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MATERIALS FOR ADVANCED TURBINE ENGINES

PROJECT COMPLETION REPORT PROJECT 2

ABRADABLE COMPRESSOR AND TURBINE SEALS VOLUME II

by
D. V. Sundberg
R. E. Dennis
L. G. Hurst
AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

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NASA-Lewis Research Center
21000 Brookpark Road, Cleveland, Ohio 44135

16. Abstract
Project 2, of a five-year cooperative Government/Industry effort--Materials for Advanced Turbine Engines (MATE), was conducted to evaluate the application and advantages of abradable coatings as gas-path seals in a general aviation turbofan engine. Abradable materials were evaluated for the high-pressure radial compressor and the axial high- and low-pressure turbine shrouds.

The project consisted of seven tasks: Task I screened a number of potentially suitable abradable materials and performed limited material properties testing. Task II evaluated all candidate materials by short-duration Interim Engine Screening Tests and selected the most promising candidates for the final engine endurance test. Task III established detail shroud design and engine build-up tolerances for hardware used in the final engine test. Task IV finalized the fabrication methods for the final-design hardware, and Task V accomplished the manufacture of hardware to support the final engine test. Task VI subjected the final-design hardware to engine endurance testing. Task VII analyzed the engine-tested hardware, compared the test results with the baseline data, and developed recommendations concerning the future use of abradable seals in the TFE731 Engine. Tasks I through V (as reported in Volume I) and Tasks VI and VII (as reported in Volume II) comprise the Project Completion Report for Project 2.

Target goals for the abradable coatings were: (1) coating/blade-tip wear ratio >15:1; (2) coating debris size <0.010 inch; (3) coating cost <10 percent of part cost; and (4) coating-erosion resistance of at least 10,000 hours. The target goals for the engine use of the abradables were: (5) reduce specific fuel consumption (SFC) by at least 1.5 percent; and (6) added cost of abradables to be less than 0.4 percent of engine cost. Goals (1), (2), (4) and (5) are associated with engine testing, and therefore, are discussed in Volume II, while the results of the cost goals (3) and (6) are included in Volume I.

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FORWARD

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 evaluate abradable coatings as gas-path seals in a general aviation turbofan engine. 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 S. G. Young of NASA-Lewis Research Center. Volume II of this report covers the Engine Testing and Post-Test Evaluation Tasks of this project.

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SUMMARY

The purpose of this program was to evaluate the effectiveness of abradable coatings for gas-path seals on the high-pressure compressor, the high-pressure turbine, and the low-pressure turbine shrouds of the AiResearch TFE731-3 Turbofan Engine. The project accomplishments included the selection of the best available abradable coatings for the TFE731-3 Engine. The goal to reduce the blade tip-to-shroud clearance, and thus, reduce the specific fuel consumption (SFC) by at least 1.5 percent was exceeded with the selected abradables. The significant accomplishments of this phase of the project are as follows:

- The specific fuel consumption was reduced 1.8 percent with the selected abradable coatings and the associated clearance reductions.

- The 150 hours of engine testing (three 50-hour tests) were completed without incident demonstrating the abradability and durability of the selected coatings.

The results of the first five tasks of this project and the achievement of their related goals are presented in Volume I (NASA CR-159600). The results of the final two tasks -- Task VI, Engine Testing, and Task VII, Post-Test Evaluation -- are presented in this document (Volume II). Table I lists the candidate abradable materials selected for the final engine testing. Selection was based on the screening test results reported in Volume I, material availability, ease of inspection, and cost.

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

TABLE I. CANDIDATE ABRADABLE MATERIALS SELECTED FOR TASK VI 150-HOUR ENGINE TEST

Engine Component	Approximate Gas Temperature, °C	(°F)	Material Identification	Material Composition
High-Pressure Compressor	426	(800)	Metco P601-10	Aluminum-Polyester
High-Pressure Turbine	1050	(1925)	UCAR AB-4[a]	Nickel-Chromium-Aluminum
			Metco P443-10 (open)[a]	Nickel-Chromium-Aluminum
Low-Pressure Turbine				
First Stage	871	(1600)	Honeycomb	Hastelloy-X
Second Stage	760	(1400)	Metco T301-10	Boron Nitride Cermet
Third Stage	650	(1200)	Metco 304NS	Bronze/Boron Nitride

[a]Each Material To Be Tested for 50 Hours With the Best Candidate Selected for the Final 50-Hour Test

- 50 hours of testing on the first set of abradable hardware. The testing consisted of performance tests, abradable wear-in tests, abradable-transient tests, and abradable-erosion tests

- 50 hours of testing on the second set of abradable hardware. The testing was the same as the first 50-hour test series

- 50 hours of testing on the best abradable components from the first two tests. The testing consisted of only performance checks and an abradable-erosion test.

Analysis of the engine test results showed that acceptable abradable materials had been identified for all components except the high-pressure turbine (HPT). Metco 601 proved to be an excellent material for the high-pressure compressor (HPC) shroud, it exceeded the cost goal and had at least a 15:1 wear ratio. Hastelloy X Honeycomb performed well in the first-stage low-pressure turbine (LPT), and was identified as the best choice for the second-stage turbine after the prime candidate (Metco T301-10) proved to be ineffective. The honeycomb showed excellent abradability with at least a 15:1 wear ratio, and could be added to the *shrouds* within the cost goal. Metco 304NS proved to be an excellent material for the third-stage low-pressure turbine, exceeding the cost goal with a 15:1 wear ratio. All candidate materials for the HP turbine exhibited excessive oxidation and/or lack of abradability, and could not be considered acceptable for this application.

As a direct result of this successful program, AiResearch has initiated action to incorporate the Metco 601 abradable coating into the TFE731-3 Production Engine. Also, further investigation of Metco 304NS coatings for both gas-path and labyrinth seals in the TFE731-3 and other engines has been started.

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 2 of NASA Contract NAS3-20073 to evaluate the application and advantages of abradable coatings as gas-path seals to reduce the fuel consumption in a general aviation turbine engine -- the AiResearch TFE731-3 Turbofan Engine. The process development included the selection of the best available abradable materials and their testing in a series of engine screening tests. The most successful candidates were then selected, manufactured as engine hardware, and engine tested for 150 hours. The overall effort included: investigation of materials and manufacturing processes; process modification; screening tests, hardware design and manufacture; and full-scale engine testing to evaluate the potential benefits of the abradable candidates.

The intent of Project 2 was to develop materials and manufacturing processes suitable for producing high-pressure compressor, high-pressure turbine, and low-pressure turbine shrouds with abradable coatings for the Garrett-AiResearch TFE731-3 Turbofan Engine. The project goals associated with this substitution were:

(1) A reduction in engine specific fuel consumption of at least 1.5 percent;

(2) A coating/blade-tip wear ratio greater than 15:1;

(3) A coating debris size of less than 0.010 inch;

(4) An erosion-resistant coating that provides at least 10,000-hours life;

(5) A coating cost not to exceed 10 percent of the part cost.

To develop these abradable shroud materials and to accomplish these goals, Project 2 was subdivided into the following seven tasks:

Task I - Manufacturing Technology
Task II - Material/Process Selection
Task III - Component Design
Task IV - Manufacturing Process Development
Task V - Component Fabrication
Task VI - Engine Testing
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 abradable materials as gas-path seals 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.

TASK VI - ENGINE TESTING

Scope

The objectives of the Task VI Engine Testing were to: (1) verify the anticipated reduction in SFC with the abradable shrouds, and (2) prove the abradability and durability of the abradable materials and the shroud designs. The program required that two complete engine sets of high-pressure compressor, high-pressure turbine, and low-pressure turbine shrouds produced in Task V be subjected to a total of 150 hours of typical engine operating conditions in an AiResearch TFE731-3 Engine.

The Task VI Engine Testing of the selected abradable coatings consisted of several performance tests, abradable wear-in tests, abradable-transient tests, and abradable-erosion tests. These tests were part of three 50-hour test segments chosen by AiResearch and approved by NASA as shown in Figures 1 and 2. The performance tests were meant to determine the effects of the abradable coatings and the associated reduction of blade-to-shroud clearances on the TFE731-3 Engine; both as an initial direct substitution and after various test cycles. The abradable wear-in, transients, and erosion tests were designed to evaluate the condition of the abradables after exposure to typical engine operating conditions. Build-up clearances were reduced to provide the desired blade contact on the abradables.

Two sets of abradable hardware were each tested for 50 hours according to the test cycle in Figure 1. In the second 50-hour test, minor adjustments were made to the clearances, and an alternate material was introduced in the HP turbine. The third 50-hour test was accomplished in accordance with the test cycle shown in Figure 2 using abradable-coated components selected from the two

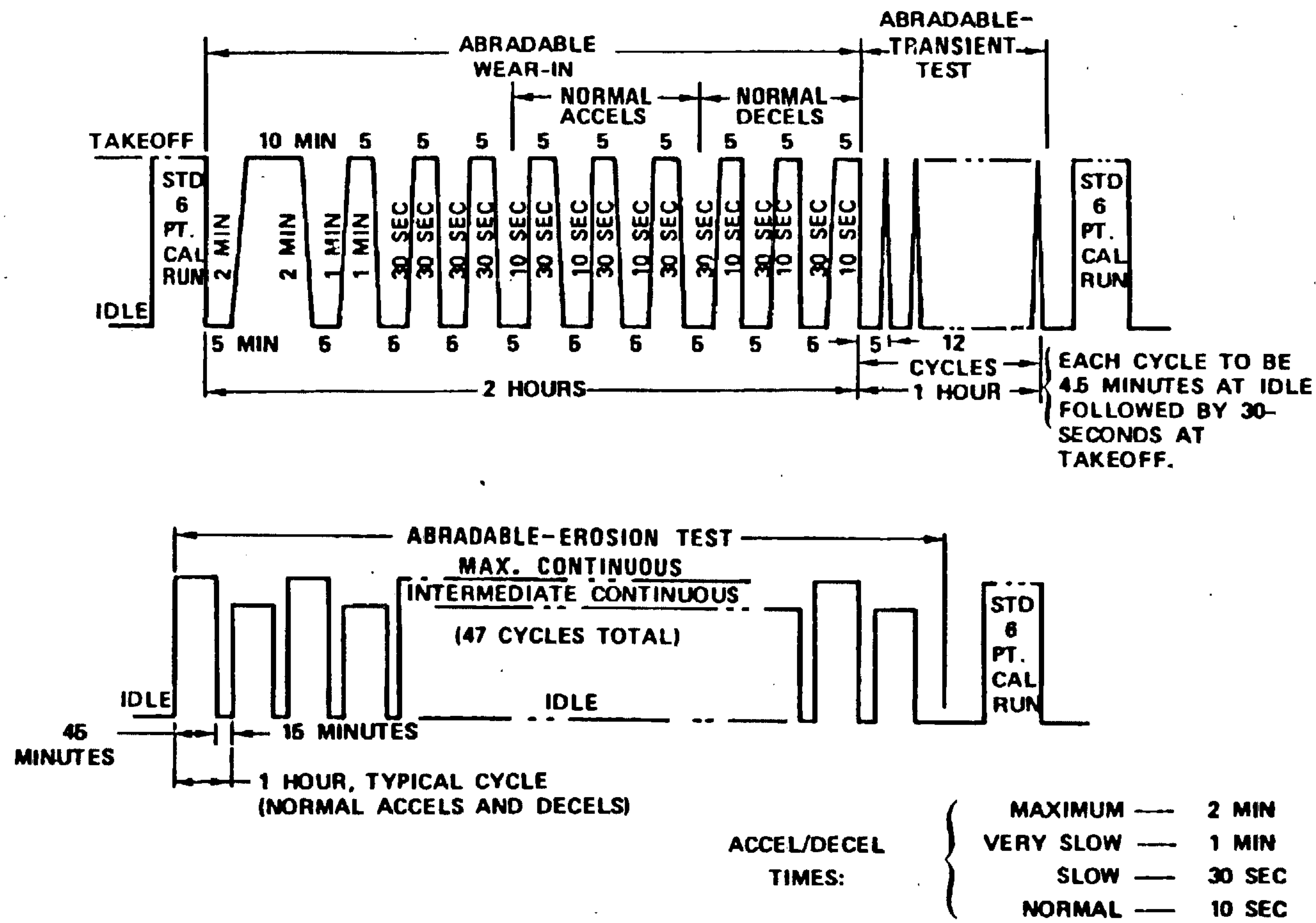
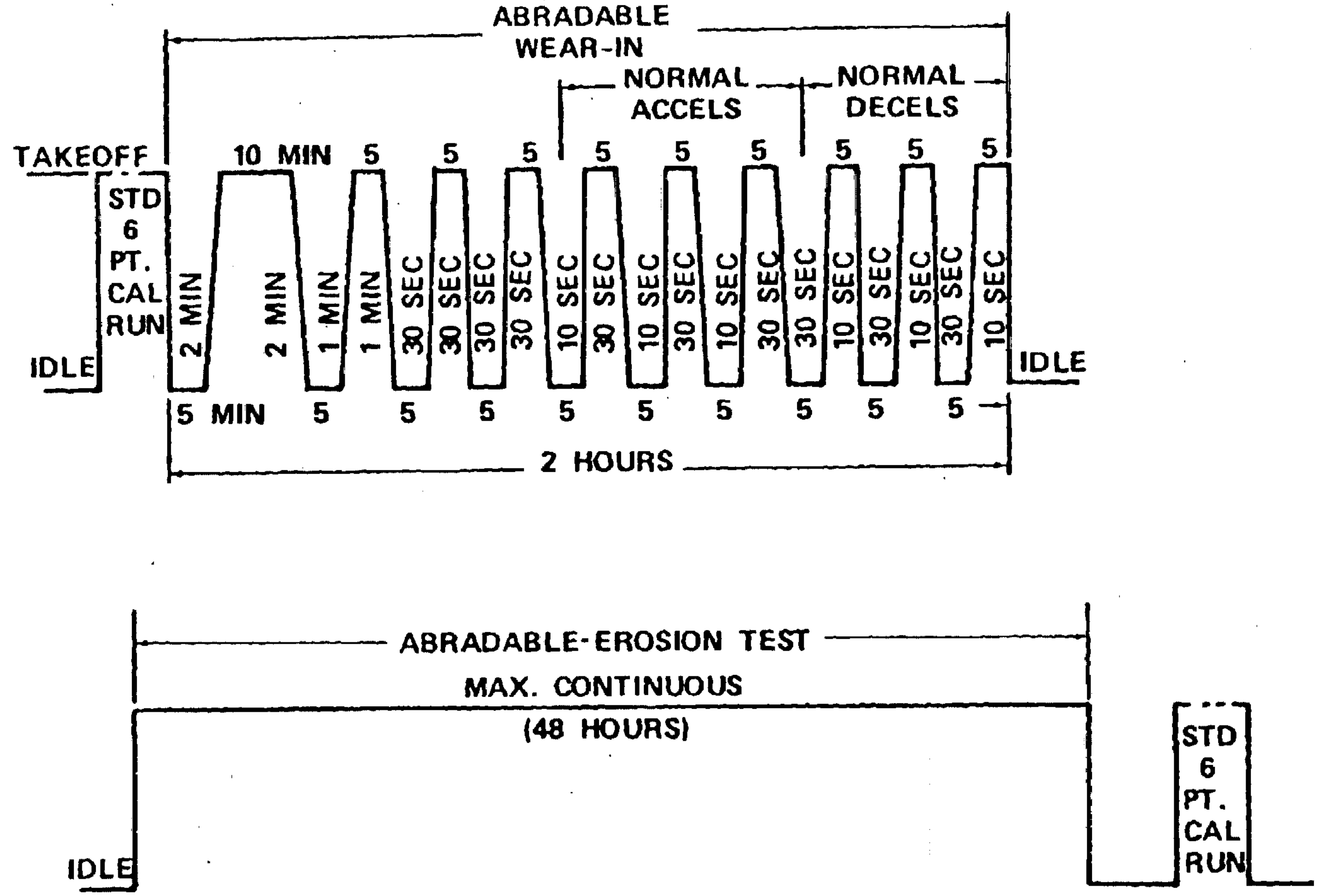


