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VOLUME 2 OF 2
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NASA

# MATERIALS FOR ADVANCED TURBINE ENGINES

## PROJECT COMPLETION REPORT
## PROJECT 1

# LOW-COST DIRECTIONALLY-SOLIDIFIED TURBINE BLADES

## VOLUME II

by

R. E. Dennis

G. S. Hoppin III

L. G. Hurst

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

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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 exothermically-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. T. Saunders, C. P. Blankenship, and R. L. Dreshfield of the Materials and Structures Division of NASA-Lewis Research Center. Volume II of this report deals with the engine testing and post-test evaluation tasks of this project. Major contributions to the success of the testing and post-test evaluations were made by Lorenzo Escriche' and S. D. Tannenbaum of AiResearch.

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## TABLE OF CONTENTS



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## LIST OF ILLUSTRATIONS

LIST OF TABLES

# 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 Project 1 of NASA Contract NAS3-20073 to develop a new material technology for manufacturing low-cost, directionally-solidifed (DS), uncooled cast turbine blades to reduce both the cost and fuel consumption of the TFE731-3 Turbofan Engine. The process development included those efforts required to carry the technology from the previously demonstrated feasibility stage through component demonstration by engine testing. 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.

The intent of Project 1 was to develop a process to produce an uncooled (solid) DS turbine blade, and to design and substitute this blade for the hollow, air-cooled, conventionally-cast turbine blade utilized in the high-pressure (HP) turbine of he 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.

To develop this blade and to accomplish these goals, 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 |

Volume I of this report covers the work accomplished in Tasks I through V. This document, Volume II, covers the Task VI Full-Scale Engine Testing and the Task VII Post-Test Evaluation. The last section of this volume includes recommendations concerning the future of uncooled DS HP turbine blades in general aviation turbofan engines.

The results of Tasks VI and VII--project completion information--are restricted by the NASA FEDD (For Early Domestic Dissemination) policy. The FEDD legend, describing the requirements of this policy, is printed on the cover of this document.

## SUMMARY

The project accomplishments included the successful development of the exothermically-heated DS casting process into a viable method for producing solid TFE731-3 HP turbine blades of a new design. High quality DS blades were cast for engine testing of MAR-M 247 and MAR-M 200+Hf alloys. These blades were finish processed through heat treatment, machining, and coating operations prior to engine testing. The goal to reduce the specific fuel consumption (SFC) of the TFE731-3 by at least 1.7 percent was exceeded with the new uncooled, high efficiency airfoil. The significant accomplishments of this phase of the project are as follows:

- The specific fuel consumption was reduced 2.4 percent with the uncooled DS blades.

- The 150 hours of typical engine testing (three 50-hour tests) were completed without incident or any turbine blade distress.

Task I of the project established a DS casting process for solid MAR-M 247 HP turbine blades employing an exothermically-heated ceramic mold. Baseline tensile and stress-rupture strengths for DS MAR-M 247 turbine blades were determined. Good reproducibility was shown with the 0.178-cm (0.070-inch) gauge diameter test specimens (minibars) machined from the DS blades. Thus, the minibar was utilized 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. The IN 792+Hf alloy was dropped from the project, as its stress-rupture strength was substantially inferior to the other three alloys. A solution heat-treatment temperature of 1505°K (2250°F) was found to produce more consistent and higher stress-rupture lives in the three remaining alloys than the 1494°K (2230°F) 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, and low- and high-cycle fatigue tests were conducted.

An uncooled turbine blade design tailored to the mechanical properties of the strong DS cast alloys was developed in Task IV. To accommodate the uncooled final design blades, modifications were made to the turbine disk, nozzle, and other high-pressure 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. A "hot-tear" castability problem with the NASA-TRW-R alloy eliminated this alloy from further consideration, and only MAR-M 247 and MAR-M 200+Hf blades were processed into engine test parts. Approximately two-thirds of the finish-processed blades were MAR-M 247.

The results of the first five project tasks and the achievement of their related goals are presented in Volume I (NASA CR-159464). The results of the final two tasks--Task VI, Engine Testing and Task VII, Post-Test Evaluations--are presented in this document (Volume II).

The Task VI engine testing was successfully completed. The required 150 hours of testing consisted of the following three 50-hour test sequences:

- 50 hours of simulated cruise cycling--high-cycle-fatigue (HCF) evaluation

- 50 hours at the maximum continuous power rati stress-rupture endurance evaluation

- 50 hours of cyclic endurance--low-cycle-fatigue (LCF) evaluation

None of the blades subjected to the 150 hours of engine testing visually showed any detrimental effects from the testing. This was verified by the post-test metallurgical evaluation of the blades during Task VII.

As a direct result of this successful component development and engine testing program, AiResearch has committed the MATE DS blade (same part number) to be the bill-of-material HP Turbine Blade on the certification testing program for the TFE731-3-100 Engine. This certification program was initiated in early 1979 and completion is estimated to be in late 19b[illegible].

## TASK VI - ENGINE TESTING

### Scope

The objectives of the Task VI Engine Testing were to: (1) verify the anticipated reduction in SFC with the DS turbine blades; and (2) prove the durability of both the material and the design of the new blade. The program required that the HP blades produced in Task V be subjected to 150 hours of typical engine operating conditions in an AiResearch TFE731-3 Engine.

The Task VI Engine Testing of the fully processed HP turbine blades consisted of back-to-back performance tests followed by three 50-hour endurance test segments chosen by AiResearch and approved by NASA. The performance test was designed to compare a TFE731-3 Engine in a production configuration with the same engine with only one modification--the MATE Project 1 DS turbine blades. The three 50-hour test segments, in the order performed, were designed to evaluate the resistance of the DS blade to high-cycle-fatigue, stress-rupture, and low-cycle-fatigue. These test conditions were chosen to allow direct comparison of the DS blades produced in this project with the production, conventionally cast, cooled, IN100 HP turbine blades. The test cycles for these three test segments are shown in Figures 1, 2, and 3. The blade substitution schedule presented in Table I was utilized to expose groups of test blades to singular and multiple loading conditions established by the test parameters of the three 50-hour tests. This substitution plan permitted comprehensive post-test evaluation of the individual and combined effects of the three test loadings by both nondestructive and destructive techniques.

