper photo on Figure 51 depicts the acicular phase formed. The lower photo depicts the second phases in this blade after chemical extraction from the matrix. The platelets present in the extracted residue were positively identified as M_6C. In fully heat-treated MAR-M 247, M_6C forms with time at about 1255°K (1800°F) from the script carbides originally present in the as-cast and heat-treated structure. This structural change has no adverse effect on either strength or ductility, as evidenced by the 1255°K (1800°F) long-time stress-rupture tests on MAR-M 247. These results were completely consistent with Larson-Miller parametric life predictions made from shorter time test data.

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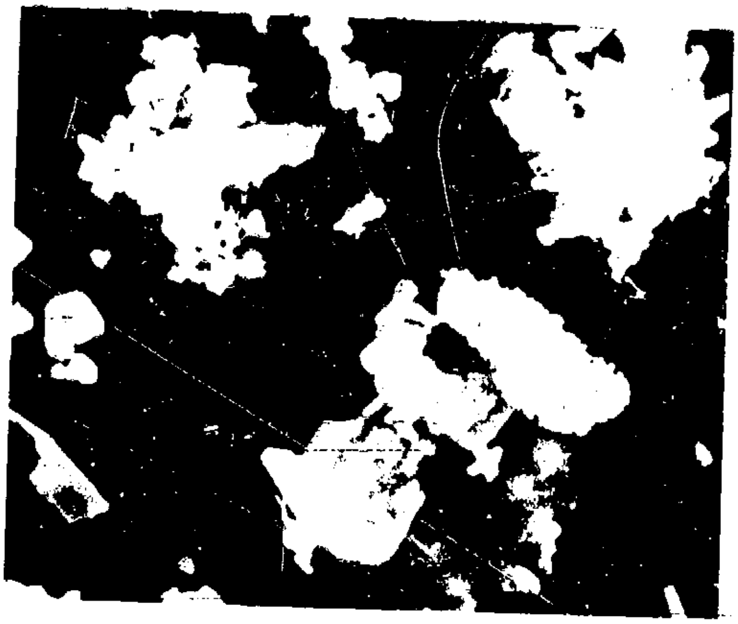

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Figure 51. Acicular Phase Formed in DS MAR-M 247 Specimen 159-14 After Exposure to 1283°K (1850°F) for 1000 Hours. Upper Photo Shows Acicular Phase in Microstructure. The Bottom Photo Shows the Second Phases After Extraction from the Matrix. Metallography by Micro-Met Laboratories, Inc.

TASK IV - BLADE DESIGN

Scope

Task IV included the design activity required for the development of a solid, uncooled, exothermically cast, DS high-pressure turbine blade for the TFE731-3 turbofan engine. This task was performed concurrently with Tasks I, II, and III. Two blade designs were established in Task IV--the preliminary (initial) design and the final design.

The preliminary design was established early in the program to provide a blade casting design suitable for use in the development of the exothermic DS casting process and associated material evaluations of Tasks I, II, and III. This design was based on preliminary MAR-M 247 data collected early in the program.

Actual material properties and other data obtained from preliminary design blades cast in each of the four alloys during the performance of Tasks I, II, and III were used in establishing the final blade design. The geometry of this design made it necessary to modify the turbine disk, nozzle, and other turbine components of the TFE731-3 Engine to permit effective integration of the blade into the engine assembly. The redesign of these turbine components was accomplished in Task IV.

Preliminary Design - High-Pressure Turbine (HPT) Blade

Aerodynamic design - preliminary design blade. The preliminary blade design using only MAR-M-247 material properties was established for design and casting purposes while a comprehensive effort was in progress on the final airfoil design. Details of the aerodynamic design of the selected preliminary blade airfoil are shown in Tables LVI through LVIII and Figures 52 through 59.

1. Vector diagram. The flow path used for the preliminary blade design was the same as the existing TFE731 Engine with the vector diagram (see Figure 52 for nomenclature) defined as follows:

(a) The radial distribution of the stator exit angle, α_1, and the rotor relative exit angle, β_2, are shown in Tables LVI and LVII and in Figure 52. In this blade, α_1 increases while β_2 decreases from hub-to-tip. This results in a higher hub reaction but lower twist, which is favorable from the viewpoint of stress and vibration. (Twist is defined as the difference in stagger angle between the tip and the hub).

(b) The vector diagram yields essentially the same pressure ratio and corrected mass flow as that of the standard engine. The distribution of the relative critical Mach numbers, flow angles at the rotor inlet and exit, and reaction are shown in Figure 54.

2. Blade geometry. This blade design is generated from two design sections, one at the hub [R = 10.77 cm (4.24 inches)] and one at the tip [R = 14.16 cm (5.57 inches)], with a linear relationship in between. The geometry data defining the blade sections is presented in Table LVIII.

TABLE LVI. STATOR EXIT FLOW ANGLE DISTRIBUTION - TASK IV PRELIMINARY DESIGN BLADE

Radius, R - cm (in.)	Stator exit flow angle, α_1, deg.
10.985 (4.325)	62.234
11.270 (4.437)	63.175
11.557 (4.550)	64.124
11.849 (4.665)	65.084
12.141 (4.780)	66.057
12.441 (4.898)	68.060
13.063 (5.143)	69.097
13.385 (5.270)	70.167
13.721 (5.402)	71.276
14.072 (5.540)	72.434

TABLE LVII. ROTOR EXIT RELATIVE FLOW ANGLE DISTRIBUTION - TASK IV PRELIMINARY DESIGN BLADE.

Radius, R cm (in.)	Rotor exit relative flow angle, β_2, deg.
10.775 (4.242)	-59.357
11.214 (4.415)	-58.757
11.613 (4.572)	-58.242
11.984 (4.718)	-57.824
12.334 (4.856)	-57.411
12.667 (4.987)	-57.003
12.984 (5.112)	-56.609
13.292 (5.233)	-56.211
13.589 (5.350)	-55.788
13.876 (5.463)	-55.377
14.155 (5.573)	-54.957

TABLE LVIII. PRELIMINARY DESIGN DS HIGH-PRESSURE TURBINE BLADE GEOMETRY AND AERODYNAMIC DATA

Item	Symbol	Units	Section	
			Hub	Tip
Radius	R	cm (in.)	10.775 (4.242)	14.755 (5.573)
Leading-Edge Radius	r_{LE}	cm (in.)	0.114 (0.045)	0.051 (0.020)
Trailing-Edge Radius	r_{TE}	cm (in.)	0.004 (0.018)	0.019 (0.008)
Leading-Edge Half-Wedge Angle	γ_{LE}	deg	12.0	10.0
Trailing-Edge Half-Wedge Angle	γ_{TE}	deg	7.0	6.0
Throat Angle		deg	-46.169	-48.059
Throat Width	W	cm (in.)	0.588 (0.231)	0.835 (0.329)
Axial Camber Chord Length	C_x	cm (in.)	2.155 (0.949)	1.626 (0.640)
Axial Blade Chord Length	C_x'	cm (in.)	2.439 (0.960)	1.641 (0.646)
Inlet Camber Angle	β_1	deg	32.0	36.0
Exit Camber Angle	β_2	deg	-54.169	-56.059
Maximum Thickness	T_{max}	cm (in.)	0.483 (0.190)	0.279 (0.110)
Suction Surface Turning Downstream of the Throat	δ	deg	15.0	14.0
Area	A	cm^2 ($in.^2$)	0.94868 (0.147047)	0.37873 (0.05870)
Spacing	S	cm (in.)	1.1672 (0.45954)	1.5334 (0.6037)
Trailing-Edge Blockage	B	%	13.0	5.2

WHERE: STATION 1 IS STATOR EXIT PLANE

STATION 2 IS ROTOR EXIT PLANE

V = ABSOLUTE VELOCITY

W = RELATIVE VELOCITY

U = BLADE VELOCITY

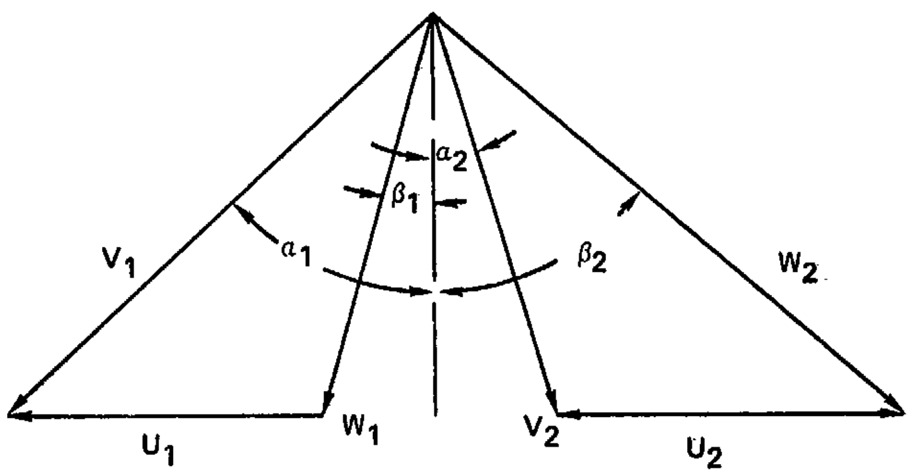


Figure 52. Vector Diagram Nomenclature

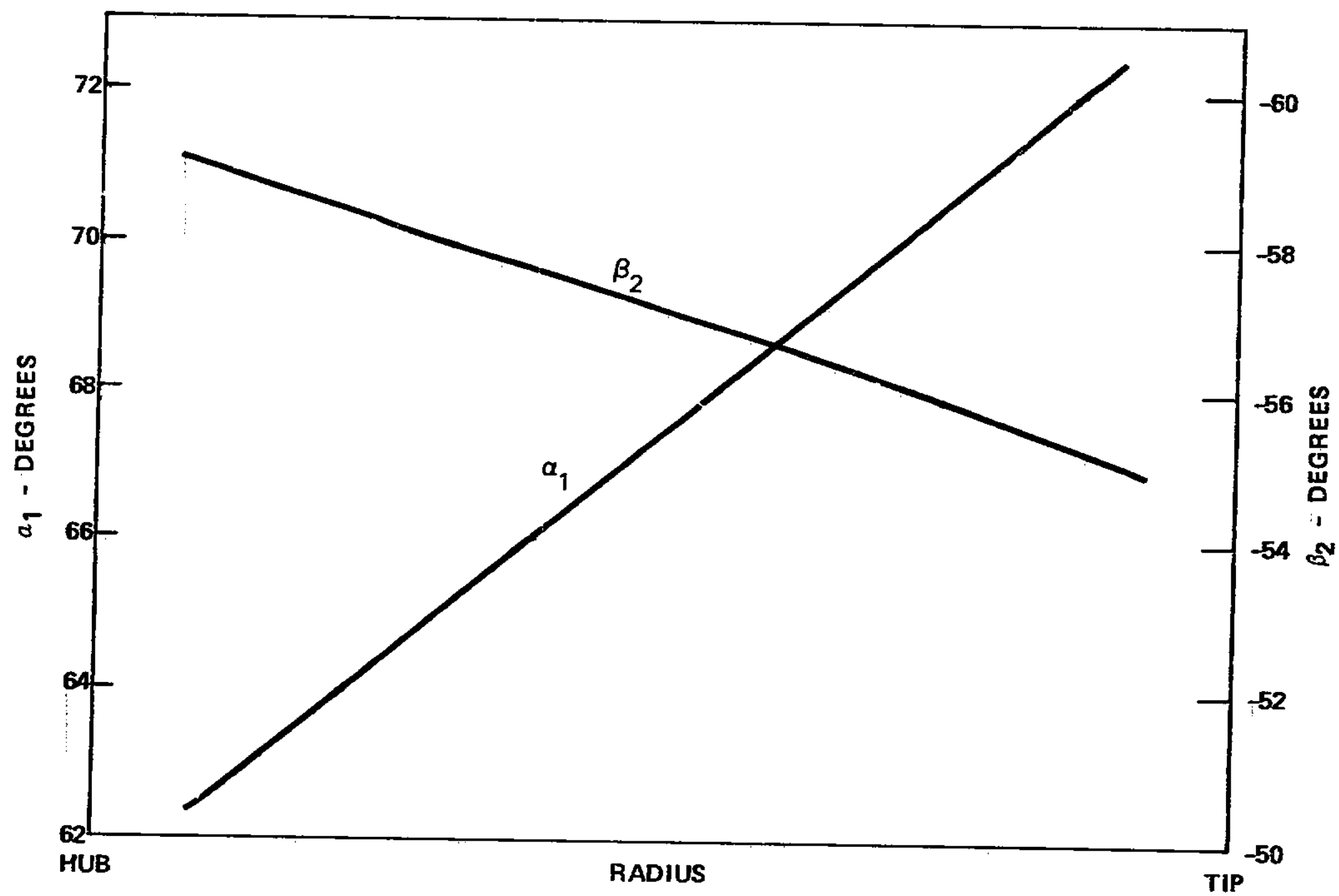


Figure 53. Radial Distributions of Stator (α_1) and Rotor Exit Angles (β_2)

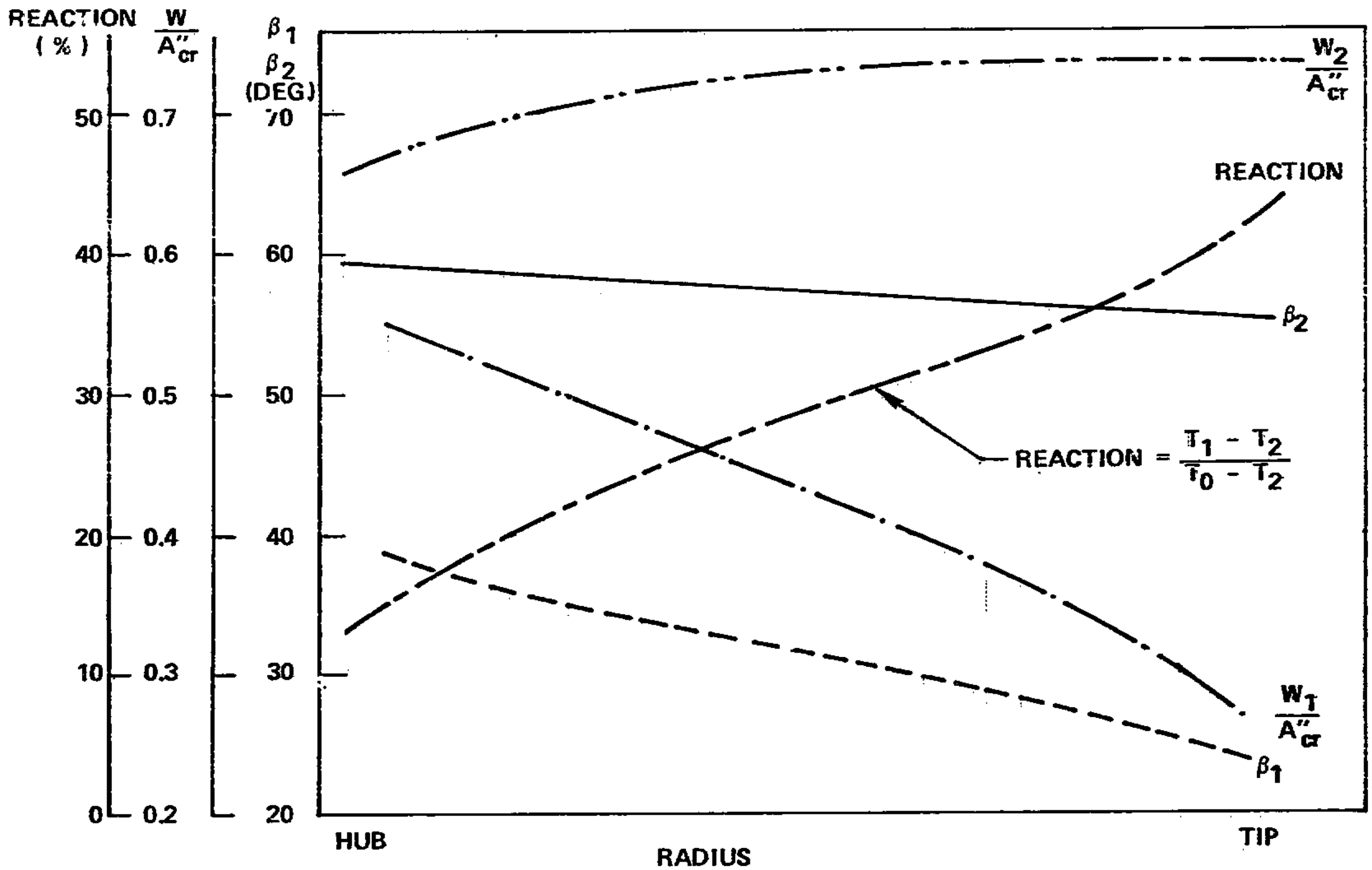


Figure 54. Vector Diagram Data for the Rotor

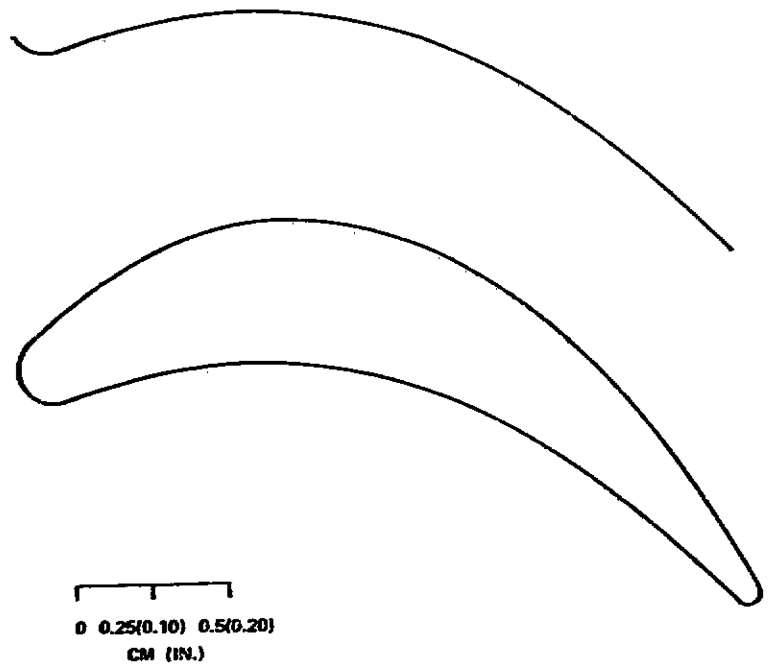


Figure 55. Rotor Hub Section
[R = 10.77 cm (4.24 in)]
Cylindrical Cut

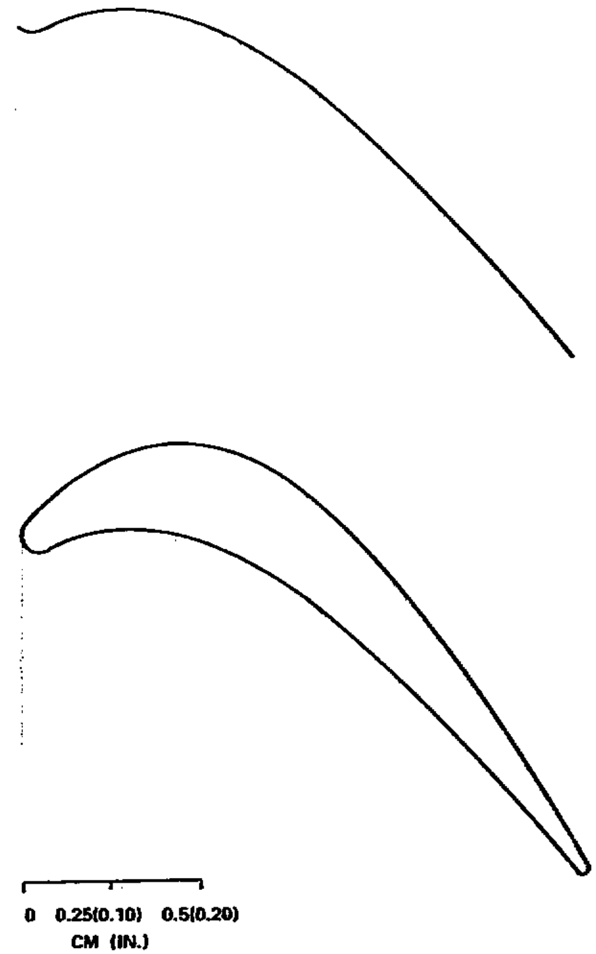


Figure 56. Rotor Tip Section
[R = 14.16 cm (5.57 in)]
Cylindrical Cut

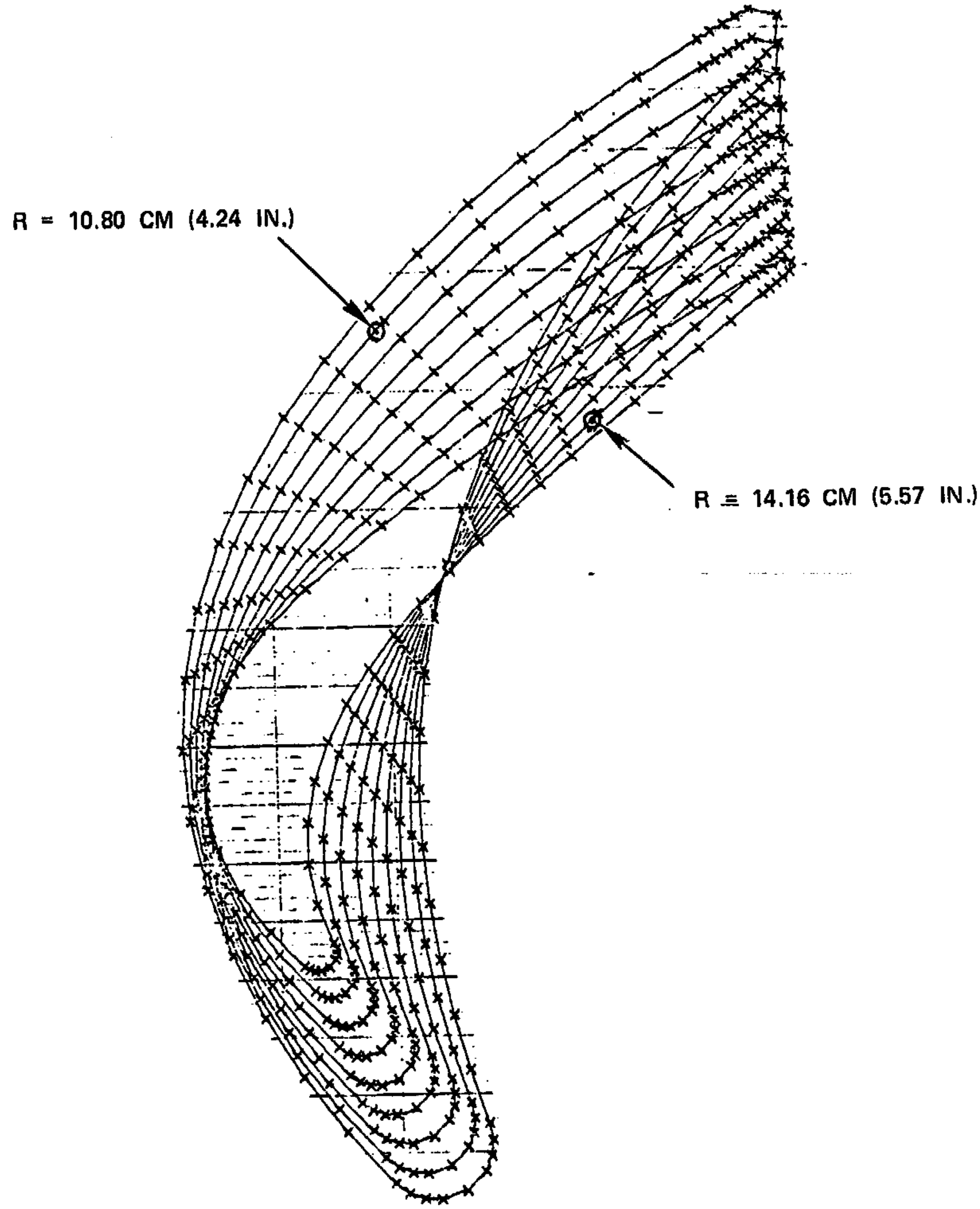


Figure 57. Rotor Stack at CG, Plane Sections

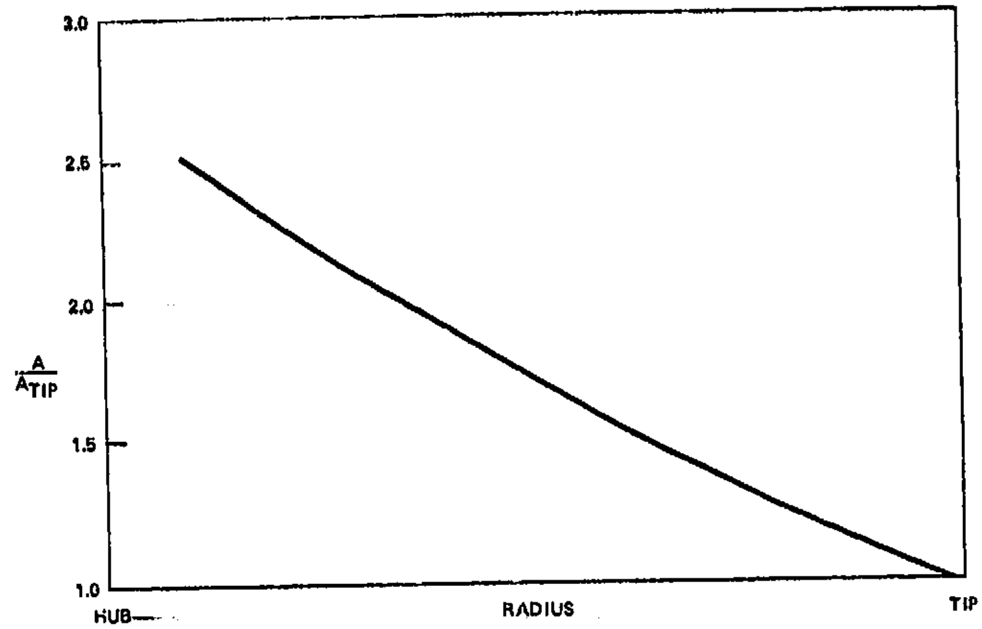


Figure 58. Area Distribution of the Rotor Blade

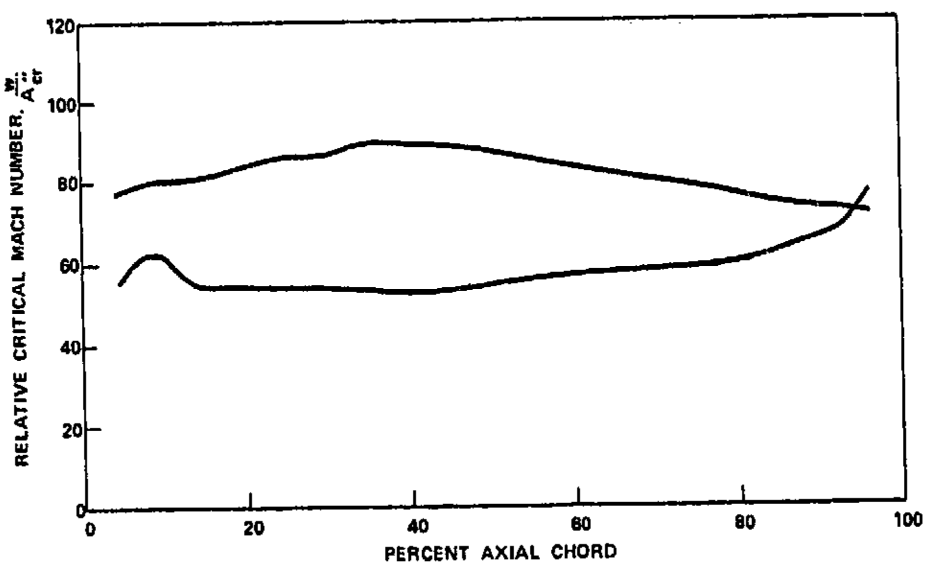


Figure 59. Loading of the Rotor Hub

The blade geometry of the hub and tip is shown in Figure 55 and 56, respectively. Figure 57 shows the stack with the blade center of gravity as the stacking axis illustrating the low-twist (14 degrees, 17 minutes) feature of this design.

A high camber with a large trailing-edge wedge angle helps avoid blade vibration problems, especially in the tip region. The preliminary design blade had a camber of 92 degrees, and a half-wedge angle of 6 degrees at the tip. The tip section of the preliminary design blade was relatively thick [T_{max}= 0.28 cm (0.11 inch)], yielding an area ratio of 2.5:1, hub-to-tip. The area distribution is shown in Figure 58.

3. Blade loading. The calculated loading of the two design sections of the preliminary design blade are shown in Figures 59 and 60.

The hub section has a degree of reaction of 13.2 percent. At this value it is inevitable that some deceleration will occur in the rear portion of the suction surface, beginning at an axial chord position of 37.5 percent. The corresponding velocity ratio for this deceleration process is 1.23, and the pressure ratio is 1.19. For the tip section, where the reaction is relatively high, it is possible to design a suction surface with continuous acceleration.