Figure 1. Test Schedule for the First and Second 50-Hour Tests



ACCEL/DECEL TIMES:

MAXIMUM	—	2 MIN
VERY SLOW	—	1 MIN
SLOW	—	30 SEC
NORMAL	—	10 SEC

Figure 2. Test Schedule for the Third 50-Hour Test

sets of hardware previously tested. The third test was designed primarily to evaluate coating-erosion resistance, and only minor changes were made in the build-up clearances.

Final Preparation of the Engine and Hardware

An AiResearch 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 was accomplished with this engine including the baseline performance calibration test to minimize 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 3 presents a photograph of the engine installed in the test facility.

To ensure that the test engine met production standards, all of the components affecting the efficiency or performance of the engine were fluorescent-penetrant inspected, cleaned, and repaired (where required) prior to assembly and testing of the baseline engine.

The abradable-coated hardware produced in Task V (Component Fabrication) was final machined in Task VI to produce the desired blade-to-shroud clearances. The diameters of the abradable coatings were not machined or ground to final test dimensions until exact rotor diameters were measured after the baseline engine performance test. This was the assembly procedure used to ensure controlled clearances for the engine tests. The rotors were remeasured after the first 50-hour test, and the shroud diameters for the second 50-hour test were adjusted as required.

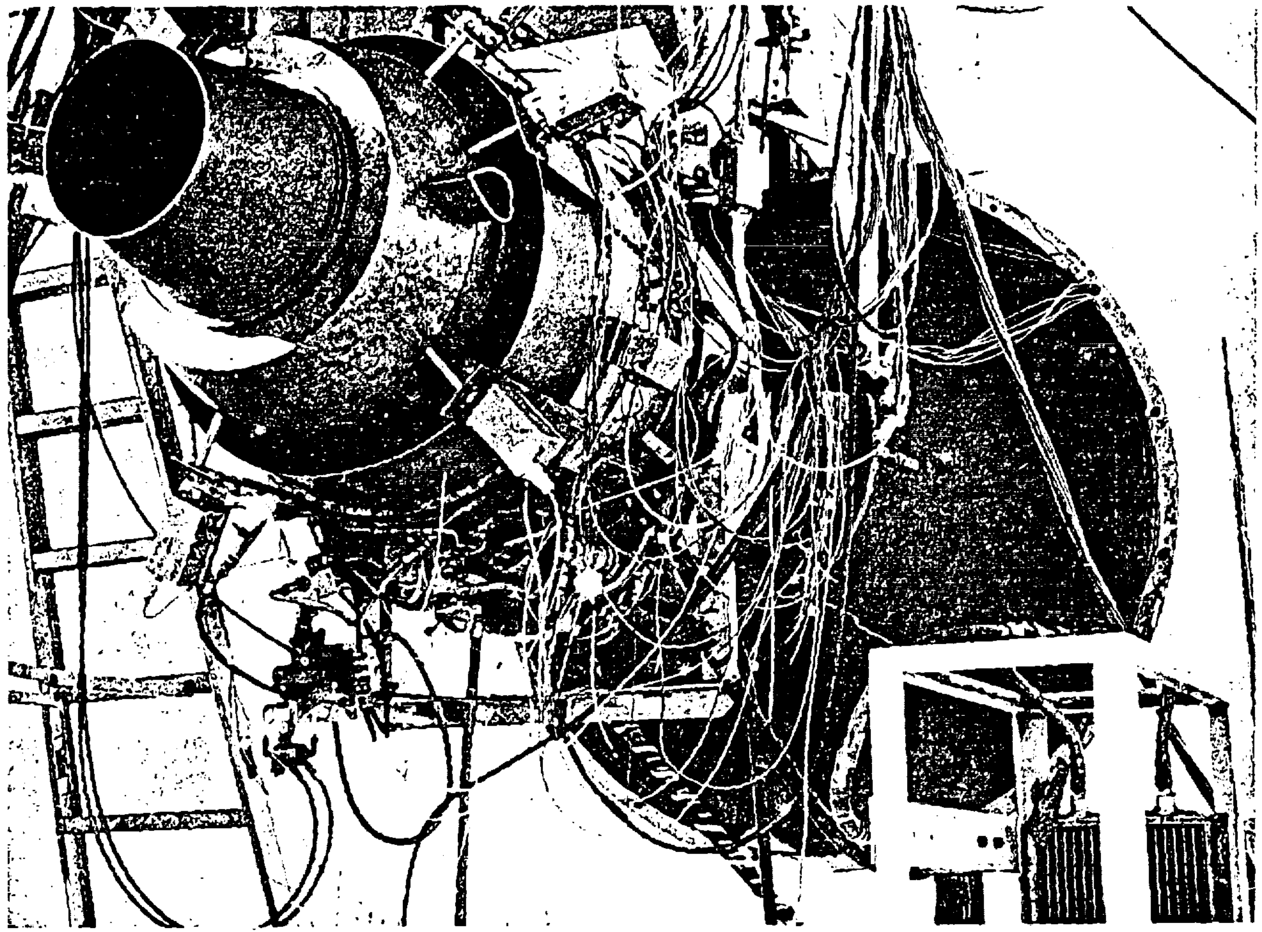


Figure 3. TFE731-3 Engine, Serial Number 7502, Installed in the Remote San Tan, Arizona, Test Facility

Engine Test Series

The Engine Testing was initiated with a six-point performance calibration test of the baseline TFE731-3 Development Engine (Serial Number 7502) utilizing the standard production engine configuration. Table II presents the engine operating conditions for each of the six calibration points.

After the six-point calibration test, the engine was completely disassembled, inspected per standard procedures, and reassembled with the first set of final machined abradable hardware [high-pressure compressor (HPC), high-pressure turbine (HPT), and low-pressure turbine (LPT) shrouds]. The blade tip-to-shroud build-up clearances are shown in Table III. A six-point performance calibration run was completed with the new abradable-coated components after the initial engine start-up.

The first 50-hour test was performed as illustrated in Figure 1. The first phase of this test was designed to provide a gradual wear-in for the abradables, and an evaluation of the reduced clearances prior to a series of standard "burst-chop" cycles. The second-test phase was meant to evaluate the erosion resistance of the abradables through a series of 47 one-hour test cycles.

During the wear-in phase of the testing, a downward step-change in performance was observed. Efforts to analyze this performance change with the engine in the remote-site test cell were not successful, and the engine was returned to Phoenix for a complete disassembly and inspection. The inspection did not reveal any obvious reason for the observed performance shift. As anticipated, the blades had contacted the coated shrouds, and the non-gas-path labyrinth seals had worn slightly. However, no chunks of abradable coating had been lost, and no significant build-up of abradable material was noted on the airfoils. No physical evidence

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 was stabilized six minutes minimum prior to recording the required performance data.

TABLE III. PRETEST (COLD ASSEMBLY) BLADE TIP-TO-SHROUD CLEARANCES (INCH)

Component	Nominal Production	First 50-Hour Test	Second 50-Hour Test
HPC	0.046	0.035	0.040
HPT	0.036	0.022	0.018
LPT 1	0.037	0.013	0.007
LPT 2	0.028	0.014	0.016
LPT 3	0.020	0.016	0.016

was discovered that would explain the change in performance, and the engine was reassembled and returned to the remote-test facility for further testing. A six-point calibration test confirmed the lower pwerformance, and the wear-in phase of the first 50-hour test was continued. Performance calibration checks were completed after the wear-in, the abradable-transient phase, and the completion of the first 50-hour test.

The engine was again disassembled, inspected, and the rotors and seals were measured. The second set of abradable-coated shrouds were then final machined and installed in the engine. The blade tip-to-shroud build-up clearances for the second 50-hour test are also shown in Table III. The dimensions selected for final machining compensated for the minor blade wear measured during the first 50-hour test, and any adjustments required to produce the desired rub. After assembly, the engine was again tested according to the plan shown in Figure 1. This second 50-hour test was completed, without incidence, in accordance with the plan shown in Figure 2. This test was designed to further evaluate the erosion resistance of the material and no attempt was made to achieve additional abradable rubs.

The engine was disassembled and all rotors and abradable-coated shrouds were inspected, accurately measured, and photographed. The post-test investigation of the hardware and the analysis of the performance data will be discussed in detail in the Post-Test Evaluation section of this report.

TASK VII - POST-TEST EVALUATION

Scope

The objectives of the Post-Test Evaluation of the engine test data and the abradable-coated shrouds were to: (1) evaluate the performance data in order to determine the benefits of reduced blade tip-to-shroud clearances on SFC; (2) evaluate the effects of the engine testing on the abradable materials; and (3) provide recommendations concerning the use of abradable coatings to reduce blade tip-to-shroud clearances in small gas-turbine engines.

The AiResearch TFE731-3 Engine utilized for the abradable evaluation is presented schematically in Figure 4. Also shown are the approximate operating conditions of the abradable components that are evaluated in this Task.

The performance of the engine with the abradable shrouds and the reduced blade tip-to-shroud clearances can only reflect the overall performance improvement of the complete engine. The effects of the individual components cannot be determined in this series of testing, but must be inferred from previous testing. Thus, the comparison between several engine configurations and various engine hardware sets can only be based on the changes to the total system.

Performance Analyses

As shown in Figure 5, the performance of the engine was constantly monitored throughout the 150-hour test by "standard" six-point performance checks as described in Table II. The purpose of these checks were twofold: (1) to keep track of the vital functions of the engine in order to avoid premature failure, and (2) to

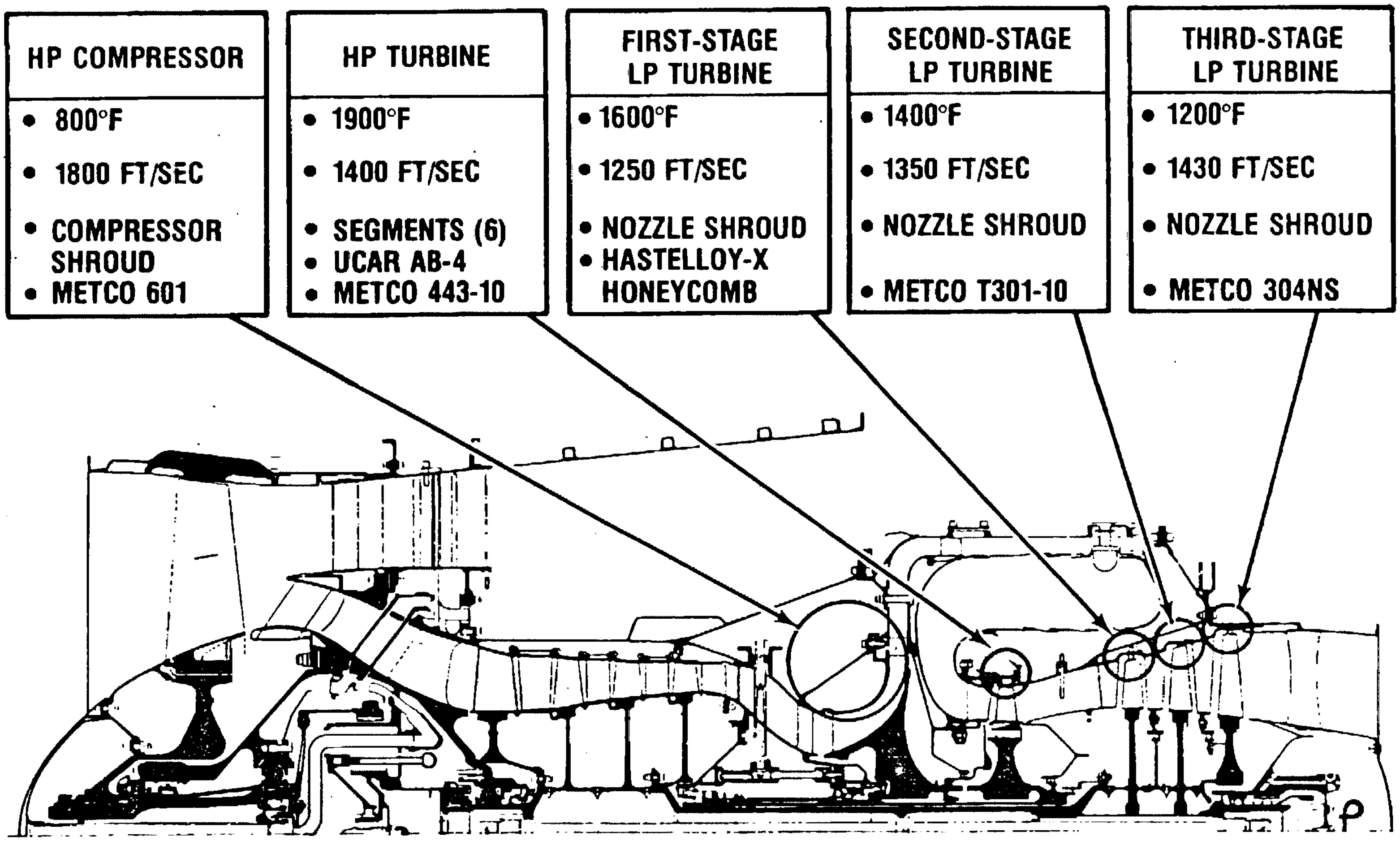


Figure 4. Cross Section of the TFE731-3 Engine Showing the Location of the Abradable Materials