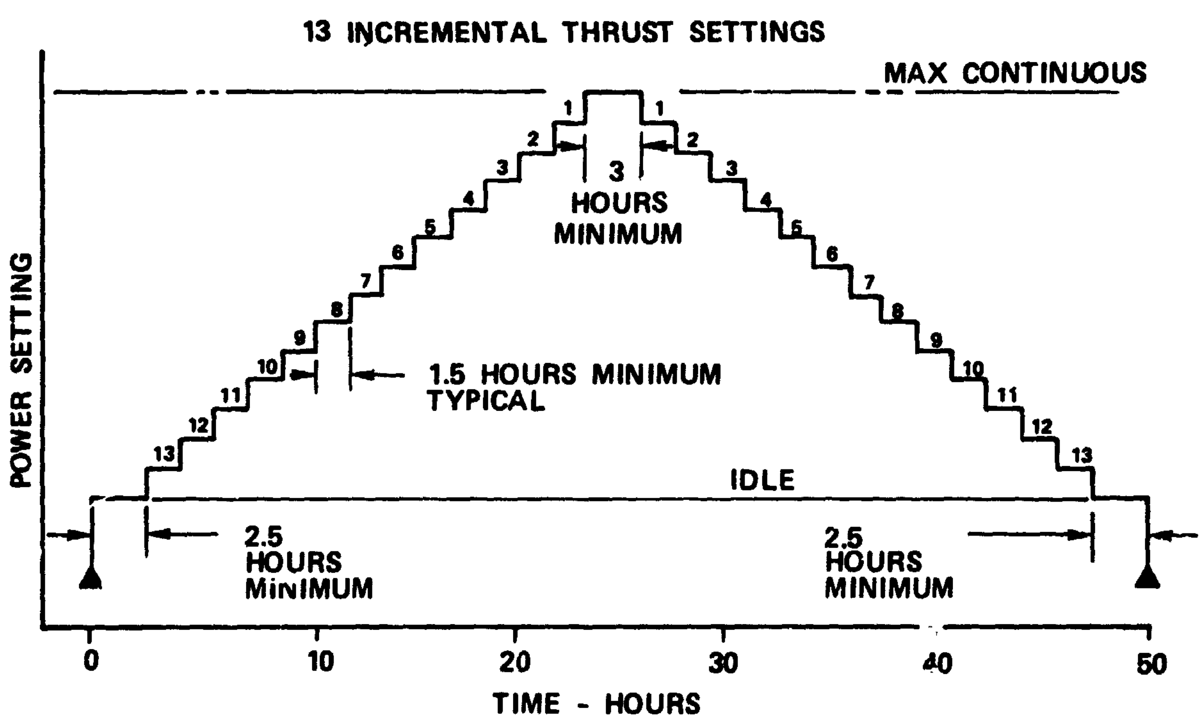


Figure 1. First 50-Hour Test -- High-Cycle-Fatigue Evaluation

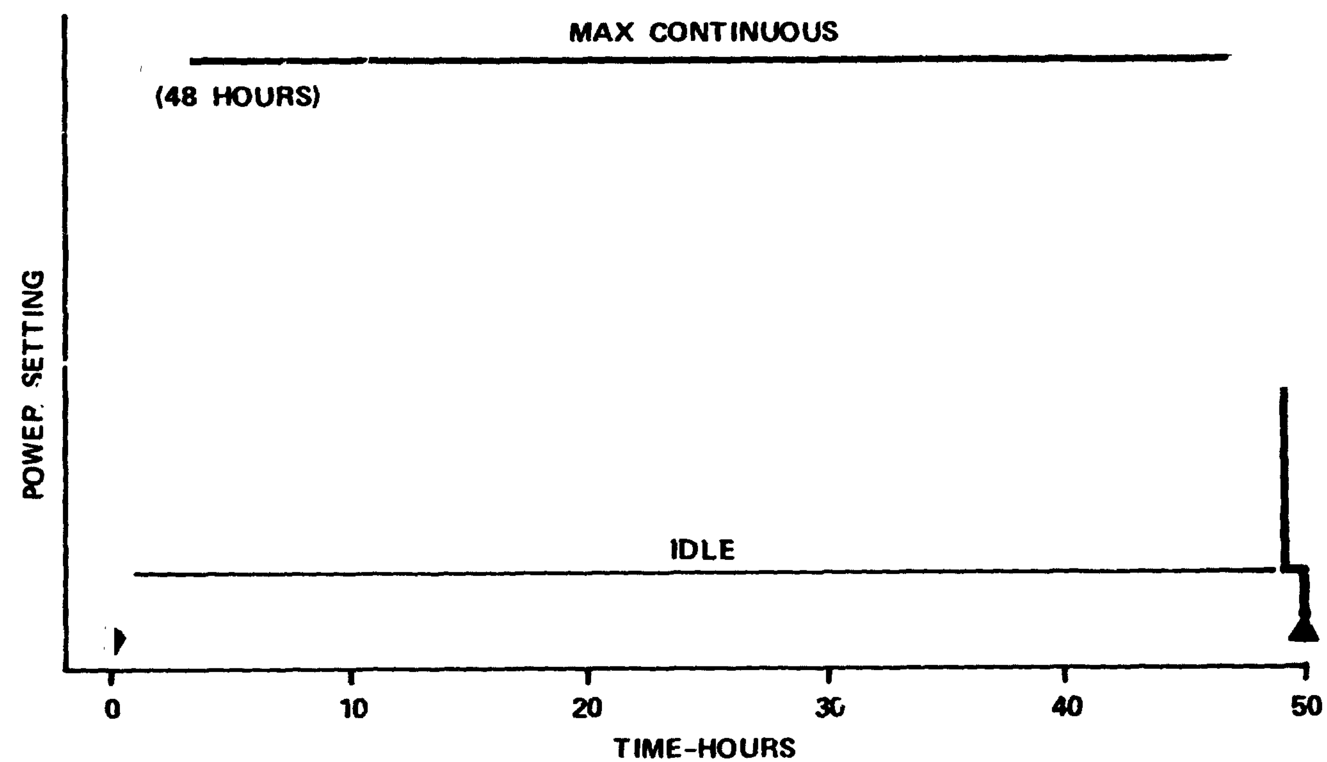


Figure 2. Second 50-Hour Test -- Stress-Rupture Evaluation

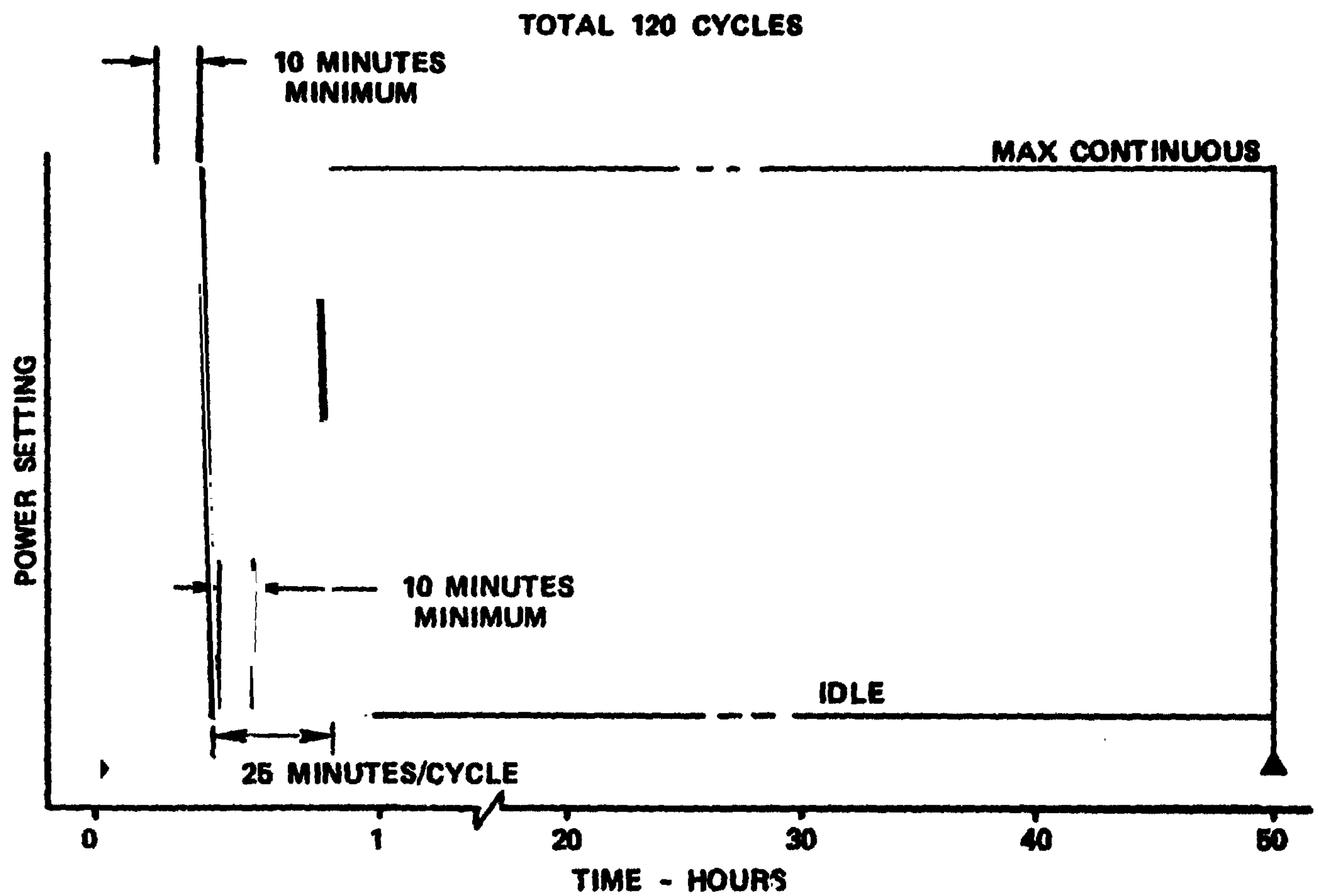


Figure 3. Third 50-Hour Test -- Low-Cycle-Fatigue Evaluation
(Normal Accels and Decels Required)

TABLE I. MATE PROJECT 1 ENGINE TEST BLADE SUBSTITUTION PLAN

| Material | Number of Blades to be Tested at the Following Conditions Prior to Inspection | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | A | B | C | A+B | A+C | B+C | A+B+C | Totals |
| MAR-M 247 | 4 | 4 | 4 | 4 | 4 | 4 | 35 | 59 |
| MAR-M 200+Hf | 3 | 3 | 3 | 3 | 3 | 3 | 6 | 24 |
| Totals | 7 | 7 | 7* | 7 | 7* | 7* | 41* | 83 |

A = 50-Hour High-Cycle Fatigue Evaluation (refer to Figure 1)

B = 50-Hour Stress-Rupture Evaluation (refer to Figure 2)

C = 50-Hour Low-Cycle Fatigue Evaluation (refer to Figure 3)

*Blades in engine at end of 150-hour test

## Final Preparation of the Engine and Hardware

A Model TFE731-3 Engine, Serial Number 7502, was selected as the development engine for the 150-hour test series. All of the testing for this project, including the back-to-back performance tests were performed with this engine, thereby minimizing the possibility of anomalous results. The remote AiResearch test facility at San Tan, Arizona, was utilized for all of the engine testing for this project. Figure 4 presents a photograph of the engine installed at the facility.

To ensure that the test engine met production standards, all of the seal shrouds, rotors, and turbine and compressor shrouds were inspected for clearances and repaired where required before testing. Repairs consisted of respraying abradable shrouds or replacing rotors as necessary. The engine hardware was also cleaned and fluorescent-penetrant inspected prior to the standard engine assembly procedure.