None of the sections exhibit a supersonic region. The maximum values of the surface critical Mach number is 0.91 for the hub and 0.81 for the tip. Therefore, the high trailing-edge wedge angle will not cause the loading to deteriorate, as shown in Figures 59 and 60.

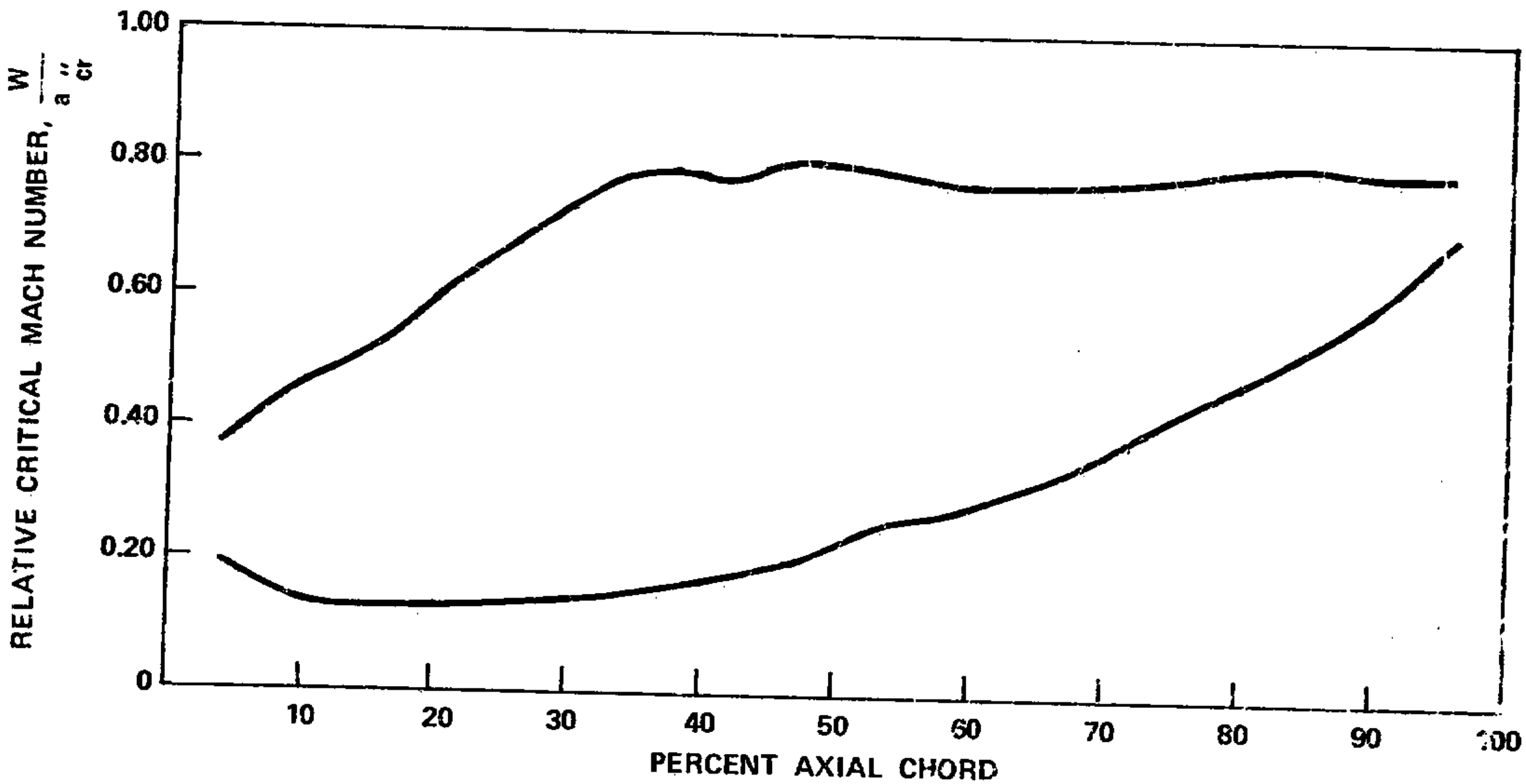


Figure 60. Loading of the Rotor Tip

The trailing-edge blockage is 13 percent at the hub and 5.2 percent at the tip. The hub values [12.2 percent at R = 10.77 cm (4.24 inch)] is comparable to the original design while the tip value (8.5 percent) is lower than the original.

Stress and thermal analyses. With the area distribution of the blade as defined in Figure 58, the average centrifugal stress was calculated at the take-off condition for MAR-M 247. These stresses are shown in Figure 61. Using the calculated stresses and average metal temperature of the uncoated blade as shown in Figure 62, the stress-rupture life of the blade airfoil was determined based on preliminary DS MAR-M 247 data as shown in Figure 63. The calculated stress-rupture life is listed in Table LIX.

TABLE LIX. CALCULATED STRESS-RUPTURE LIFE SHOWING CRITICAL SECTION AT TAKEOFF CONDITIONS

Radius, cm (inches)	Calculated Stress, MPa (ksi)	Temperature, °K (°F)	Normalized Stress-Rupture Life
11.18 (4.40)	211.7 (30.7)	1193 (1688)	1.37
11.43 (4.50)	199.9 (29.0)	1208 (1714)	1.03
11.68 (4.60)[a]	189.6 (27.5)	1213 (1724)	1.00
11.94 (4.70)	175.8 (25.5)	1215 (1727)	1.64
12.19 (4.80)	162.0 (23.5)	1215 (1727)	2.74

a Critical Section

The calculated life for the critical section at take-off conditions was considered acceptable for the preliminary design blade with reference to operation in the expected environment of the planned 150-hour cyclic engine test.

No effort was made in the preliminary design activity to define a blade shank or platform.

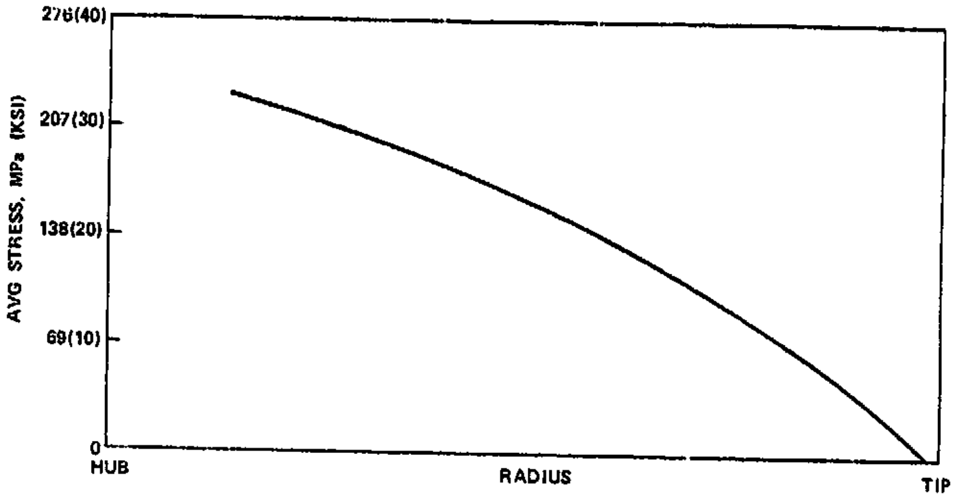


Figure 61. Average Centrifugal Stress -- Preliminary MATE HPT Blade Design

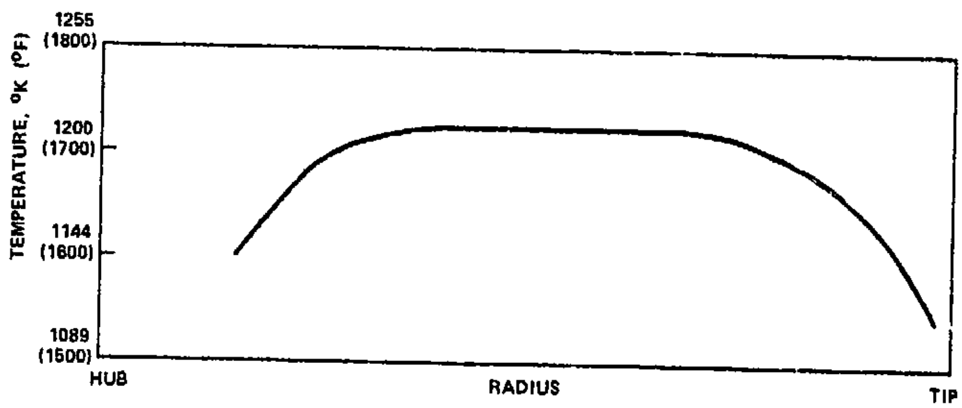


Figure 62. Metal Temperature -- Preliminary MATE HPT Blade Design

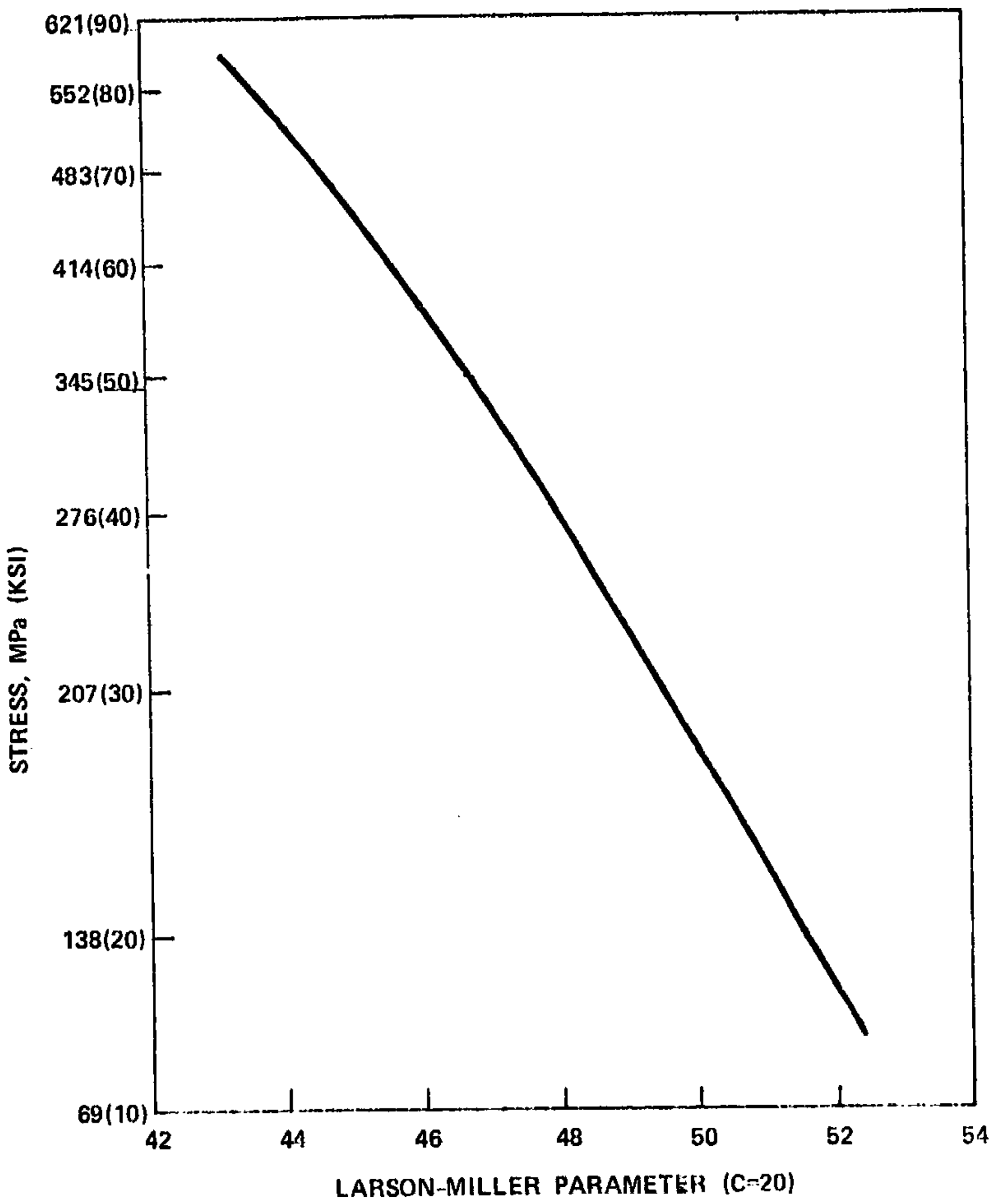


Figure 63. Preliminary Stress-Rupture Data, Directionally-Solidified MAR-M 247

Final Design - High-Pressure Turbine Blade

The final design of the uncooled exothermically cast directionally-solidified high-pressure turbine blade for the TFE731-3 utilized the material properties of DS MAR-M 247 as determined in Task III. This material was selected based on the test results obtained in this project, plus excellent potential for future high-temperature applications in the gas turbine industry. As in all turbine blade designs, the final design was the result of many interactions and tradeoffs between aerodynamics, metal temperatures, stresses, vibrations and other considerations. Only the final results of these analyses are presented herein.

Aerodynamic design - final design blade. Details of the aerodynamics of the final design blade are presented in Table LX and Figures 64 through 77.

1. Vector Diagram. A different vector diagram is required for the final design blade even though the flow path is the same as the original TFE731 high-pressure turbine.

Figures 64 through 67 present characteristic data of the mixed-out vector diagrams. Figure 64 shows the absolute critical Mach numbers and the flow angles at the stator inlet and exit. Figure 65 shows the relative critical Mach numbers and the relative flow angles at the rotor inlet and exit, while Figure 66 shows the rotor reaction. The low twist diagram yields a high hub reaction (14.3 percent), while the tip reaction is slightly lower than previous designs. This reaction results in a higher total relative temperature, T", in the hub region. T", non-dimensionalized by the absolute total temperature at the turbine inlet versus the radius, is shown in Figure 67.

TABLE LX. FINAL DESIGN TFE731-3 HIGH-PRESSURE TURBINE BLADE GEOMETRY AND AERODYNAMIC DATA

Item	Symbol	Units	Section Hub	Section mean	Section Tip
Radius	R	cm (in.)	10.774 (4.242)	12.375 (4.872)	14.155 (5.573)
Leading-Edge Radius	r_{LE}	cm (in.)	0.114 (0.045)	0.076 (0.030)	0.051 (0.020)
Trailing-Edge Radius	r_{TE}	cm (in.)	0.044 (0.018)	0.032 (0.013)	0.019 (0.008)
Leading-Edge Half-Wedge Angle	γ_{LE}	deg	12.0	11.0	10.0
Trailing-Edge Half-Wedge Angle	γ_{TE}	deg	7.0	6.5	6.0
Throat Angle	β	deg	-49.922	-47.421	-46.490
Throat Width	W	cm (in.)	0.520 (0.205)	0.696 (0.274)	0.862 (0.339)
Axial Camber Chord Length	C_x	cm (in.)	2.409 (0.949)	1.905 (0.750)	1.626 (0.640)
Axial Blade Chord Length	C_x'	cm (in.)	2.443 (0.962)	1.955 (0.770)	1.641 (0.645)
Inlet Camber Angle	β_1	deg	32.0	37.0	45.0
Exit Camber Angle	β_2	deg	-57.922	-55.921	-55.490
Maximum Thickness	t_{max}	cm (in.)	0.483 (0.190)	0.305 (0.120)	0.165 (0.065)
Suction Surface Turning Down-stream of the Throat	δ	deg	15.0	15.0	15.0
Area	A	cm^2 ($in.^2$)	0.9876 (0.1531)	0.5317 (0.0824)	0.3109 (0.0482)
Spacing	S	cm (in.)	1.1672 (0.4595)	1.3405 (0.5278)	1.5335 (0.6037)
Trailing-Edge Blockage	B	%	14.3	8.5	4.4
Inlet Critical Mach Number		W_1/A_{cr}"	0.563	0.456	0.268
Exit Critical Mach Number		W_2/A_{cr}"	0.667	0.735	0.736
Inlet Relative Flow Angle	β_1	deg	39.7	32.6	23.5
Exit Relative Flow Angle	β_2	deg	-61.6	-57.8	-53.1

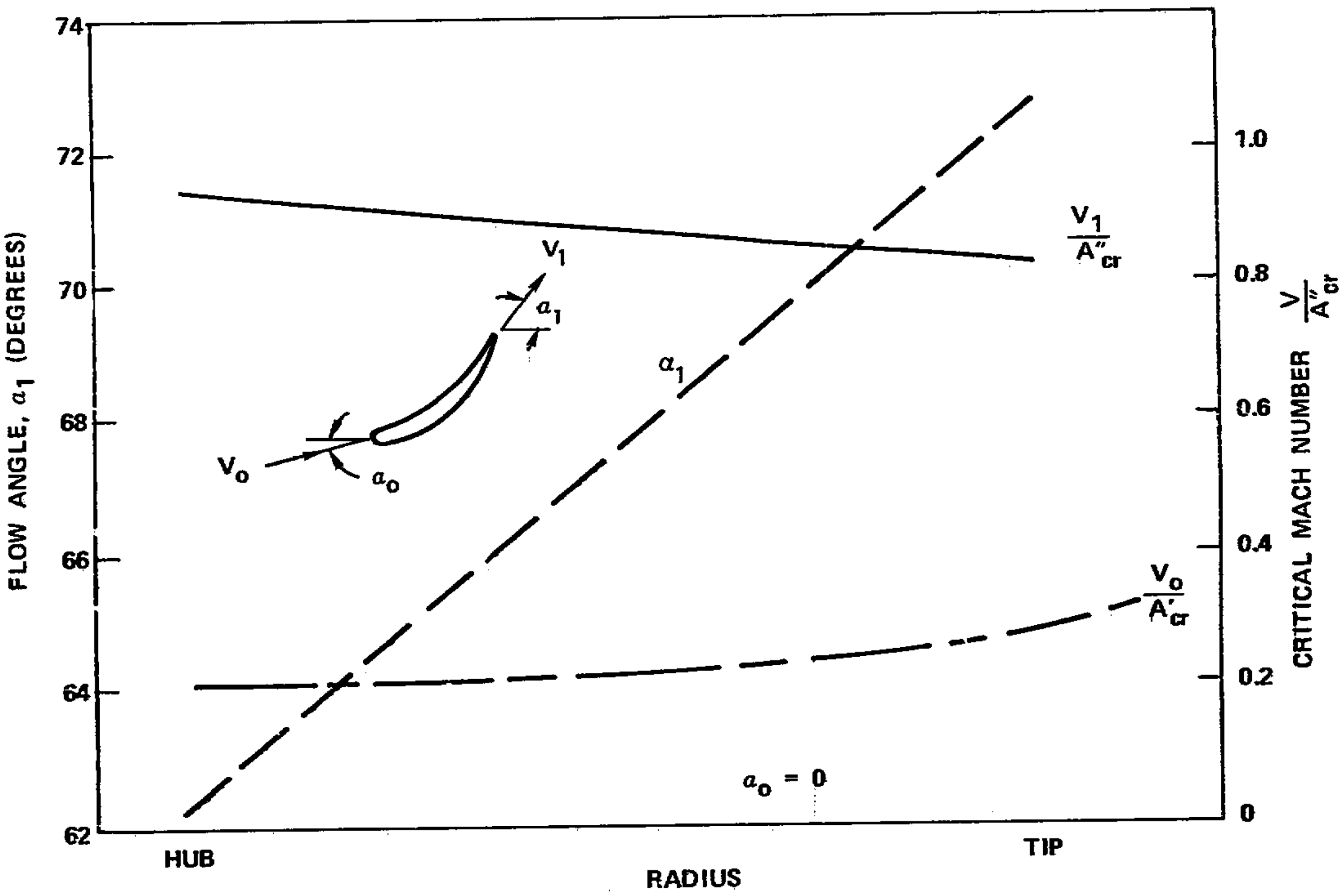


Figure 64. Critical Mach Numbers and Flow Angles Versus Radius for the Stator

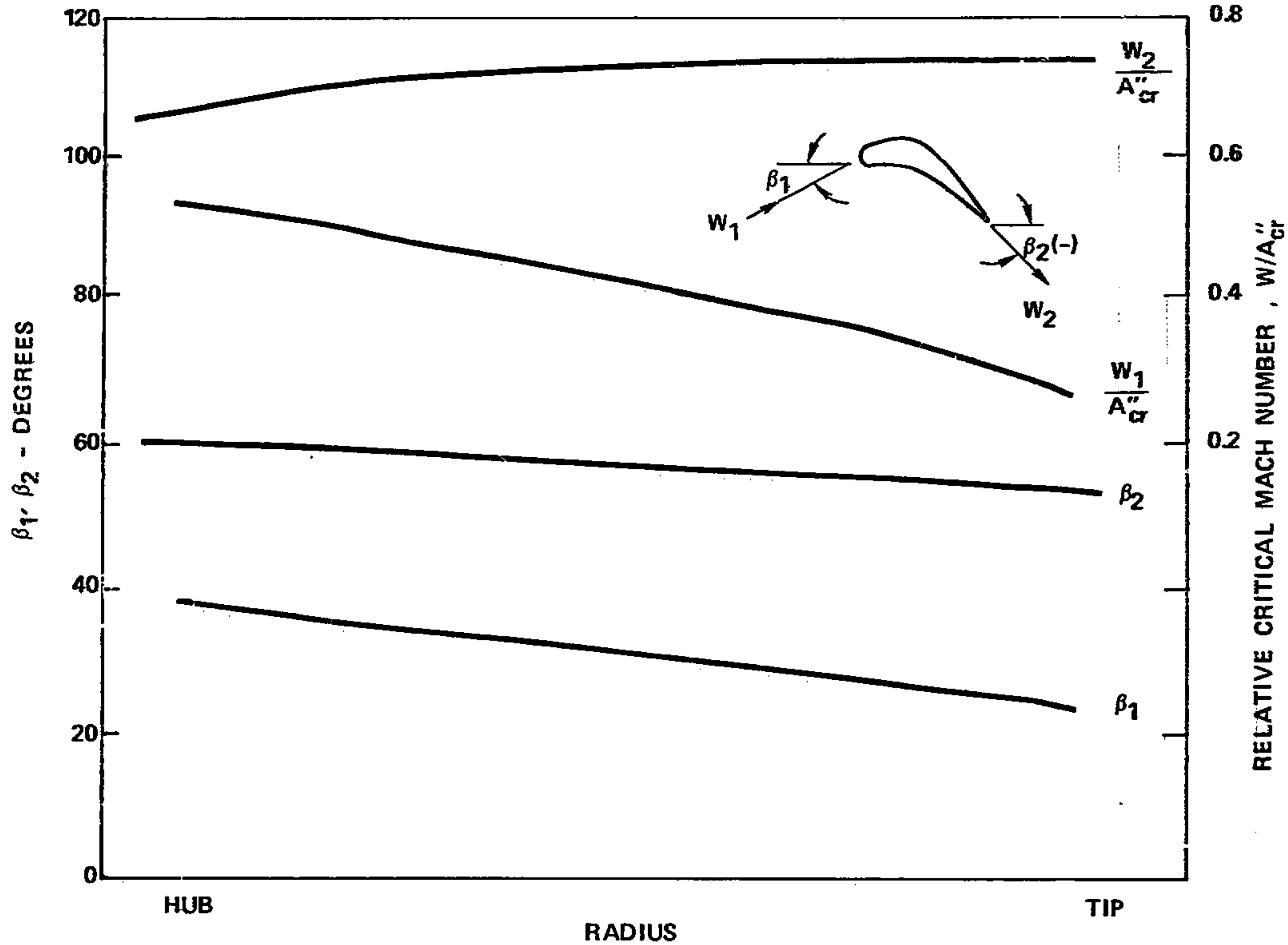


Figure 65. Critical Mach Numbers and Flow Angles Versus Radius for the Rotor

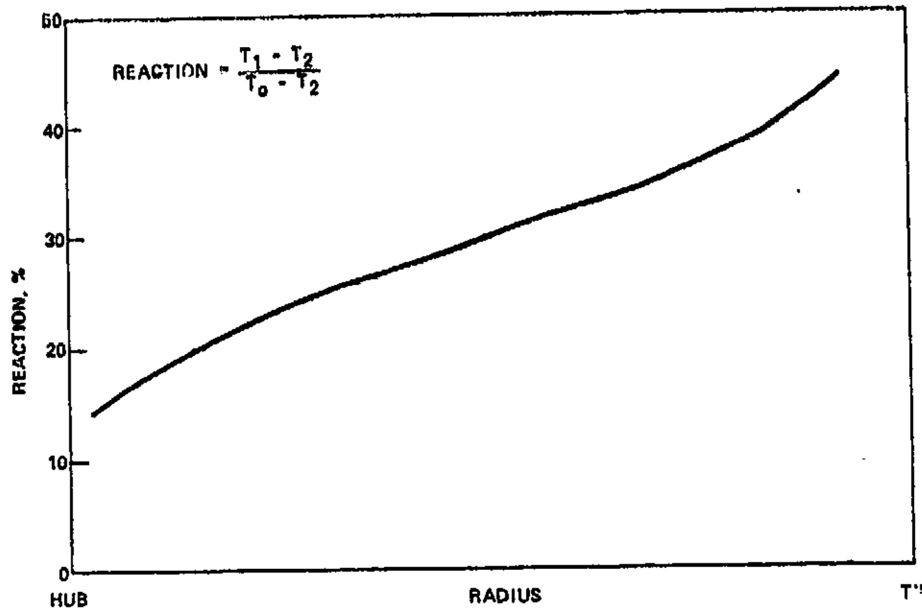


Figure 66. Reaction Versus Radius

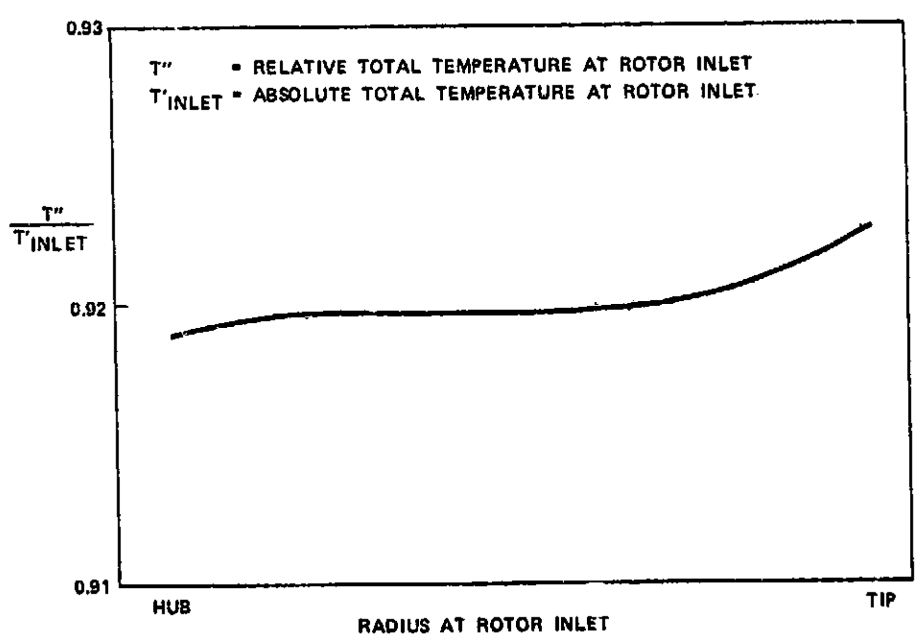


Figure 67. Rotor Relative Total Temperature Nondimensionalized by the Inlet Absolute Total Temperature Versus Radius