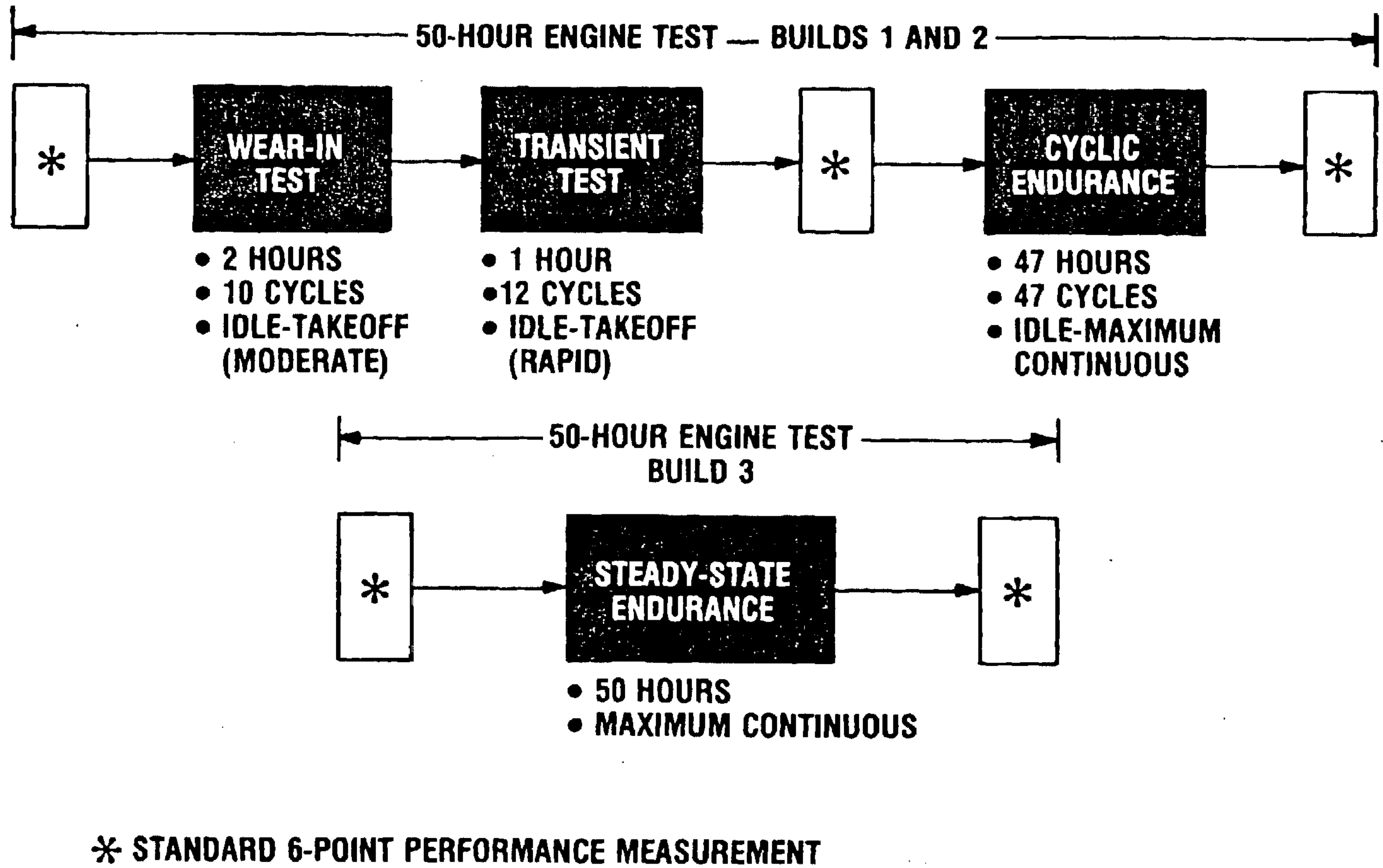


Figure 5. Abradable Engine Testing Cycles

determine any change in performance due to hardware substitution, engine wear, etc. The results of these performance checks are summarized in Table IV. All performance information is presented in terms of SFC that has been corrected to standard conditions for ease of comparison. An attempt has been made to separate the effects of the gas-path seals from all other performance variables such as labyrinth seal wear, geometric variables, etc. Since this engine could not be physically optimized to show all performance improvements in terms of SFC, it was necessary to analytically convert changes in other performance parameters, such as a lower T_5, to a change in SFC.

Hardware Evaluation

The tested abradable-coated engine hardware was sectioned and examined in a manner similar to that utilized in Task II, Volume I, of the Project Completion Report. Evidence of wear, erosion, blade-metal transfer, and bond integrity were noted, as well as the metallurgical characteristics of the abradable material. Table V identifies the shrouds used in each of the three 50-hour test series, and denotes which were tested for 50 hours and which accumulated 100 hours. The specific analysis of the test hardware is separated by engine component, i.e., the high-pressure compressor, the high-pressure turbine, and the low-pressure turbine.

High-Pressure Compressor

The centrifugal high-pressure compressor shroud reaches a temperature of approximately 426°C (800°F) at the rotor-exit diameter. The blade-tip speed at that point is 548 m/sec (1800 ft/sec) at engine take-off conditions. The shroud cross section, including the plasma-sprayed Metco 601 coating, is shown in Figure 6. The coating was applied in the AiResearch production plasma-spray facility.

TABLE IV. SUMMARY OF THE PERFORMANCE IMPROVEMENTS BASED ON "STANDARD" SIX-POINT CALIBRATION RUNS

Performance Check Point	Performance Improvement Shown as a Reduction in SFC (%) Compared to the Baseline TFE731-3 Engine Without Abradables		
	Build 1	Build 2	Build 3
Prewear-In	1.8	1.7	----
Pre-Endurance	1.7	1.6	1.5
Post-Endurance	1.5	1.4	1.3

TABLE V. ABRADABLE-COATED SHROUD IDENTIFICATION*

Component	50-Hour Test Series		
	First	Second	Third
High-Pressure Compressor	S/N A-101	S/N C-201	S/N A-101
High-Pressure Turbine	UCAR AB-4	Metco 443	UCAR AB-4
Low-Pressure Turbine			
First Stage	S/N A-102	S/N C-202	S/N C-202
Second Stage	S/N A-103	S/N C-203	S/N A-103
Third Stage	S/N A-104	S/N C-204	S/N C-204

*Identified by either serial number (S/N)or material designations

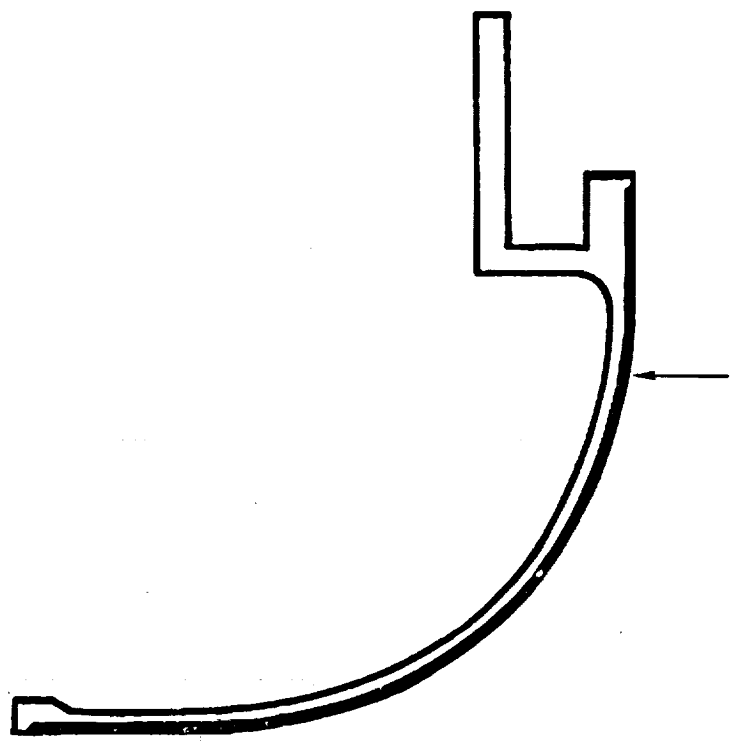
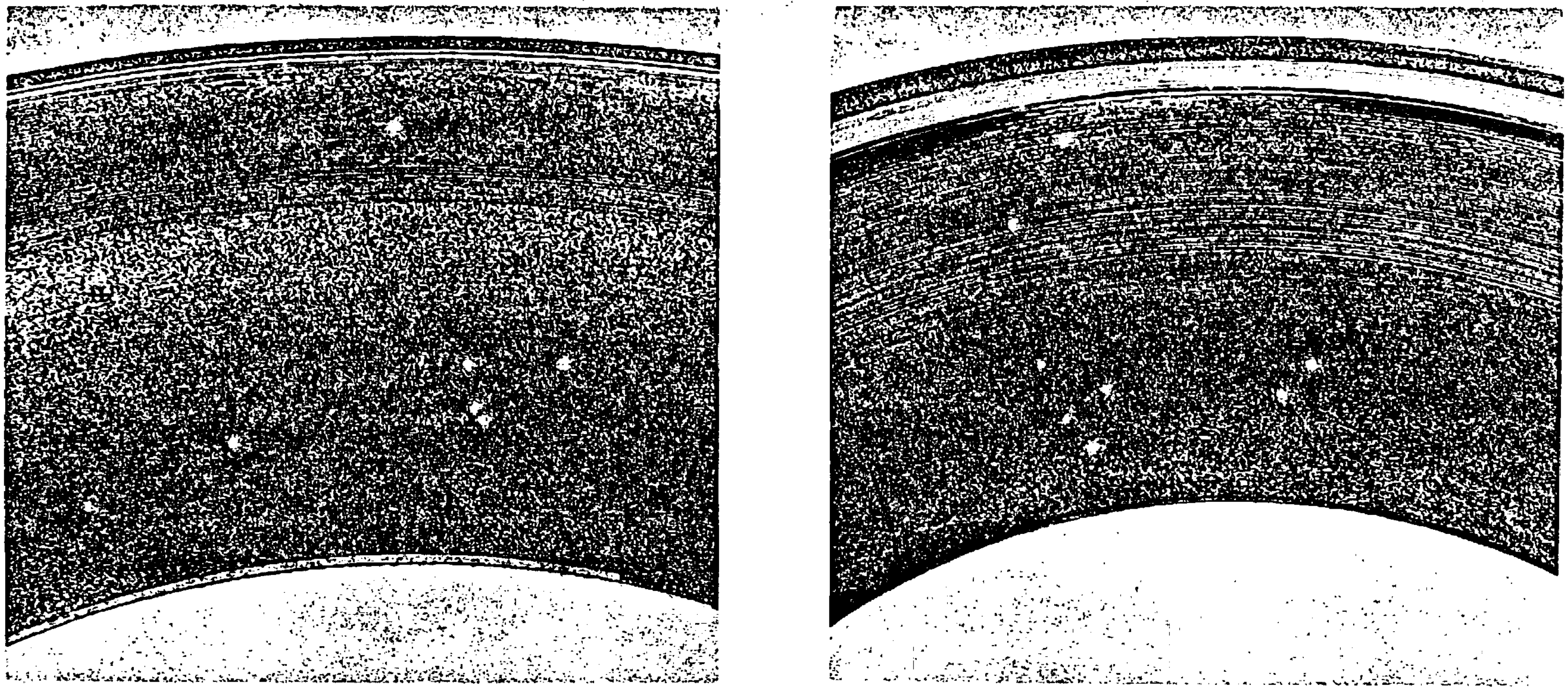


Figure 6. Cross Section of the High-Pressure Compressor Shroud Showing the Metco 601 Coating

Figure 7 shows portions of the two test shrouds after 50 and 100 hours of testing (Serial Numbers C-201 and A-101, respectively). The deepest rub grooves in both shrouds are 0.305-mm (0.012-inch) and 0.254-mm (0.010-inch) deep, respectively, and occur over 360 degrees. Figure 8 presents the condition of the titanium alloy (Ti-6Al-2Sn-4Zr-2Mo) centrifugal impeller blades before and after the 150-hour test. Note that the blade surfaces were virtually unchanged after the test and had no measurable dimensional changes.