## Test Series

The order of testing consisted of two back-to-back performance tests followed by the three 50-hour endurance tests. The back-to-back performance test consisted of two standard 6-point calibration runs as shown in Table II. The first test was run with the engine in the standard production configuration, and the second test was run after the engine was rebuilt with the MATE DS turbine hardware. Only the hardware required to incorporate the MATE blades in the turbine section were changed for this test.

During the performance test with the MATE hardware, a problem developed with the turbine shroud segments. In the production configuration the cooling air that exits from the tips of the cooled turbine blades reduces the temperature of the turbine shrouds; but with the uncooled MATE blades, the cooling air was

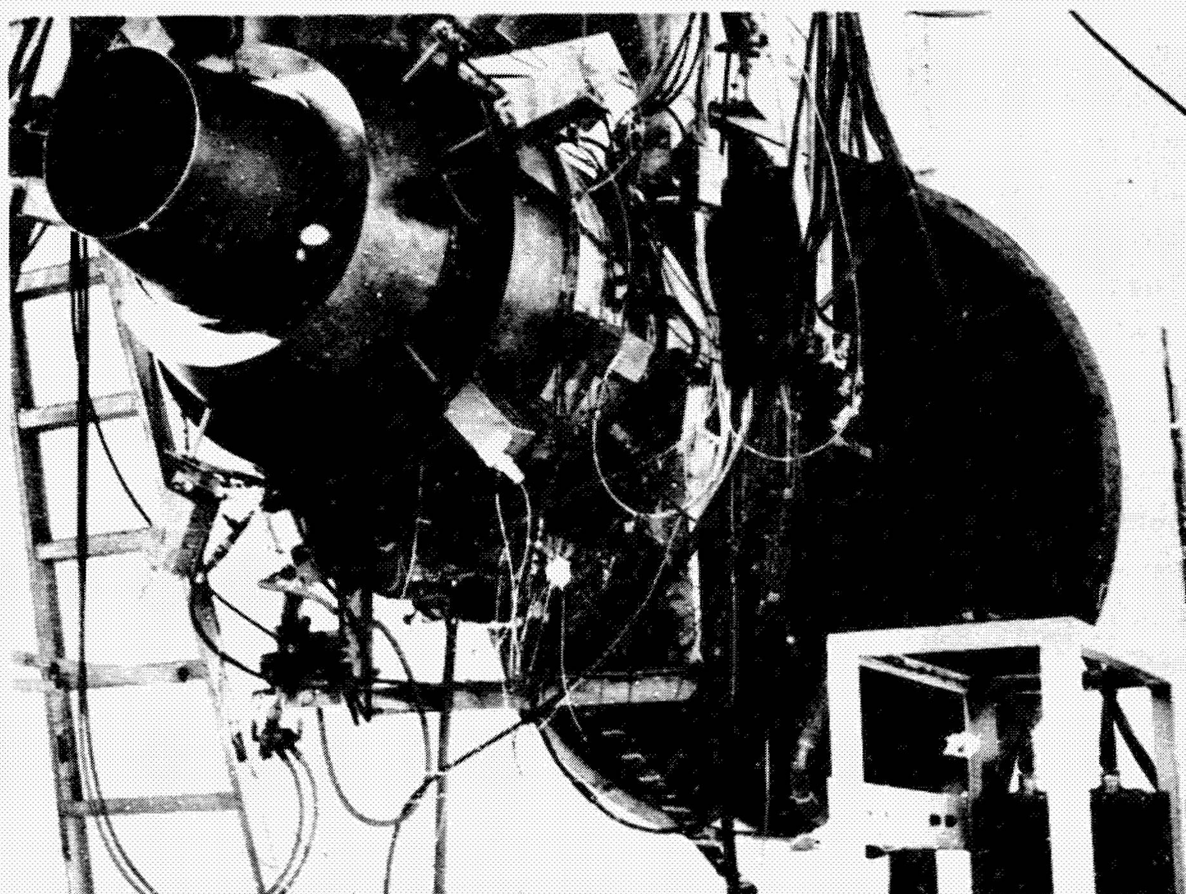

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Figure 4. Model TFE731-3 Engine Installed in the Remote
Test Facility at San Tan, Arizona



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TABLE II. SIX-POINT PERFORMANCE CALIBRATION SCHEDULE

| Test Point | Thrust |
|---|---|
| 1 | Idle |
| 2 | Maximum Continuous (MC) |
| 3 | 90-percent MC |
| 4 | 75-percent MC |
| 5 | 50-percent MC |
| 6 | 25-percent MC |

Note: Each test point stabilized 6 minutes minimum prior to recording the required performance data.

eliminated causing the shroud segments to run hotter. The clearance gaps between the shroud segments had not been increased to allow for the greater thermal expansion of the hotter individual shrouds. Thus, the shroud segments could not freely expand circumferentially, and local buckling occurred that forced the ends of two shroud segments to move radially inward. This buckling eliminated the blade-to-shroud clearance and caused a blade-tip rub. This rub, approximately 0.015-cm (0.006-inch) deep, removed the blade coating from the tips but did not result in any blade failures. The condition of a typical blade after the rub is shown in Figure 5. Figure 6 is a view of the complete rotor with the DS blades after the performance test.

When the performance data was reduced to standard-day conditions, it indicated that:

- o The baseline (standard) engine was well within production test limits. This engine, after the addition of the MATE DS blades, showed a substantial performance improvement.

- o The performance of the MATE DS blades in the test engine was excellent and exceeded the MATE goal of reducing SFC by 1.7 percent. The measured reduction in SFC at sea-level take-off conditions was 2.4 percent of which approximately 1.3 percent was attributed to the elimination of blade cooling air and 1.1 percent to a more efficient aerodynamic design with the thinner uncooled MATE airfoil.

The tip-rub experience during the performance run removed approximately 0.015 cm (0.006 inch) from the tips of the tested blades. After disassembly and inspection of the engine, the rubbed blade tips were deburred to eliminate any sharp corners. No attempt was made to recoat the local areas near the rub zone

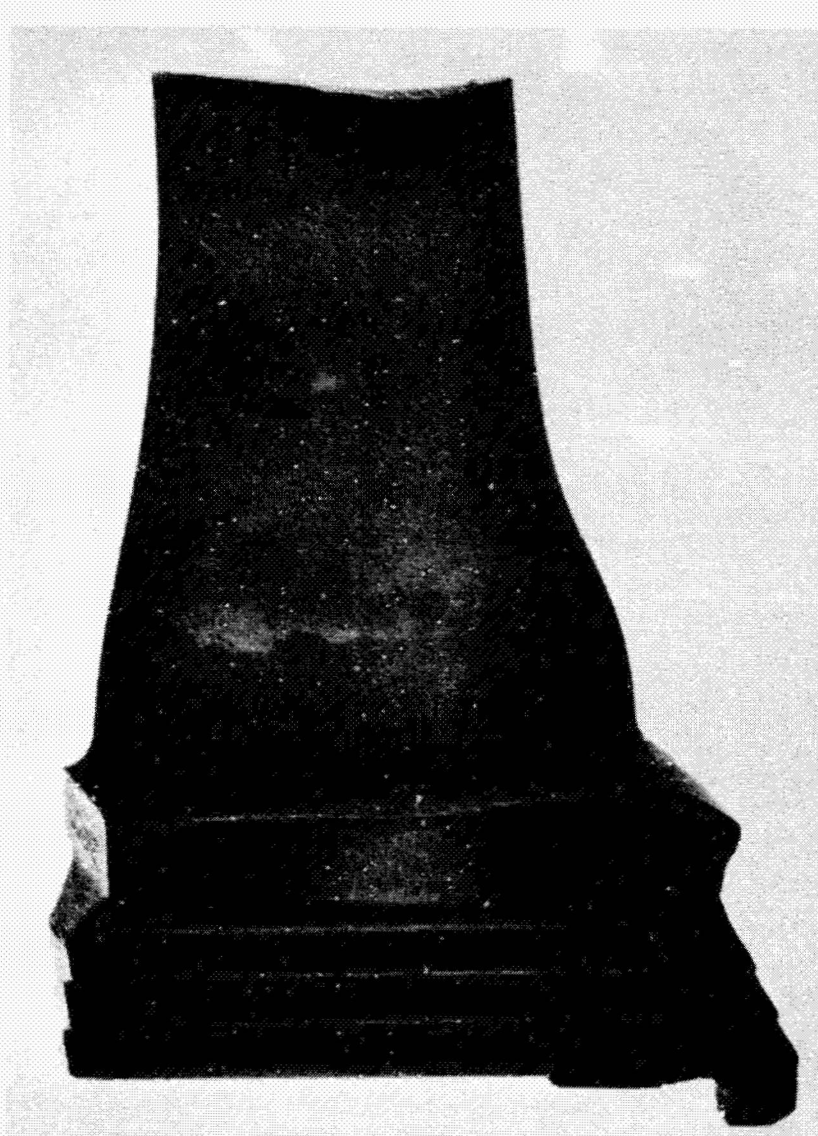

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Figure 5. MATE DS Turbine Blade After Tip-Rub