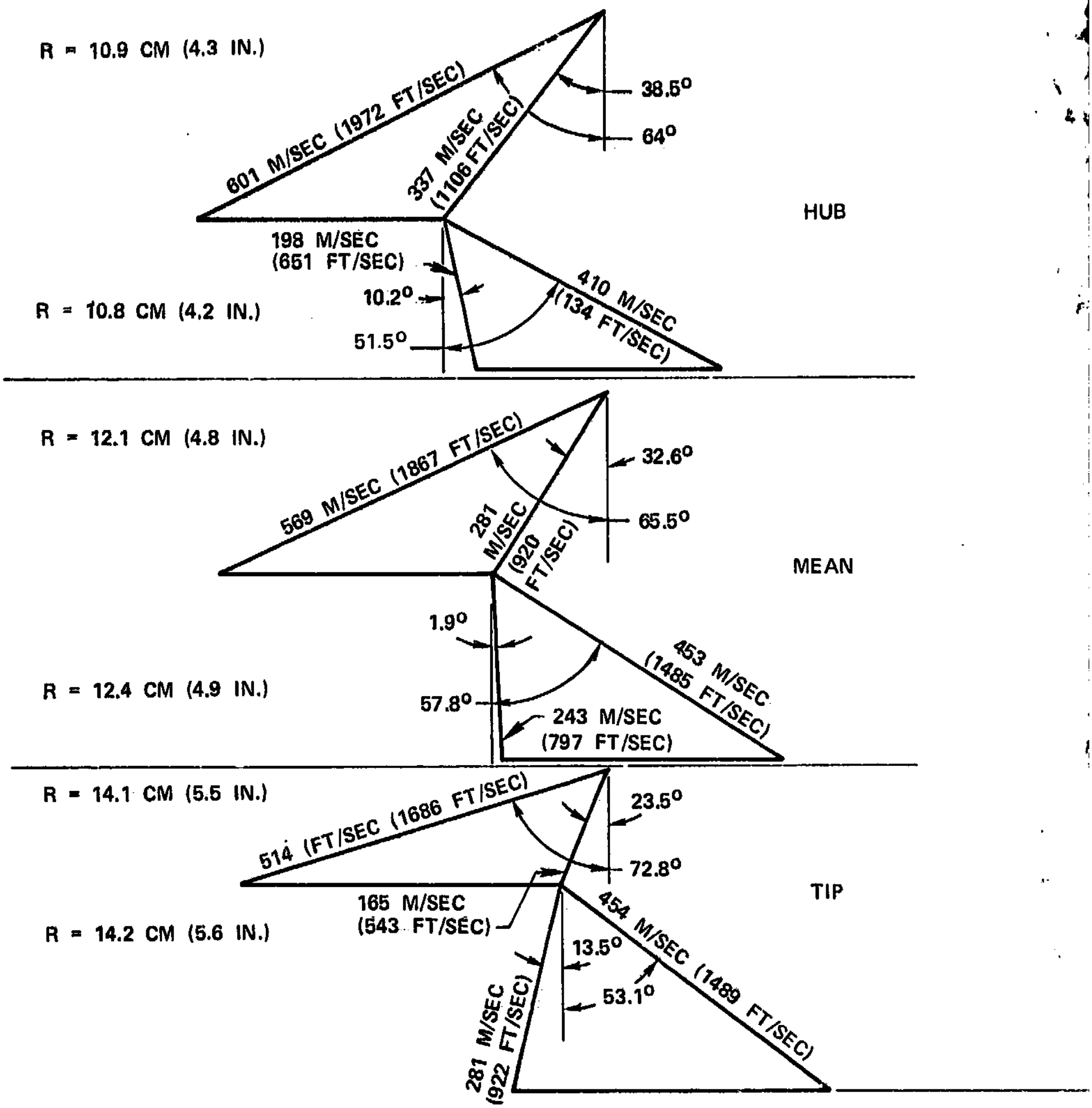


Figure 68. Velocity Triangles of the Final Design

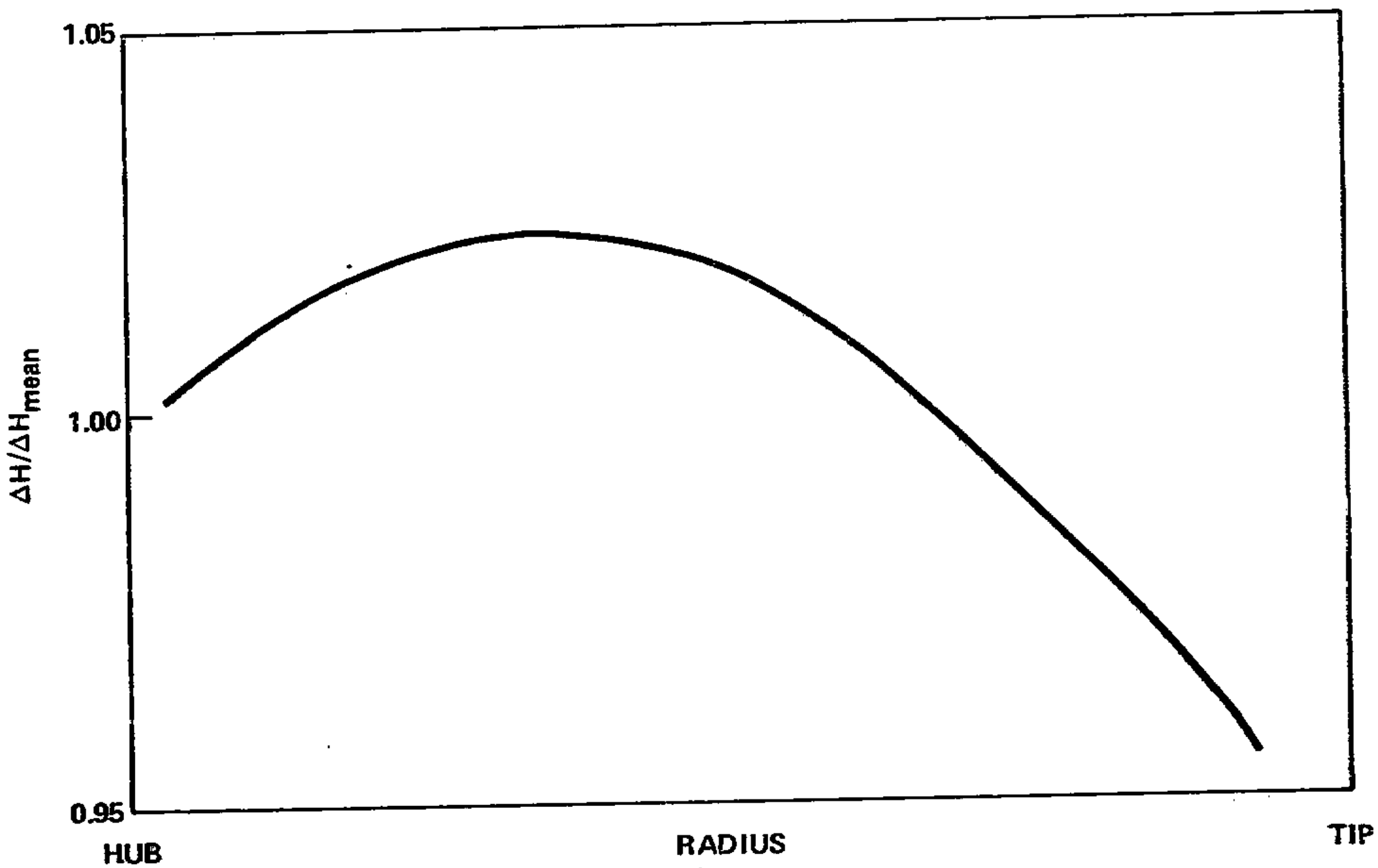


Figure 69. Work Distribution

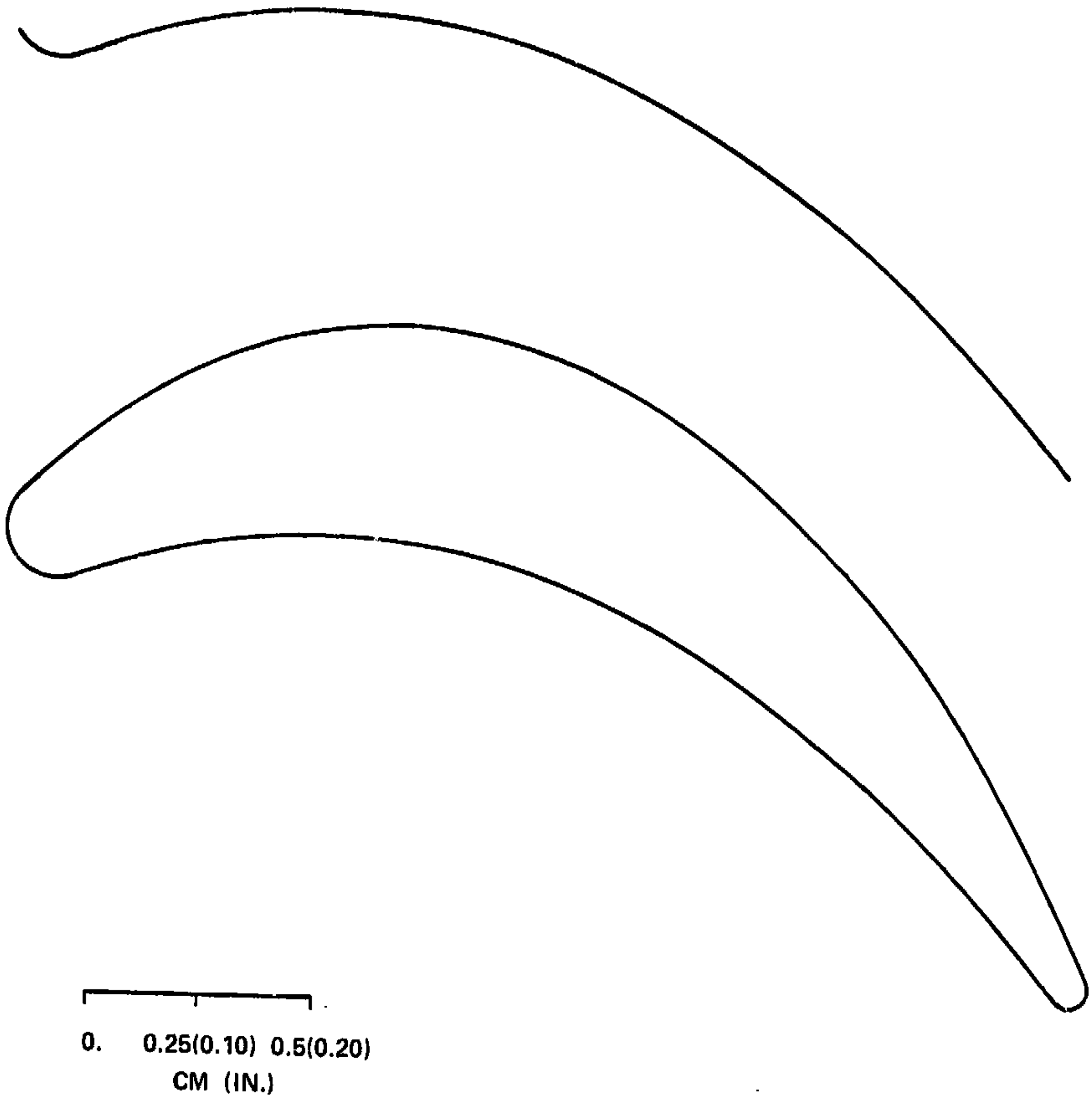


Figure 70. Rotor Hub Section [R = 10.77 cm (4.242 in.)] of the MATE Final Design

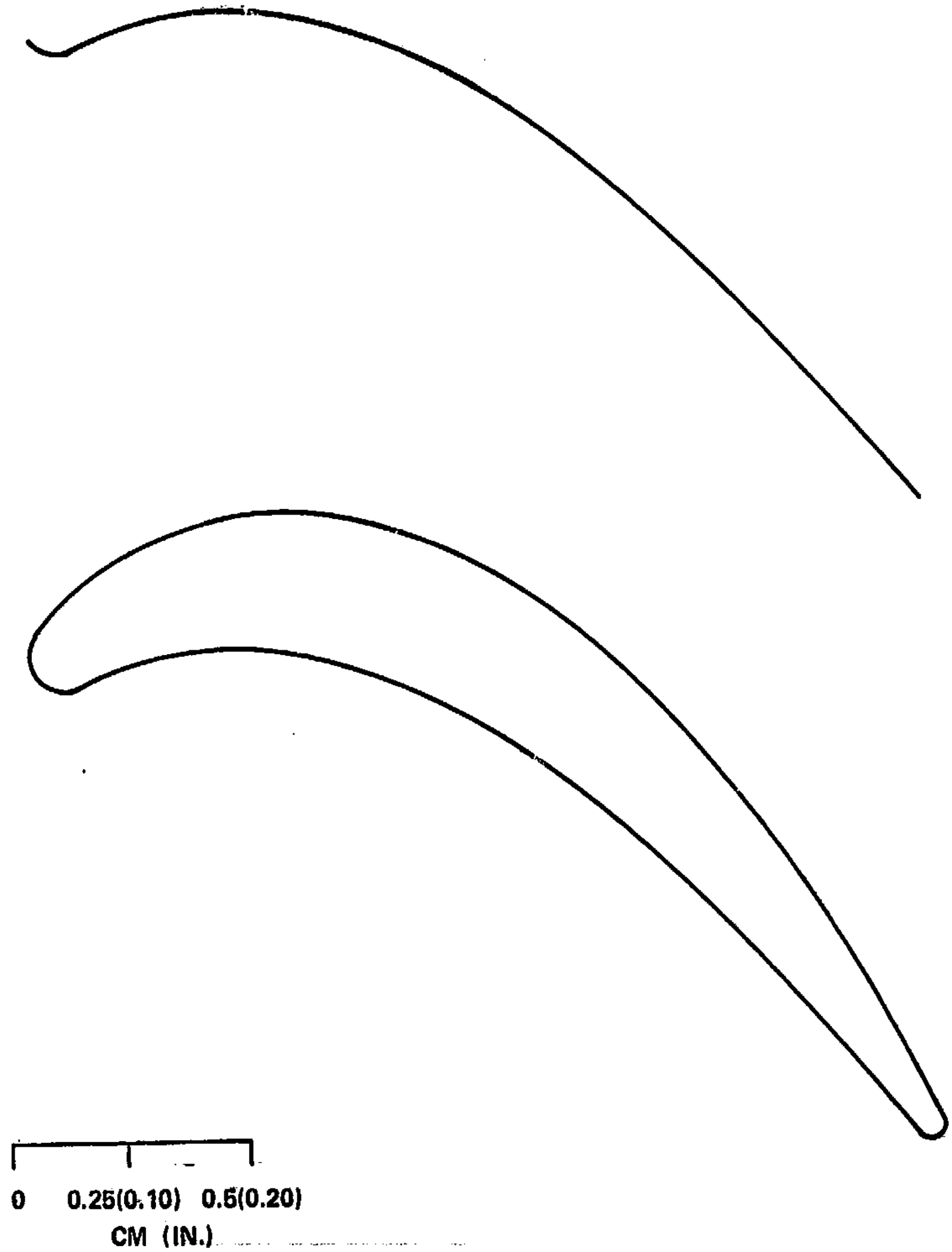


Figure 71. Rotor Mean Section [R = 12.37 cm (4.872 in.)] of the MATE Final Design

C-3

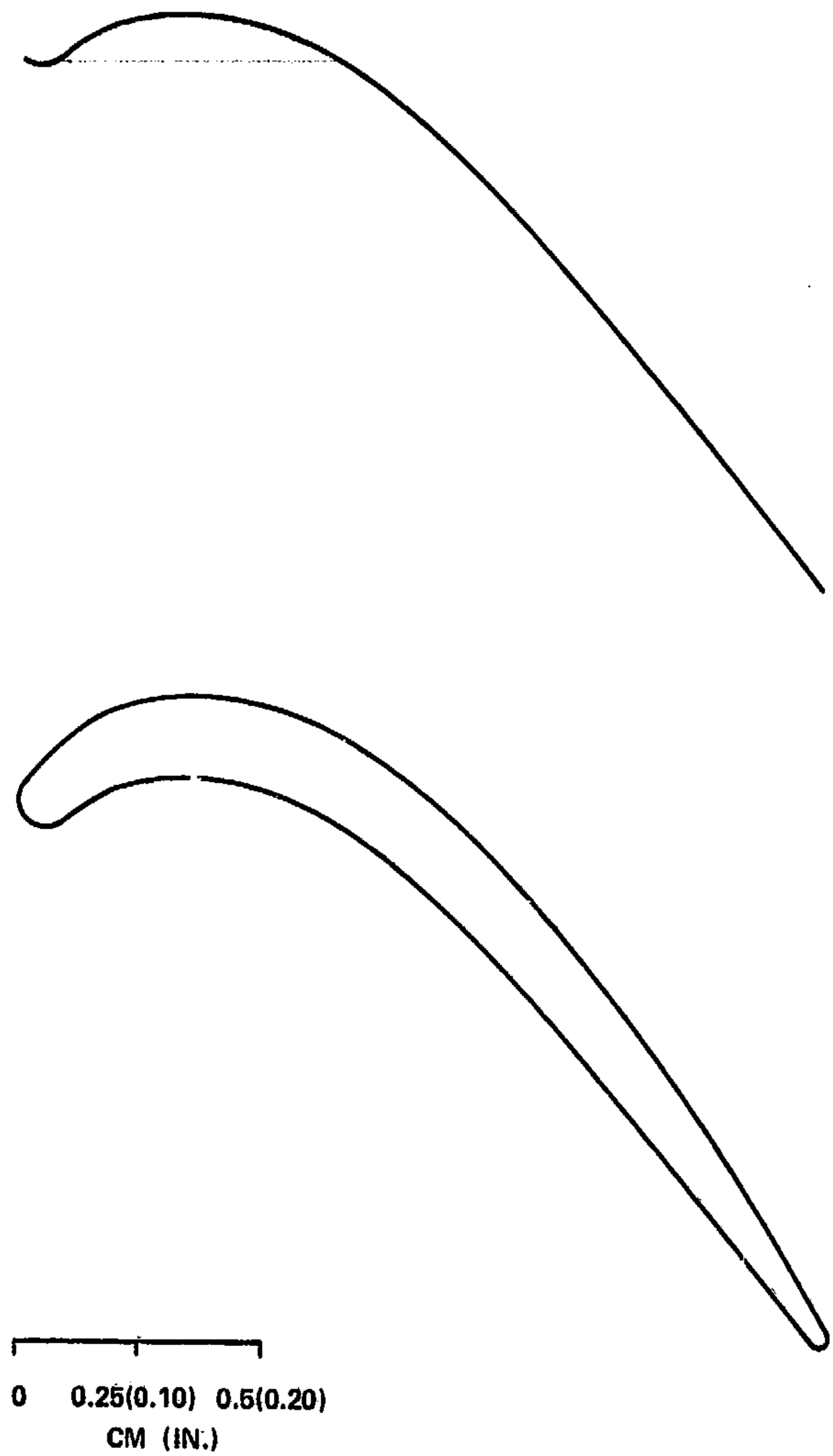


Figure 72. Rotor Tip Section [R = 14.16 cm (5.57 inches)] of the MATE Final Design

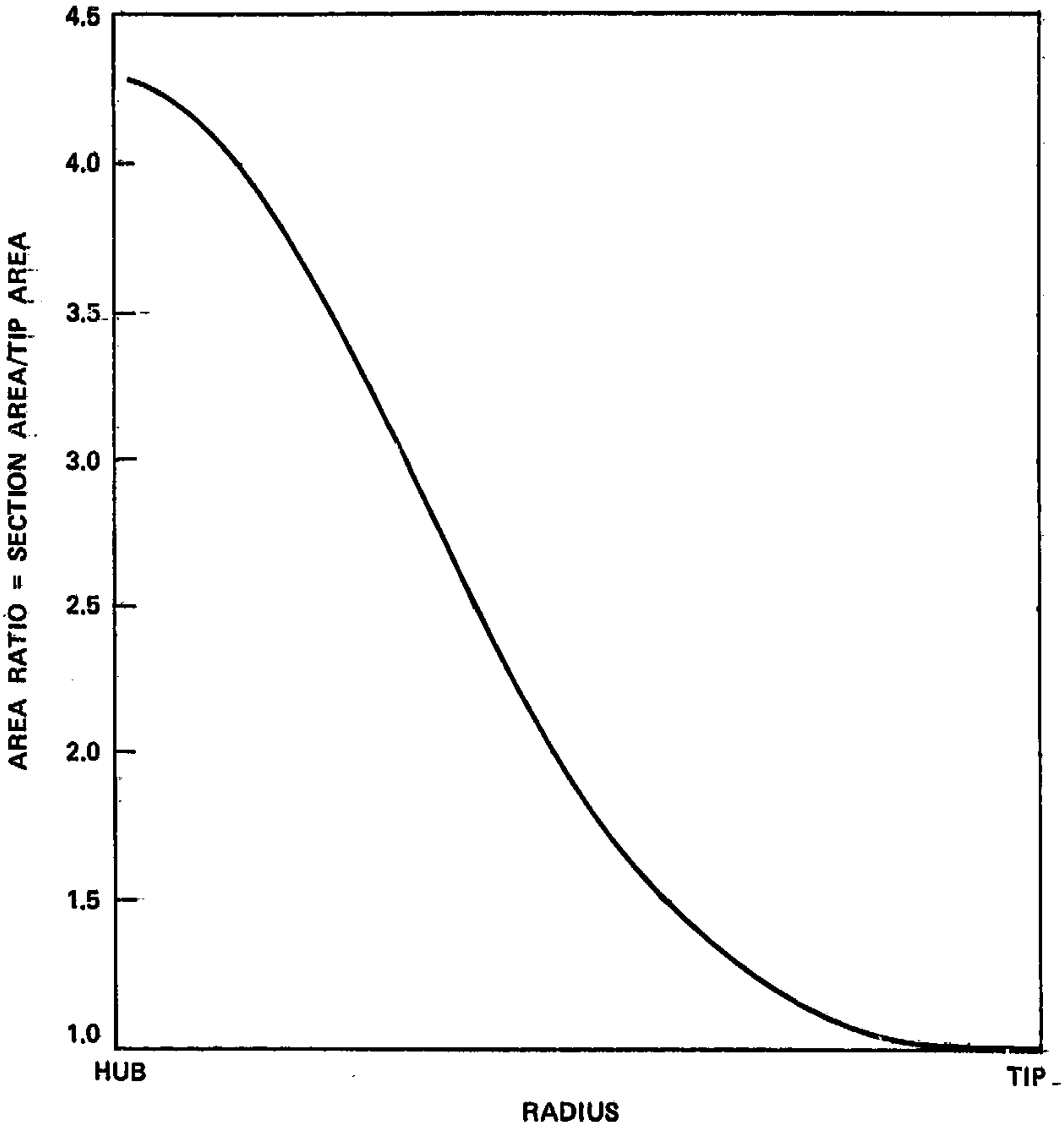


Figure 73. Final HPT Blade Area Distribution

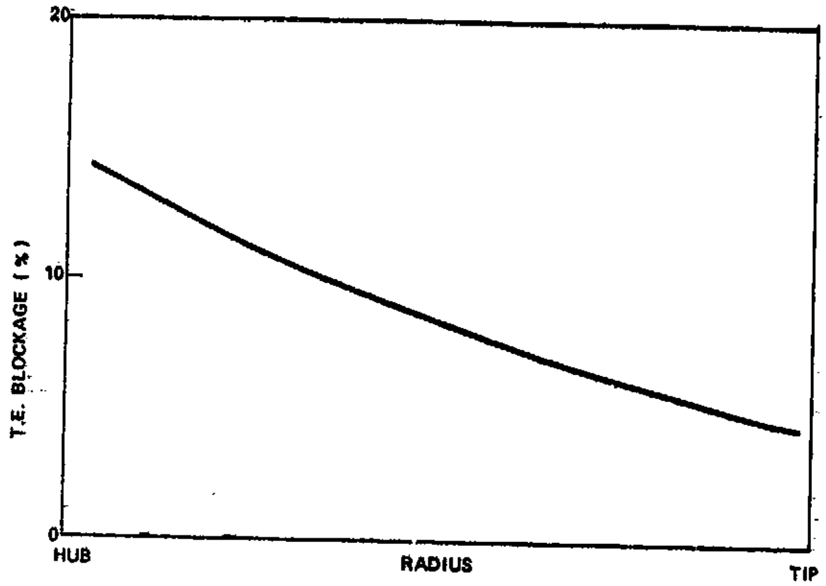


Figure 74. Trailing-Edge Blockages Versus Radius

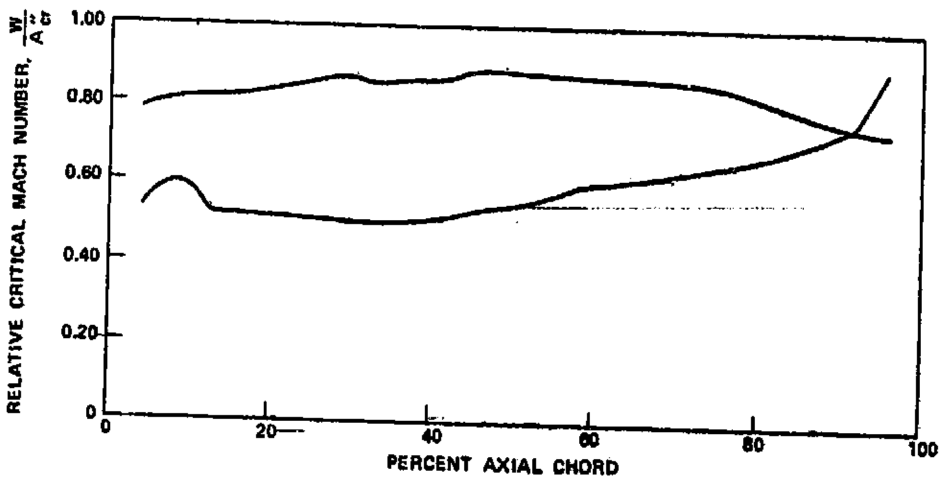


Figure 75. Rotor Hub Section Loading [R = 10.77 cm (4.24 inches)] of the Final Design

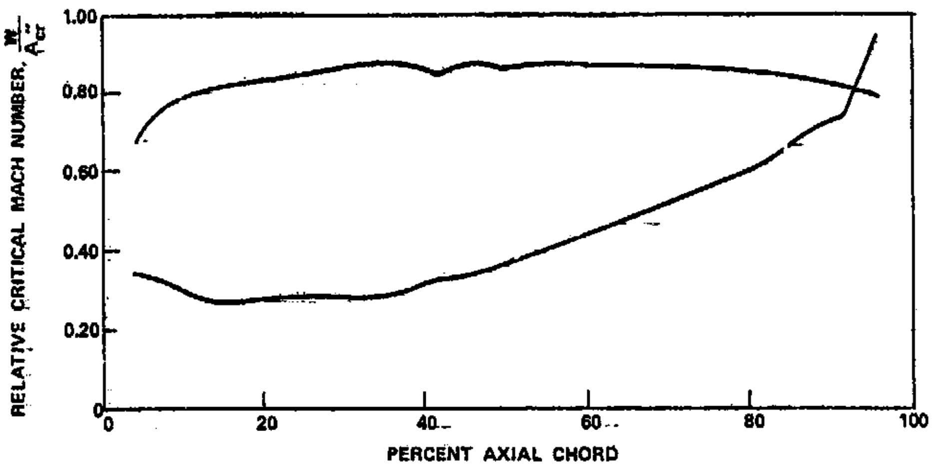


Figure 76. Rotor Mean Section Loading (R = 12.37 cm (4.87 inches)] of the Final Design

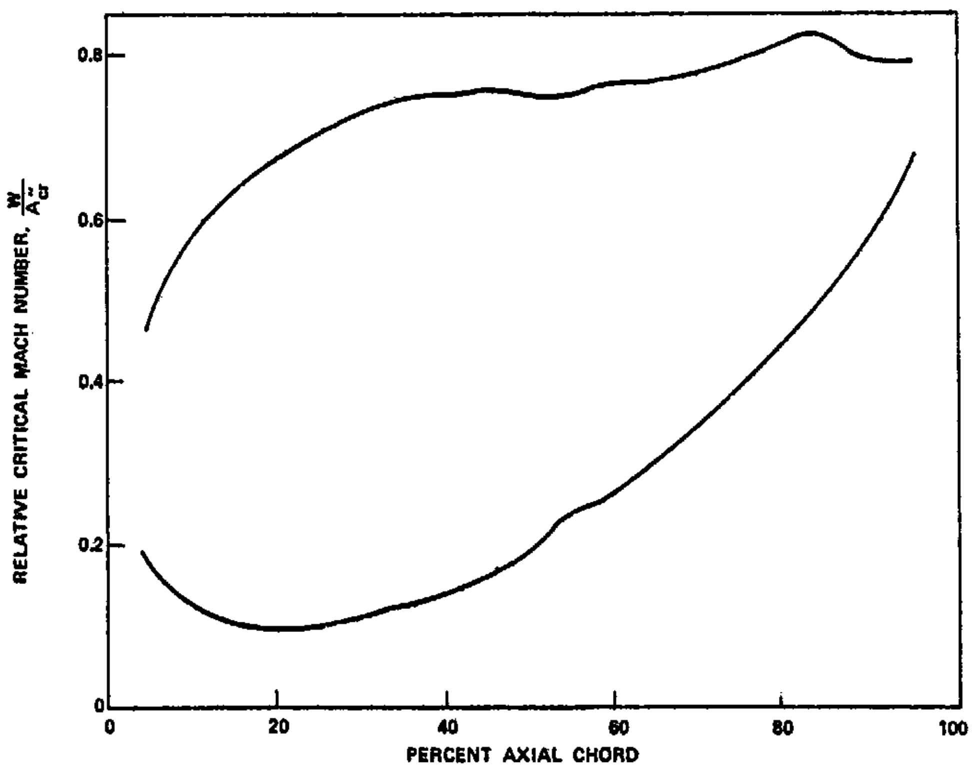


Figure 77. Rotor Tip Section Loading [R = 14.16 cm (5.57 inches)] of the Final Design

The velocity triangles corresponding to the hub, the mean, and the tip streamlines are shown in Figure 68. Low-twist aerodynamic design requires little variation of stagger angles from hub to tip. To achieve this, the radial variation of both the inlet and the exit blade angles, β_1 and β_2 must be minimized. The small radial variation of β_1 is obtained by:

(a) Increasing the stator exit flow angle at tip, and reducing it at hub (Figure 64): This will yield a higher relative inlet flow angle to the rotor at the tip, and decrease that at the hub. This results in a difference of only 15 degrees between hub and tip (Figure 65).

(b) Using negative incidence for the tip portion: Negative incidence will increase the inlet blade angle in the tip region, resulting in a small variation of the inlet blade angle.

The small radial variation of β_2 is obtained by decreasing the exit flow angle β_2 at tip, and increasing it at hub, (Figure 65).