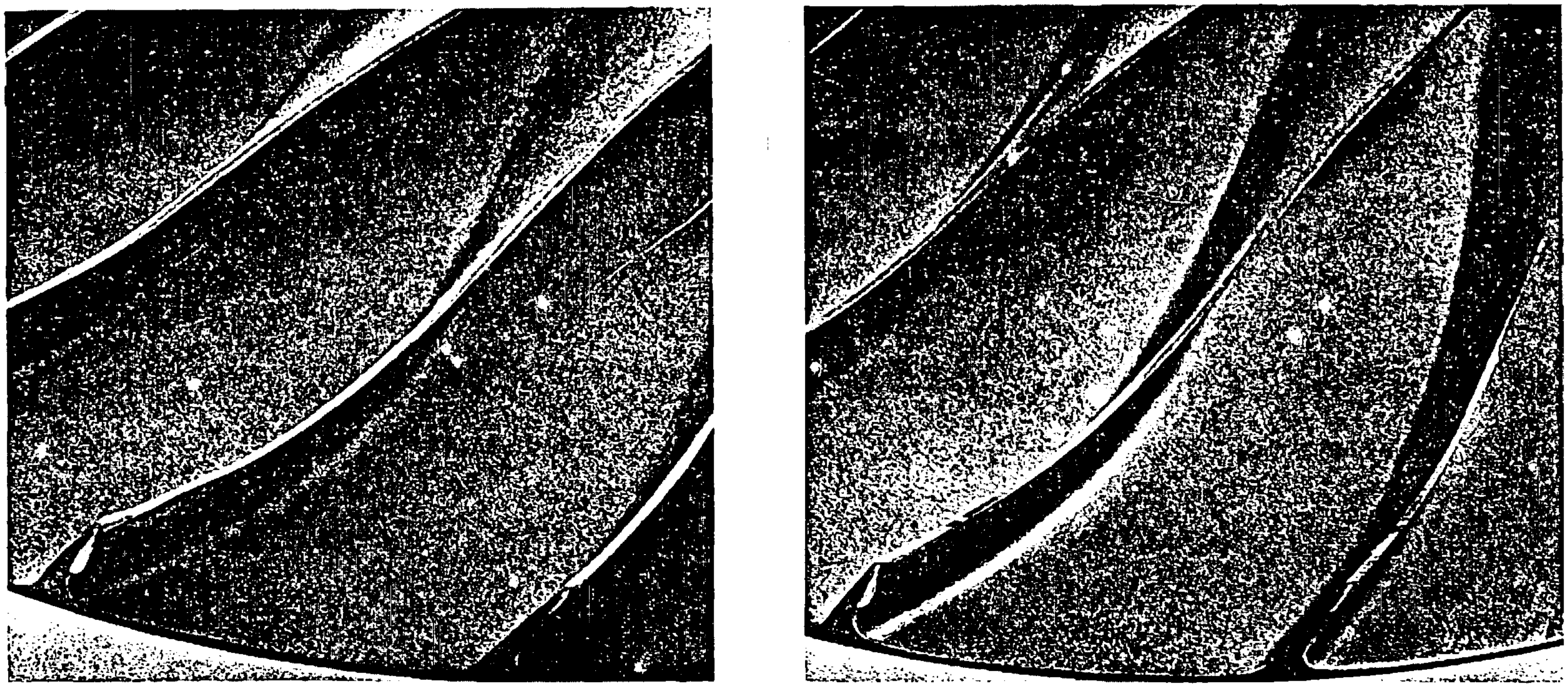
The abradable mechanism of Metco 601 is, apparently, unlike any other material evaluated. Figure 9 shows the surface topography as seen in the Scanning Electron Microscope (SEM) plus a polished cross section of a rub area from each of the two shrouds. The deeper grooves appear to be due to Metco 601 attaching to the impeller blades and actually machining itself. This is substantiated by the rubbed surfaces which do not exhibit any trace of titanium as might be expected from the blade contact. At engine teardowns, a slight buildup of Metco 601 was observed on the blades corresponding to the deepest wear grooves. The buildup material was not firmly attached and disappeared with additional testing. This abradable mechanism appears unique to Metco 601 in this analysis of the engine test hardware. The wear ratio of the abradable is defined as the amount of material removed from the abradable coating divided by the amount of material removed from the blades. For both impeller shrouds, this ratio was greater than the 15:1 program goal. There was no evidence of heat generation during blade contact, and the Metco 601 remained well bonded to the shroud. The exposure of the shroud (Serial Number A-101) to temperatures in excess of 400°C (750°F) for 100 hours without change indicates that the usable temperature range of the material could, in all probability, be extended beyond the 343°C (650°F) recommended by METCO, Inc. This conclusion was also confirmed by the results of the high-temperature exposure study completed in Task II.



(a) Serial Number C-201--
After 50 Hours of Testing

(b) Serial Number A-101--
After 100 Hours of Testing

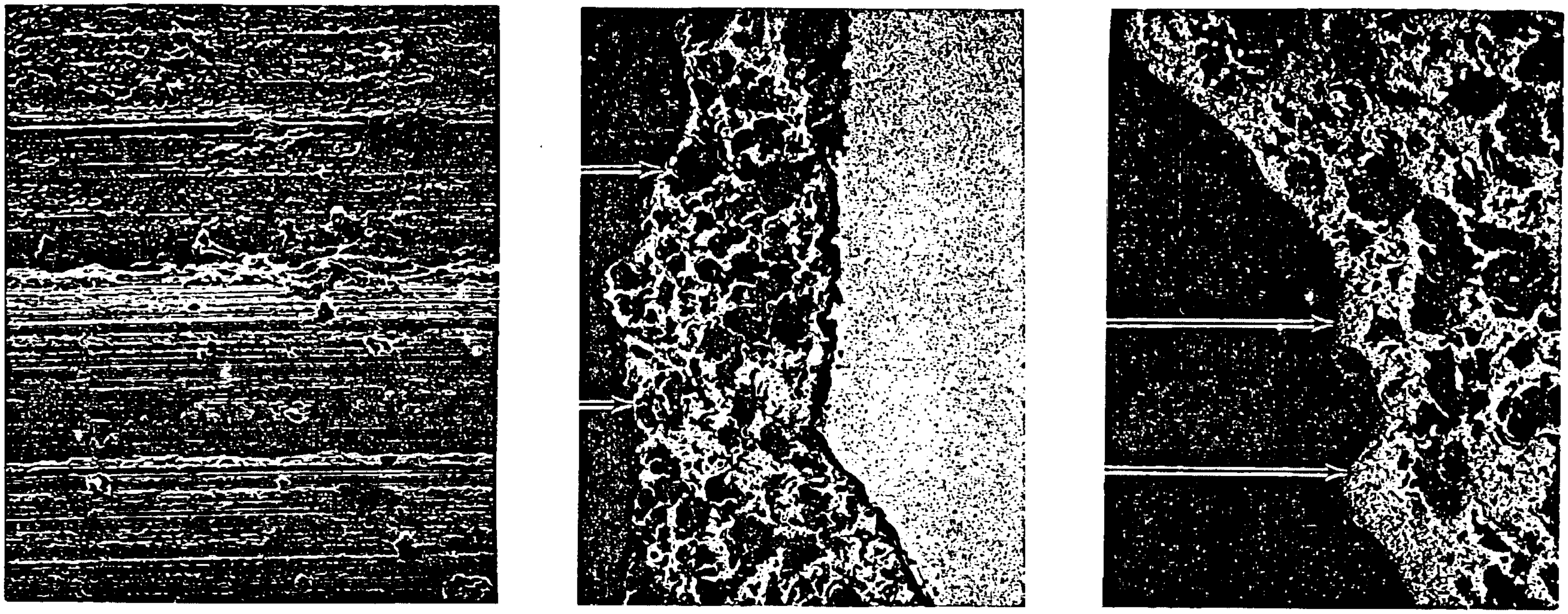
Figure 7. Metco 601 Coated High-Pressure Compressor Shrouds After Engine Testing (Mag.: 1/2X)



(a) Before Test

(b) After Test

Figure 8. Titanium-Alloy Centrifugal Impeller Before and After the 150-Hour Engine Test (Mag.: 1/2X)



(a) Serial Number C-201--
SEM of Surface
(Mag.: 100X)

(b) Serial Number C-201--
Cross Section
(Mag.: 50X)

(c) Serial Number A-101--
Cross Section
(Mag.: 100X)

Figure 9. SEM and Optical Metallographic Description of the Surface of the Engine Tested Metco 601. (Arrows Show Rubbed Surface)

High-Pressure Turbine

The high-pressure turbine shroud consists of six HS-25 alloy* (also known as L-605) segments held by a backup ring and retainer. The assembly is shown in Figure 10. The HPT operating conditions at take-off are 1050°C (1925°F) gas-temperatures and 420-m/sec (1400-ft/sec) tip speed. The abradable material tested in the first and third 50-hour tests was UCAR AB-4 while Metco 443 (Modified) was evaluated in the second 50-hour test. Volume I of the Project Completion Report includes a discussion on why the two materials were chosen for testing in this phase of the program.

1. UCAR AB-4. The six shroud segments coated with 13.79-MPa (2000-psi) tensile-strength AB-4 were provided by Union Carbide Corporation as fulfillment of the subcontract effort from Tasks I and II. The material was brazed on the shroud segments using LM Microbraz (AMS 4777 type), and X-ray inspected for evidence of braze wicking. No braze wicking was detected and the assembly was ground to a diameter of 0.10 mm (0.004 inch) over the upper limit. This oversize condition combined with precise centering of the rotor in the AB-4 shroud resulted in no blade-tip rubs during either of the two 50-hour test series. Without a rub, the abradability of AB-4 cannot be assessed in this evaluation even though it demonstrated the best abradability in the HPT during the Task II screening tests.

In spite of the absence of a rub, several conclusions concerning this material can be reached. Figure 11 presents one of the tested segments with evidence of gas erosion on the corners and in the region where cooling air exits from the blade tips. The surface, as seen in the SEM and the cross section through one of the eroded regions, is shown in Figure 12. Examination of the microstructure shows that the aluminum-rich-outer layer on the 80-percent nickel, 20-percent chromium particles is being depleted

*HS-25 is a registered trade name of Cabot Corporation.

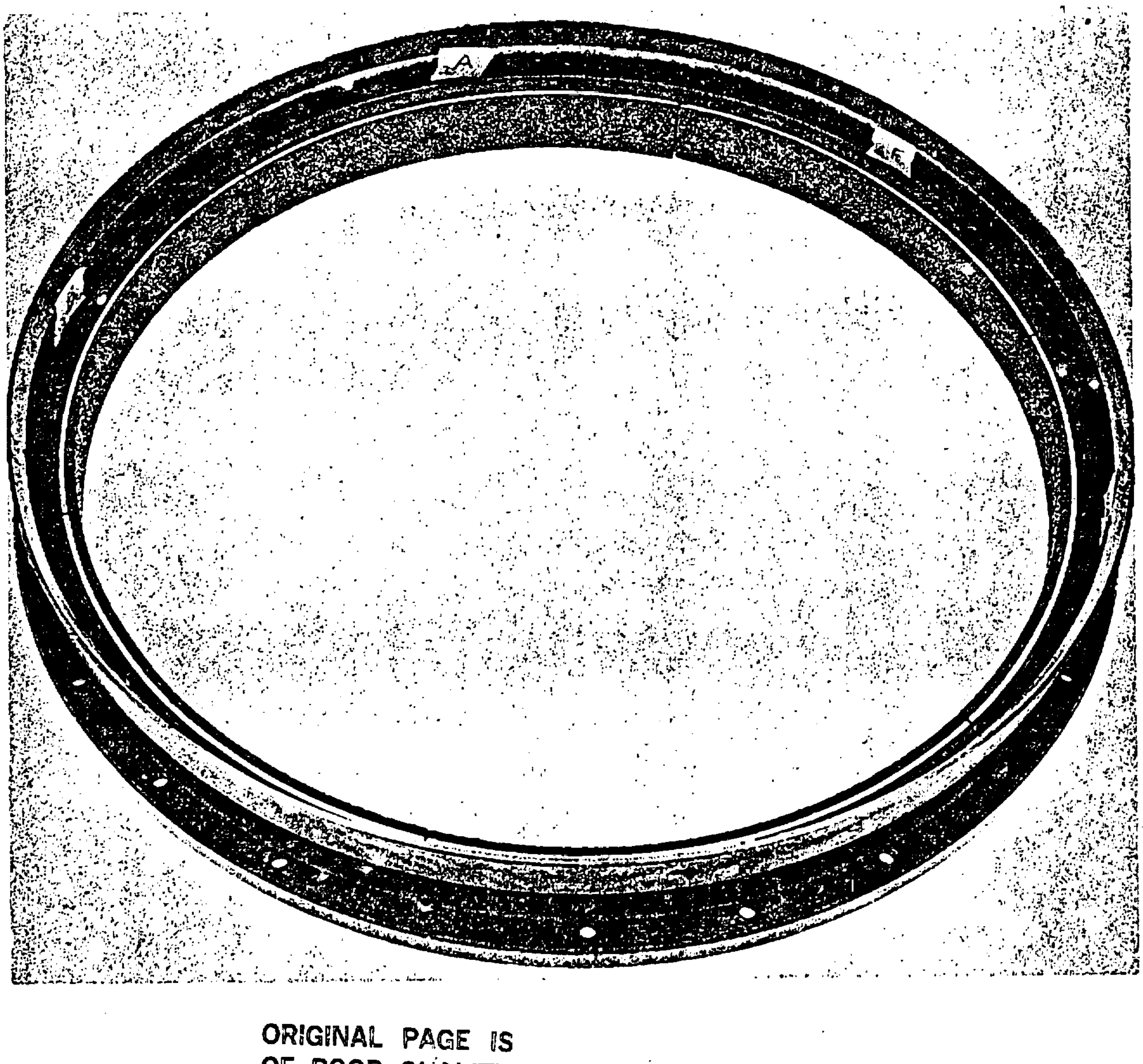


Figure 10. High-Pressure Turbine Assembly Prior to Engine Testing (Mag.: 1/2X)