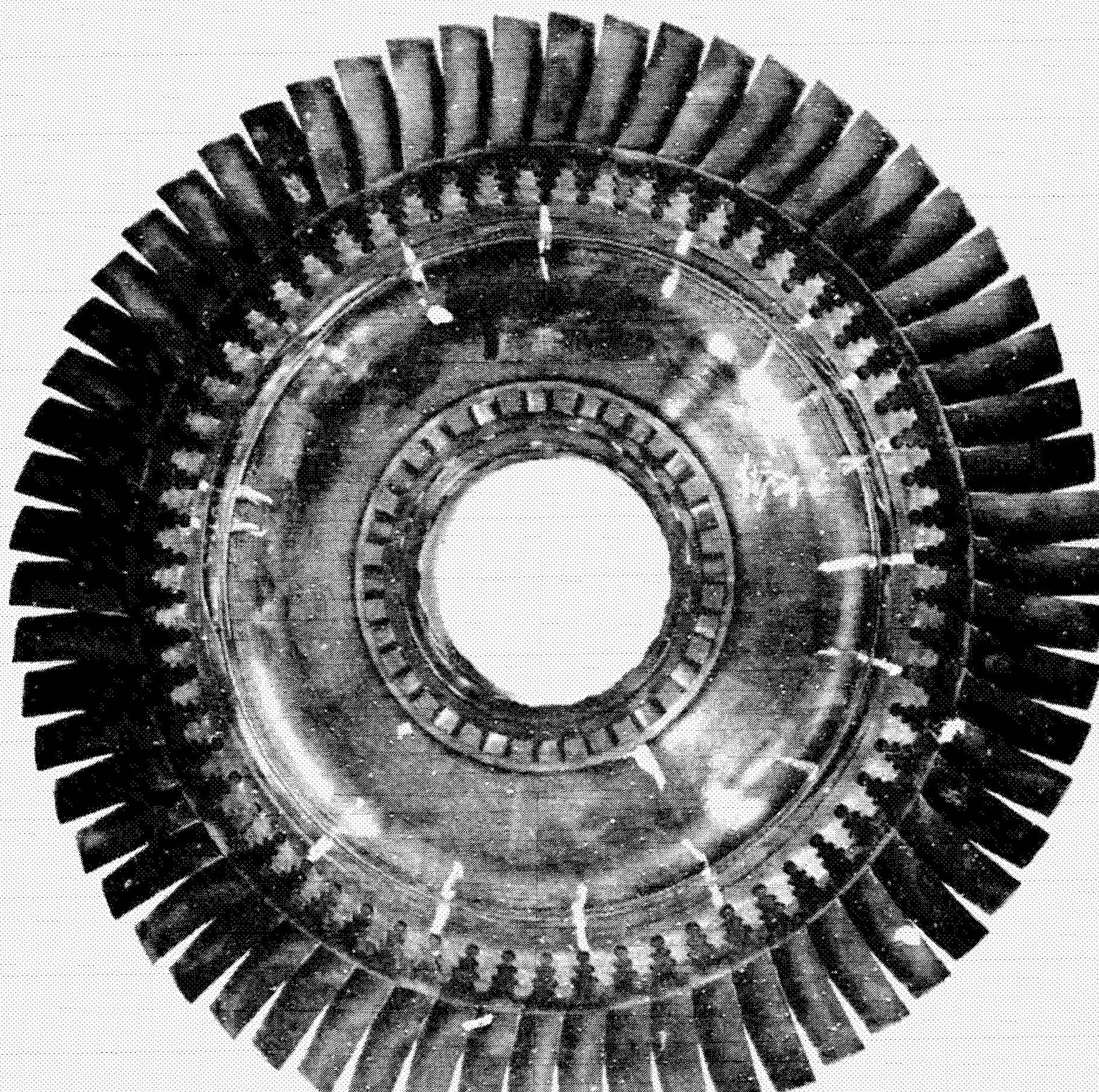

Figure 6. High-Pressure Turbine Disk With DS Blades After the Back-To-Back Performance Tests (Note the Appearance of the Blade Tips )



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prior to further testing. All new blades that were substituted into the disk were trimmed an equivalent amount to provide a uniform rotor-tip diameter. The wheel was assembled, balanced, and then installed in the engine. New shroud segments were procured with their chords trimmed 0.025 cm (0.010 inch) to allow for the additional circumferential thermal growths.

A vibratory problem not associated with the tip-rub was noted during the performance testing at the Flight Idle (Test Point No. 6) with a first-torsional resonance. This vibratory problem was eliminated by substituting a standard TFE731-3 36-vane stator for the 26-vane stator designed for the DS blade and used in the performance testing. Both stators are shown on the Interference Diagram in Figure 7. The production 36-vane stator did not present any severe performance penalties and was utilized for the remainder of the MATE DS blade endurance testing. This substitution was confirmed by back-to-back performance tests with the 26- and 36-vane stators.

The test cycle followed for the first 50-hour endurance test is shown in Figure 1. Standard instrumentation was utilized throughout the endurance testing. No operating problems occurred during this test, and all test parameters were within limits. Post-test inspection of the DS blades and other hardware revealed no significant distress of the DS blades or any other component, and the blades were removed for evaluation in accordance with the blade substitution plan shown in Table I. The rotor was then rebalanced with the new blades, and the engine was reassembled for the second 50-hour endurance test.

The stress-rupture-endurance test cycle used in the second 50-hour test is depicted in Figure 2. Again, no engine testing problems were encountered and no distressed parts were found during the post-test inspection. The rotor was reassembled,

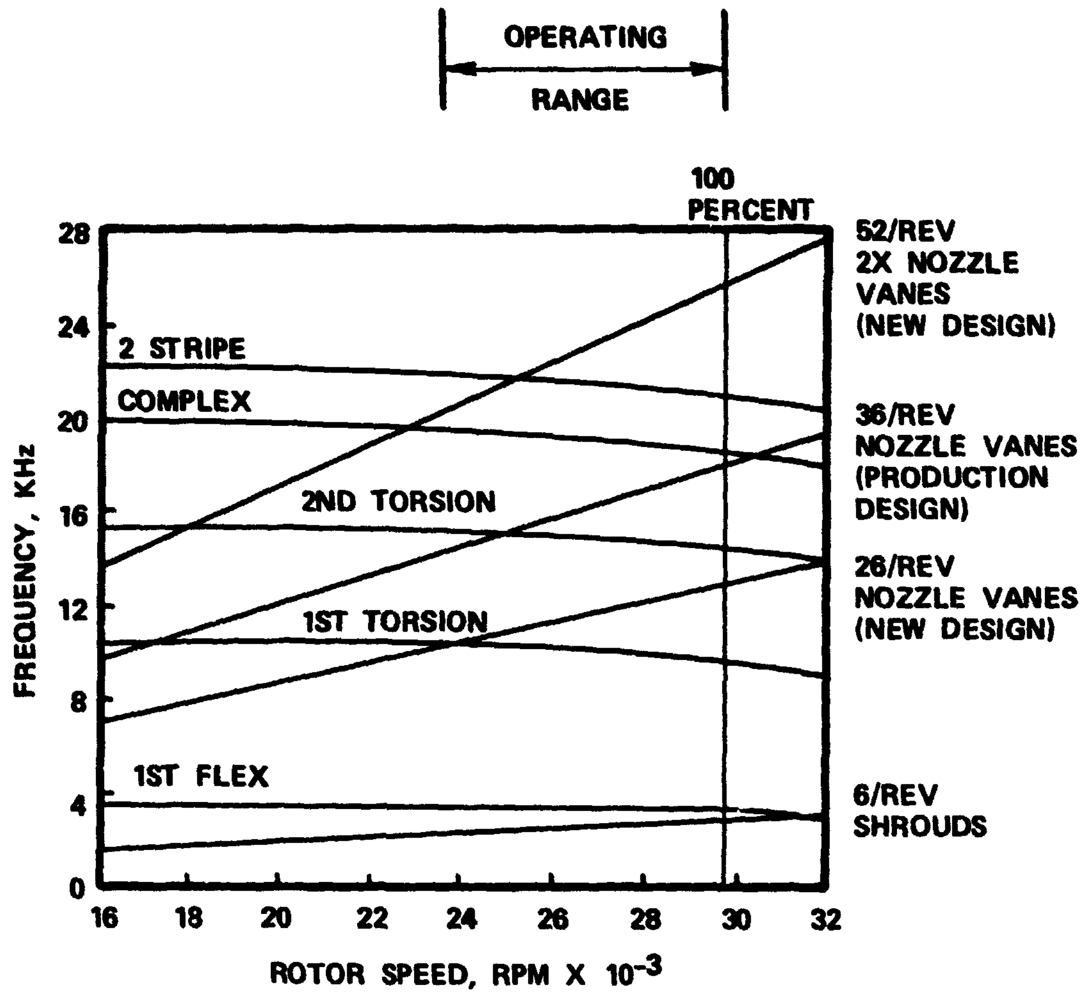


Figure 7. Interference Diagram for the MATE TFE731-3 Turbine Blades

balanced, and installed in the engine after the second set of sample DS blades were removed for evaluation according to Table I.