This design yields a work distribution as shown in Figure 69. The curve shows the work distributions nondimensionalized by the average value for the whole stage (H_m). The work distribution provides nearly zero average exit swirl and very low exit loss. For example, the mass-momentum averaged values at the turbine exit are:

Exit Swirl Angle = 1.81 degrees

Exit Absolute Critical Mach Number = 0.386

2. Blade Geometry. Three cylindrical design sections are used at the following radii to define this blade:

Hub: R = 10.77 cm (4.24 in.)
Mean: R = 12.38 cm (4.87 in.)
Tip: R = 14.16 cm (5.57 in.)

The inlet and exit conditions are obtained from the vector diagram (see Figure 65).

The blade configuration is directed toward high camber, low twist, and a large trailing-edge wedge angle with a thicker trailing edge to avoid vibratory problems. However, a large trailing-edge wedge angle and a thick trailing edge can result in a large efficiency penalty, especially in the transonic range. They also tend to decrease the area ratio if they result in a larger tip area. The twist may eventually be further decreased by moving the tip nose down and the hub nose up, while maintaining both the blade angles and throat width. The final blade geometry was generated through a number of iterations to obtain the best compromise between mechanical, thermal, and aerodynamic requirements.

The blade geometry data for these three design sections are given in Table LX. The three design sections are shown in Figures 70, 71 and 72. The area dictribution for plane sections is shown in Figure 73 and the trailing-edge blockage is shown in Figure 74.

The lean and tilt for this blade are shown below:

Radius, cm (in.)	Lean Relative to CG [cm (in.)]	Tilt Relative to CG [cm (in.)]
10.774 (4.242)	-0- (0)	-0- (0)
12.375 (4.872)	0.0625 (0.0246)	0.0622 (0.0245)
14.155 (5.573)	-0- (0)	0.1358 (0.0535)

Positive lean is toward the direction of rotation. Positive tilt is toward the trailing edge.

3. Rotor Blade Loading. Figures 75 through 77 show the critical Mach number versus axial distance for the three design sections. For the hub section where the reaction is only 14.3 percent, it is inevitable to have a deceleration in the rear portion of the suction surface. This mild deceleration will not cause separation of the boundary layer. The reaction of the mean section is high enough to achieve a continuous acceleration of the suction surface. The suction surface of the tip section has a minor deceleration.

The relative critical Mach number is subsonic everywhere. Consequently, the high wedge angle and high turning as well as the higher thickness at the trailing edge have no adverse effects on the loading. The resulting high turning contributes to a higher loading in the rear portion, resulting in a nearly constant suction surface velocity near the trailing edge for the tip section.

The trailing-edge blockage ranges between 14.3 percent to 4.4 percent from hub-to-tip (Table LX and Figure 74).

Thermal Analysis. The metal temperatures of an uncooled turbine blade are primarily dependent upon the temperature of the gas stream relative to the blade (T_B). Conduction into the blade/disk firtree, radiation, and other factors have only minor effects on blade-metal temperature. The nominal total gas stream temperatures, (T_{GAS}), relative gas temperatures (T_B), and corresponding blade-metal temperatures (T_{METAL}) are shown in Figure 78. Details of the thermal finite-element model and temperature results are shown in Figures 79 and 80. These temperatures were determined considering limited cooling air supplied to the blade/disk firtree region. Reduced cooling air and the forward seal plate were retained for the uncooled DS blade design because:

(a) A limited amount of cooling air is required for the Waspaloy disk firtrees

(b) Minimum hardware changes were desired when adapting the DS blades to the production TFE731-3 Engine for the required engine testing

(c) The forward seal plate provides a limited amount of vibration damping for the HPT blade, especially in the lower, stronger vibratory modes

Stress analysis. Part of the design philosophy for the final DS blade design was aimed at increasing the blade life at the "critical section". Traditionally, this section is between 1/4 and 1/3 span where the combination of increasing blade-metal temperature and decreasing centrifugal stress results in minimum stress-rupture life. As shown by the normalized stress-rupture life in Figure 81, the blade critical section occurs at 11.68 cm (4.60 inches) radius.

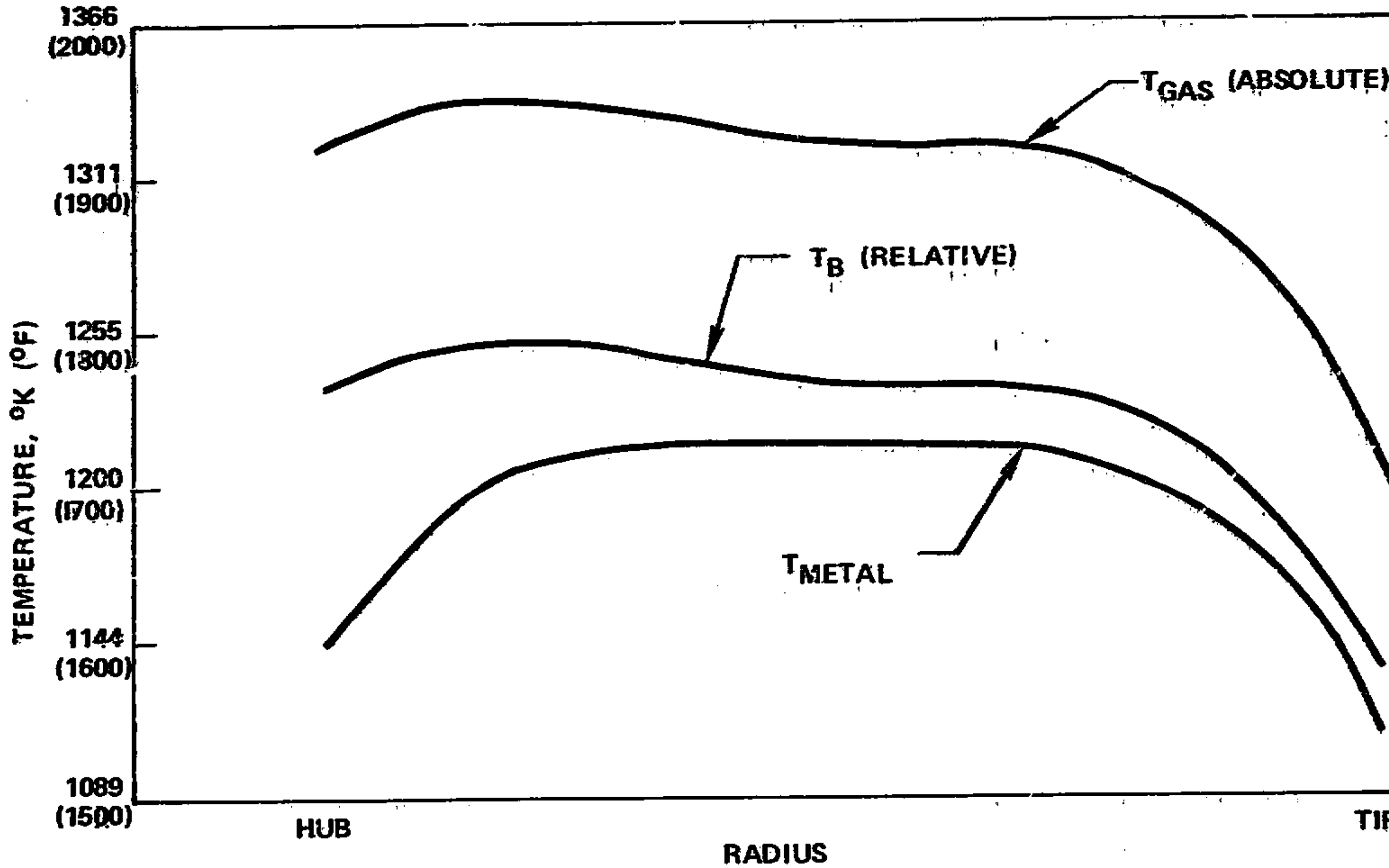


Figure 78. HPT Blade Temperatures -- Final Design MATE

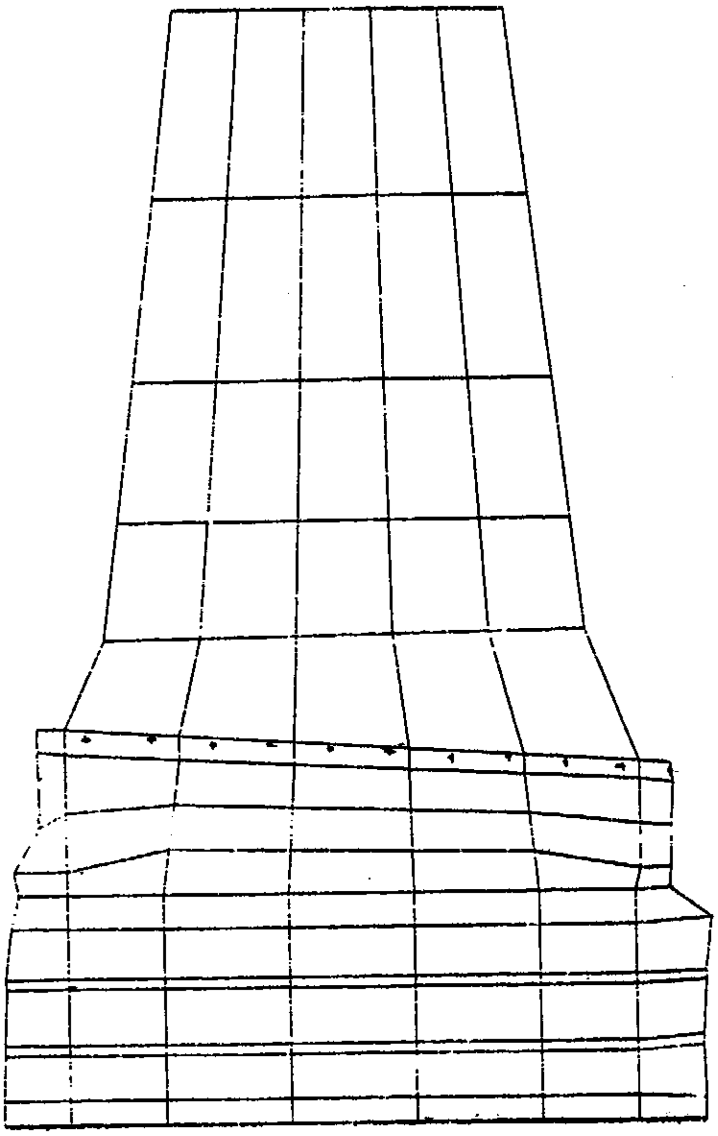


Figure 79. Grid for Thermal Model

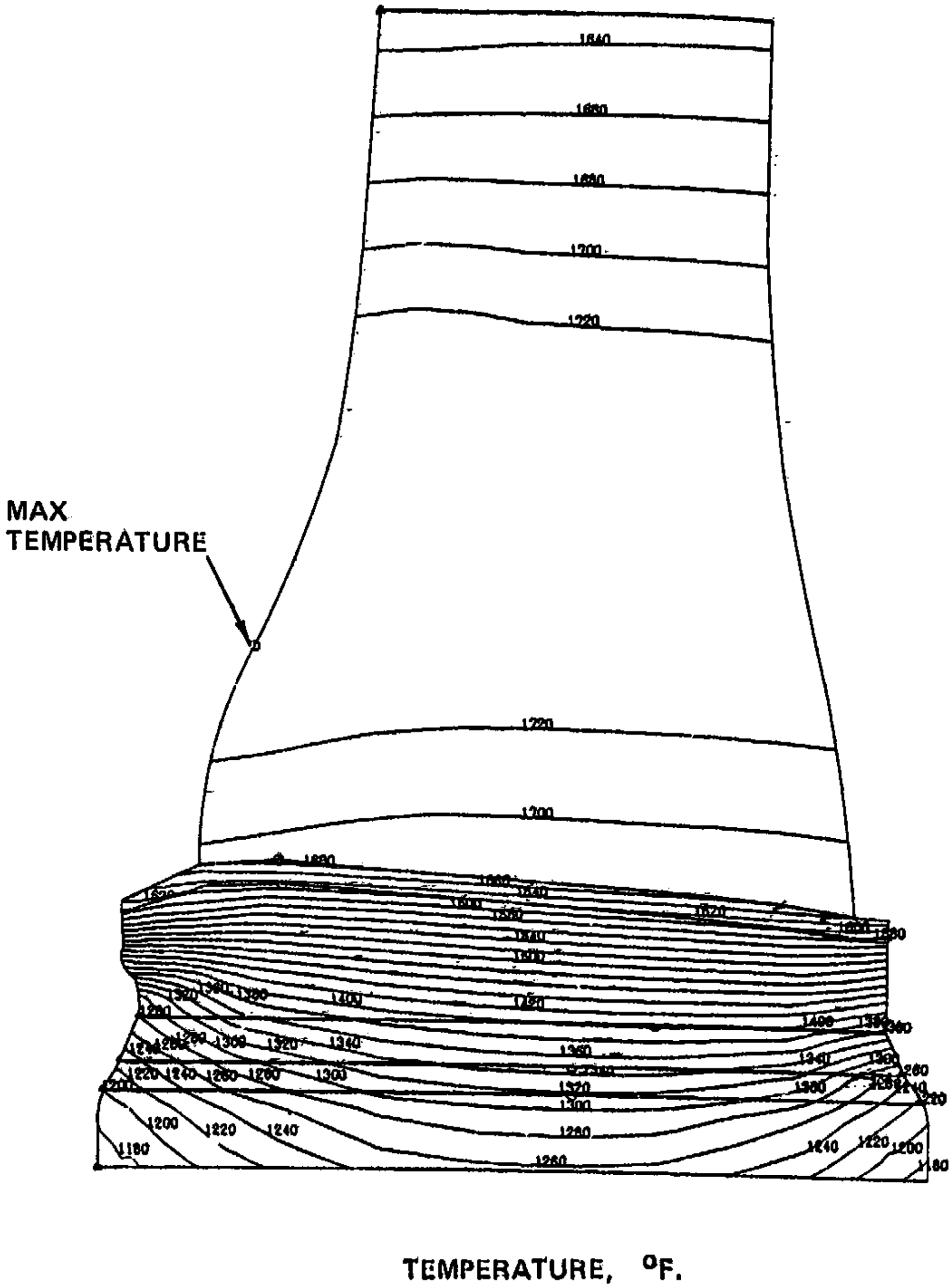


Figure 80. Shank Model Final MATE Blade Design

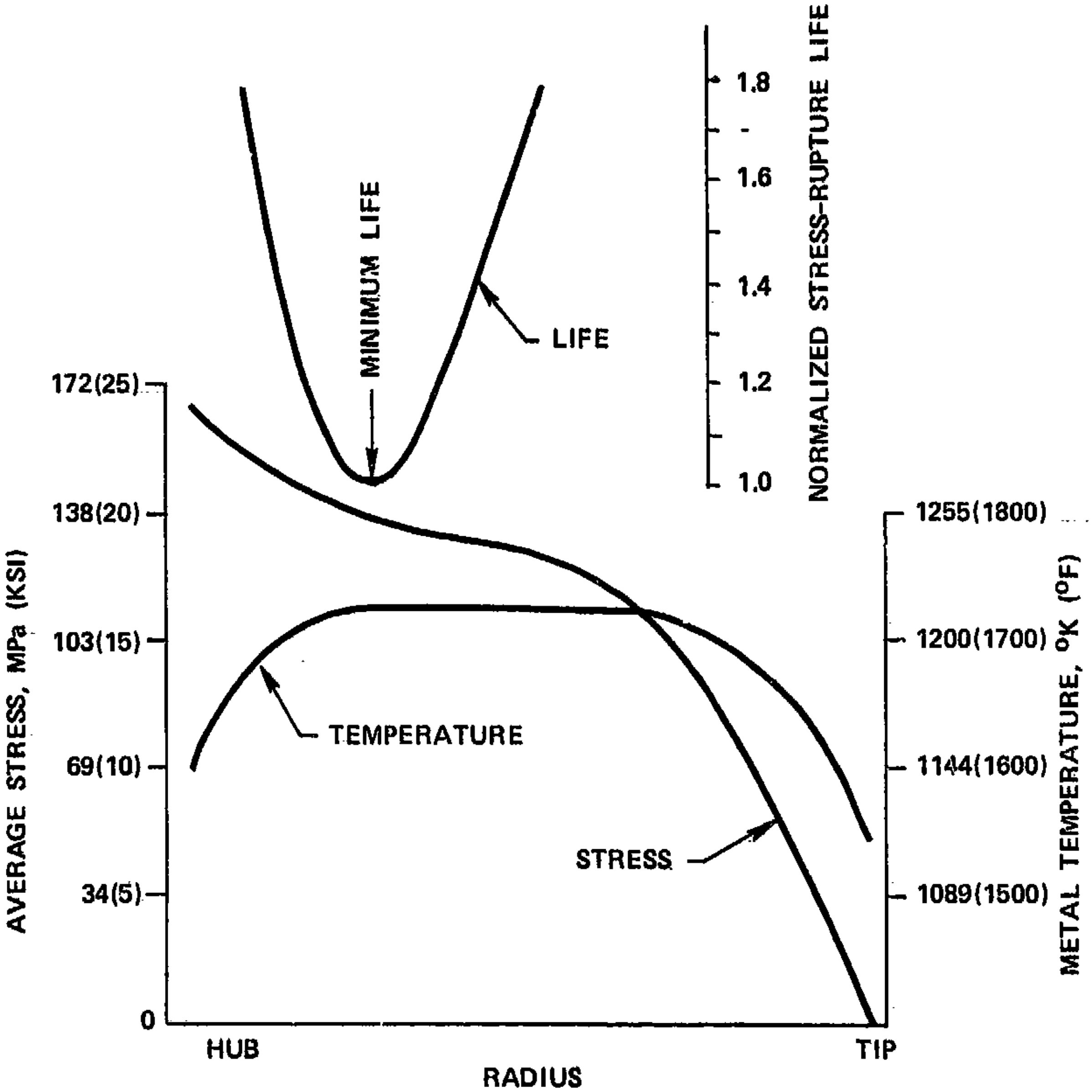


Figure 81. Minimum Stress-Rupture Life

The nominal blade centrifugal stresses are based on the following equation.

$$\sigma_{CENT.} = F/A = \frac{\rho V R \omega^2}{Ag}$$

where: CENT = Centrifugal stress at the critical sections

A = Cross section area of the critical sections

ρ = Density of blade material

V = Volume of blade material above critical section

R = Radius to center of gravity of volume (V)

g = Gravitational constant

ω = Rotational velocity of the airfoil

To reduce the stress at this section two precepts were followed:

- o Minimize the area of the blade tip section--this tends to reduce the load on the critical section and therefore the stress

- o Maximize the area of the critical section--this tends to reduce the stresses by increasing the area over which the load is applied.

Using these two ideas plus maintaining areas at a minimum radially inward from both the tip and critical sections results in the blade cross-section area distribution as shown earlier in Figure 73, and an average stress distribution as shown in Figure 82.

Results of the detailed stress analysis are presented in Figures 83 through 91. The finite-element nodal breakdown for the stress analysis is shown in Figures 83, 84 and 85. The equivalent stress results for both the pressure and suction sides of the airfoil are shown in Figures 86 and 87, respectively, with the trailing-edge stress versus radius shown in Figure 88. The equivalent stress distribution and deformation of the critical section is shown in Figure 89, and the equivalent stresses in the shank region are shown in Figures 90 and 91. The equivalent stress is a calculated stress that equates an existing triaxial stress field to an equivalent uniaxial stress, based on the distortion energy theory of elasticity. This "equivalent" stress can then be compared more realistically to available uniaxial material strength data.

Vibration analysis. The final design of the uncooled high-pressure turbine blade was designed to operate aerodynamically with a new 26-vane nozzle. Details of this nozzle design are covered in a subsequent section of this report. The interference vibration diagram for the final design blade is shown in Figure 92.

Final Design - High-Pressure Turbine Vane

Aerodynamic design. The stator vane was redesigned to match the final design uncooled, low twist high-pressure turbine blade. The velocity triangles and vector diagrams are shown in Figure 68. Design constants for this vane are as follows:

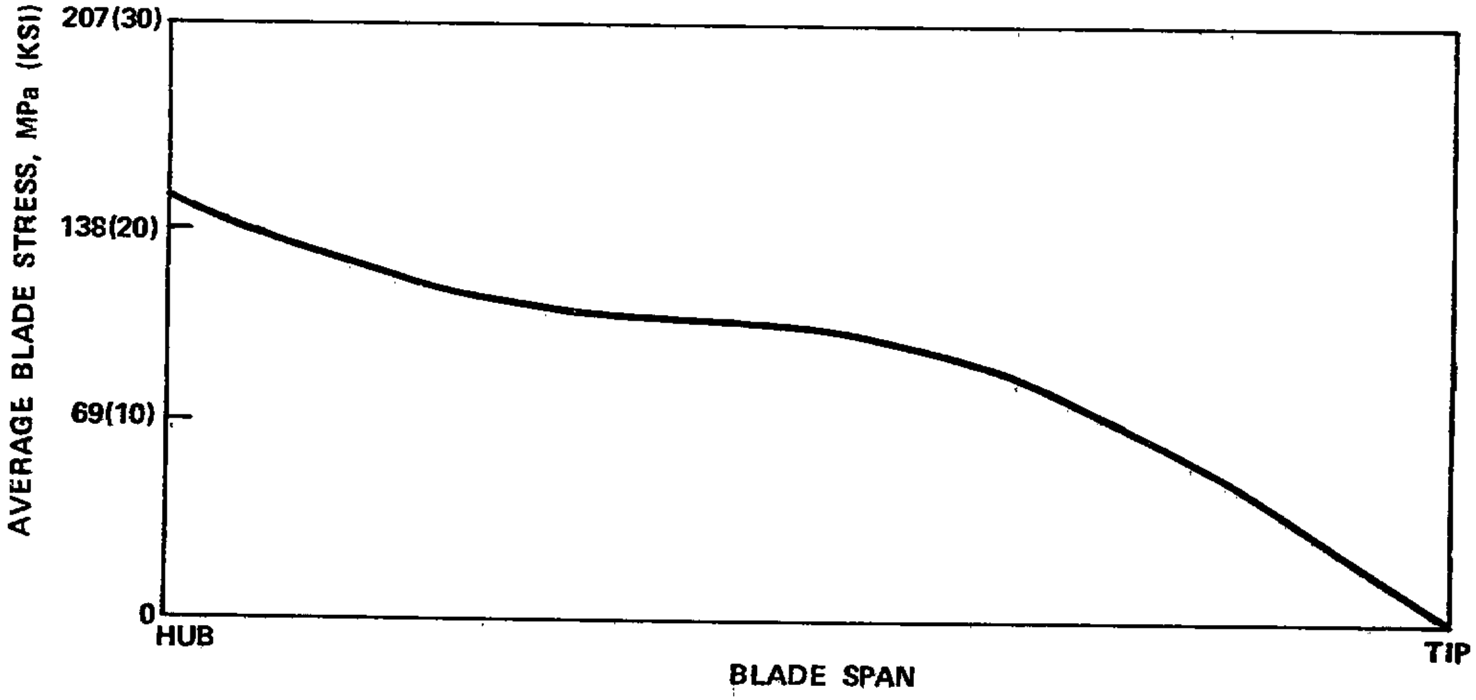


Figure 82. Average Stress Distributions for Final MATE Blade Design

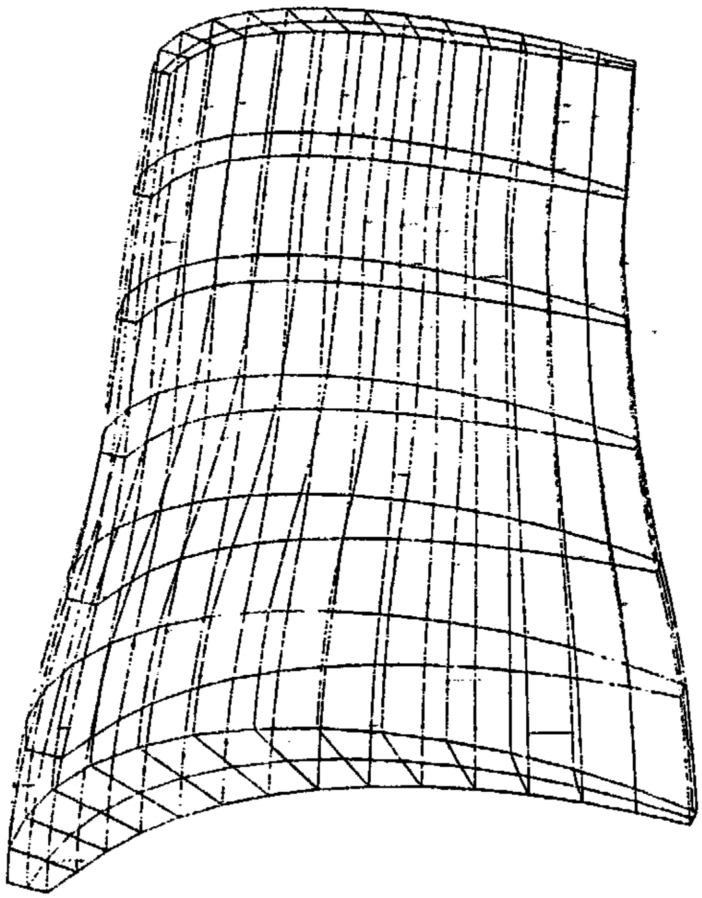


Figure 83. Final MATE Blade Airfoil Design

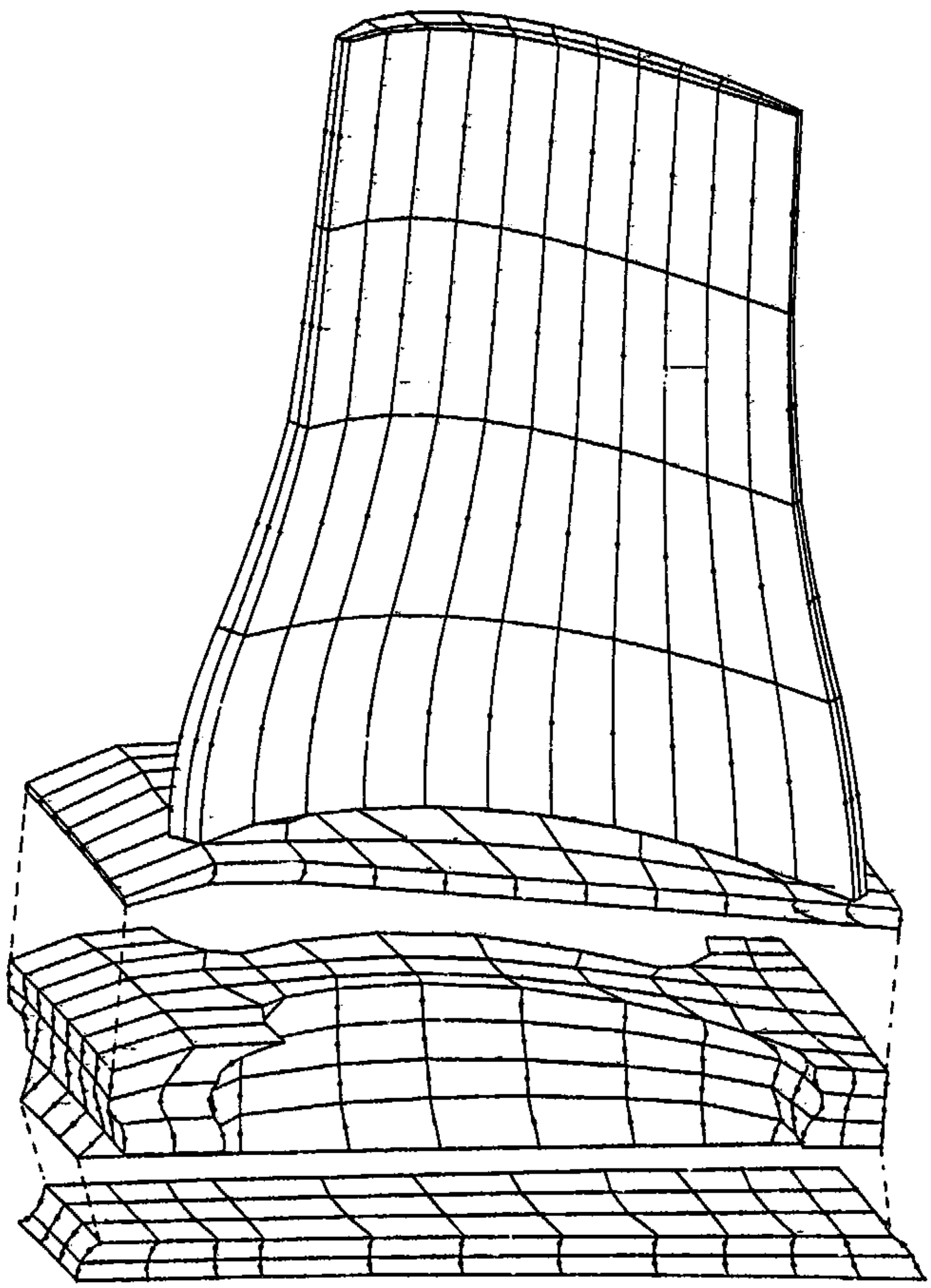


Figure 84. Final Blade Design -- Airfoil, Platform, and Shank

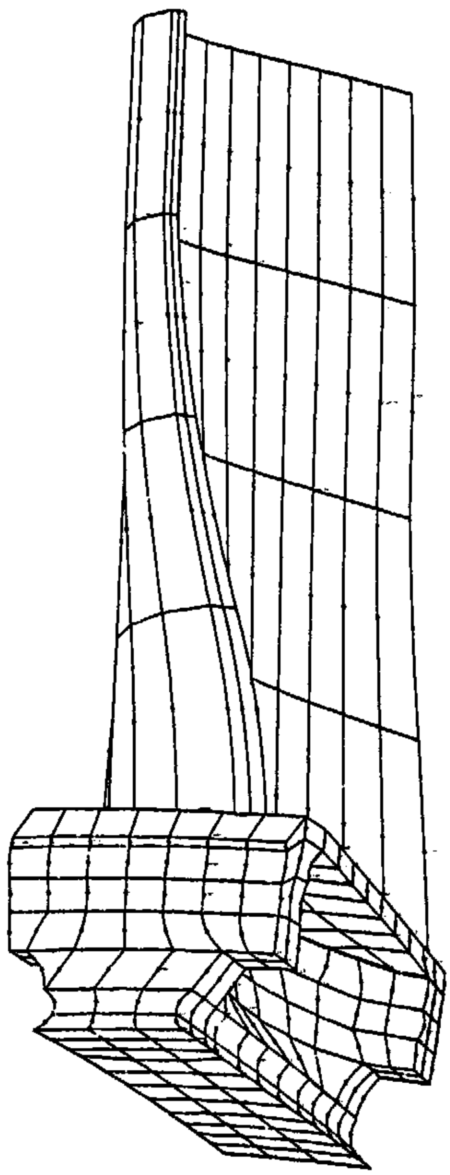


Figure 85. Final MATE Blade Design

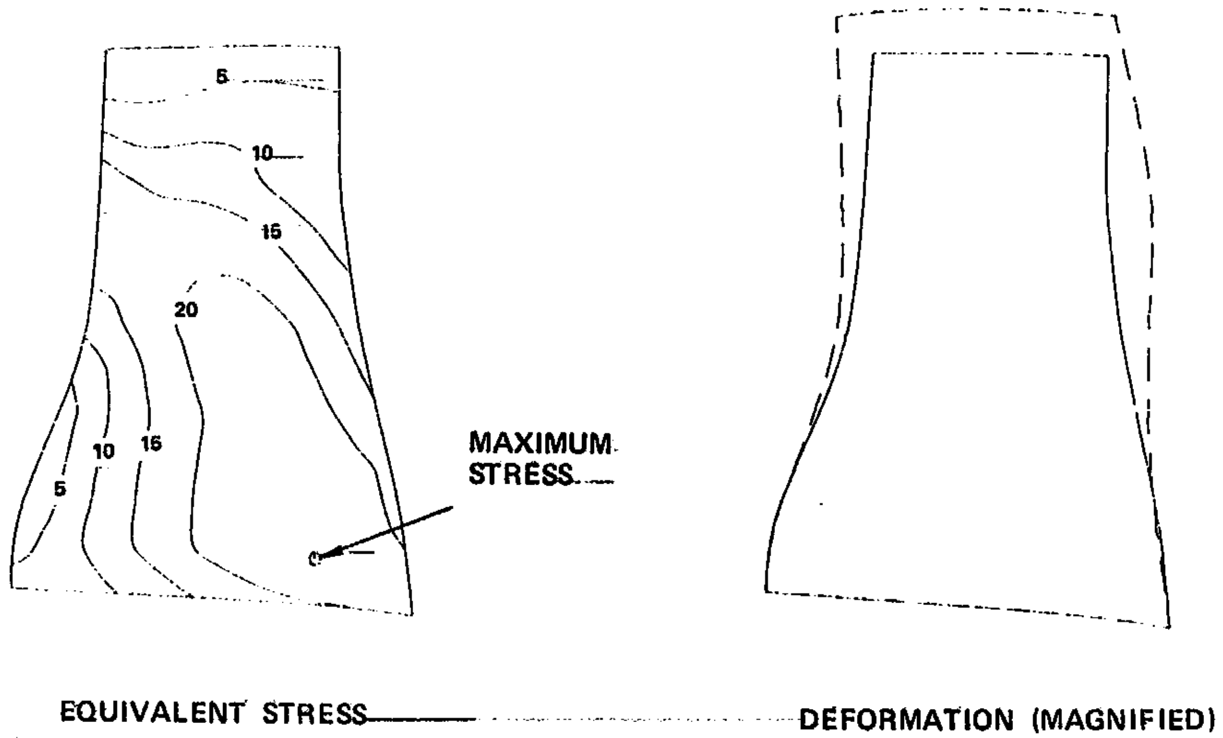


Figure 86. Pressure Side Stresses (KSI) and Deflections at 29,692 RPM

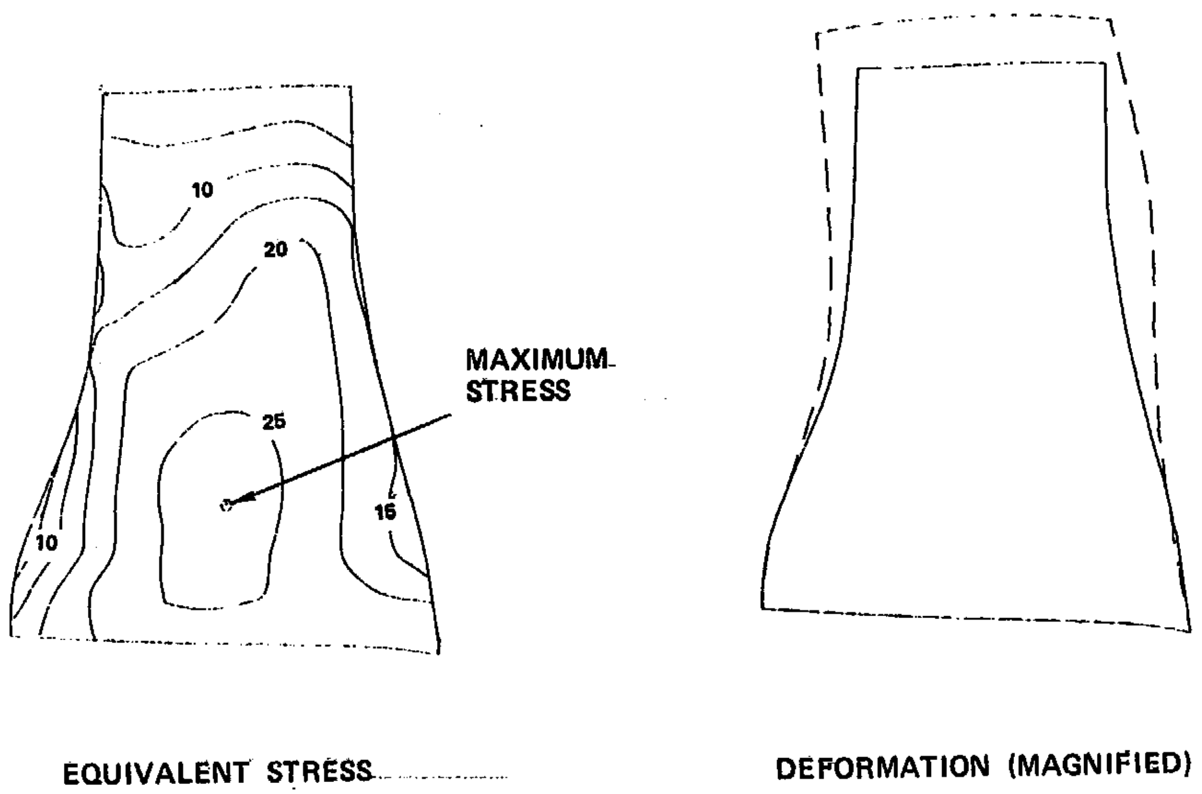


Figure 87. Suction Side Stresses (KSI) and Deflections at 29,692 RPM

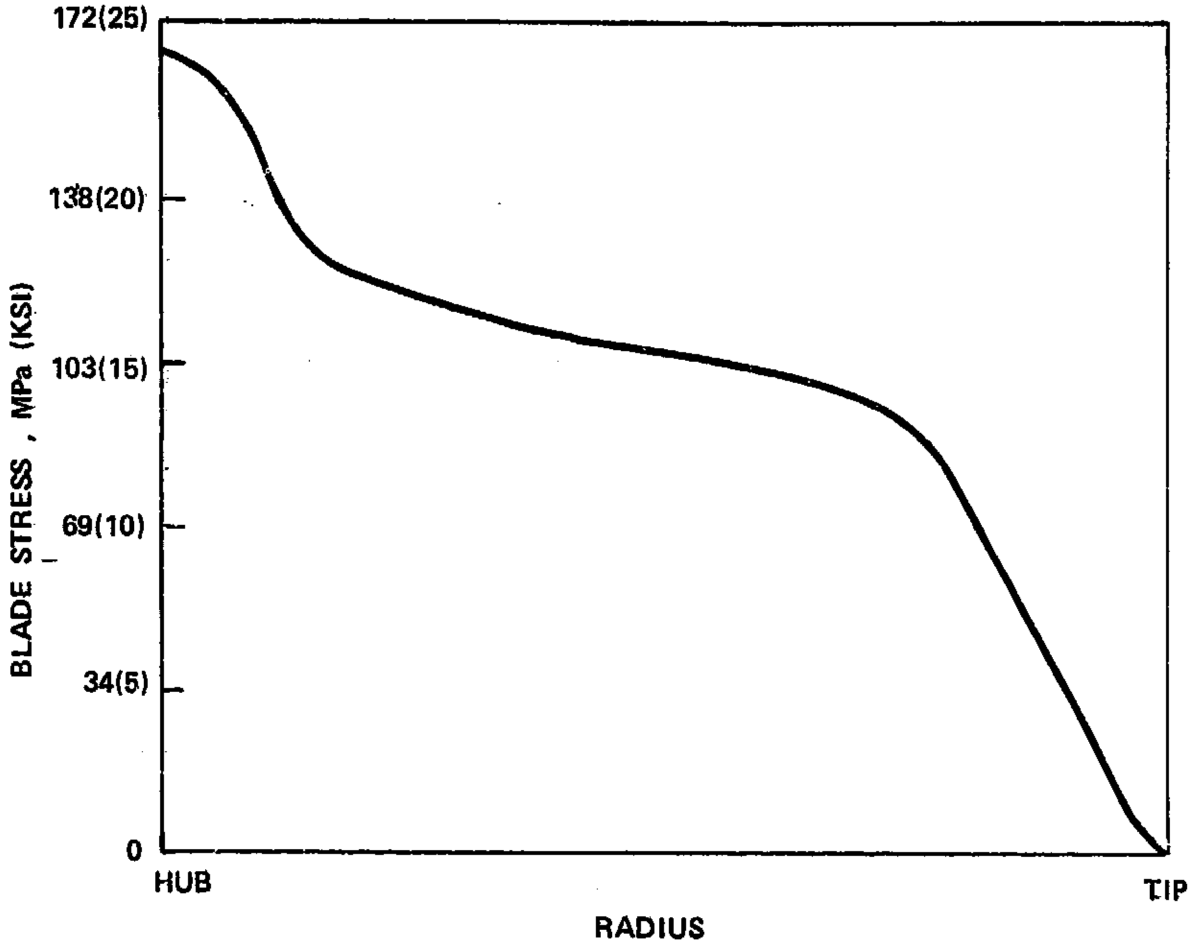
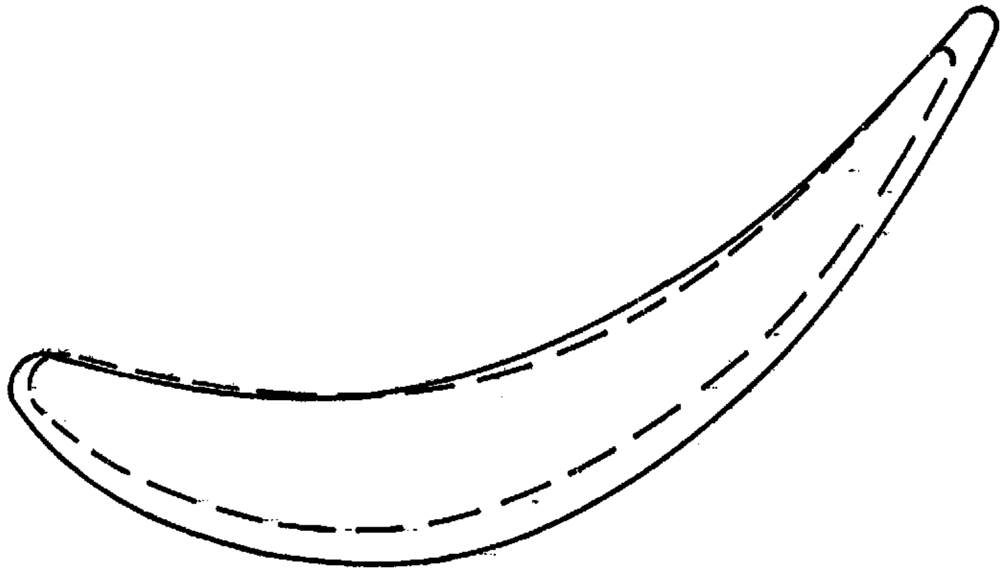
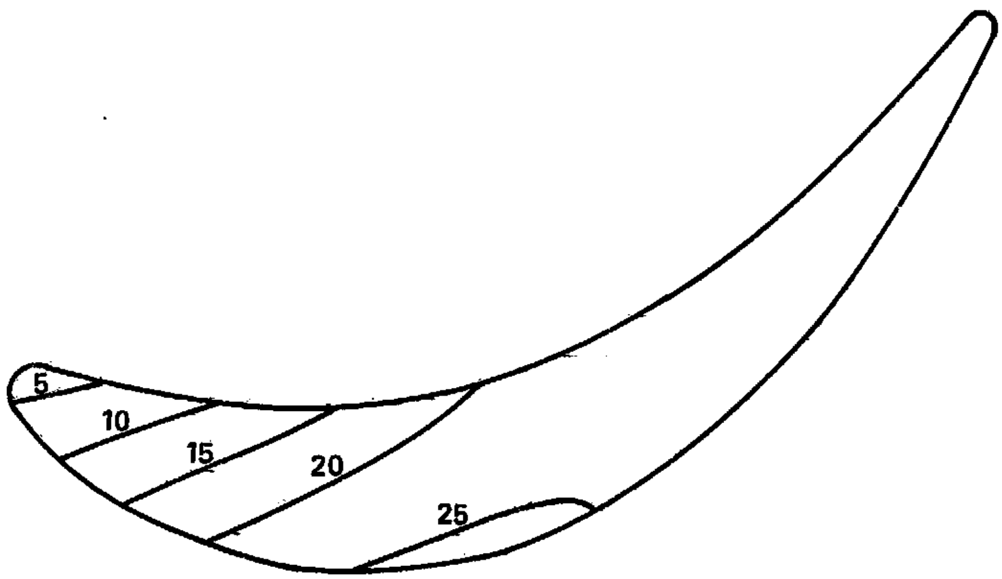


Figure 88. Final MATE Blade Design Trailing-Edge Stresses



DEFORMATION, MAGNIFIED



EQUIVALENT STRESS (KSI)

Figure 89. Final MATE Design at 29,692 RPM

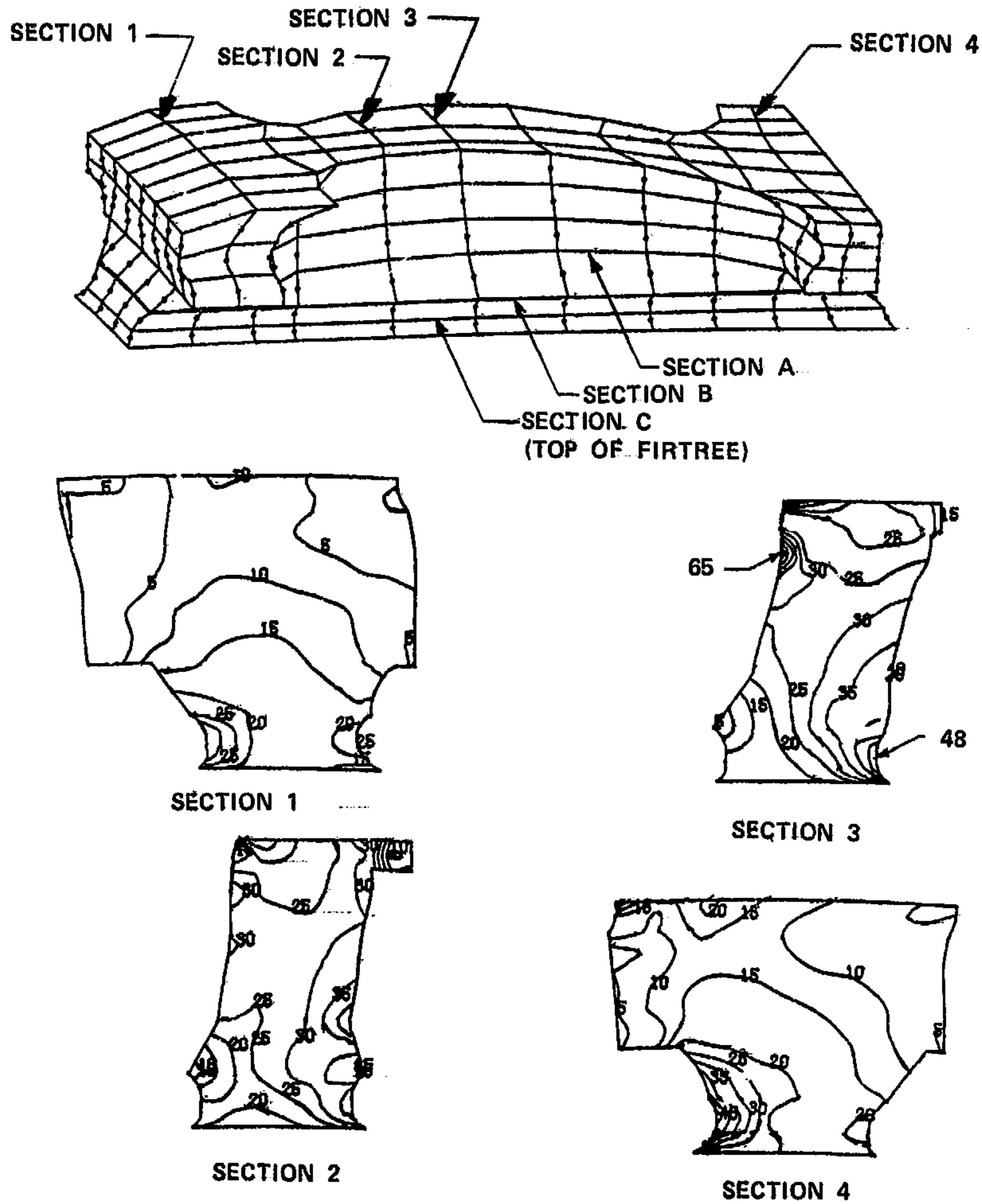


Figure 90. Equivalent Shank Stresses (KSI)--Airfoil and Platform Removed

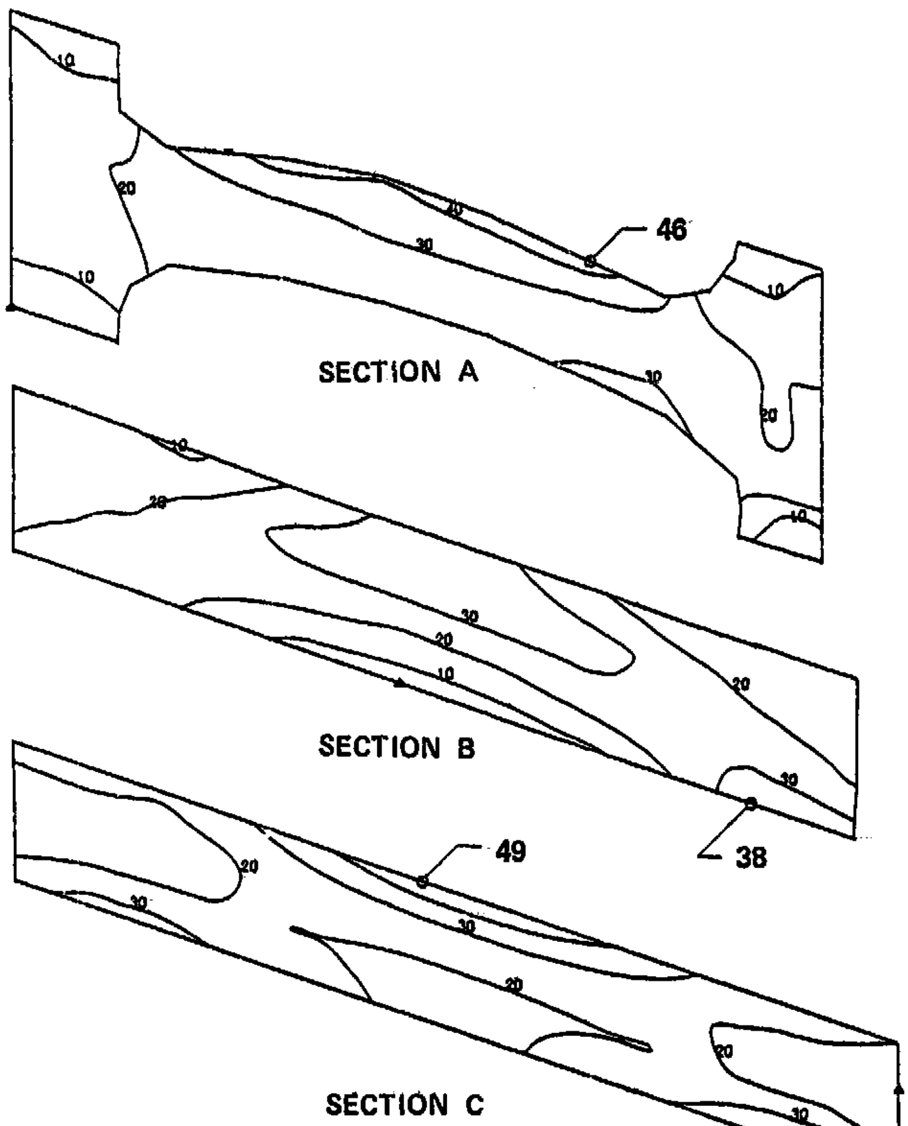


Figure 91. Equivalent Shank Stresses (KSI)

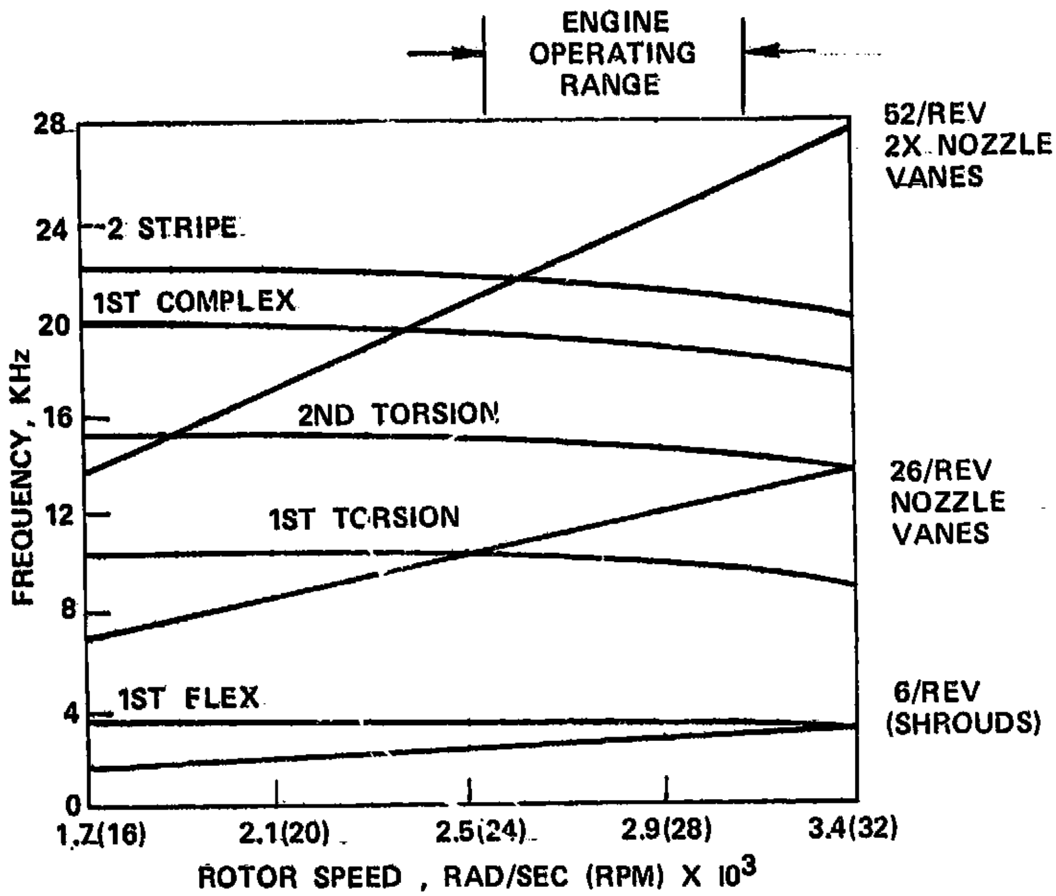


Figure 92. TFE731 Vibration Interference Diagram -- MATE Final Design, DS MAR-M 247 Blades; Machined, Heat Treated, and Coated

(a) The number of vanes was fixed at 26

(b) Airfoil sections must have sufficient thickness to allow for cooling

(c) The axial chord length must fit the existing engine flow path

Satisfying these conditions does not create any difficulty at the tip (shroud) section, but for the hub sections some minor problems were encountered. A compromise was made to slightly decrease the maximum thickness to obtain satisfactory loading while utilizing a cooling tube with a smaller area at the hub. Table LXI contains the geometry parameters necessary to generate both the hub and tip design sections. Table LXII shows the integrated throat area versus stagger. Figures 93 and 94 show the two design sections, while Figure 95 is a stack of plane sections. Vane loading is shown in Figure 96 and 97.

Thermal analysis. Details of the vane temperature calculations are shown in Figures 98 through 103. The pressure distribution around the two vane sections (base and tip) are shown in Figures 98 and 99, while Figures 100 and 101 show the heat-transfer coefficients used in the thermal calculations. The resulting calculated adiabatic wall temperatures are shown in Figures 102 and 103 for the base and tip sections.