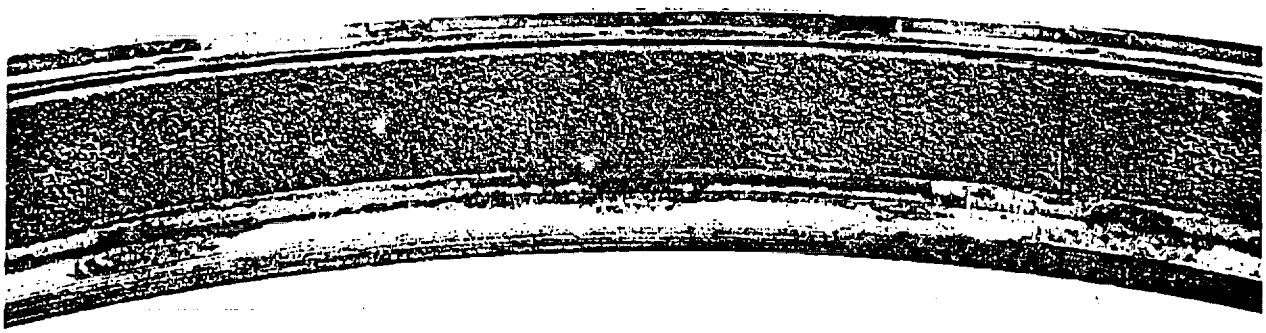
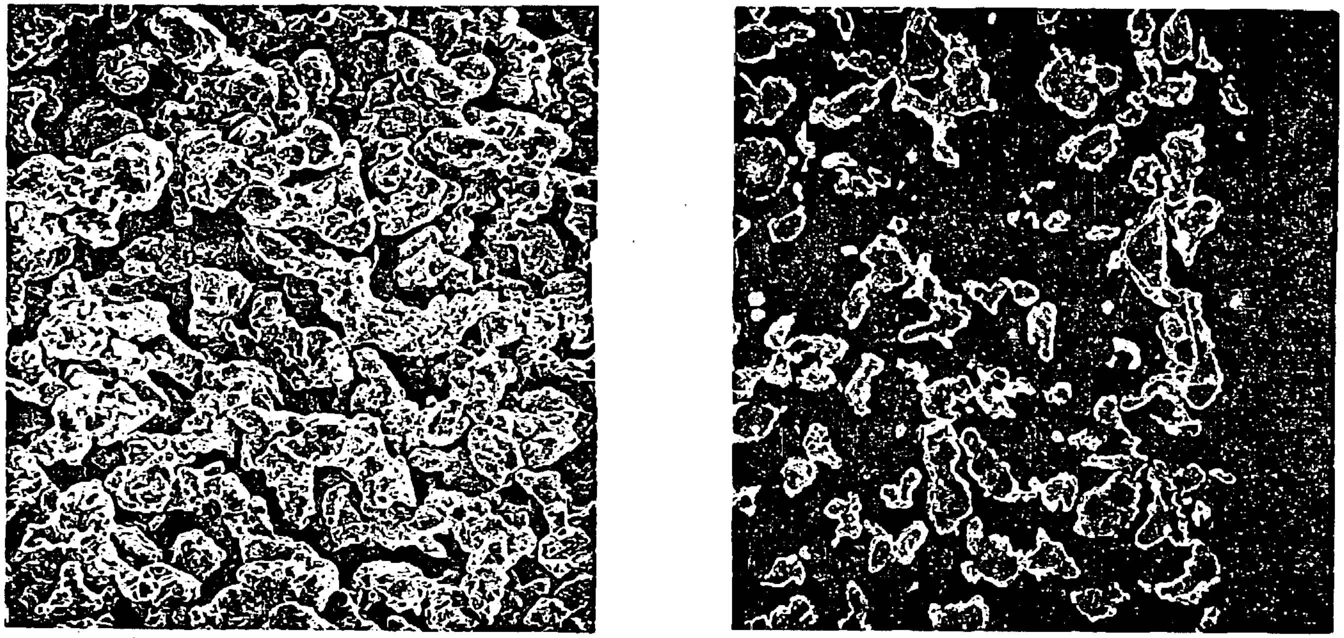


Figure 11. UCAR AB-4 High-Pressure Turbine Segment
After 100 Hours of Engine Testing



(a) Surface SEM

(b) Cross Section

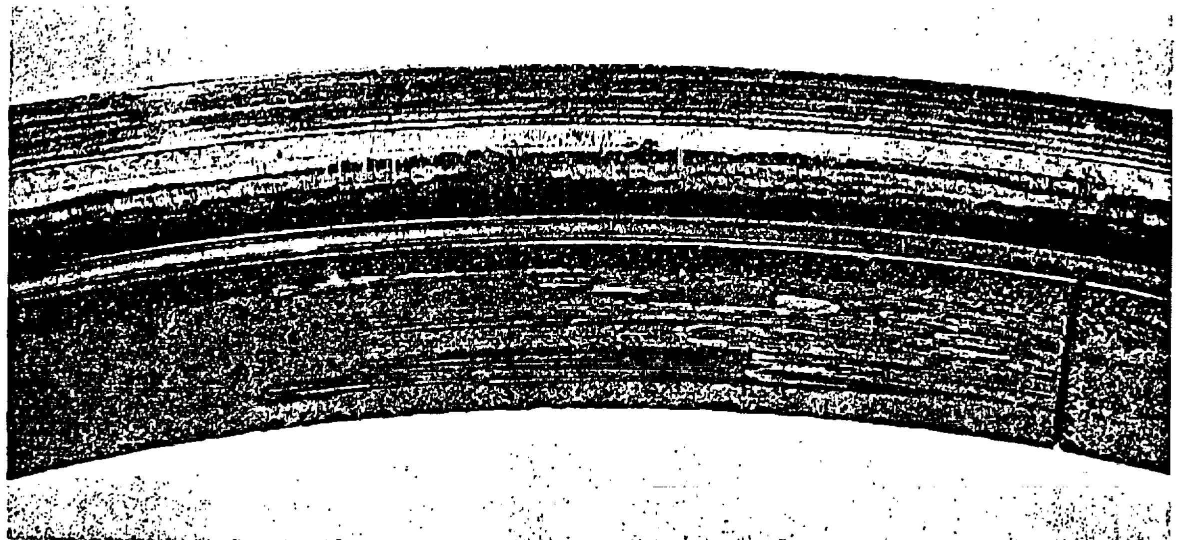
Figure 12. SEM Surface Analysis and Cross-Section Microstructure of UCAR AB-4 After 100 Hours of Engine Testing (Mag.: 50X)

at the coating surface. This loss of aluminum causes the structure to be susceptible to oxidation and breakdown of the interparticle diffusion bonds, which accentuates the erosion by removing individual particles or clusters of particles. The conclusion from these observations is that the engine operating temperature exceeds the long-time oxidation resistance temperature of UCAR AB-4, and a progressive erosion would continue to occur until the entire coating layer was removed. Therefore, AB-4 is not recommended for further testing in the temperature range of 1038°C (1900°F) and above. The maximum usable temperature for AB-4 was not determined in this program.

2. Metco 443 (Modified). A set of HPT shroud segments were coated with Metco 443 by plasma spraying at the METCO, Inc. facility in New York. The standard spray parameters were modified to yield a more open, less-dense microstructure than conventional Metco 443, without changing the relative elemental composition--6-percent aluminum and 94-percent nickel-chromium (80 percent - 20 percent). The shroud assembly containing the Metco 443 (Modified) material was then ground to the final diameter.

Rotor contact was achieved on this shroud near the 6 o'clock position during the 50-hour test. Figure 13 shows both the Metco 443 (Modified) shroud and the tips of the HPT rotor blades after the rub. The coating did not exhibit any abradability, and there was no measurable amount of material removed. Conversely, the rotor diameter was reduced approximately 0.64 mm (0.025 inch), and there was evidence of blade-alloy deposit on the shroud segment.

The SEM analysis of the surface revealed cracking, excessive heat generation, and a layer of IN100 blade alloy. This was confirmed in the cross section where a layer of blade alloy was observed welded to the Metco 443. Figure 14 shows both the SEM and the cross-section photomicrograph.



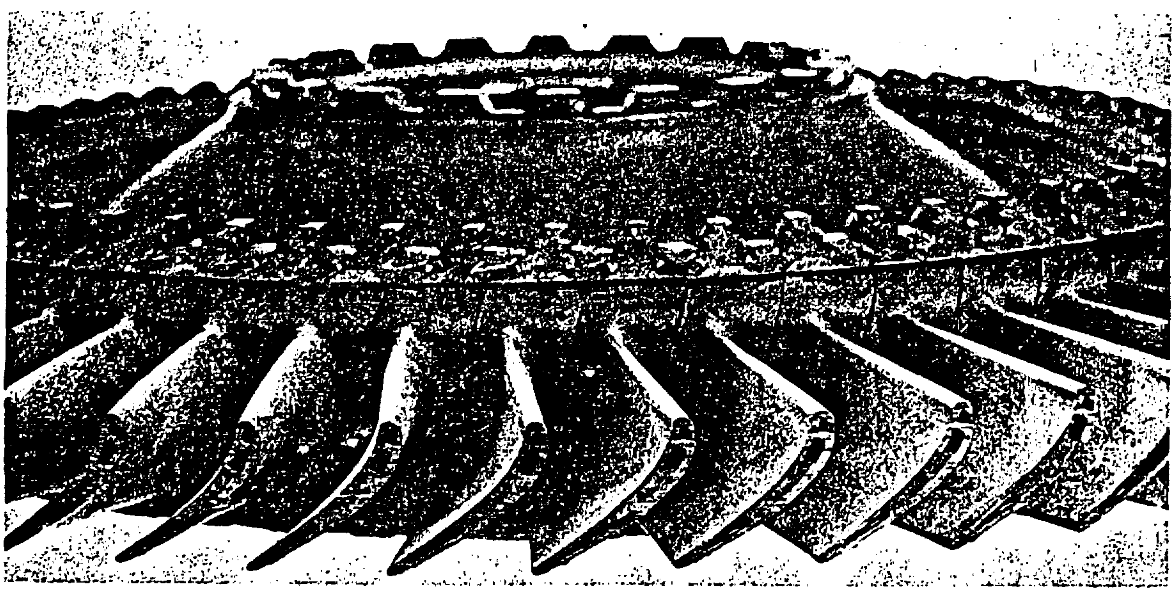


Figure 13. Metco 443 (Modified) Shroud and High-Pressure Turbine Rotor Blade Tips After Contact During the Engine Test

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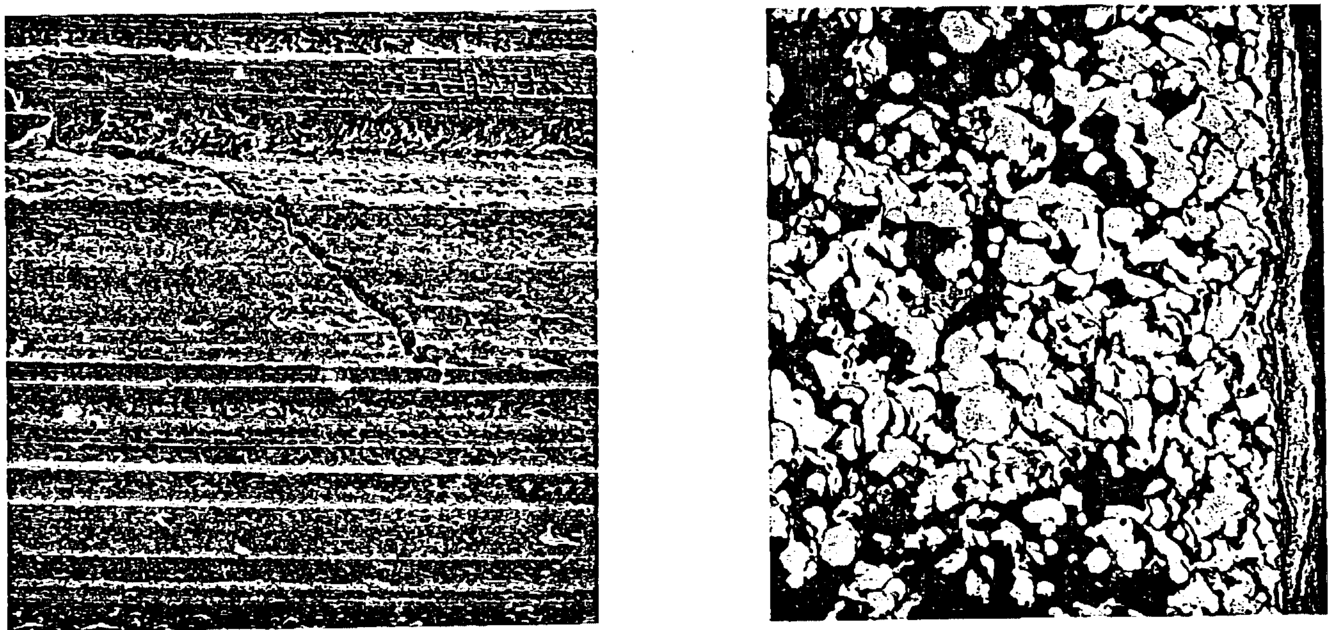

(a) Surface SEM
(Mag.: 50X)

(b) Cross Section
(Mag.: 100X)

Figure 14. SEM Surface Analysis and Cross-Section Microstructure of Metco 443 (Modified) After 50 Hours of Engine Testing

The total lack of abradability was probably caused by hardening of the coating during the 50 hours of engine testing. Initially, the coating hardness was 55 to 58 $R_{15}y$, but after testing, the hardness had risen to 90 $R_{15}y$. This hardening is thought to be caused by the formation of nickel-aluminide within the microstructure, which was not present to any extent in the as-sprayed condition. Based on these results, Metco 443 (Modified) is not recommended for further evaluation as an abradable material in the HPT.

The poor results obtained with both HPT abradable candidate systems indicates that further investigations are required to develop abradable materials for use at 1038°C (1900°F) and above.

Low-Pressure Turbine

The low-pressure turbine in the TFE731-3 Engine consists of three stages. Each turbine stage consists of a cast one-piece integral nozzle-shroud and a rotor containing inserted blades with double-knife-edge tip shrouds. Since the operating conditions and selected abradable materials are different for the three stages, each will be discussed separately.

1. First Stage. The first-stage LPT shroud operates at a maximum temperature of 871°C (1600°F) with an approximate blade-tip speed of 381 m/sec (1250 ft/sec) at takeoff. The shroud structural material is cast Alloy 713LC, and the shrouded turbine blades are cast IN100. Hastelloy-X honeycomb was brazed into the shroud inside diameter using LM Nicrobraz at an AiResearch approved vendor, Pyromet, San Carlos, California. The honeycomb had a 1.6-mm (0.0625-inch) cell size fabricated from 0.05- to 0.08-mm (0.002- to 0.003-inch) thick foil. The shrouds were inspected for braze-joint quality using AiResearch Specification EMS52337, Capillary Testing of Open-Face Honeycomb Structures. Both shrouds

(Serial Numbers A-102 and C-202, with 50 and 100 hours of engine testing, respectively) were in excellent shape after testing. Figure 15 presents Serial Number C-202 after testing. The blade contact was nearly 360 degrees on both shrouds with the depths of the wear grooves varying from 0.08mm to 0.3mm (0.003 inch to 0.012 inch).