The third 50-hour test, designed to provide a limited evaluation of the low-cycle-fatigue capability of the DS blade, is shown in Figure 3. No significant engine testing problems were encountered during this test, and engine performance was consistent with previous testing. The post-test inspection revealed that there were no blades with any indication of distress. Figures 8 and 9 present photographs of typical leading and trailing edges of the blades tested for the entire 150 hours. The results of the metallurgical evaluation of the DS blades are presented in the Post-Test Evaluation section of this report.

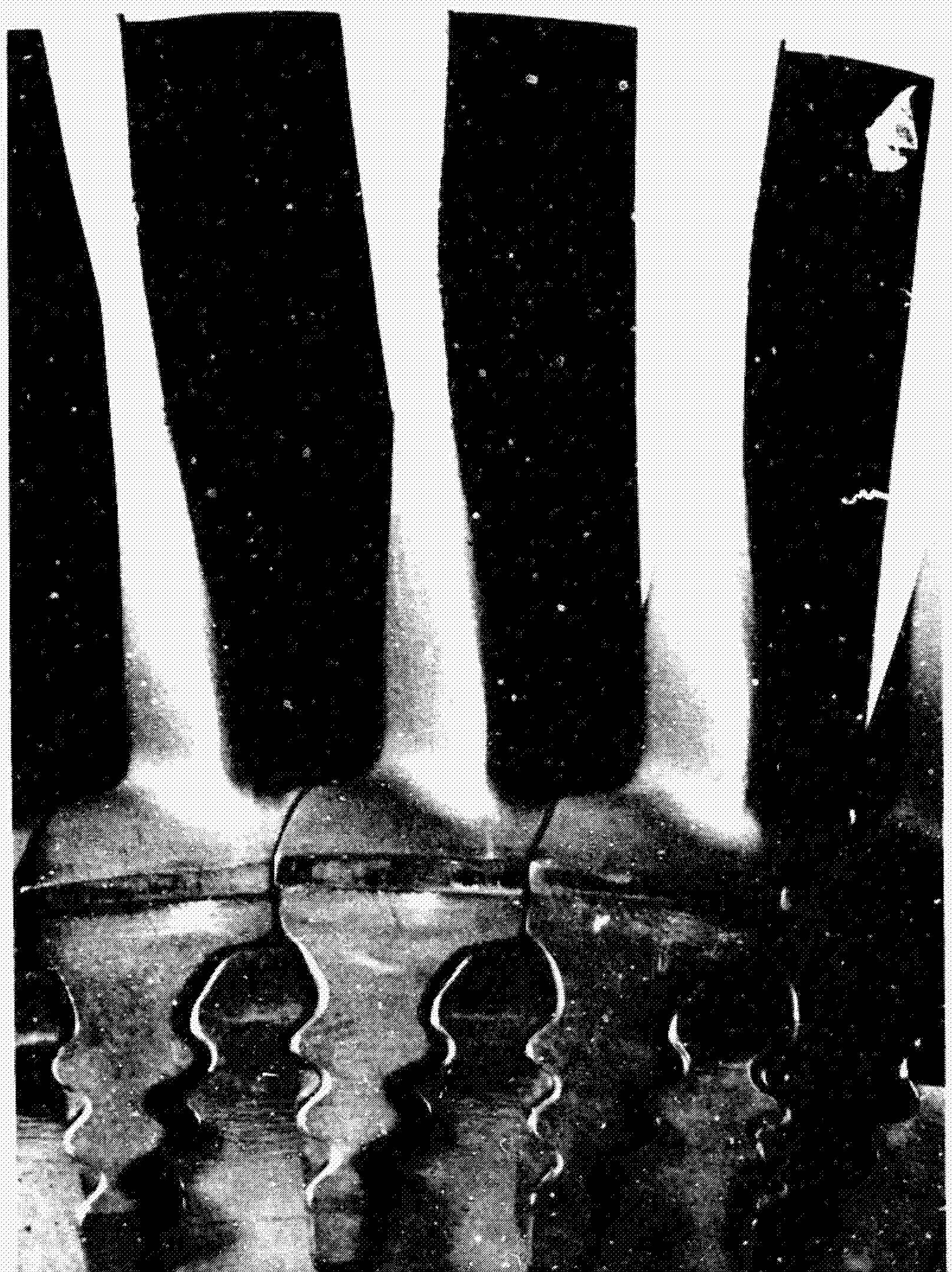

Figure 8. Leading-Edge View of Typical Blades Subjected to the Entire 150 Hours of Endurance Testing

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Figure 9. Trailing-Edge View of Typical Blades Subjected to the Entire 150 Hours of Endurance Testing

## TASK VII - POST-TEST EVALUATION

### Scope

The objectives of the post-test evaluation of the DS turbine blades tested in Task VI are to: (1) evaluate the effects of the engine testing on those blades; and (2) provide recommendations concerning the use of DS blades in the TFE731 Engine. As indicated in the description of the endurance testing, several turbine blades of each of the two alloys were removed from the HP turbine wheel after each of the three 50-hour test sequences (according to the plan presented in Table I). These blades were selected at random; although an effort was made to pick both a "typical" blade and the "worst" blade from those that had run for 50, 100, or the entire 150 hours of testing.

### Blade Evaluation

The serial numbers and the alloys of the blades selected for metallurgical evaluation are listed in Table III. Figure 10 depicts the seven blades selected for detailed examination after the third 50-hour test. The mark on the suction side of the blade S/N 367 identifies the area in which a 0.025-cm (0.010-inch) long coating crack was found. Inspection of this indication by binocular microscope at 40X magnification showed it to be a shallow crack within the coating and of no significance.

Although no extraneous deposits were found on any blades after the first 50-hour test segment, small white spots were noticed on all blades after the second and third test segments. These spots are shown in Photographs A and B of Figure 11. Figure 12 shows the areas sectioned to assess the microstructures of the seven blades and evaluate the small white spots.

TABLE III. MATE HP TURBINE BLADES EXAMINED AFTER COMPLETION OF PLANNED ENDURANCE TESTING IN A TFE731-3 TURBOFAN ENGINE

| Engine Test[a] | Blade Serial Numbers | |
|---|---|---|
| | MAR-M 247 | MAR-M 200+Hf |
| Test A | 385 | 1 |
| Tests A and B | 367 | 212 |
| Test A, B, and C | 341 | 13 and 216 |

[a]Test A - 50-hour high-cycle-fatigue evaluation (refer to Figure 1)

Test B - 50-hour stress-rupture evaluation (refer to Figure 2)

Test C - 50-hour low-cycle-fatigue evaluation (refer to Figure 3)