Design parameters. Stress analysis of cooled turbine vanes is an inexact science. As the structures become more complex for cooled or hollow airfoils, the effects of thermal gradients, thermal transients, pressure distribution, and other factors become more difficult to predict with the desired accuracy. Traditionally, vane design is accomplished by comparing the design parameters of the new vane with an older proven design. When this is accomplished, and an acceptable design is produced, the next step

TABLE LXI. DESIGN DATA FOR THE 26 VANE TFE731 HIGH-PRESSURE TURBINE STATOR

Item	Symbol	Units	Section	
			Hub	Tip
Radius	R	cm (in.)	10.985 (4.325)	14.072 (5.540)
Leading-Edge Radius	r_{LE}	cm (in.)	0.190 (0.075)	0.216 (0.085)
Trailing-Edge Radius	r_{LE}	cm (in.)	0.038 (0.015)	0.038 (0.015)
Leading-Edge Half-Wedge Angle	γ_{LE}	deg	20.0	20.0
Trailing-Edge Half-Wedge Angle	γ_{TE}	deg	5.0	6.0
Throat Angle	β	deg	-57.541	-64.441
Throat Width	W	cm (in.)	1.13720 (0.44772)	1.03647 (0.40806)
Axial Camber Chord Length	C_x	cm (in.)	1.905 (0.750)	2.533 (0.997)
Axial Blade Chord Length	C_x	cm (in.)	1.905 (0.750)	2.557 (1.007)
Inlet Camber Angle	β_1	deg	0.0	0.0
Exit Camber Angle	β_2	deg	-62.541	-70.441
Maximum Thickness	t_{max}	cm (in.)	0.406 (0.160)	0.549 (0.216)
Suction Surface Turning Downstream of the Throat	δ	deg	10.0	12.0
Area	A	$cm^2 (in.^2)$	0.8123 (0.1259)	1.9021 (0.2948)
Spacing	S	cm (in.)	2.654 (1.045)	3.401 (1.339)
Trailing-Edge Blockage	B	%	6.2	6.7
Inlet Critical Mach Number		V_1/A_{cr}'	0.208	0.260
Exit Critical Mach Number		V_2/A_{cr}'	0.947	0.805
Inlet Absolute Flow Angle	β_1	deg	0.0	0.0
Exit Absolute Flow Angle	β_2	deg	62.234	72.434
Integrated Throat Area Between R = 10.985 cm (4.325 in.) and 14.07 cm (5.54 in.)	--	$cm^2 (in.^2)$	87.23 (13.52)	

TABLE LXII. 26-VANE TFE731 HIGH-PRESSURE TURBINE STATOR - INTEGRATED THROAT AREA VS. STAGGER

β_s - (β_s) Design, degrees	Integrated throat area between R = 10.985 cm (4.325 in.) and 14.07 cm (5.54 in.), cm^2 ($in.^2$)
-4.0	101.767 (15.774)
-3.0	98.180 (15.218)
-2.0	94.561 (14.657)
-1.0	90.909 (14.901)
0	87.232 (13.521)
1.0	83.529 (12.947)
2.0	79.800 (12.369)
3.0	74.103 (11.786)
4.0	72.258 (11.200)

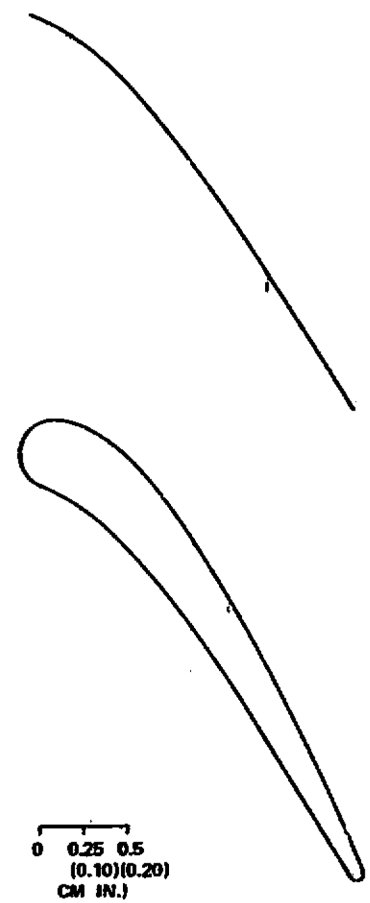


Figure 93. Hub Section of 26-Vane Stator

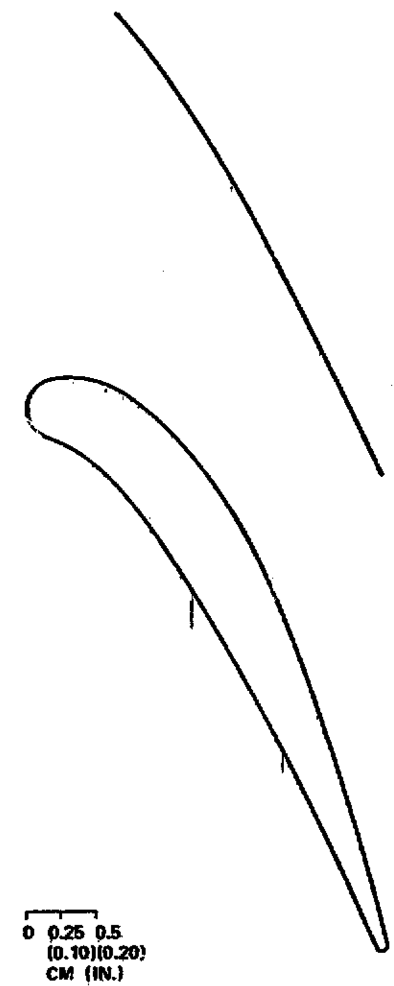


Figure 94. Tip Section of 26-Vane Stator

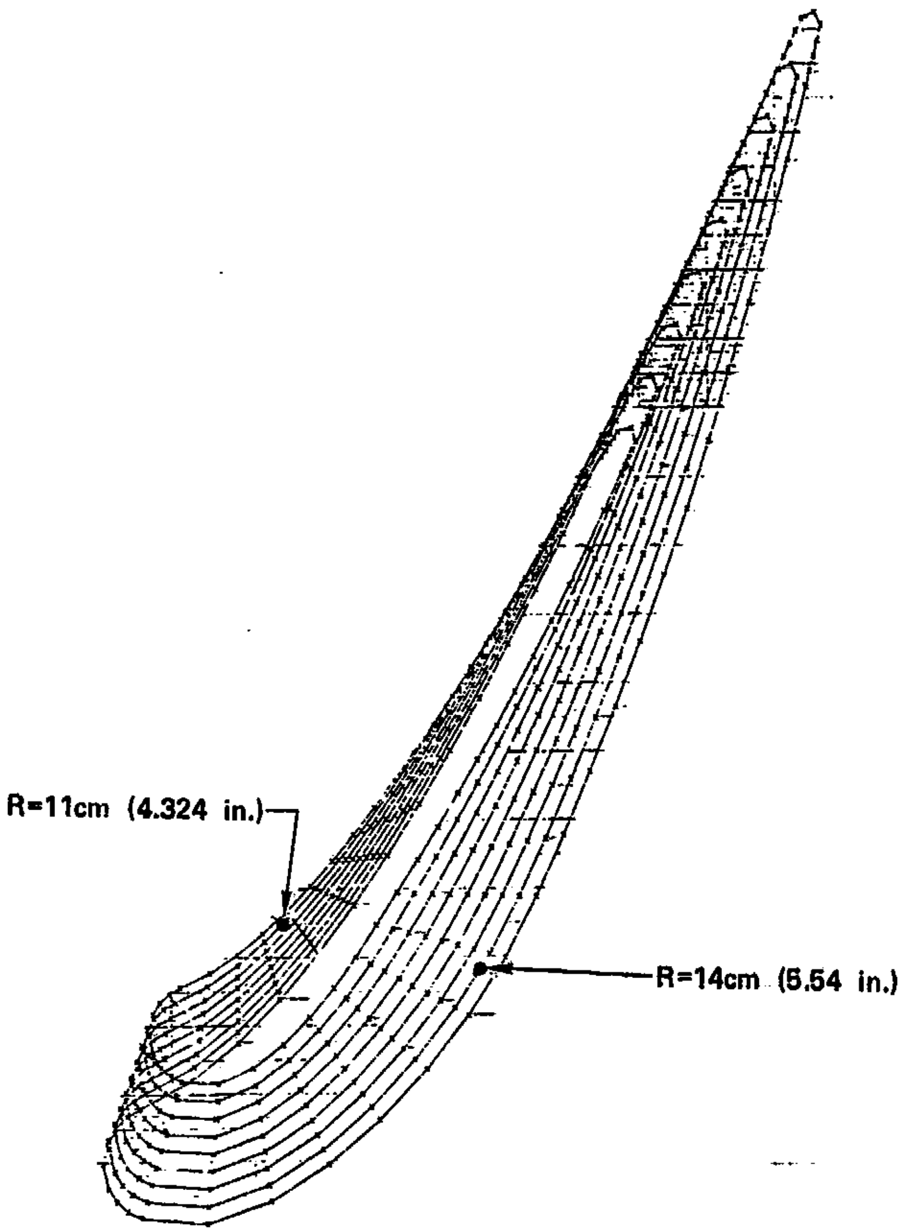


Figure 95. Stack of the 26-Vane Stator (Plane Sections)

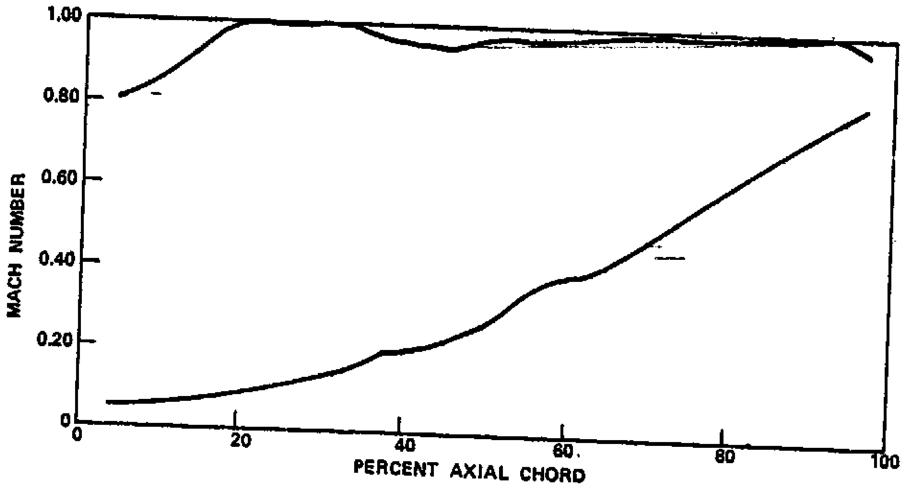


Figure 96. Stator Hub Section Loading

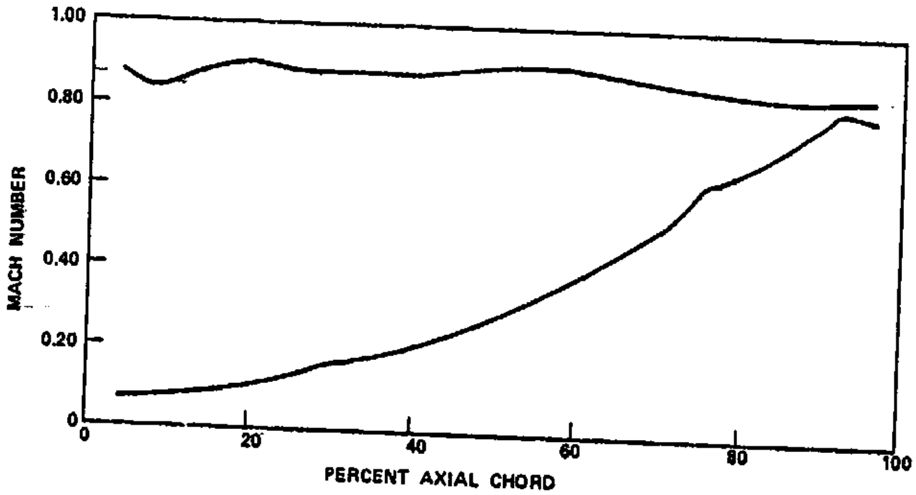


Figure 97. Stator Tip Section Loading

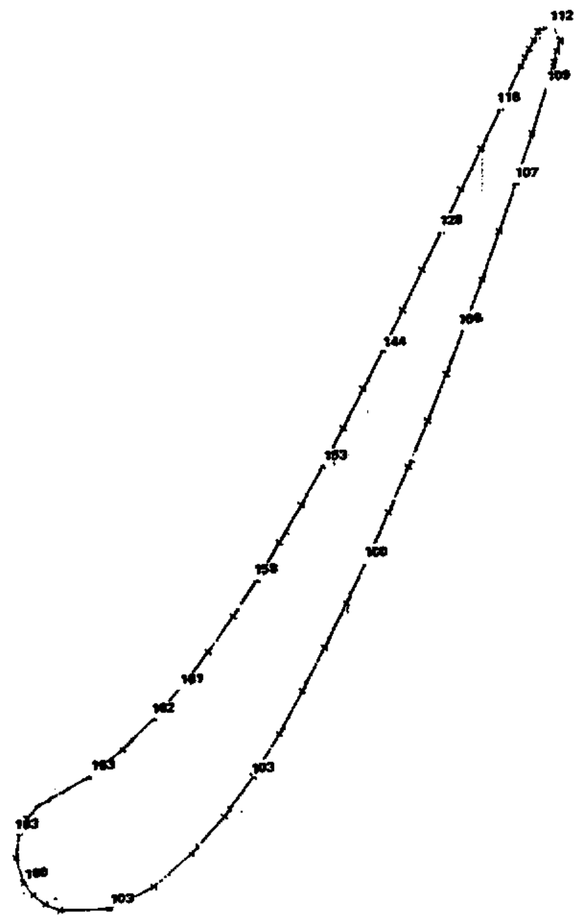


Figure 98. Pressure Distribution Base Section (PSI)

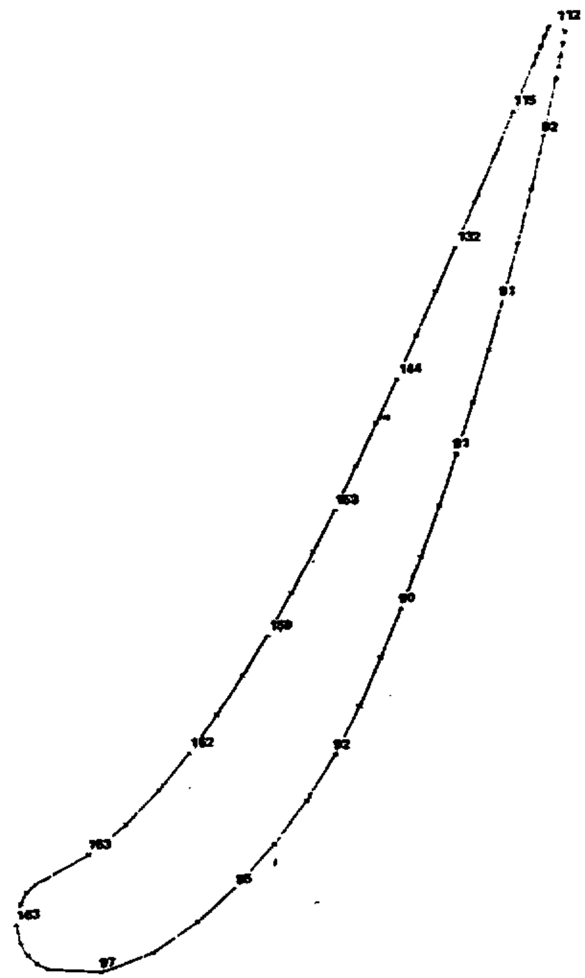


Figure 99. Pressure Distribution Tip Section (PSI)

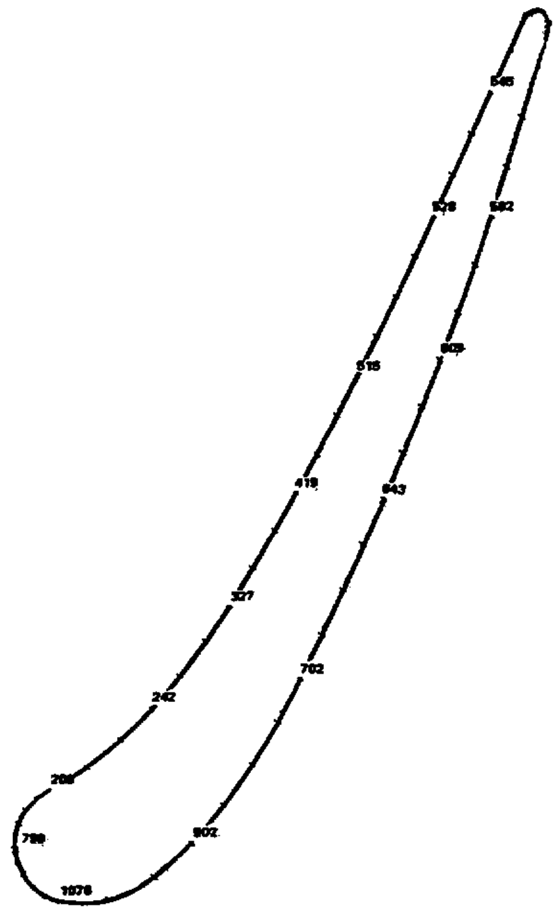


Figure 100. Heat Transfer Coefficients--Base Section

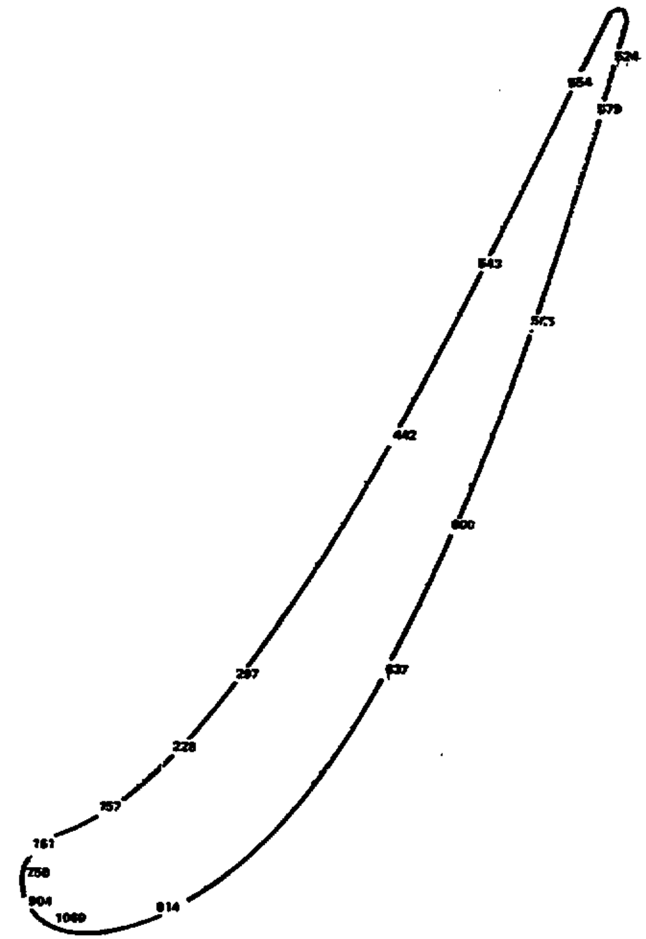


Figure 101. Heat Transfer Coefficients--Tip Section

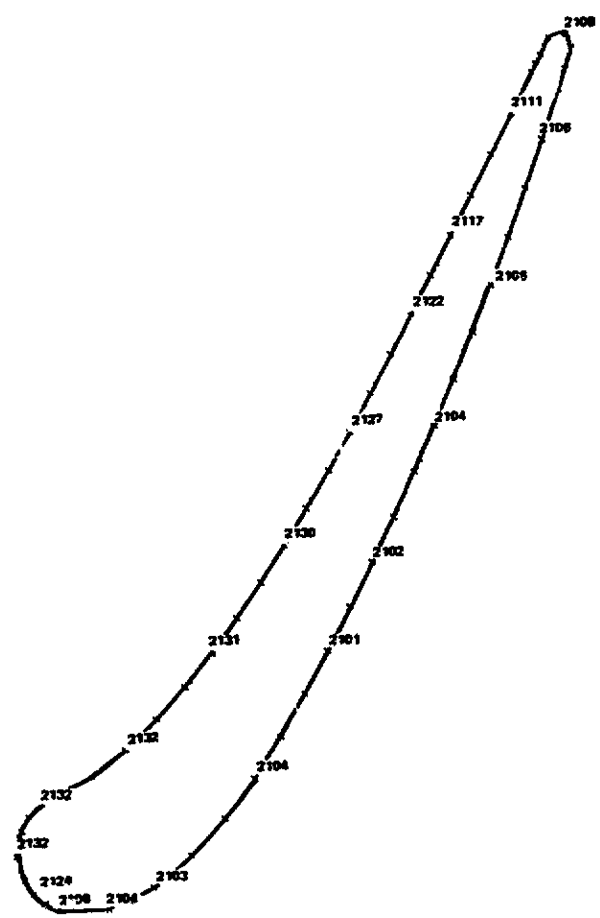


Figure 102. Adiabatic Wall Temperatures--Base Section (°F)

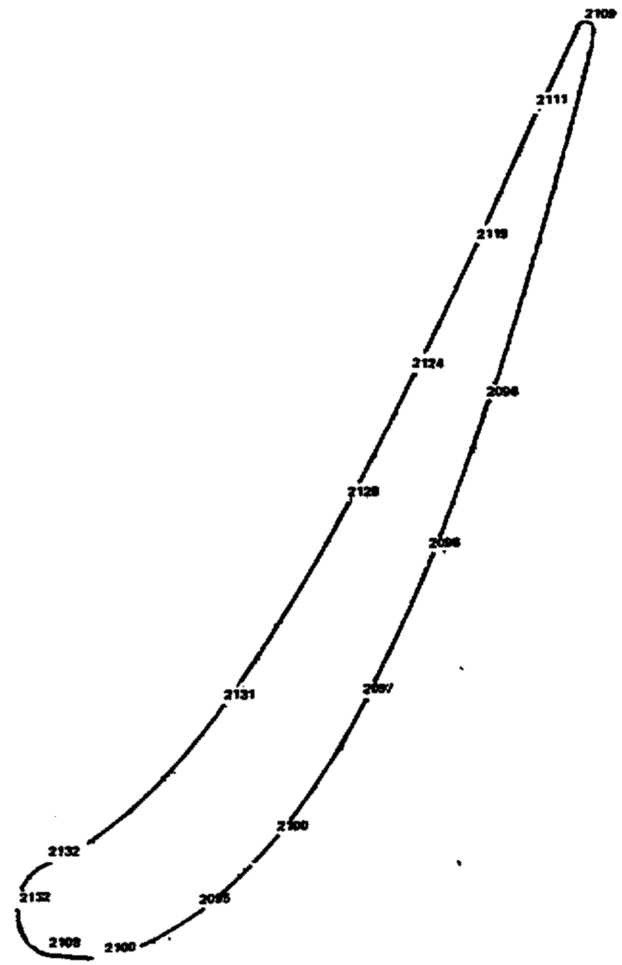


Figure 103. Adiabatic Wall Temperatures--Tip Section (°F)

is to construct the new vane and subject it to comprehensive testing and evaluation. Table LXIII shows the result of the parametric study between the new vane (26/nozzle), and the standard TFE731-3 vane (36/nozzle). As can be seen in this table, the new cooled 26-vane design compares favorably with the cooled production vane.

Final Design - Other Components

The high-pressure turbine section of the standard TFE731-3 Engine is shown in Figure 104. Both the final design of the DS high-pressure turbine blade and the new 26-vane high-pressure turbine nozzle were added to the high-pressure turbine section as shown in Figure 105. This design requires a minimum number of new parts, thus utilizing most of the existing engine test hardware.

High-pressure turbine disk - Part Number 3072748-1. The high-pressure turbine disk designed for the uncooled DS turbine blade utilizes the same disk contour, firtree configuration, and curvic coupling as the TFE731-3 disk. Only the rim area has been changed to accept the new blade. With cooling air retained for the disk firtree and the blade rim load essentially unchanged, the stresses in the disk have not been appreciably affected by this redesign.

High-pressure turbine shroud - Part Number 3072344-3. The circumferential length of the high-pressure turbine shroud segments has been shortened to allow greater unrestrained circumferential expansion. The cooling air discharged out the blade tip in the TFE731-3 blade design maintains the shroud segments at a lower temperature than when they operate with the uncooled DS blade. This higher metal temperature of the shrouds results in greater linear expansion of the supported shroud segments, thus requiring more clearance between segments.

TABLE LXIII. DESIGN PARAMETERS - TASK IV TFE731-3 HIGH-PRESSURE TURBINE NOZZLE VANE

Parameter	Production vane, 36-vane nozzle		Final design vane, 26-vane nozzle	
A. External surface area, cm^2 ($in.^2$)	799.57	(123.933)	692.75	(107.376)
B. Impingement tube:				
(1) Inlet area, cm^2 ($in.^2$)	0.126	(0.0195)	0.295	(0.0457)
(2) Inlet Mach number	0.1337		0.0728	
C. Leading-edge cooling:				
(1) Inlet velocity, cm/sec (in./sec)	12,220	(4811)	12,134	(4777)
(2) Leading-edge diameter, cm (in.)	0.396	(0.156)	0.406	(0.160)
(3) Leading-edge average thickness	0.051	(0.020)	0.051	(0.020)
D. Cooling passages around tube:				
(1) Flow area, suction side, cm^2 ($in.^2$)	0.0632 [56%]	(0.0098)	0.0568 [56%]	(0.0088)
(2) Flow area, pressure side, cm^2 ($in.^2$)	0.0490 [44%]	(0.0076)	0.0445 [44%]	(0.0069)
(3) Avg. wall temp., suction side, °K (°F)	1136	(1586)	1098	(1517)
(4) Avg. wall temp., pressure side, °K (°F)	1059	(1446)	1070	(1446)
(5) Avg. wall temp., leading edge, °K (°F)	844	(1450)	1061	(1450)
E. Pin fin passage:				
(1) Pin diameter, cm (in.)	0.051	(0.020)	0.051	(0.020)
(2) Pin-wall fillet radius, cm (in.)	0.038	(0.015)	0.051	(0.020)
(3) Spacing, flow direction, cm (in.)	0.188	(0.074)	0.190	(0.075)
(4) Spacing, transverse direction, cm (in.)	0.127	(0.050)	0.127	(0.050)
(5) Pins per row	4-3		4-3	
(6) Pin blockage, %	20.3		20.5	
F. Band dimensions:				
(1) Inner band thickness, cm (in.)	0.13/0.18	(0.05/0.07)	0.13/0.18	(0.05/0.07)
(2) Outer band thickness, cm (in.)	0.13/0.20	(0.05/0.08)	0.13/0.18	(0.05/0.07)

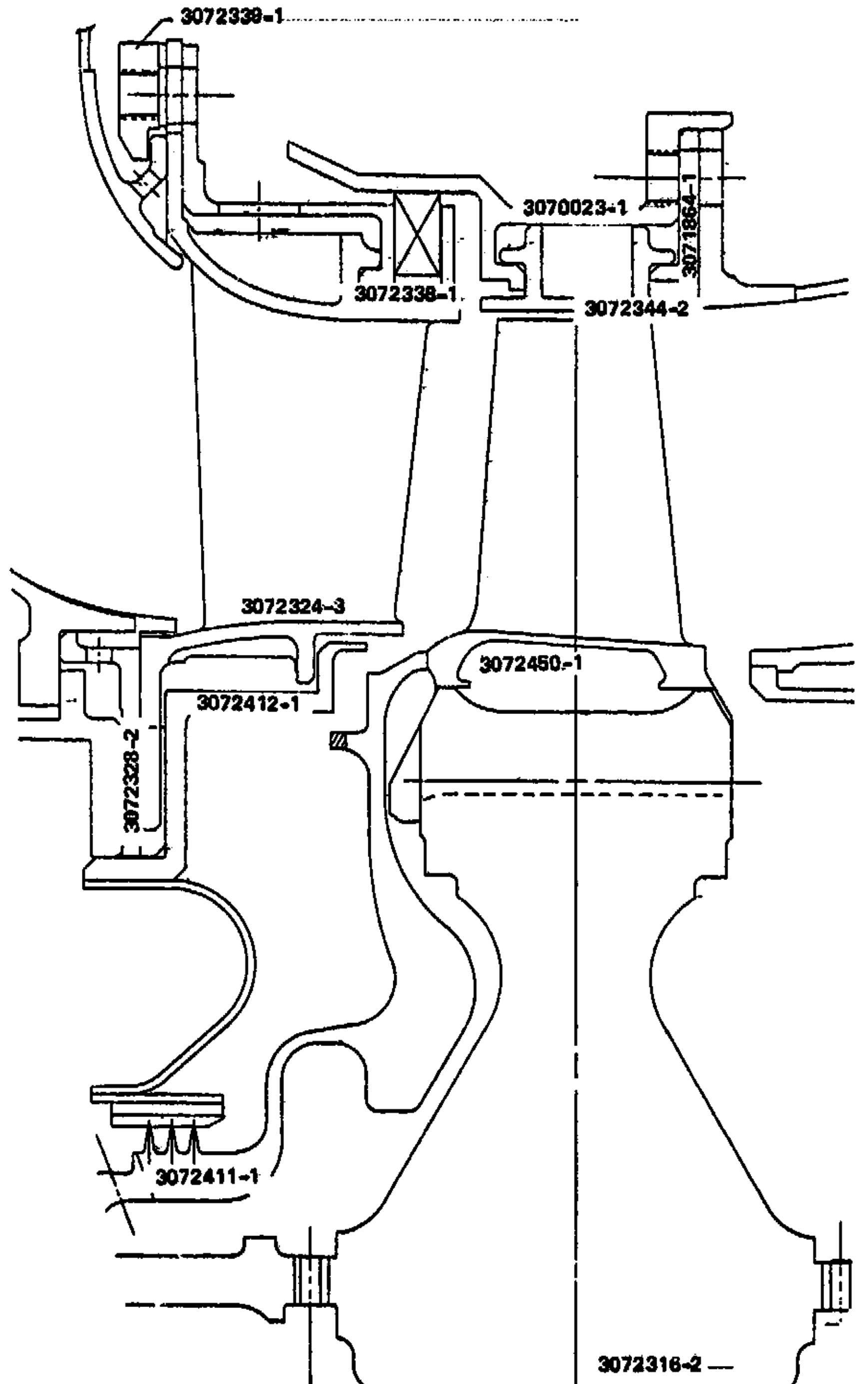


Figure 104. TFE731-3 Turbine with Cooled IN100 Blade

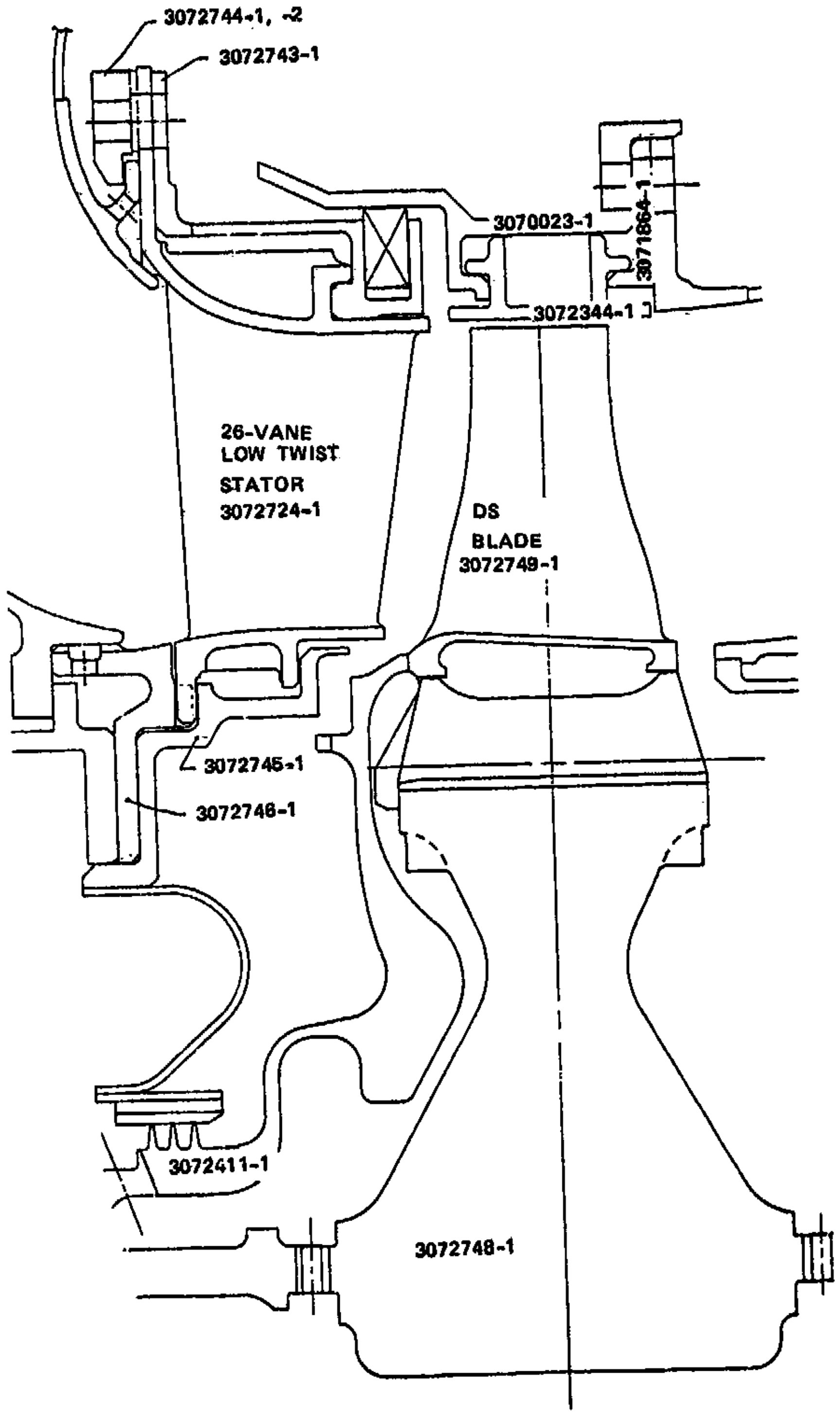


Figure 105. TFE731 Turbine with Uncooled DS MAR-M 247 Blades

High-pressure turbine nozzle supports - Part Numbers 3072743-1; 3072744-1 and 2; 3072745-1; and 3072746-1. New supports were produced to adapt the 26-vane stator to the existing high-pressure turbine structure. These are all static components with no significant stress/life problems.