Figure 16 shows the honeycomb surface of Serial Number A-102 as observed in the SEM, plus a photomicrograph of a typical cross section through the structure. Of interest is the braze wicking that occurs at the honeycomb nodes (contact points for foil strips). As shown in Figure 16, the turbine blades rubbed the braze alloy but did not suffer any damage. The wear ratio for the first-stage LPT was 15:1 indicating very little blade wear. A slight trace of blade alloy was detected in the wear tracks, as measured by X-ray analysis in the SEM.

The overall performance of the Hastelloy-X honeycomb was excellent. Abradability was rated good, and the program wear-ratio goal of 15:1 was achieved. There was no evidence of disbonding or oxidation of the Hastelloy-X foil.

2. <u>Second Stage</u>. The second-stage LPT shroud operates at a maximum temperature of 760°C (1400°F) with an approximate tip speed of 411 m/sec (1350 ft/sec) at takeoff. The shroud structure and the shrouded turbine blades are both cast Alloy 713LC. Metco 301 (Modified) was thermosprayed on the inside diameter of the shroud by METCO, Inc., New York, using parameters developed in Task II and a bond coat of Metco 450. Metco 301 has a nominal composition of 4-percent aluminum, 5.5-percent boron-nitride with the balance nickel-chromium (80 percent - 20 percent).

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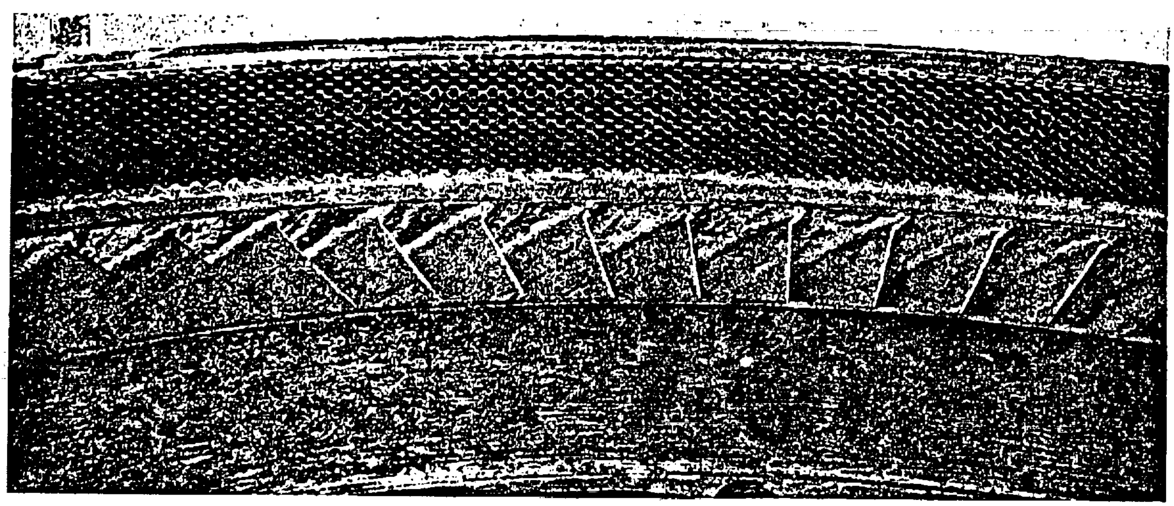
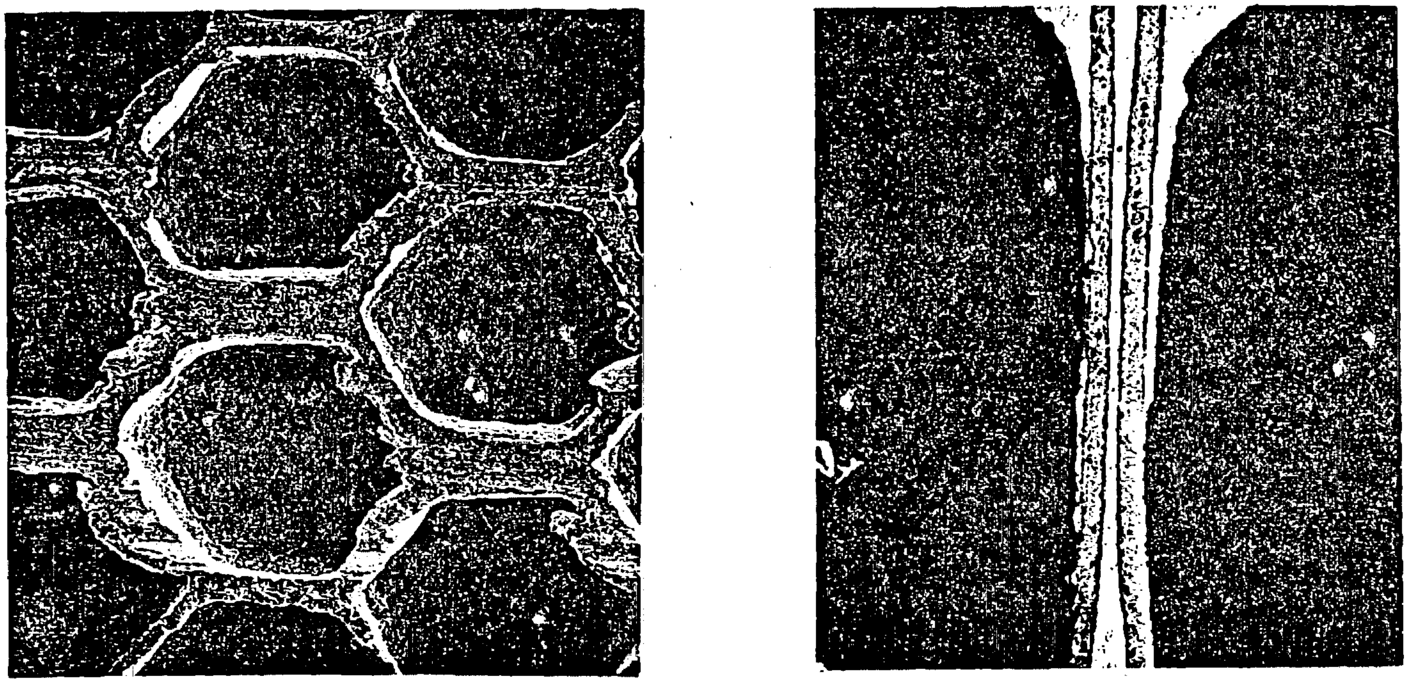


Figure 15. First-Stage Low-Pressure Turbine Shroud, Serial Number C-202, After 100 Hours of Engine Testing



(a) Surface SEM
(Mag.: 20X)

(b) Cross Section
(Mag.: 50X)

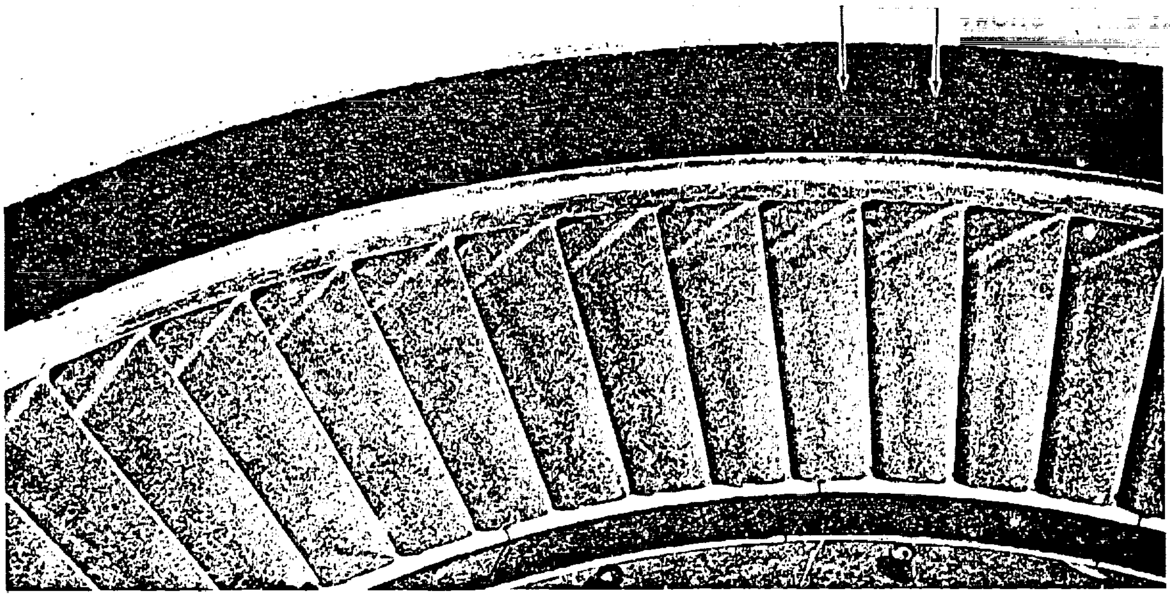
Figure 16. SEM Surface Analysis and Cross-Section Microstructure of Hastelloy-X Honeycomb After 50 Hours of Engine Testing

Figure 17 shows the two shrouds after removal from the engine. Serial Number C-203, which was run in the second 50-hour test, shows an erosion groove that occurred between the knife edges of the blade. The probable cause of this 0.3-mm (0.012-inch) deep groove was abradable-coating particles trapped between the knife edges and rotating with the rotor until they could escape downstream. No appreciable rotor-blade wear was noted during this test series.

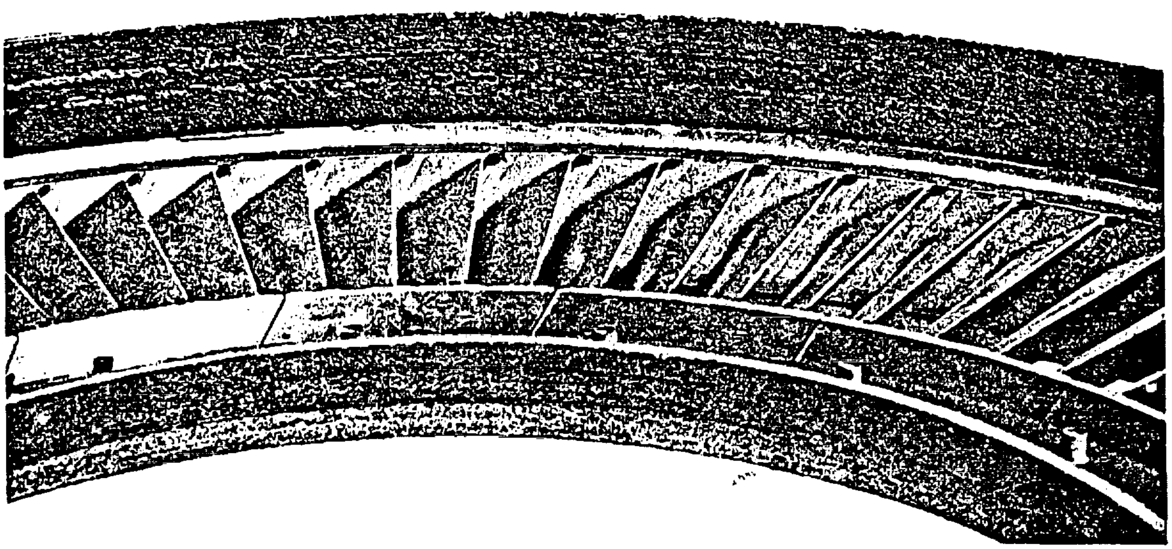
Shroud Serial Number A-103 was run in the first and third 50-hour test series. Preliminary results at the end of the first 50 hours showed that the Metco 301 was not as abradable as predicted, and that the rotor diameter had been reduced approximately 0.12 mm (0.005 inch). No erosion of the coating was observed. During the third 50-hour test, (second test for A-103), blade wear totaling 0.36 mm (0.014 inch) on the diameter was observed with a maximum coating wear of 0.13 mm (0.005 inch) per side. The resultant wear ratio was, therefore, less than 1:1 and considered "poor".

Examination of the surface under the SEM and the microstructure (Figure 18) of the cross section disclosed that the Metco 301 was not really abradable, and that blade alloy had been transferred to the coating surface. The hardness of the coating increased slightly from approximately 45 $R_{15}y$ to 52 $R_{15}y$ after the 100-hour exposure.

The results of the Final Engine Test did not verify those found in the Task II Screening Test. The difference may be due to the extended time at operating temperature causing the hardness of the Metco 301 to increase, thus, reducing the abradability. Based on the 100-hour test results, further evaluation of Metco 301 is not recommended.