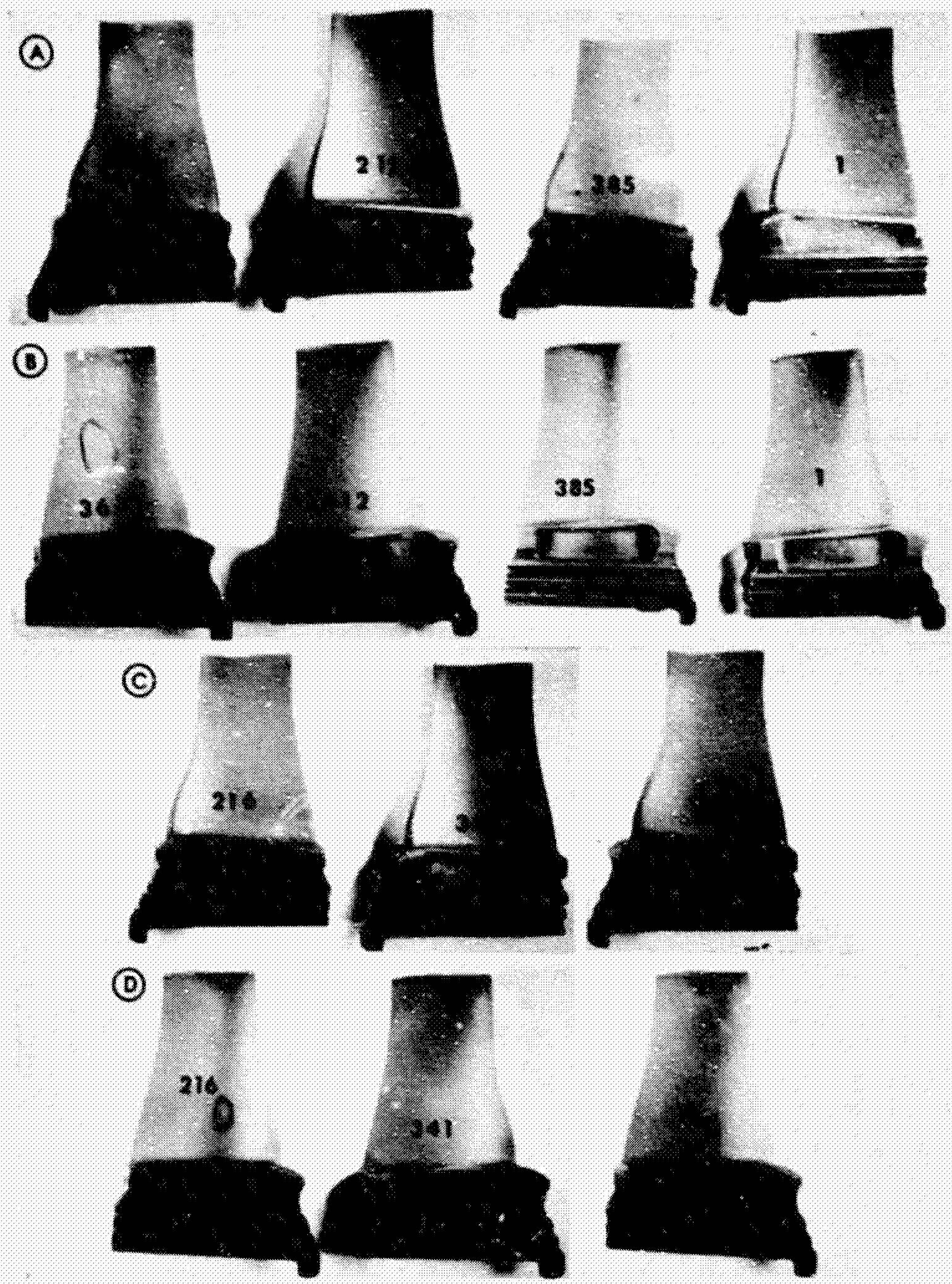


Figure 10. TFE731 MATE HP Turbine Blades After Engine Testing. The Numbers Denote the Blade Serial Numbers. Photos (A) and (C) Show the Pressure Side of the Blades, and Photos (B) and (D) Show the Suction Side (Mag.: 1X)



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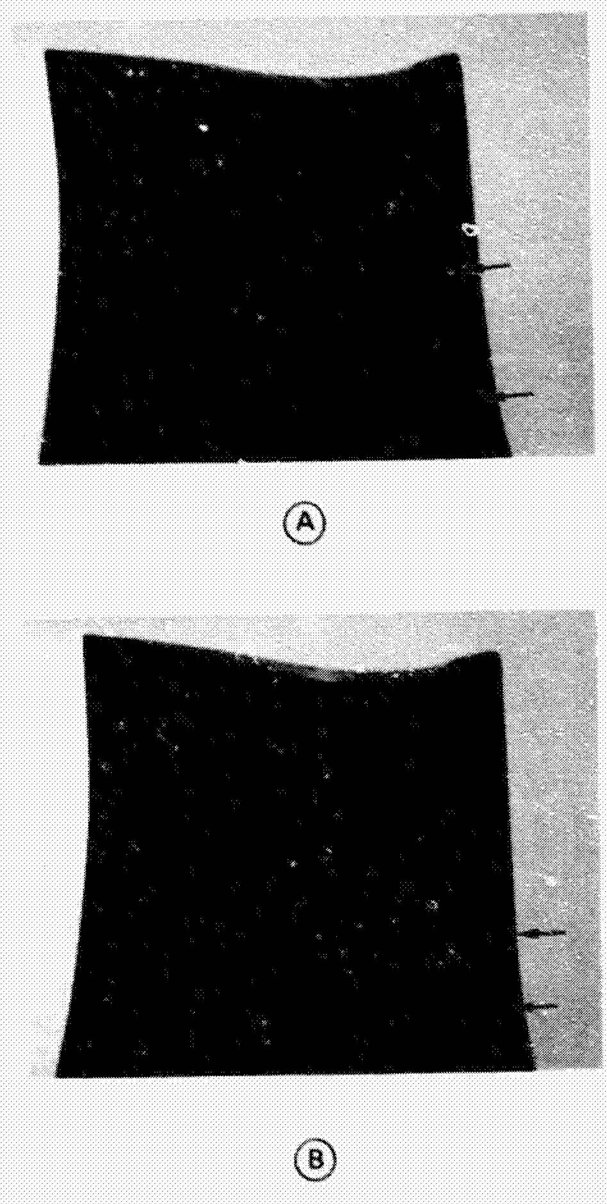

Figure 11. Photomacrographs Showing Blade-Tip Rub Areas and the White Deposit on Blade Leading Edges. (a) MAR-M 200+Hf Blade S/N 13. (b) MAR-M 247 Blade S/N 341. The Arrows Indicate the White Deposit on the Leading Edges

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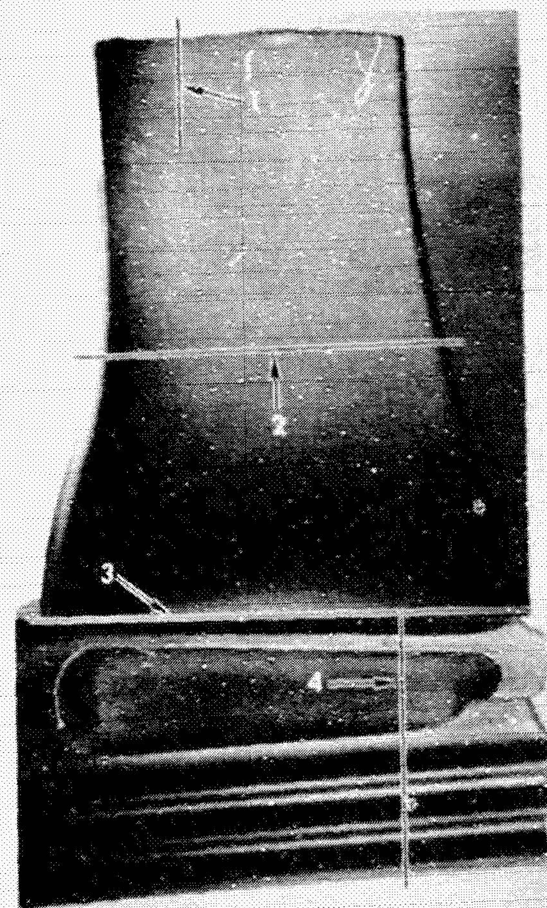


Figure 12. The Pressure Side of MAR-M 247 Blade S/N 341 Showing Microsection Locations. The Arrows Denote Sections: 1 - Blade-Tip Rub Area; 2 - Midspan; 3 - Airfoil Base; and 4 - Platform and Dovetail

Figures 13 and 14 present typical microstructures of the DS blades--blade S/N 341 (MAR-M-247) and blade S/N 13 (MAR-M 200 +Hf), respectively. These blades suffered tip-rub damage during the performance test but were tested for the full 150 hours. As anticipated, oxidation and alloy depletion occurred at the tip where the coating was removed during the tip-rub, but other areas of the blades showed normal alloy and coating microstructures. More eutectic is evident in the MAR-M 200+Hf blade than the MAR-M 247 blade--probably due to the higher hafnium content of MAR-M 200+Hf alloy. Figure 15 presents the mid-span structure of four other engine-tested blades, both the alloy and coating structures are normal.

SEM Energy Dispersive Analysis by X-ray (EDAX) of the white deposit on the leading edges of blades S/N 13 and 341, indicated that the spots were high in zirconium and magnesium (see Figure 16). An investigation revealed that the test engine utilized a plasma-sprayed, magnesia-stabilized zirconia thermal-barrier coating on the transition liner immediately forward of the high-pressure turbine. This coating had spalled in spots during the engine testing, and some material was deposited on the blade leading edges.

Coating-thickness measurements were made at airfoil cross-sections located as shown on Figure 12. Ten measurements per section were collected and averaged, with the results reported in Table IV. All measured thicknesses were within the coating specification tolerance of 0.0025 to 0.005 cm (0.001 to 0.002 inch).

An effort was made to determine the growth of the DS blades by measuring the tip radius of selected blades after 50, 100, and 150 hours of testing. This measurement was accomplished in the rotor to eliminate any variables in the attachment area. The results of these measurements, although widely scattered, showed no significant blade growth over the 150-hour endurance test.