TASK V - COMPONENT MANUFACTURE

Scope

The objective of Task V was to accomplish the manufacture and quality acceptance of at least two complete sets of solid exothermically cast DS high-pressure turbine blades for the TFE731-3 Engine for testing in Task VI. In addition, this task included the design, manufacture, and quality acceptance of a modified turbine disk and other engine components necessary to the installation of the DS turbine blades in the test engine.

The manufacture, preliminary inspection, and quality certification of the blade castings were accomplished by Jetshapes. The machining, coating, heat treatment, and final inspection of the test blades, and the manufacture of the modified turbine disk and other required engine parts were accomplished by AiResearch in conjunction with production-qualified suppliers.

Blade Manufacture

1. Blade configuration. Two solid exothermically cast DS TFE731-3 high-pressure turbine blade designs were produced in the performance of Project 1:

(a) The MATE preliminary design blade(AiResearch Drawing SKP 17560), which was utilized for the casting efforts in Tasks I, II, and III.

(b) The MATE final design blade (AiResearch Drawing 3072749), which is the blade designed in Task IV and manufactured in Task V.

Figure 106 shows the unmachined castings for each of these designs. The larger physical size of the final design casting is

Figure 106. Exothermically Cast DS TFE731-3 Turbine Blade Castings for Project 1 Showing Preliminary (Left) and Final (Right) Designs

apparent in this figure. The larger casting is the result of the addition of extra machining stock to both ends of the cast blade root to provide a casting that could be used to machine two different shank designs.

2. Blade Acceptability Standards. Based on the results of Tasks I through III, a materials specification for MAR-M 247, and an acceptability standard for directionally-solidifed turbine blades were prepared. These were utilized for procurement of the MATE final design blade (Part 3072749). The MAR-M 247 materials specification is included in this document as Appendix A, and the acceptability standards are included as Appendix B.

3. Mold Configuration. The first castings poured in Task V were produced from MAR-M 247, MAR-M 200+Hf, and NASA-TRW-R alloys employing a 20-blade mold. This mold was developed in previous tasks, and consisted of five radial spokes with provisions for four blade castings per spoke. Due to the larger physical size of the final design blade, it was necessary to modify this mold configuration to allow more room for exothermic material. After trying several different configurations, it was determined that the best mold design to exothermically cast the final design blades was a 15-blade mold having five radial spokes with provisions for three blade castings in each spoke. This design allowed the proper ratio of exothermic material per casting to be maintained.

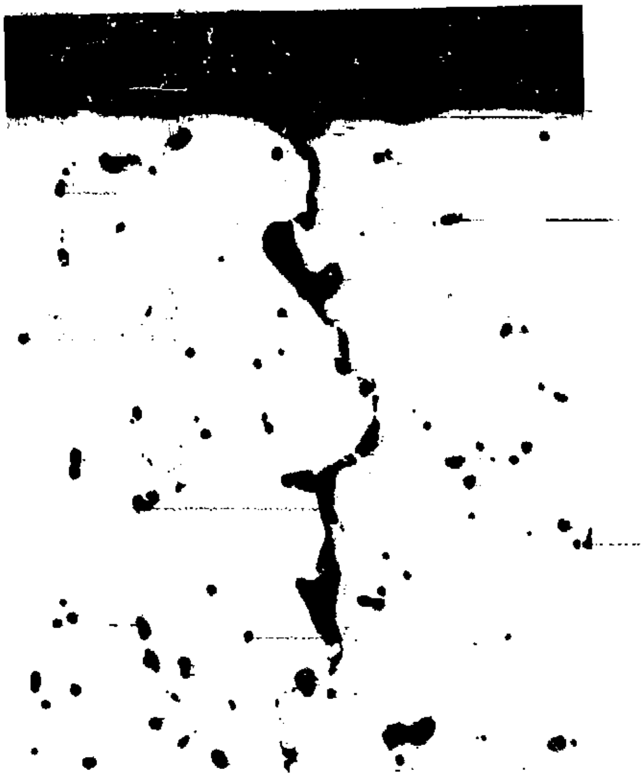
To provide assurance that the modified mold configuration had not adversely affected the stress-rupture strength of the blades, six longitudinal-grain-orientation mini-bar test specimens were machined from DS MAR-M 247 blades of the final design configuration. Each specimen was from a blade cast in a different mold, and each was subjected to stress-rupture testing at 1255°K/207 MPa (1800°F/30 ksi). The times-to-failure of these six specimens were, in hours: 77.7, 77.9, 100, 119.9, 84.7 and 99.6. Based on Task III data, the expected average life of these blades was approximately 100 hours. The actual average test life of the six Task V specimens was 93.3 hours. In Task I, the average life of similar test specimens machined from preliminary design blades and tested under the same test conditions was 79.6 hours. Thus, the Task V final design blades, with the improved heat treatment and refined casting process, exhibited a minimum life equal to or greater than the average life of blades produced earlier in the program.

4. Final material selections. Fluorescent-penetrant inspection of the NASA-TRW-R alloy blades cast in Task V revealed crack-like indications on the thin blade platforms. Visual inspection at 10X and metallography confirmed that cracks were present. None of the geometrically identical Task V blades cast in the other two alloys had a similar problem.

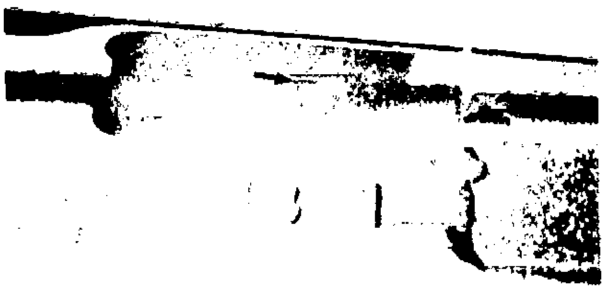
Figure 107 shows an example of a cracked NASA-TRW-R alloy blade and the microstructure in the cracked area. The nature and location of the crack is a typical example of a casting "hot tear". This can occur in thin cast sections when a highly alloyed superalloy separates (tears) at a grain boundary during solidification due to inadequate hot strength of the grain boundary.

Approximately 90 percent of the NASA-TRW-R castings clearly exhibited platform hot tears. Since data generated in Tasks II and III indicated that NASA-TRW-R had the lowest strength of the three alloys originally selected for engine testing, it was eliminated from the engine test program rather than attempt to correct its castability problem. Blade castings planned for this alloy were replaced with DS MAR-M 247 castings to support the engine test with the same total number of castings.

(a) (MAG.: 1X)



(b) (MAG.: 100X)



(c) (MAG.: 1X)

Figure 107. Photographs Illustrating "Hot Tear" Cracks Found in the Platform Areas of Task V Exothermically Cast DS NASA-TRW-R Alloy Turbine Blade Castings. Arrows on (A) and (C) Identify Typical Crack Locations. Photomicrograph (B) Shows the Intergranular Path of the Crack

5. Blade finishing.—All MAR-M 247 and MAR-M 200+Hf castings were solution heat treated in a vacuum at 1505°K (2250°F) for two hours, followed by inert gas quenching. The blades were then finish machined to the final design configuration established in Task IV. Figure 108 shows a typical MAR-M 247 blade as-cast and after finish machining. The pressure and suction sides of two finished blades are shown in Figure 109. After machining, all blades were coated with the RT-21 aluminide coating at 1255°K (1800°F) for 5 hours, followed by air cooling, then aged for 20 hours at 1144°K (1600°F) and followed by air cooling.

6. Blade Acceptability. After the 15 blade-per-mold process had been refined, approximately 525 blades in the three program alloys were poured at Jetshapes. Screening inspections to AiResearch acceptability criteria were made at Jetshapes, while final inspection was performed at AiResearch using production quality assurance inspectors. Table LXIV summarizes the overall blade acceptability results, casting yields, and number of finished blades required and accepted for engine testing.

Of the rejected blades, all 21 of the NASA-TRW-R alloy blade castings were rejected for platform hot tears found during fluorescent-penetrant inspection (FPI). Blades from the other two alloys were rejected for a combination of discrepancies: visual, grain, FPI, and X-ray. In general, there were more rejects of the MAR-M 200+Hf alloy than MAR-M 247 for hafnium-oxide inclusions. These manifested themselves as either high-density inclusions found by X-ray, or surface indications found by FPI. The bulk of the rejections by AiResearch of parts shipped by Jetshapes were for interpretations of the DS grain acceptability limits.

The 59-percent yield achieved by Jetshapes for the DS MAR-M 247 blades was considered very good for a new blade design at the beginning of the learning curve. Experience suggests that

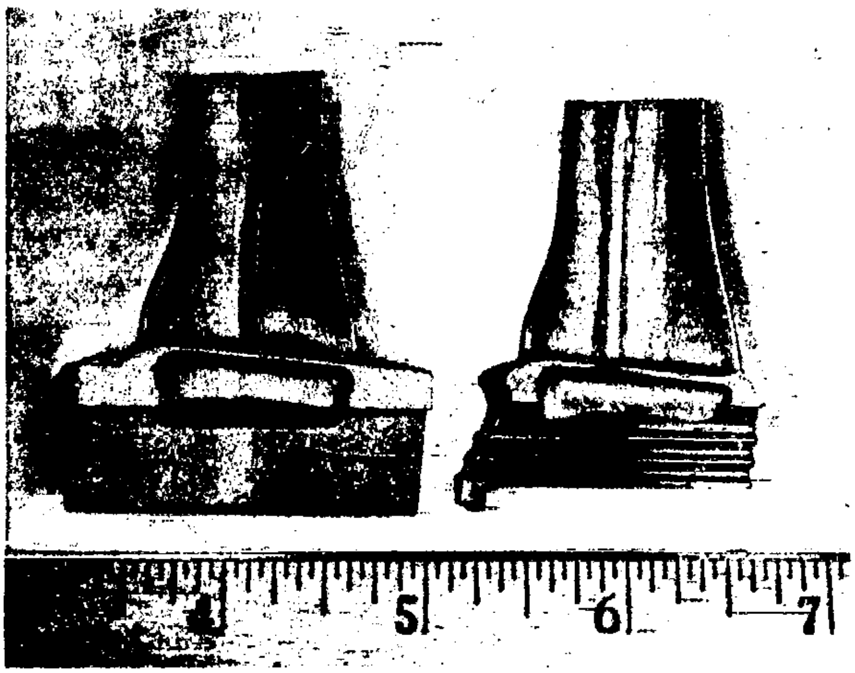


Figure 1C8. As-Cast and Finish-Machined Exothermically Cast DS TFE731-3 Final Design Blades of MAR-M 247

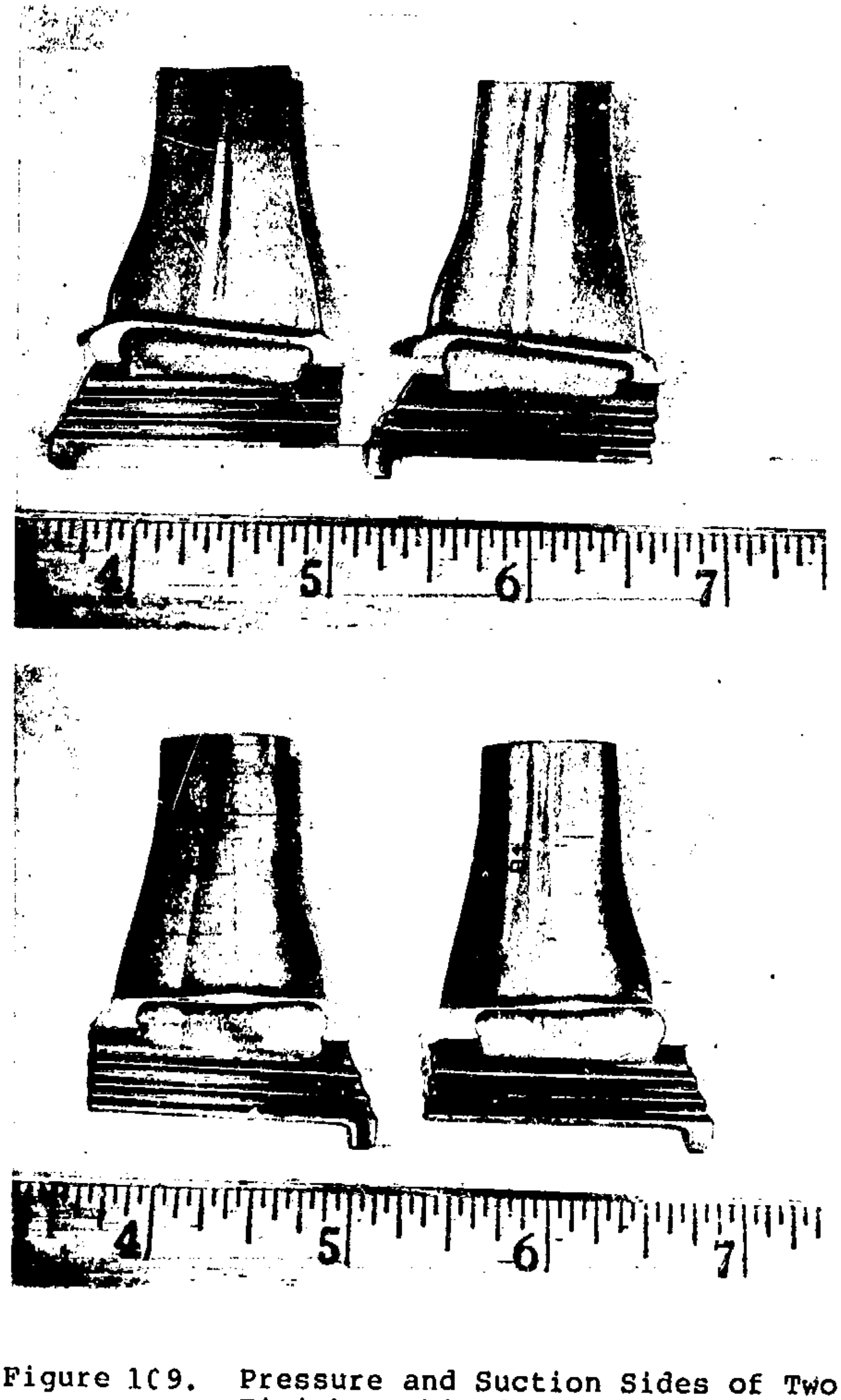


Figure 109. Pressure and Suction Sides of Two Finish-Machined Exothermically Cast DS TFE731-3 Final Design Blades

TABLE LXIV. SUMMARY OF THE YIELD OF THE FINAL DESIGN DIRECTIONALLY-SOLIDIFIED TFE731-3 TURBINE BLADES CAST IN TASK V

	Alloy			Total
	MAR-M 247	MAR-M 200+Hf	NASA-TRW-R	
Approximate number of blades cast by Jetshapes	300	165	60	525
Number of blades shipped to AiResearch by Jetshapes	199	103	29	331
Number of blades accepted by AiResearch	176	74	8	258
Approximate overall yield (%)	59	45	13	---
Number of finished blades accepted for engine testing	95	56	0[a]	151
Number of finished blades required by contract	93	31	0[a]	124

[a]NASA-TRW-R alloy eliminated from Project 1 prior to machining blades.

this yield will improve to 70 to 85 percent in production quantities.

Special Engine Components Manufacture

As described herein in Task IV, Blade Design, certain parts of the high-pressure turbine section required redesign to adapt the standard TFE731-3 design to best accommodate the final blade design of the chosen blade alloys. As a part of Task V, the required special hardware was manufactured as shown in Table LXV for assembly into the test engine.

TABLE LXV. SPECIAL HIGH-PRESSURE TURBINE HARDWARE MANUFACTURED FOR TFE731-3 ENGINE TEST OF EXOTHERMICALLY CAST DS HIGH-PRESSURE TURBINE BLADES

Part Number	Nomenclature	Quantity
3072748-1	High-pressure turbine (HPT) Disk	1
3072344-3	HPT shroud segment	6
3072724-1	HPT nozzle segment	13
3072743-1	HPT nozzle outer seal support	1
3072744-1	HPT nozzle outer retainer	1
3072744-2	HPT nozzle outer retainer	1
3072745-1	HPT nozzle inner retainer	1
3072746-1	HPT nozzle anti-rotation ring	1

COST AND WEIGHT OBJECTIVES

The Project 1 cost and weight goals (contractual objectives) are listed below. The SFC objective will be discussed in Volume II of this report.

- Reduce engine weight at least 1 percent
- Reduce engine manufacturing costs at least 3.2 percent
- Reduce engine maintenance costs at least 6.2 percent

In the limited time available for this Project, it was obviously not feasible to achieve long-term production objectives. However, several conclusions and projections can be formulated with reasonable confidence based on the knowledge gained in manufacturing and testing the uncooled DS HP turbine blades. Actual engine testing of the DS blades was accomplished in a modified TFE731-3 Engine, with hardware changes kept to a minimum to avoid unrelated component development problems during the 150-hour test. If the turbine section of the engine were redesigned to fully utilize the uncooled DS turbine blade several major changes could be accomplished as listed below:

- Eliminate the forward seal plate - since cooling air is not required for the DS blade, this component can be eliminated.

- Redesign the firtree connector - since the DS MAR-M 247 blade material has superior properties as compared to the present production equiaxed IN100, both the circumferential and axial dimensions of the firtree could be reduced through a redesign of the firtree connector.

- Redesign the HP turbine disk - since the rim load would be substantially reduced due to the new blade/firtree design, the turbine disk could be redesigned utilizing a stronger disk alloy to reduce disk weight without adversely affecting engine life.

Engine Weight

Engine weight savings can be considered as either "actual" weight reductions associated with changes that could be achieved with components in the current engine or weight savings that are possible if the engine cycle parameters such as bypass ratio and pressure ratio are optimized. The "actual" weight reduction calculations are shown below. It is not necessary to consider the optimized engine cycle to meet the weight reduction goal.

Total Engine Weight (TEW)	= 722 lbs
Eliminate Seal Plate	= 3.2 lbs
Reduced Weight of Redesigned HPT Disk	= 4.3 lbs
Total Weight Reduction (TWR)	= 7.5 lbs
Total Engine Weight Reduction	$= \frac{TWR}{TEW} = \frac{7.5}{722}$
	= 1.04 percent

Manufacturing Costs

By replacing the production cooled HP turbine blades with uncooled DS turbine blades, the overall manufacturing costs of the TFE731-3 Engine can be reduced by more than 3.2 percent. Two major manufacturing cost factors are associated with this proposed change:

- Direct manufacturing cost savings to the HP turbine stage from material and component design changes.

- Savings achieved by optimizing the engine cycle parameters to reduce the core engine size and weight.

Direct Costs - The uncooled (solid) DS castings are higher yield, less expensive castings that require less machining than the conventional cooled (cored) TFE731-3 HP turbine blades. Figure 110 shows a relative cost comparison between the conventional cooled IN100 HPT blade used in the TFE731-3 Engine and the MATE DS blade designed in this project for the TFE731 Engine. The changes in configuration and processing will yield a 1.5-percent engine manufacturing cost savings for production quantities. By redesigning the HP turbine disk to utilize the stronger MAR-M 247 DS blade material in the rim area and incorporating a stronger disk material (such as Rene' 95), a 23-percent weight savings can be realized. This weight/cost savings is offset, however, by a 41-percent increase in raw material cost which results in no cost savings for the disk redesign. Since the redesigned HP turbine blades and disk no longer require cooling, the entire cost associated with the HP turbine seal can be eliminated resulting in a 0.4-percent savings. Thus, a direct manufacturing cost savings of 1.9 percent can be realized by optimizing the HP turbine section to fully utilize the characteristics of the uncooled DS MAR-M 247 turbine blades.

Optimized Engine Costs - Table LXVI summarizes the change in cycle parameters for the TFE731-3 Engine with DS blades. The optimized cycle must be incorporated to fully utilize the characteristics of the DS turbine blades.

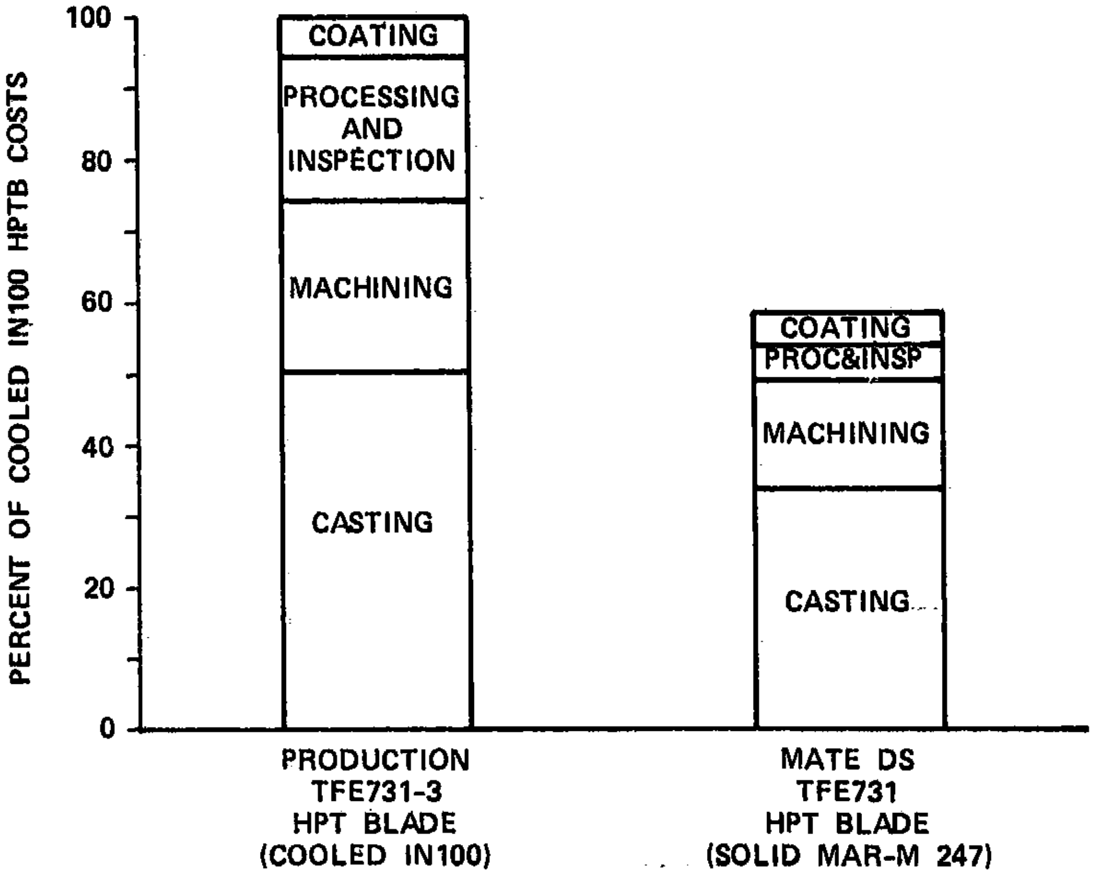


Figure 110. Relative Blade Costs of the TFE731 HP Turbine Blade Production Versus MATE DS

TABLE LXVI. CHANGES IN ENGINE PARAMETERS FOR CONSTANT CRUISE THRUST TO FULLY UTILIZE THE DS TURBINE BLADES IN THE TFE731-3

Parameter	Production Engine Baseline Cooled (Cored) Equiaxed IN100	MATE Project 1 Uncooled (Solid) DS MAR-M 247	
		Standard Cycle	Optimized Cycle
T_4 °K (°F)	1327 (1930)	1327 (1930)	1327 (1930)
TSFC	0.818	0.814	0.721
Pressure Ratio (PR)	18.0	18.0	25.0
Bypass Ratio (BPR)	2.7	2.7	4.6

AiResearch prepared a cost/benefit analysis (NASA CR135265) as a part of the MATE Program Project 0. This document illustrates that scaling of engine weight, with changes in bypass ratio, can be approximated by the following relationship:

$$\frac{\Delta WE}{WE} = \frac{WE_C}{WE}\left(1 - \frac{BPR_{baseline}}{BPR_{new}}\right)$$

where: WE = Engine Weight

WE_C = Engine Core Weight

BPR = Bypass Ratio

A weight breakdown for the TFE731-3 Engine showed that 50.5 percent pounds of the total engine weight is core weight. Using this data, plus the bypass ratio shown in Table LXVI, the analytical model predicts that a 21-percent weight savings can be realized by optimizing the engine for DS blades. This is based on the reality that as the bypass ratio is increased at a constant thrust, the size of the core and all of its components will decrease.

The cost model for engine scaling purposes is simply:

Cost is proportional to Weight

This cost model is based on small weight changes from the baseline engine. The calculated 21-percent weight savings is a very significant weight change, and could be accomplished only with extensive redesign and technology changes to the engine. Therefore, the cost savings would probably not be as significant as the weight reduction due to the added costs to incorporate advanced technology components. The significant change in core size would, however, yield cost savings that would reduce the overall engine cost considerably more than 1.3-percent.

Total Costs - Adding the cost savings due to cycle optimization (1.3 percent) to the direct manufacturing cost savings previously discussed (1.9 percent), yields a total engine manufacturing cost reduction of at least 3.2-percent.

Engine Maintenance Costs

The engine maintenance cost is comprised of preventive maintenance (inspection), overhaul, unscheduled maintentance (repair of failures), and incorporation of service bulletins.

The baseline costs for preventive maintenance, overhaul, and unscheduled maintenance are established from experience on similar applications. The incorporation of service bulletins is assumed to be 5 percent of the sum of the engine preventive maintenance cost, overhaul cost, and unscheduled maintenance cost.

The change in engine life (TBO) and the resultant effect in cost can be determined by using an engine overhaul cost model that may be expressed as a composite for the entire engine. The basic model for engine overhaul cost (EOC) is:

$$\text{EOC} = \sum_{\text{Module}} \left\{ (\text{BMOC}) \left(\frac{\text{BMTBO}}{\text{MTBO}} \right) \left(1 + \frac{1}{3} \left[\frac{\Delta\text{MMC}}{\text{BMMC}} \right] \right) \right\}$$

where:

BMOC = Baseline module overhaul cost (assumed at one-third manufacturing cost)

BMTBO = Baseline module time-between-overhaul

MTBO = Module time-between-overhaul

MMC = Module manufacturing cost

BMMC = Baseline module manufacturing cost

The module cost in the equation above is expressed as a fraction of engine cost.