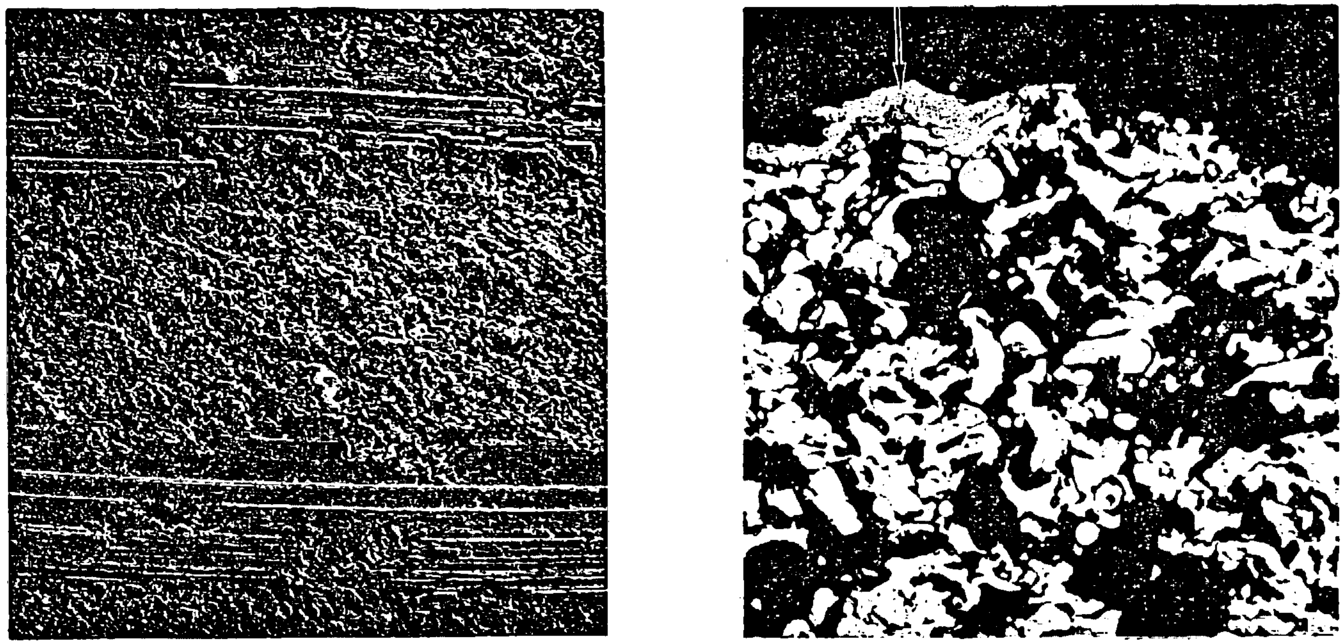


(a) Serial Number C-203--After 50 Hours of Testing



(b) Serial Number A-103--After 100 Hours of Testing

Figure 17. Second-Stage Low-Pressure Turbine Shrouds Coated with Metco 301 After Engine Testing. (Arrows Show Erosion Groove in C-203)



(a) Surface SEM
(Mag.: 20X)

(b) Cross Section
(Mag.: 100X)

Figure 18. SEM Surface Analysis and Cross-Section Microstructure of Metco 301 After 100 Hours of Engine Testing. (The Arrow in the Cross Section Shows Deposited Blade Alloy)

Since engine testing proved that the abradable material chosen for the second-stage LPT was not acceptable, it was necessary to select another abradable for this component. Solabrade was tentatively selected as the alternate abradable after reviewing the remaining materials that were found acceptable for the second-stage LPT (Table XV, Volume I). However, honeycomb was substituted for the Solabrade because of the following reasons:

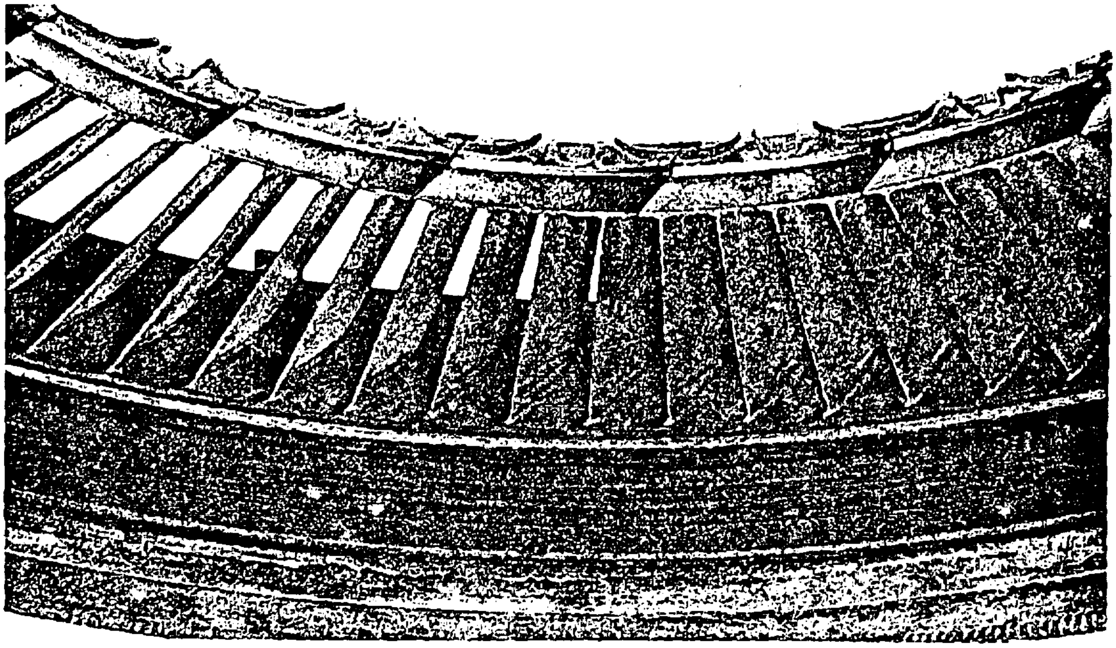
- o Screening tests in the first-stage LPT proved that honeycomb and Solabrade were essentially equal in terms of abradability

- o Honeycomb had been proven as an acceptable abradable material through an extensive 150-hour engine test

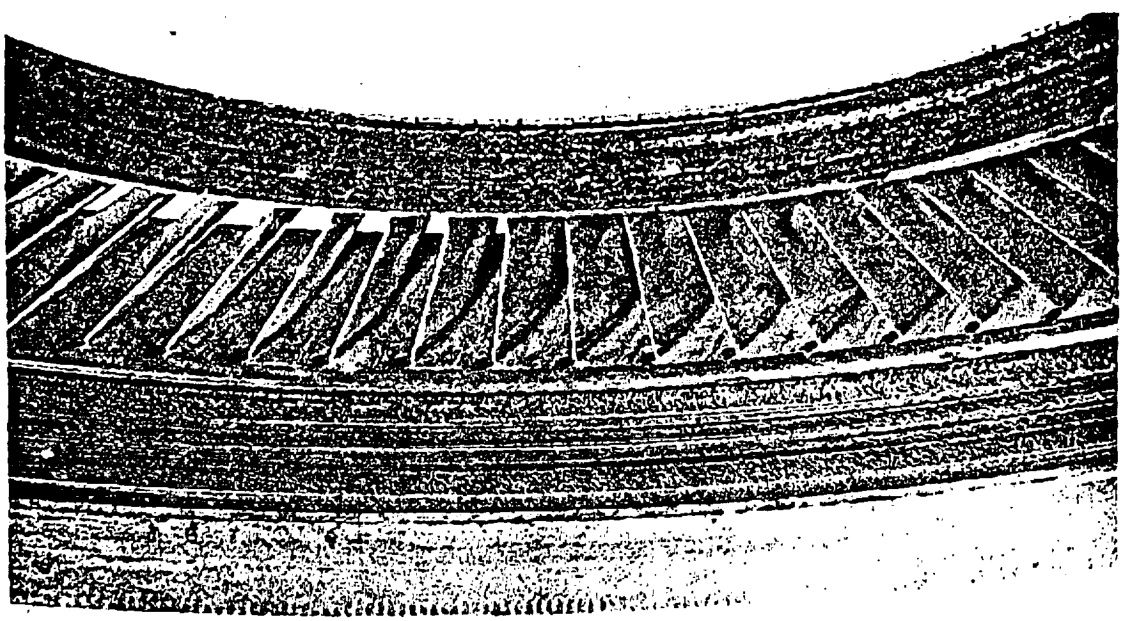
- o When cost and inspectability are considered, honeycomb was again chosen over Solabrade, as in the first-stage LPT.

3. Third Stage. The third-stage LPT operates at a maximum temperature of 650°C (1200°F) with an approximate rotor-tip speed of 436 m/sec (1430 ft/sec) at take-off. The shroud structure is cast HS-31, and the shrouded turbine blades are cast Alloy 713LC. Metco 304NS was thermosprayed on the shroud inside diameter by METCO, Inc., New York, using parameters developed in Task II and a bond coat of Metco 450. Metco 304NS has the nominal composition of 7-percent boron-nitride and 93-percent aluminum-bronze (89.5-percent Cu, 9.5-percent Al, and 1.0-percent Fe).

Figure 19 shows the two shrouds after engine testing. Serial Number A-104 was tested for 50 hours while Serial Number C-204 was tested for 100 hours. Both shrouds were rubbed the full 360 degrees to depths from 0.025 to 0.10 mm (0.001 to 0.004 inch) for A-104, and from 0.05 to 0.356 mm (0.002 to 0.014 inch) for C-204. Measured blade wear was minimal, and the overall wear ratio for the material is greater than 15:1.



(a) Serial Number A-104--After 50 Hours of Testing

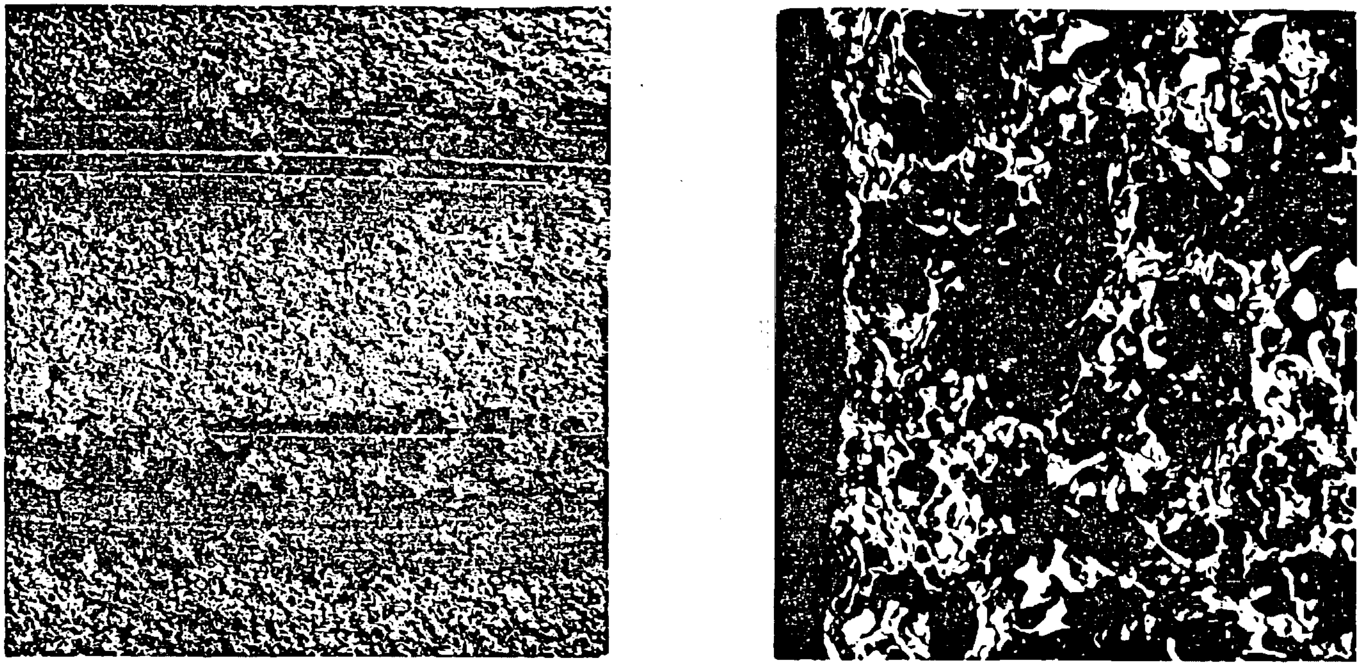


(b) Serial Number C-204--After 100 Hours of Testing

Figure 19. Third-Stage Low-Pressure Turbine Shrouds Coated with Metco 304NS After Engine Testing (Mag.: 1/2X)

The surface (as shown in the SEM) and the cross-section microstructure are presented in Figure 20. Very slight traces of blade alloy were identified on the surface, and there was no evidence of excessive heat generation. The pre- and post-test hardness of the Metco 304NS was 51 $R_{15}y$ and 57 $R_{15}y$, respectively, after 100 hours of exposure. There is no detectable change in the microstructure.

The abradability of Metco 304NS is considered "excellent" based on the wear ratio and the metallurgical characteristics.



(a) Surface SEM
50 Hours of Testing
(Mag.: 10X)

(b) Cross Section
100 Hours of Testing
(Mag.: 100X)

Figure 20. SEM Surface Analysis and Cross-Section Microstructure of Metco 304NS After Engine Testing

CONCLUSIONS

Based upon the results of the engine testing and the evaluation of the abradable materials presented in this report, the following conclusions were reached:

- Metco 601 has been identified as an excellent abradable material for the HPC shroud. This material meets or exceeds all of the abradable evaluation standards, including the cost goal.

- An acceptable abradable material was not identified for the HPT shroud segments. The UCAR AB-4 material, with slight modifications, appears to offer the most potential in this area, if the long-term oxidation problem at temperatures above 1038°C (1900°F) can be solved.

- Hastelloy-X Honeycomb has been identified as the best abradable material currently available for the first-stage LPT shroud. Although a spray coating was originally desired for this component, based on lower costs, none could be found that would compare to the overall performance of honeycomb.

- Hastelloy-X Honeycomb has also been identified as an acceptable abradable material for the second-stage LPT shroud after an acceptable spray coating could not be found. The Metco T301-10 material evaluated for this component was not abradable, and an attempt to apply Metco 304NS for this higher-temperature component was not successful.

- Metco 304NS has been identified as an excellent abradable material for the third-stage LPT shroud. This material meets all the abradable evaluation standards, including cost.

- The SFC of the TFE731-3 was reduced by adding abradable gas-path seals to a production engine, thus, allowing the blade tip-to-shroud clearances to be reduced.

  <u>Goal</u>: Reduce SFC, by at least 1.5 percent.

  <u>Demonstrated</u>: Measured SFC reduced by 1.8 percent.

  <u>Potential</u>: With engine components optimized to maximize SFC benefits, analysis indicates production engine SFC could be reduced by 2.5 percent.

- All coating debris appeared to be smaller than the goal of 0.010 inch. Only fine powder was produced during this testing, and there were no significant "chunks" or FOD attributed to coating debris.

- Based on the results of this limited engine testing and previous bench testing, it is expected that the selected abradable coatings will be able to achieve the part-life goal of 10,000 hours.

- The materials selected and tested in the HPC (Metco P601-10), the first-stage LPT turbine (Hastelloy-X Honeycomb), and the third-stage LPT (Metco 304NS) will achieve a wear ratio of at least 15:1 in engine operation.

- The materials tested in the HPT (UCAR AB-4 and Metco P443-10) and the second-stage LPT (Metco T301-10) did not yield a minimum wear ratio of 15:1.

RECOMMENDATIONS

After completing the engine testing and the post-test evalua-n of the abradable coatings, the following action items are ommended for abradable gas-path seals:

- o Incorporate the following materials as abradable seals in the TFE731 Engine.