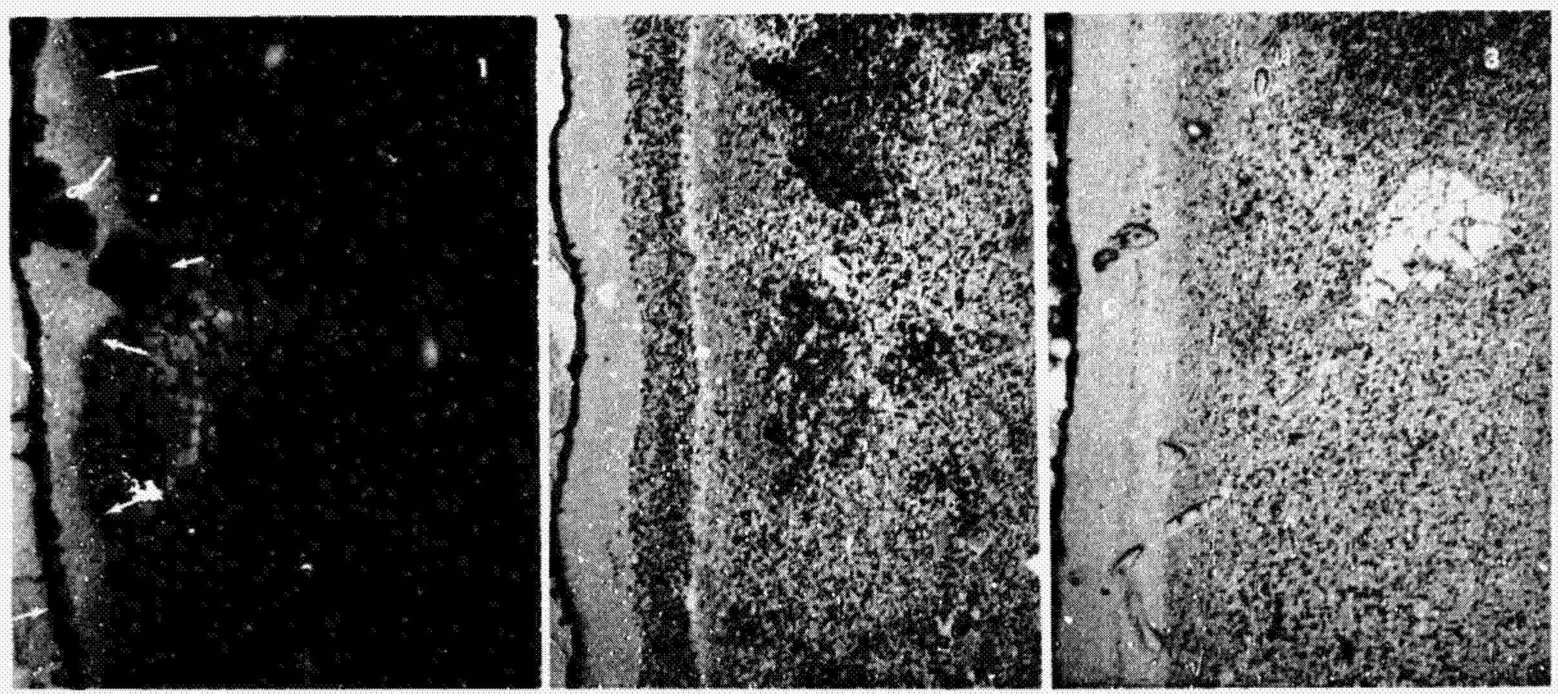


Figure 13. Representative Photomicrographs of MAR-M 247 Blade S/N 341. The Numbers Denote Sections Indicated in Figure 12. Section 1 is Through the Tip-Rub Damage Area Shows Alloy Depletion and the Oxidation; Section 2 Through the Mid-Span and Section 3 Through the Airfoil Base Show Normal Alloy and Coating Structures. The Letter C denotes Coating (Etchant: Oxalic Acid) (Mag.: 500X)

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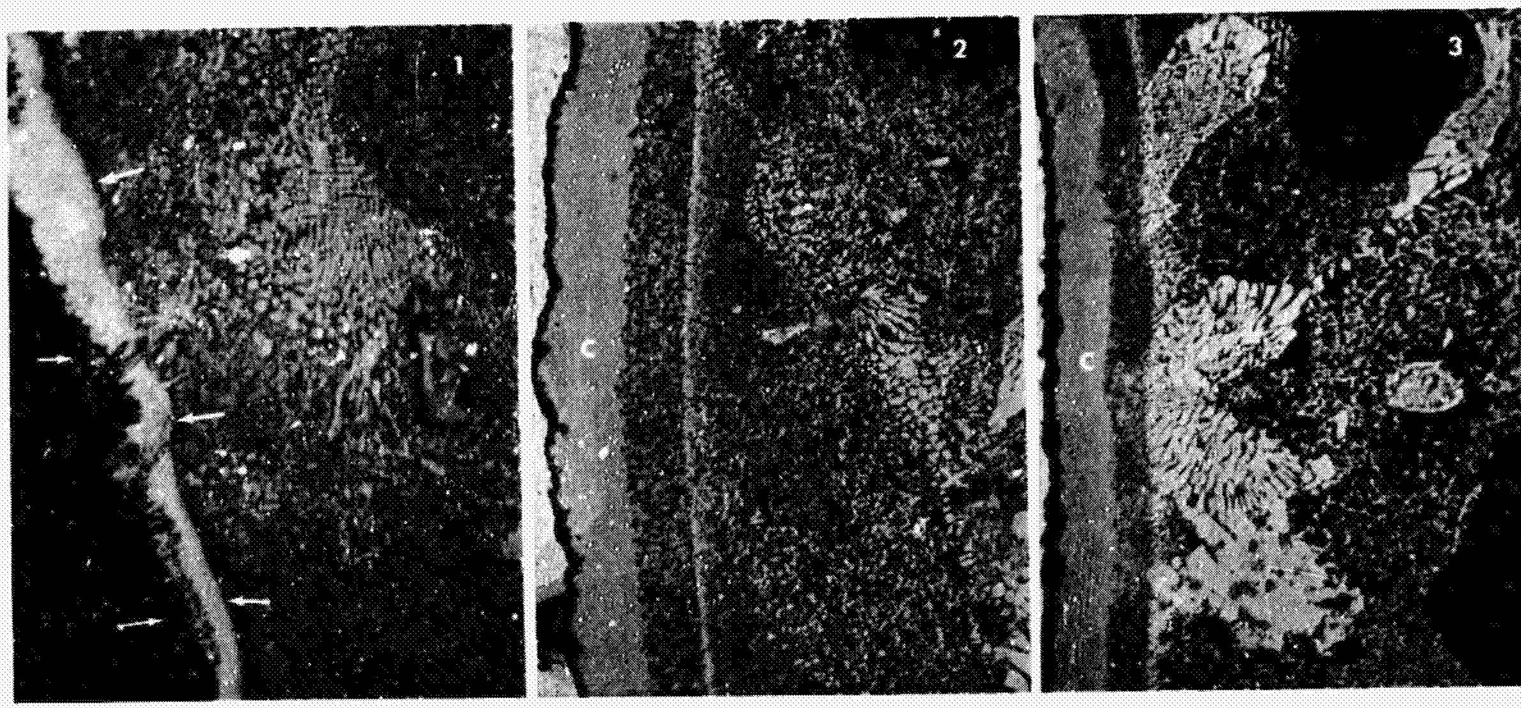


Figure 14. Representative Photomicrographs of DS MAR-M 200+Hf Blade S/N 13. The Numbers Denote Sections Indicated in Figure 12. Section 1 is Through the Tip-Rub Damage Area Shows Alloy Depletion and Oxidation; Section 2 Tnrough the Mid-Span and Section 3 Through the Airfoil Base Show Normal Alloy and Coating Structures. The Letter C Denotes Coating (Etchant: Oxalic Acid) (Mag.: 500X)



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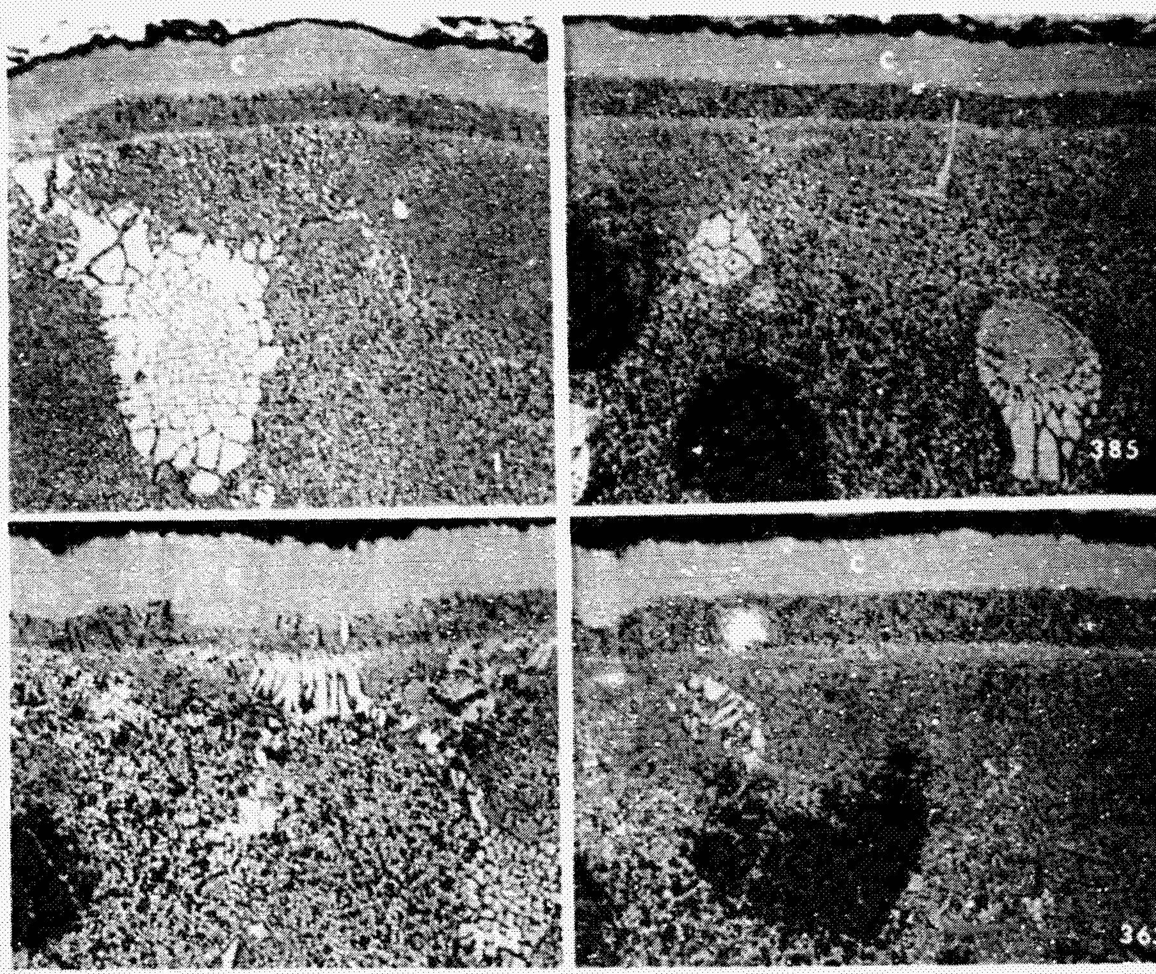