The effect of engine unscheduled maintenance on cost, resulting from changes in reliability (MTBF), can be determined by using an engine repair cost model. The basic model for engine repair cost (ERC) is:

$$\text{ERC} = \sum_{\text{Module}} \left\{ (\text{BMRC}) \left(\frac{\text{BMMTBF}}{\text{MMTBF}} \right) \left(1 + \frac{3}{4} \left[\frac{\Delta\text{MMC}}{\text{BMMC}} \right] \right) \right\}$$

where:

BMRC = Baseline module repair cost

BMMTBF = Baseline module mean-time-between-failure

MMTBF = Module mean-time-between-failure

Replacing a hollow, thin walled, cooled turbine blade with a solid uncooled blade naturally results in a more rugged engine configuration. Such items as foreign object damage (FOD), recoating, particle erosion, etc., are more detrimental to a cooled turbine blade than a solid airfoil. Also, the reliability of the components supplying the blade cooling air no longer directly affects the blade life. Conservatively, assuming that this more rugged component will increase both the time-between-overhaul (TBO) and the mean-time-between-failure (MTBF) by only 10 percent, the resulting change in maintenance cost can be calculated as follows:

Baseline Maintenance Cost*

o	Engine Inspection	$\$ 600 \times 10^6$
o	Engine Repair	804×10^6
o	Engine Overhaul	3260×10^6
o	Incorporate Service Bulletins	233×10^6
	Total Cost	$\$4897 \times 10^6$

$$\text{ERC} = \$804 \times 10^6 \left\{ \left(\frac{\text{MTBF}}{1.1 \times \text{MTBF}} \right) \left(1 + \frac{3}{4} \left[\frac{\Delta\text{MMC}}{\text{MMC}} \right] \right) \right\}$$

if $\Delta\text{MMC} = 0$**

$$\text{ERC} = 804 \times 10^6 \left[\frac{1}{1.1} (1 + 0) \right]$$

$$\text{ERC} = \$731 \times 10^6$$

$$\text{EOC} = \$3260 \times 10^6 \left\{ \left(\frac{\text{MTBO}}{1.1 \times \text{MTBO}} \right) \left(1 + \frac{1}{3} \left[\frac{\Delta\text{MMC}}{\text{MMC}} \right] \right) \right\}$$

if $\Delta\text{MMC} = 0$**

*Based on 25-year life-cycle costs of the engines for a business jet fleet of 4000 aircraft.

**Manufacturing costs actually decrease when the DS turbine blades are incorporated; however, for this analysis the manufacturing cost difference was assumed equal to zero.

$$EOC = 3260 \times 10^6 \left[\frac{1}{1.1} (1 + 0) \right]$$

$$EOC = \$2964 \times 10^6$$

Revised Maintenance Costs

o	Engine Inspection	$\$\ 600 \times 10^6$
o	Engine Repair	731×10^6
o	Engine Overhaul	2964×10^6
o	Incorporate Service Bulletins	233×10^6
	Total Costs	$\$4528 \times 10^6$

$$\text{Reduced Maintenance Costs} = \frac{4897 \times 10^6 - 4528 \times 10^6}{4897 \times 10^6}$$

$$= 7.5 \text{ Percent}$$

CONCLUSIONS

A consistent process to produce solid directionally-solidified TFE731-3 high-pressure turbine blades using exothermically heated molds was developed at Jetshapes, Inc. The process produced acceptable directional-grain structures in four alloys and three turbine blade configurations. The alloys were: MAR-M 247; MAR-M 200+Hf; IN 792+Hf, and NASA-TRW-R.

Stress-rupture screening tests at 1033°K and 1255°K (1400°F and 1800°F) on bars machined from DS cast and heat treated blades of the four alloys showed MAR-M 247 to be the strongest of the four alloys and IN 792+Hf the weakest.

A 1505°K (2250°F) solution heat treatment developed for DS MAR-M 247 improved the stress-rupture strength of the alloy over the baseline strength established with the 1494°K (2230°F) solution treatment.

Property data to provide turbine blade design data was generated on MAR-M 247, MAR-M 200+Hf, and NASA-TRW-R as follows, with the bulk of the data generated on MAR-M 247.

(1) Mechanical properties

- Tensile tests in the range of room temperature to 1144°K (1600°F) on both longitudinal and transverse bars machined from blades.

- Stress-rupture tests over the temperature range of 1033°K to 1311°K (1400° to 1900°F) on longitudinal and transverse bars machined from blades.

- Low-cycle-fatigue tests at room temperature and 1033°K (1400°F).

- High-cycle-fatigue tests at room temperature and 1144°K (1600°F).

(2) Physical properties

- Thermal expansion and thermal conductivity over the range of room temperature to 1255°K (1800°F).

- Modulus of elasticity in the grain-growth direction over the range of room temperature to 1144°K (1600°F).

(3) Environmental resistance (bare and aluminide coated)

- Dynamic oxidation resistance at 1310°K (1900°F) for 510 hours.

- Hot-corrosion (sulfidation) resistance at 1200°K (1700°F) for 310 hours.

A new solid high-pressure turbine blade was designed for the TFE731-3 Engine to maximize aerodynamic efficiency and blade life using directionally-solidified MAR-M 247. A new turbine nozzle aerodynamically compatible with this blade was also designed. Minor redesigns were incorporated on other turbine components such as the disk, shrouds, nozzle retainers, etc., to allow testing in the TFE731-3 Engine.

Specifications and acceptance criteria for DS MAR-M 247 turbine blades were developed and are included as Appendices A and B of this report.

Exothermic DS cast turbine blades of MAR-M 247, MAR-M 200+Hf, and NASA-TRW-R were cast for engine testing. The NASA-TRW-R blades were eliminated from engine testing consideration due to "hot tears" in the platform.

Directionally-solidified blades of MAR-M 247 and MAR-M 200+Hf were finish processed through machining and coating, and were made available for TFE731-3 Engine testing. Other turbine hardware required for the test was manufactured and assembled into a factory test engine.

The incorporation of solid DS MAR-M 247 HP turbine blades into an optimized cycle TFE731-3 Engine would result in manufacturing cost reductions exceeding the 3.2-percent Project 1 goal.

The incorporation of solid DS MAR-M 247 HP turbine blades into the existing TFE731-3 Engine with a redesigned HP turbine would reduce engine weight by 1.04 percent, exceeding the Project 1 goal of 1.0 percent.

Maintenance costs of a TFE731-3 Engine with solid DS MAR-M 247 HP turbine blades would be reduced 7.5 percent due to greater blade durability, exceeding the Project 1 goal of 6.2 percent.

Engine test results and post-test evaluations are described in Volume II of this report.

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APPENDIX A

MAR-M 247 MATERIAL
SPECIFICATION

(2 Pages)

APPENDIX A
MAR-M 247 MATERIALS SPECIFICATION

1. APPLICATION

1.1 MAR-M 247 is a cast nickel-base superalloy used for turbine wheels, nozzles, and blades, at temperatures up to 1800°F.

2. APPLICABLE DOCUMENTS

2.1 The following documents form a part of this specification to the extent referenced herein.

2.1.1 AiResearch Specifications

EMS52300	Classification and Inspection of Castings
EMS52330	Master Heat Preparation of Nickel-Base Alloys
MC5014	Marking Requirements
C5041	Surface Cleaning Treatments for Corrosion- and Heat-Resistant Alloys

2.1.2 Aerospace Material Specification

AMS 2280	Trace Element Control, Nickel Alloy Castings

3. TECHNICAL REQUIREMENTS

3.1

Composition	Suggested Aim	Range
Carbon	0.15	0.13-0.17
Chromium	8.25	8.00-8.80
Molybdenum	0.70	0.50-0.80
Tantalum	3.00	2.80-3.30
Aluminum	5.50	5.30-5.70
Titanium	1.00	0.90-1.20
Hafnium	1.50	1.20-1.60
Boron	0.015	0.01-0.02
Zirconium	0.05	0.03-0.08
Cobalt	10.00	9.00-11.00
Tungsten	10.00	9.50-10.50
Manganese	--	0.20 Max.
Sulfur	--	0.015 Max.
Silicon	--	0.20 Max.
Iron		0.50 Max.
Nickel	Remainder	Remainder

3.1.1 Trace elements shall be controlled in accordance with AMS 2280, Class 2.

3.2 Production of master heats, remelting of master heats and pouring of castings shall be accomplished under vacuum.

3.3 A master heat shall be made from EMS52330, Class I material.

3.3.1 When specified, a master heat may be made from Class III material.

3.4 Castings shall be poured only from remelted master heat metal.

3.4.1 A master heat is previously refined metal of a single furnace charge.

3.5 Separately cast test bars shall be cast from every master heat and tested.

3.5.1 If the configuration permits, test specimens shall also be machined from cast parts.

3.5.1.1 Specimens may be machined from any area of the casting, unless otherwise specified.

3.5.2 Separately cast test bars may be either cast to size or cast oversize and machined.

3.5.3 Separately cast test bars shall be cast into the same type of refractory mold as the castings for which the master heat is to be used.

3.5.4 Any metal treatments, such as superheating and hot topping, to be used on castings shall also be used on separately cast test bars when qualifying the master heat for use in those castings.

3.6 All castings, including separately cast test bars, shall be cast into molds utilizing mold inoculation as used for grain size control.

3.7 Castings shall be supplied in the as-cast condition.

3.7.1 Cast parts shall be heat treated for 20 hours at 1600°F.

3.8 Cast parts after heat treat shall have a hardness of HRC 30-40.

4. PROCESS CONTROL

4.1 Castings shall be cleaned in accordance with AiResearch Specification C5041 as required.

4.2 Heat treatment shall follow all other thermal exposure, e.g., coating and brazing operations, which may occur during processing of parts.

5. INSPECTION

5.1 All castings shall be visually, penetrant-, and X-ray-inspected in accordance with EMS52300.

5.2 The supplier shall perform all testing for conformance to chemical limits.

5.3 The supplier shall perform all mechanical-property testing.

5.3.1 Test specimens shall be heat treated for 20 hours at 1600°F prior to testing.

FORM P5703-2

5.3.2 For mechanical-property testing, separately cast test specimens shall have a 0.25-inch-diameter gauge section 1 inch long between radii.

5.3.3 Tensile tests shall be performed with a strain rate of 0.005 inch per inch per minute through the yield point, at which time the strain rate may be increased to a cross head speed of 0.2 inch per minute.

5.3.4 Stress-rupture test specimens shall be tested under a constant stress of 105,000 psi at a temperature of 1400 (±5°F).

5.3.5 Stress-rupture test specimens shall be tested under a constant stress of 29,000 psi at 1800 ±5°F.

6. IDENTIFICATION AND PACKING

6.1 Each casting shall be identified with part number and master heat number in accordance with specification MC5014.

7. APPROVAL OR PROCUREMENT

7.1 To assure uniformity of quality, sample castings from new or reworked master patterns shall be approved by the purchaser.

7.2 Supplier shall use the same casting technique, including rate of cooling after casting, and, if heat treatment is specified, the same heat-treating procedure for production castings as for approved sample castings.

8. REPORTS

8.1 The supplier of castings shall furnish with each shipment a report listing the results of the mechanical-property tests, results of the chemical analysis, and a statement that the castings conform to the requirements of this specification.

8.1.1 This report shall include the purchase order number, master heat number and code symbol, if used, material specification number and its revision letter, part number, and quantity from each heat.

8.2 The supplier of finished or semifinished parts shall furnish with each shipment a report showing the purchase order number, materials specification number, contractor or other direct supplier of castings, part number, and quantity.

8.2.1 When castings for making finished or semifinished parts are produced or purchased by the parts supplier, the parts supplier shall inspect castings from each master heat or master heat lot represented and shall include in the report a statement that the castings conform, or shall include copies of laboratory reports showing the results of tests to determine conformance.

8.3 The supplier shall state in the report the relative proportion of revert or virgin material used in preparation of the master heat.

9. QUALITY CONTROL

9.1 Castings shall be uniform in quality and condition, sound, and free from foreign materials and from internal and external imperfections in excess of those allowed in EMS52300 for the specific class and grade.

9.2 At the option of AiResearch, a casting shall be selected from any castings received and shall be inspected in accordance with the applicable requirements for that part.

9.3 Parts and material not conforming to the requirements of this specification shall be rejected.

APPENDIX B

ACCEPTANCE STANDARDS FOR
DIRECTIONALLY SOLIDIFIED TURBINE BLADES

(7 Pages)

APPENDIX B

ACCEPTANCE STANDARDS FOR DIRECTIONALLY-SOLIDIFIED TURBINE BLADES

1. APPLICATION

1.1 This specification establishes the acceptance standards for directionally solidified MAR-M 247 turbine blades.

1.1.1 MAR-M 247 is a cast, nickel-base superalloy used for turbine wheels, nozzles, and blades at temperatures up to 1800°F.

1.1.2 When cast directionally solidified there is a significant improvement in creep-rupture properties as compared to conventionally cast material.

2. APPLICABLE DOCUMENTS

2.1 The following documents form a part of this specification to the extent referenced herein.

2.1.1 AiResearch Specifications

EMS55447 Nickel Alloy Castings, Investment, Corrosion - and Heat Resistant, MM-0011 (MAR-M247)

2.1.2 Military Specifications

MIL-I-6866 Inspection, Penetrant Method of

MIL-I-25135 Inspection Materials, Penetrant

MIL-STD-00453 Radiographic Inspection

2.1.3 Aerospace Material Specifications

AMS 2280 Trace Element Control

3. TECHNICAL REQUIREMENTS

3.1 Composition

3.1.1 Chemical composition shall be in accordance with EMS55447, with trace elements in accordance with AMS 2280, Class 2.

3.2 Master Heat Requirements

3.2.1 Castings shall be poured only from remelted master heat metal.

3.2.1.1 A master heat is previously refined metal of a single furnace charge.

3.2.2 The master heat shall be in accordance with EMS52330, Class I. The use of gates, sprues, risers, or rejected castings is not permitted.

3.2.3 Remelting of master heats and pouring of castings shall be accomplished under vacuum.

3.2.4 Master heats shall be qualified by testing specimens machined from blades.

3.2.4.1 If the blade design does not allow specimens to be machined from it, then blades P/N 3072111 shall be cast along with the other blades and test specimens shall be machined from these blades.

3.3 Grain Orientation

3.3.1 Prior to removal of DS starter material, each blade shall be chemically etched for a time sufficient to lightly reveal the grain orientation.

3.3.1.1 Etching procedures and recommended etching solutions are shown in Appendix I.

3.3.2 The leading and trailing edges shall consist of a single grain with no grain boundary intersection (termination) at the leading and trailing edges.

3.3.3 Columnar grains shall be parallel within 15° of the major axis of the airfoil.

3.3.4 Divergence or convergence between any two columnar grains shall be less than 20°.

3.3.5 The airfoil midspan chord shall consist of a minimum of 5 grains, with no single grain exceeding 40% of the width.

3.3.6 No equiaxed grains are permitted in the blade.

3.3.7 All columnar grains which extend into any part of the finished casting dimensions must originate within a chill zone no greater than 3/16 inch above the chill block surface.

3.4 Heat Treatment

3.4.1 All blades shall be solution heat treated prior to any abrasive blasting operation after removal of the castings from the mold.

3.4.1.1 Solution heat treat blades at 2250°F $\pm 10°$ in vacuum for 2 hours. Blades shall be rapid inert gas cooled to below 1800°F.

3.4.2 Following solution heat treatment, blades to be tested shall be given a simulated coating cycle of 1800°F ± 25 for 5 hours and still air cooled, followed by aging at 1600°F ± 25 for 20 hours.

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3.5 Metallographic Inspection

3.5.1 A blade from each heat treat lot shall be metallographically examined for incipient melting and gamma-prime solutioning, for information only. A 500X photomicrograph of a representative area shall be submitted to AiResearch Receiving Inspection for transmittal to Materials Engineering.

3.6 Mechanical Properties

3.6.1 Tensile test specimens, machined from fully heat treated blades, tested at room temperature shall meet the following minimums:

Ultimate tensile strength (ksi)	140
0.2 percent yield strength (ksi)	120
Elongation (percent in 4D)	7.0
Reduction of area (percent in 4D)	7.0

3.6.2 Stress-rupture test specimens machined from fully heat treated blades, tested at a temperature of 1400°F ±5° and a stress of 105,000 psi shall have a minimum life of 80 hours.

3.6.3 Stress-rupture test specimens machined from fully heat-treated blades tested at 1800°F ±5° and a stress of 30,000 psi shall have a minimum life of 60 hours.

3.7 Surface condition

3.7.1 The maximum depth of intergranular attack allowable after any processing is 0.0005 inch.

3.7.2 Blade surfaces shall show no evidence of recrystallization, alloy depletion, or carbide oxidation.

4. PROCESS CONTROL

4.1 Cooling rate from solution-heat-treat temperature shall be sufficiently fast to meet mechanical properties.

4.2 Solution heat-treat furnaces shall be qualified by the casting supplier and approved by AiResearch.

4.2.1 To qualify a furnace, the casting supplier must heat treat a minimum of 15 blades in a furnace loaded to the maximum production heat treat capacity, and test to the mechanical-property requirements (five blades per condition). A simulated load by weight may be used.

5. INSPECTION

5.1 Visual Inspection - All blades shall be inspected in accordance with Table I.

5.2 Fluorescent Penetrant Inspection

5.2.1 All blades shall be processed per MIL-I-6866 with a Group V or VI level penetrant per MIL-I-25135.

5.2.2 Fluorescent penetrant indications shall be correlated with the allowable visual imperfections and the accept/reject criteria of Table II.

5.2.3 Evaluation of smeared or unsharp indications may be performed by wiping the indication one time only with a swab or brush dipped in solvent.

5.3 Radiographic Inspection - All blades shall be radiographically inspected per MIL-STD-00453 to the acceptance standards defined in Table III.

5.4 Master heats shall be tested by the casting supplier for conformance to chemical limits. Chemical tests shall be performed on a blade cast from the master heat.

5.4.1 Overall chemistry may be determined at any location within the blade. Hafnium shall be determined at both the tip and the root of the blade.

5.5 Master heats shall be tested by the casting supplier for mechanical properties. A minimum of three specimens for each test condition shall be tested.

5.6 The casting supplier shall test two blades from each solution-heat-treat lot, one in tensile and one at the higher temperature creep-rupture conditions of EMS52332, to verify conformance to the mechanical-property requirements.

5.7 A sample from each heat-treat lot received shall be inspected by AiResearch for intergranular attack, recrystallization, alloy depletion, and carbide oxidation.

6. IDENTIFICATION AND PACKING

6.1 Each casting shall be identified with part number and master heat number in accordance with specification MC5014.

7. APPROVAL OR PROCUREMENT

7.1 Approval of the supplier's fixed process and process changes shall be in accordance with EMS52332.

8. REPORTS

8.1 The supplier of castings shall furnish to AiResearch Receiving Inspection with each shipment a report listing the results of the mechanical-property tests for each solution-heat-treat lot and master heat, the results of the chemical analysis from one casting per master heat representing the part number shipped, and a statement that the castings conform to the requirements of this specification.

8.1.1 This report shall include the purchase order number, master heat number and code symbol, if used, solution-heat-treat number, material specification number and its revision letter, part number, and quantity from each heat.

8.2 The supplier of finished or semifinished parts shall furnish with each shipment a report showing the purchase order number, materials specification number, contractor or other direct supplier of castings, part number, and quantity.

8.2.1 When castings for making parts are produced or purchased by the parts supplier, the parts supplier shall inspect castings from each master heat or master heat lot represented and shall include in the report a statement that the castings conform, or shall include copies of laboratory reports showing the results of tests to determine conformance.

9. QUALITY CONTROL

9.1 Castings shall be uniform in quality and condition, sound, and free from foreign materials and from internal and external imperfection in excess of those allowed in this specification.

9.2 All parts received by AiResearch after approval of the supplier's fixed process shall be sampled in accordance with an established statistical control plan. The sample shall be submitted to Materials Engineering on a CMR for mechanical-property testing, verification of chemistry, metallographic examination, and inspection of surface condition.

9.2.1 Failure to meet the fixed process established control limits indicates probability of a fixed process change. (See Approval or Procurement section.)

9.3 Parts and material not conforming to the requirements of this specification shall be rejected.

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TABLE I. VISUAL ACCEPTANCE CRITERIA.

AREA			VISUAL IMPERFECTIONS (7)(9)				
			NEGATIVES		POSITIVES (3) (5) (6)		NONINTERPRETABLE (1) (2)
			Dia.	Depth	Dia.	Height	
AIRFOIL	A		.010	.010	.010	.005	Max. of 5 per .25 x .25 area.
AIRFOIL	B		.015 (4)	.010	.020	.005	Max of 10 per .25 x .25 area.
PLATFORMS			.010	.010	.020	.005	Max. of 5 per .25 x .25 area.
BASE	AS CAST		(8)	(8)	(6) (8)	(6) (8)	(8)
BASE	MACHINED		.010	.010	N/A	N/A	Max. of 5 per .25 x .25 area

(1) Generally porosity, concentrated in local areas with no individual indication exceeding .010 dia. x .010 depth.
(2) Limited to 2 areas per surface.
(3) .010 parting line allowed in fillet radii, .003 max. on leading and trailing edges.
(4) A cluster of these indications not to exceed .125 dia. and should be separated by .25 of good area.
(5) A cluster of these indications should not exceed 5 per .25 x .25 area and 2 areas per surface.
(6) Gate witness of .030 allowed on stock added surfaces.
(7) Thru or like imperfections appearing on opposite sides are not acceptable providing they are interpretable.
(8) Indications which will be removed in machining are acceptable.
(9) Linear, cold shut, or crack-like imperfections are not acceptable.

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TABLE II. FLUORESCENT PENETRANT ACCEPTANCE CRITERIA.

AREA		PENETRANT INDICATIONS (3) (6)	
		INDIVIDUAL BLEED OUT	NONINTERFERE-TABLE (1) (2)
AIRFOIL	A	.010	Max. of 5 per .25 x .25 area
	B	.030 Dia. (5)	Max. of 10 per .25 x .25 area
PLATFORMS		.030 Dia. (5)	Max. of 5 per .25 x .25 area
BASE	AS CAST	(4)	(4)
	MACH-INED	.010	Max. of 5 per .25 x .25 area

(1) Generally porosity, concentrated in local areas with no individual indication exceeding .010 dia. x .010 depth.
(2) Limited to 2 areas per surface.
(3) Thru or like imperfections appearing on opposite sides are not acceptable providing they are interpretable.
(4) Indications which will be removed in machining are acceptable.
(5) A cluster of these indications not to exceed .125 dia. and should be separated by .25 of good area.
(6) Linear, cold shut, or crack-like imperfections are not acceptable.

TABLE III. RADIOGRAPHIC ACCEPTANCE CRITERIA.

BLADE AREA	RADIOGRAPHIC INDICATIONS			
	Elongated	Round or oval	Limits	Spacing Factor (2)
A	none	.020	2 areas per blade	5 x
B	.030	.040	(1) max. of 3 per blade	2 x
BASE	none	.020	2 areas per surface	5 x

(1) Maximum of two at a single radial position.
(2) Minimum spacing between indications is determined by circumscribing a circle around the larger indication and multiplying its diameter by the spacing factor.

ACID ETCHING METHODS

This appendix offers alternate methods for etching cast blades prior to inspection. These etching methods are utilized to accomplish two purposes, (1) to obtain an etch sufficient to expose grain boundaries prior to macrograin inspection, and (2) to obtain a cleaning etch. When specified, the cleaning etch shall be used prior to fluorescent-penetrant inspection.

CAUTION: Mixing of solutions and etching of parts must be accomplished in an area with adequate exhaust ventilation, as toxic fumes are liberated from the etchants.

Method 1

Etching Solution:

	100 gal	Approx. 1 liter
Muriatic Acid (20° Be)	80 gal	757 ml
Anhydrous Ferric Chloride, $FeCl_3$	135 lbs	154 g
Nitric Acid (42° Be)	2 gal	19 ml
Water	11 gal	106 ml

1 Add ferric chloride to muriatic acid. Allow to dissolve.
2 Add nitric acid.
3 Add water.

a) A new solution shall be prepared when a suitable etch is not obtained within 12 minutes.
b) Do not replenish to maintain volume.

Procedure:

1. Load parts in etching basket, keeping level below basket rim.
2. Immerse parts basket in etching solution maintained at room temperature (75-100°F).
3. Check progress of etch after 6 minutes and every 2 minutes thereafter by removing one casting, rinsing, and visually inspecting progress of etch. Once the etch time required is established for that particular run of castings, the following loads can be run without checking. Typical etching time is 6-10 minutes.

   a) Immersion time for cleaning etch shall be 20-30 seconds.
4. Remove from etching solution and rinse in clean, cold water.
5. Immerse in alkaline cleaner solution for 3 minutes.
6. Remove from cleaner and rinse in clean, cold water.
7. Air-water nozzle scrub each individual casting clean.
8. Blow loaded basket free of excess water with air only.

Method 2

Etching Solution:

		Approx 2 liters
Muriatic acid (20° Be)	90% by vol	(1615 ml)
Glacial acetic acid	5% by vol.	(85 ml)
Nitric acid (42° Be)	5% by vol.	(85 ml)
Ferric chloride	to saturation	(12.5 lbs)

1. Add acetic acid to muriatic acid while cautiously agitating the mixture.
2. Gently heat the mixture and add sufficient ferric chloride to raise the boiling point to 150-160°F.
3. Cool saturated solution to <100°F, then cautiously add nitric acid while agitating the etchant. CAUTION: Never add nitric acid to the etchant when temperature is above 100°F.

   a) The etchant shall be discarded when the etching time requires more than two minutes to delineate the macrograin structure.

Procedure:

1. Pack parts in suitable tray or basket so that airfoils do not come in contact with each other.

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2. Immerse in acid etchant (150 ±10°F) for a minimum length of time to bring macro-grain structure visible to unaided eye. Maximum exposure time in the etchant shall be limited to two minutes. The etchant or parts shall be agitated to aid in obtaining uniform etching and to minimize the exposure time.

   a) Immersion time for cleaning etch shall be 10-20 seconds.

3. Rinse thoroughly in running tap water.
4. Desmut by immersing in concentrated hydrogen peroxide (H_2O_2, 35 percent). Hand brush or air-water power flush surfaces of the etched parts to remove residual smut.
5. Rinse in running tap water.
6. Rinse in hot tap water and dry.

Method 3

Etching Solution:

Muriatic acid (20° Be)	90% by vol.	
Hydrogen Peroxide (30-35%)	10% by vol.	(or sufficient quantity to obtain a satisfactory etch)

1. Add hydrogen peroxide to muriatic acid while cautiously agitating the mixture.

   a) Make up solution just prior to usage.
   b) Whenever possible, the etching solution container should be immersed in a tap water rinse tank for the purpose of dissipating the heat liberated during the etching process, so that an etching time cycle can be established.
   c) The etchant shall be discarded when the etching time requires more than five minutes to delineate the macrograin structure.

Procedure:

1. Pack parts in suitable tray or basket so that airfoils do not come in contact with each other.
2. Immerse in acid etchant maintained at room temperature (75-100°F) for a minimum length of time (5 min. max.) to bring macrograin structure visible to unaided eye when inspecting for grain size and casting irregularities.

   a) Immersion time for cleaning etch shall be 10-25 seconds.

3. Rinse in running tap water. Hand brushing or air-water power flushing may be required if residual smut is not removed during the rinse cycle.
4. Rinse in hot tap water and dry.

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15. Supplementary Notes

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16. Abstract

A low-cost process for manufacturing high stress-rupture strength directionally-solidified high-pressure turbine blades was successfully developed for the TFE731-3 Turbofan Engine. This development was the result of Project 1 of the Materials for Advanced Turbine Engines (MATE) Program, a five-year cooperative Government/Industry effort. The goals of this project were to: (1) reduce engine specific fuel consumption (SFC) at least 1.7 percent; (2) reduce engine manufacturing costs at least 3.2 percent; (3) reduce engine weight at least 1 percent; and (4) reduce engine maintenance costs at least 6.2 percent. These benefits were anticipated by the substitution of solid, uncooled directionally-solidified turbine blades for hollow, cooled, equiaxed-grain, turbine blades.

Task I established the basic processing parameters using MAR-M 247 and employing the exothermic directional-solidification process in trial castings of turbine blades. Task II evaluated the nickel-based alloys MAR-M 247, MAR-M 200+Hf, IN 792+Hf, and NASA-TRW-R as directionally-solidified cast blades. Task III further evaluated the three alloys with the highest stress-rupture strengths. In Task IV a new turbine blade, disk, and associated components were designed using previously determined material properties. Task V manufactured sufficient DS blades and other hardware for the required engine testing. Task VI subjected exothermically-cast directionally-solidified turbine blades of MAR-M 247 and MAR-M 200+Hf to engine test. Task VII analyzed the engine test results and compared the results to the originally established goals.

Results of Project 1 showed that the stress-rupture strength of exothermically heated, directionally-solidified MAR-M 247 turbine blades exceeded program objectives and that the performance and cost reduction goals were achieved.

17. Key Words (Suggested by Author(s))		18. Distribution Statement
Turbine-Blade	Columnar-Grain	Star Category 26
Directional-Solidification	MAR-M 247	
Alloy-Selection	MAR-M 200+Hf	
Ni-base Alloys	IN 792 + HP	
Investment Casting	NASA-TRW-R	
Exothermic-Heating		

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