  High-Pressure Compressor - Metco 601

  Low-Pressure Turbine

First Stage	- Hastelloy-X Honeycomb
Second Stage	- Hastelloy-X Honeycomb
Third Stage	- Metco 304NS

- o Reduce the build-up clearances of the TFE731 Engine appropriately for the new gas-path abradable seals.

- o Investigate new, low-cost abradable systems for the TFE731 high-pressure turbine and the low-pressure turbine in the 760°C (1400°F) range.

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Manufacturing Div.
Attn J. Zubeckis
400 Main St.
East Hartford, CT 06108

Pratt and Whitney Aircraft
Attn J. Moore
Box 2691
West Palm Beach, FL 33402

Solar
Div. of Int. Harvester
Attn A. Stetson
P.O. Box 80966
San Diego, CA 92138

Solar
Div. of Int. Harvester
Attn A. Metcalfe
P.O. Box 80966
San Diego, CA 92138

Teledyne CAE
Mat. Dev. and Manuf. Engr.
Attn R. Beck
P.O. Box 6971
Toledo, OH 43612

Williams Research
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2280 W. Maple
Walled Lake, MI 48081

Williams Research
Attn Library
2280 W. Maple
Walled Lake, MI 48081

Williams Research
Attn J. Jones
2280 W. Maple
Walled Lake, MI 48081

Williams Research
Attn J. Carlton
2280 W. Maple
Walled Lake, MI 48088

Airco Temescal
Attn D. Boone
2850 Seventh St.
Berkeley, CA 94710

Arizona State University
Attn M. C. Shaw
Engineering Sciences Dept.
Tempe, AZ 85281

Battelle Memorial Inst.
Attn S. Rubin
505 King Ave.
Columbus, OH 43201

Battelle Memorial Inst.
Attn D. Niesz
505 King Ave.
Columbus, OH 43201

Battelle Memorial Inst.
Attn Technical Library
505 King Ave.
Columbus, OH 43201

Pratt and Whitney Aircraft
Attn J. Miner
Box 2691
West Palm Beach, FL 33402

Pratt and Whitney Aircraft
Attn M. Maguire
Box 2691
West Palm Beach, FL 33402

Pratt and Whitney Aircraft
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East Hartford, CT 06108

Pratt and Whitney Aircraft
Commercial Products
Attn L. Shiembob
400 Main St.
East Hartford, CT 06108

Pratt and Whitney Aircraft
Attn R. J. Hecht
Box 2691
West Palm Beach, FL 33402

AVCO Lycoming Div.
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550 S. Main St.
Stratford, CT 06497

AVCO Lycoming Div.
Attn P. Bania
550 S. Main St.
Stratford, CT 06497

Solar
Div. of Int. Harvester
Attn J. Vogan
P.O. Box 80966
San Diego, CA 92138

Solar
Div. of Int. Harvester
Attn Wm. Compton
P.O. Box 80966
San Diego, CA 92138

Curtiss-Wright Corp.
Attn R. Yellin
1 Passaic St.
Wood Ridge, NJ 07075

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Mat. Dev. and Manuf. Engr.
Attn Wm. Wagner
P.O. Box 6971
Toledo, OH 43612

AVCO Lycoming Div.
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550 S. Main St.
Stratford, CT 06497

General Electric Co.
Attn C. Sims, Bldg. 53
Gas Turb. Prod. Div.
Schenectady, NY 12345

Detroit Diesel Allison
Attn D. H. Jacobson
P.O. Box 894
Indianapolis, IN 46206

Detroit Diesel Allison
Attn D. Clingman
P.O. Box 894
Code W-5
Indianapolis, IN 46206

Detroit Diesel Allison
Attn B. A. Ewing
P.O. Box 894 T-27
Indianapolis, IN 46206

Airco Temescal
Attn S. Mutialu
2850 Seventh St.
Berkeley, CA 94710

Detroit Diesel Allison
Attn M. Herman
P.O. Box 894
Indianapolis, IN 46206

Detroit Diesel Allison
Attn B. Schectr 5827/W5
P.O. Box 894
Indianapolis, IN 46206

Detroit Diesel Allison
Attn E. S. Nichols
Dept. 5827
P.O. Box 894
Indianapolis, IN 46206

Curtiss-Wright Corp.
Attn J. Mogul
1 Passaic St.
Wood Ridge, NJ 07075

Beech Aircraft Corporation
Attn C. A. Rembleske
9709 E. Central Ave.
Wichita, KS 67201

Bendix Research Labs
Attn K. Rhee
10.5 Mile Road
Southfield, MI 48075

Boeing Comm. Airplane Co.
Attn W. Blissell 13-27
P.O. Box 3707
Seattle, WA 98124

Boeing - Wichita Div.
Attn Wm. F. Schmidt
org. 75930 Propulsion
Wichita, KS 67210

Brown Boveri Turbo. Inc.
Attn L. Engel
711 Anderson Ave. N
St. Cloud, MN 56301

Westinghouse Electric Co.
Attn P. Wall
P.O. Box 9176
Lester, PA 19113

Brunswick Corporation
Attn A. Erickson
Technetics Division
2000 Brunswick Lane
Deland, FL 32720

Rockwell International
Attn L. L. McHughes
General Aviation Div.
5001 N. Rockwell Ave.
Bethany, OK 73008

SCM Glidden Metals
Attn K. M. Kulkarni
11000 Cedar Ave.
Cleveland, OH 44106

Sorcery Metals
Attn P. Hanson
P.O. Box 1600
Delray Beach, FL 33444

Special Metals, Inc.
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Middle Settlement Road
New Hartford, NY 13413

Stellite Division
Cabot Corporation
Attn J. Klein
1020 West Park Ave.
Kokomo, IN 46901

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Cabot Corporation
Attn D. Acuncius
1020 West Park Ave.
Kokomo, IN 46901

Sundstrand
Attn D. Augustine
4747 Harrison Ave.
Rockford, IL 61101

Swearingen Aviation Corp.
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P.O. Box 32486
San Antonio, TX 78284

Teledyne Allvac
Attn F. Elliott
P.O. Box 759
Monroe, NC 28110

Teledyne Allvac
Attn R. Kennedy
Wm. Thomas
P.O. Box 759
Monroe, NC 28110

TRW, Inc.
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23555 Euclid Ave.
Cleveland, OH 44117

TRW Inc.
Attn J. McCarthy
23555 Euclid Ave.
Cleveland, OH 44117

TRW Inc.
Attn D. Maxwell
23555 Euclid Ave.
Cleveland, OH 44117

TRW Inc.
Attn T. Piwonka
23555 Euclid Ave.
Cleveland, OH 44117

TRW Inc.
Attn E. A. Steigerwald
Metals Division
Minerva, OH 44567

Union Carbide Corp.
Attn R. Tucker
Coatings Service Dept.
1500 Polco St.
Indianapolis, IN 46224

United Airlines - SPOEG
Attn J. K. Goodwine
San Francisco Airport
CA 94128

United Tech Research Center
Attn B. Thomson
East Hartford, CT 06108

United Tech Research Center
Attn Library
East Hartford, CT 06108

Universal Cyclops
Attn L. Lherbier
650 Washington Road
Pittsburgh, PA 15228

Universal Cyclops
Attn Wm. Kent
650 Washington Road
Pittsburgh, PA 15228

Vought Corp.
Attn W. R. Boruff 2-53220
P.O. Box 5907
Dallas, TX 75222

Vought Corp.
Attn O. H. Cook 2-53400
P.O. Box 5907
Dallas, TX 75222

Vought Corp.
Attn Library
2-50370/TL 7-67
P.O. Box 5907
Dallas, TX 75222

Vought Corporation
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Hampton Tech Center
3221 N. Armistead Ave.
Hampton, VA 23666

Hampton Technical Center
Attn W. A. Lovell
3221 N. Armistead Ave.
Hampton, VA 23666

Westinghouse R & D Center
Attn D. Thomas
Beulah Road
Pittsburgh, PA 15235

Westinghouse R & D Center
Attn J. W. Clark
Beulah Road
Pittsburgh, PA 15235

Howmet Turbine Comp. Div.
Attn. W. Freeman
500 Terrace Plaza
Muskegon, MI 49443

Howmet Corporation
Technical Center
Attn L. Dardi
699 Benston Road
Whitehall, MI 49461

Howmet Corporation
Technical Center
Attn N. G. Lirones
699 Benston Road
Whitehall, MI 49461

Howmet Corporation
Austenal Division
Attn F. Jaeger
Dover, NJ 07801

Howmet Corporation
Turbine Components Div.
Attn Mr. Burd
Dover, NJ 07801

Howmet Corporation
Turbine Components Div.
Attn E. Carozza
Dover, NJ 07801

Huntington Alloys Div.
International Nickel Co.
Attn F. Perry
Huntington, WV 25720

IIT Research Institute
Attn M. A. Howes
10 West 35th Street
Chicago, IL 60616

International Nickel Corp.
Attn J. Benjamin
Sterling Forest
Suffern, NY 10901

International Nickel Corp.
Attn Library
Sterling Forest
Suffern, NY 10901

Jetshapes, Inc.
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Rockleigh Industrial Park
Rockleigh, NJ 07647

Kaman Sciences Corp.
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Garden of the Gods Road
Colorado Springs, CO 80907

Kaman Sciences Corp.
Attn W. Long
Garden of the Gods Road
Colorado Springs, CO 80907

Kawecki Berylco Ind.
Attn E. R. Laich
P.O. Box 1462
Reading, PA 19603

Kelsey Hayes
Attn M. Ziobro
Utica, NY 13503

Kelsey Hayes Co.
Attn W. G. Koby
Heintz Div.
Front St. and Olney Ave.
Philadelphia, PA 19120

Thomas McNamara
Consultant
42701 Main St., SP 154
San Jacinto, CA 92383

MCIC
Battelle Memorial Inst.
Attn H. Mindlin
Columbus, OH 43201

Martin Marietta
Attn C. H. Lund
15 N. Windsor Road
Arlington Hts, IL 60004

METCO Inc.
Attn V. Lanza
1101 Prospect Ave.
Westbury, L.I., NY 11590

METCO Inc.
Attn C. Lewis
3400 A Oak Cliff Road
Atlanta, GA 30340

METCO Inc.
Attn W. Menth
1101 Prospect Ave.
Westbury, L.I., NY 11590

Minnesota Mining Corp.
Attn J. Johnson
3M Center
St. Paul, MN 55101

Pan American World Airways
Attn W. B. Hibbs
Pan Am Building
New York, NY 10017

RSC Materials Tech.
Attn B. Cremisio
P.O. Box 312
Cinton, NY 13323

Rocketdyne Division
Attn J. Frandsen
Rockwell International
5633 Canoga Ave.
Canoga Park, CA 91304

Rockwell International
Attn N. Paton
Science Center
Thousand Oaks, CA 91360

Rockwell International
Attn V. Taylor
General Aviation Div.
5001 N. Rockwell Ave.
Bethany, OK 73008

Westinghouse Electric Co.
Attn E. Crombie A-603
P.O. Box 9174
Lester, PA 19113

Westinghouse R & D Center
Attn D. Moon
Beulah Road
Pittsburgh PA 15235

Westinghouse Electric Co.
Attn R. L. Ammon
P.O. Box 10864
Pittsburgh, PA 15236

Westinghouse Electric Co.
Attn D. Goldberg
P.O. Box 10864
Pittburgh, PA 15236

Union Carbide Corp.
Attn M. Henika
Parma Tech Center
Parma, OH 44130

Chromalloy-PMT
Attn R. Elbert
13434 Floyd Circle
Dallas, TX 75243

Brunswick Corporation
Attn T. J. Morrison
Technetics Div.
2000 Brunswick Lane
Deland, FL 32720

Cameron Iron Works
Attn Library
P.O. Box 1212
Houston, TX 77001

Union Carbide Corp.
Attn E. G. Farris
Parma Tech Center
Parma, OH 44130

Cannon-Muskegon Corp.
Attn R. Schwer
P.O. Box 506
Muskegon, MI 49443

Carpenter Technology Corp.
Attn G. DelCorso
A. Walsh
R/D Lab, Bldg. 68
Reading, PA 19603

Cessna Aircraft Co.
Attn A. Kavie
(Turbofan)
Wallace Division
P.O. Box 7704
Wichita, KS 67277

Cessna Aircraft Co.
Attn C. Gonzales
(Turboprop)
Wallace Division
P.O. Box 7704
Wichita, KS 67277

Union Carbide Corp.
Attn G. Whitemars
Parma Tech Center
Parma, OH 44130

Crysler Corp.
Attn Witherow
P.O. Box 1118
Detroit, MI 48231

Climax Molybdnum Co.
Attn Wm. Hagel
P.O. Box 1568
Ann Arbor, MI 48106

Colt Industries
Attn E. Dulis
Crucible Inc., Mat'ls. Rsch.
P.O. Box 88
Pittsburgh, PA 15230

DCI Inc.
Attn R. Engdahl
[illegible] Victory Drive
Herndon, VA 22070

Union Carbide Corp.
Attn P. Timmel
Parma Tech Center
Parma, OH 44130

Defense Marketing Services
Attn D. Franus
Northfield St.
Greenwich, CT 06830

Delta Airlines
Attn W. J. Overend
Atlanta Airport
Atlanta, GA 30320

Douglas Aircraft Co.
Attn Library
McDonnell Douglas Corp.
3855 Lakewood Blvd.
Long Beach, CA 90846

Engelhard Industries
Attn E. Grider
Route 152
Plainville, MA 02762

Ford Motor Company
Attn C. Feltner
Metallurgical Dept.
P.O. Box 2053
Dearborn, MI 48121

Ford Motor Company
Attn Y. Telang
Metallurgical Dept.
P.O. Box 2053
Dearborn, MI 48121

Gates Learjet Corp.
Attn T. Reichenberger
P.O. Box 7707
Wichita, KS 67277

General Motors Corp.
Attn A. Bell
Advanced Prod. Engr.
Technical Center
Warren, MI 48090

General Motors Corp.
Attn K. Bly 73-S
Technical Center
Warren, MI 48090

Gould Inc.
Attn F. Hostetler
17000 St. Clair Ave.
Cleveland, OH 44110

Gould Inc.
Attn G. Davies
540 E. 105th St.
Cleveland, OH 44108

Grumman Aerospace Corp.
Attn C. Hoelzer C32-5
Bethpage, NY 11714