Figure 15. Representative Mid-Span Microstructures at Location 2 of Figure 12. Photos At Left Are MAR-M 200+Hf and the Photos At the Right Are MAR-M 247. The Letter C Denotes Coating. The Blade Serial Numbers Are At the Lower Right of Each Photo. No Abnormalities Were Found on These 50- and 100-Hour Test Blades (Etchant: Oxalic Acid) (Mag.: 500X)

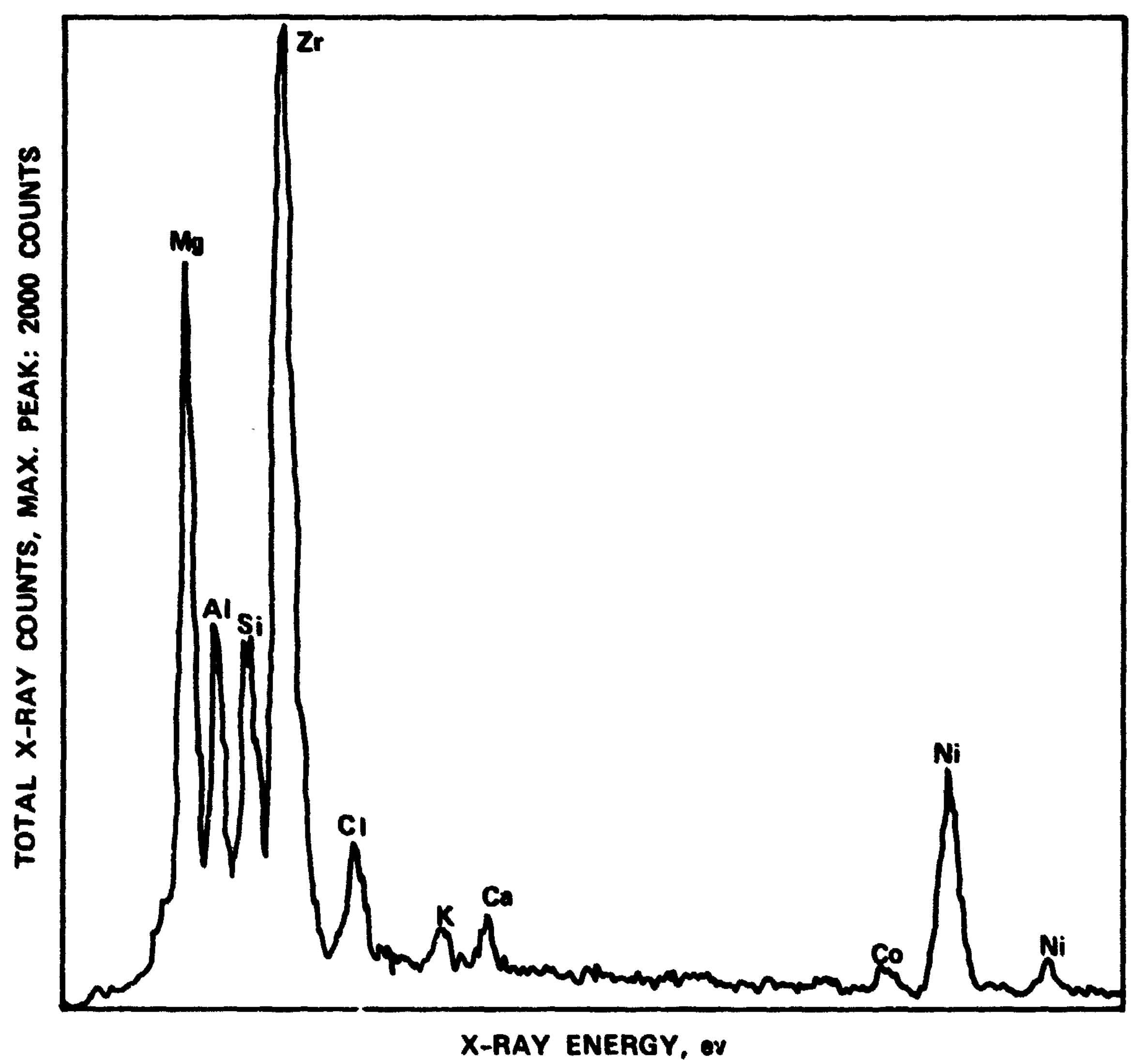


Figure 16. EDAX Analysis of the White Deposit on the Leading Edoes of Blades S/N 13 and 341 as Shown in Figure 11

TABLE IV. AVERAGE COATING THICKNESS ON ENGINE-TESTED HP TURBINE BLADES OF MAR-M 247 AND MAR-M 200 +Hf

[Specification requirement is 0.0025 to 0.005 cm (0.001 to 0.002 inch)]

| Blade Serial No. | Blade Alloy | Coating Thickness at Mid-Span Section, cm (inch) | Coating Thickness at Base Section, cm (inch) |
|---|---|---|---|
| 385 | MAR-M 247 | 0.0030 (0.0012) | -- |
| 367 | MAR-M 247 | 0.0033 (0.0013) | -- |
| 341 | MAR-M 247 | 0.0036 (0.0014) | 0.0028 (0.0011) |
| 1 | MAR-M 200+Hf | 0.0030 (0.0012) | -- |
| 212 | MAR-M 200+Hf | 0.0038 (0.0015) | -- |
| 13 | MAR-M 200+Hf | 0.0030 (0.0012) | 0.0038 (0.0015) |

## METALLURGICAL SUMMARY

There was no significant deterioration of any of the DS turbine blades throughout the three 50-hour endurance tests. Some oxidation occurred at the blade tips where the coating had been removed during the tip-rub experienced in the performance testing. A small amount of plasma-sprayed, magnesia-stabilized zirconia spalled upstream of the turbine during the second and third 50-hour test segments. This material lightly coated the blade leading edges, but did not damage them. The RT-21 protective aluminide coating was unaffected by the 150 hours of endurance testing and prevented airfoil oxidation.

From a metallurgical standpoint, the 150 hours of testing that the MATE DS turbine blades underwent in the TFE731-3 Engine was an unqualified success. None of the MATE DS high-pressure turbine blades (MAR-M 247 or MAR-M 200+Hf) showed any indications of distress at the conclusion of the testing. Therefore, those blades that were not cut up for metallurgical examination are available and suitable for further testing.

# CONCLUSIONS

Based upon the results of the engine testing and the evaluation of the DS turbine blades presented in this report, the following conclusions were reached:

- The specific fuel consumption of the TFE731-3 Engine was reduced by substituting the uncooled DS turbine blade for the production cooled blade.

  Goal: Reduce SFC by at least 1.7 percent

  Demonstrated: Measured SFC reduced by 2.4 percent

- The MATE uncooled DS blades showed no distress when subjected to the 150-hour endurance test.

- The MATE uncooled DS turbine blade design provides an alternate HP turbine blade for the TFE731-3 Engine, which is unique in providing both improved performance and reduced cost.

## RECOMMENDATIONS

After completing the engine testing and the post-test evaluation of the DS turbine blades, the following recommendations can be made for uncooled DS turbine blades in the TFE731 Engine size class.

- o Incorporate the MATE uncooled DS turbine blade into an advanced version of the TFE731-3 Turbofan Engine for certification and production.

- o Provide additional engine testing at typical operating conditions for the MATE blades previously tested in this project.