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MATERIALS FOR ADVANCED TURBINE ENGINES

PROJECT COMPLETION REPORT
PROJECT 2

ABRADABLE COMPRESSOR AND TURBINE SEALS

VOLUME 1

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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 candidate for the final engine endurance test. Task III consisted of 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 abradables in the TFE731 Engine. Tasks VI and VII will be reported in Volume II of the project completion report.

Target goals for the abradable coatings were: (1) coating/blade-tip wear ratio >15:1; (2) coating debris <0.010 inch; (3) coating cost <10 percent of part cost; (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. Goals (1), (2), (4) and (5) are associated with engine testing and therefore discussed in Volume II, while the results of the cost goals (3) and (6) are included in Volume I. All cost goals were met or exceeded.

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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 evaluate the suitability of 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 quidance of N.T. Saunders, C.P. Blankenship, and S.G. Young of the NASA-Lewis Research Center. Major contributions to the success of the program were made by E. G. Farrier and P. J. Timmel, Jr. of Union Carbide; A. Erickson of Brunswick Corporation; J. Reardon and C. Lewis of Metco, Inc.; and G. Cremer of Solar Turbines International, Division of International Harvester.

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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 Contract NAS3-20073 to evaluate the application and advantages of abradable coatings as gas-path seals in a general aviation turbine engine--the AiResearch TFE731-3. Abradable seal materials were evaluated for use on the high-pressure compressor, the high-pressure turbine, and the low-pressure turbine shrouds as illustrated in Figure 1.

The evaluation process included: the initial screening and selection of candidate materials; the determination of the physical and performance characteristics of the candidate materials through interim full-scale engine testing; the selection of materials showing greatest potential for further evaluation; the development of the final process parameters, and the demonstration of these materials by a full-scale engine test.

Target goals for the abradable coatings were:

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

(2) coating debris size less than 0.254-mm (0.010 inch)

(3) coating cost less than 10 percent of part cost

(4) coating-erosion resistance at least 10,000 hours

The target goal for the engine use of the abradables is:

(5) reduce specific fuel consumption (SFC) by at least 1.5 percent

This document constitutes Volume I of a two-volume report presenting the results of the investigations and tests performed under MATE Project 2, Abradable Compressor and Turbine Seals. This volume covers all of Project 2 except Tasks VI and VII, the Final Full-Scale Engine Test and Post-Test Analysis. Those tasks are the subjects of Volume II of this Project Completion Report.

Project 2 was divided into the following tasks:

Task I - Manufacturing Technology
Task II - Material/Process Selection
Task III - Component Design

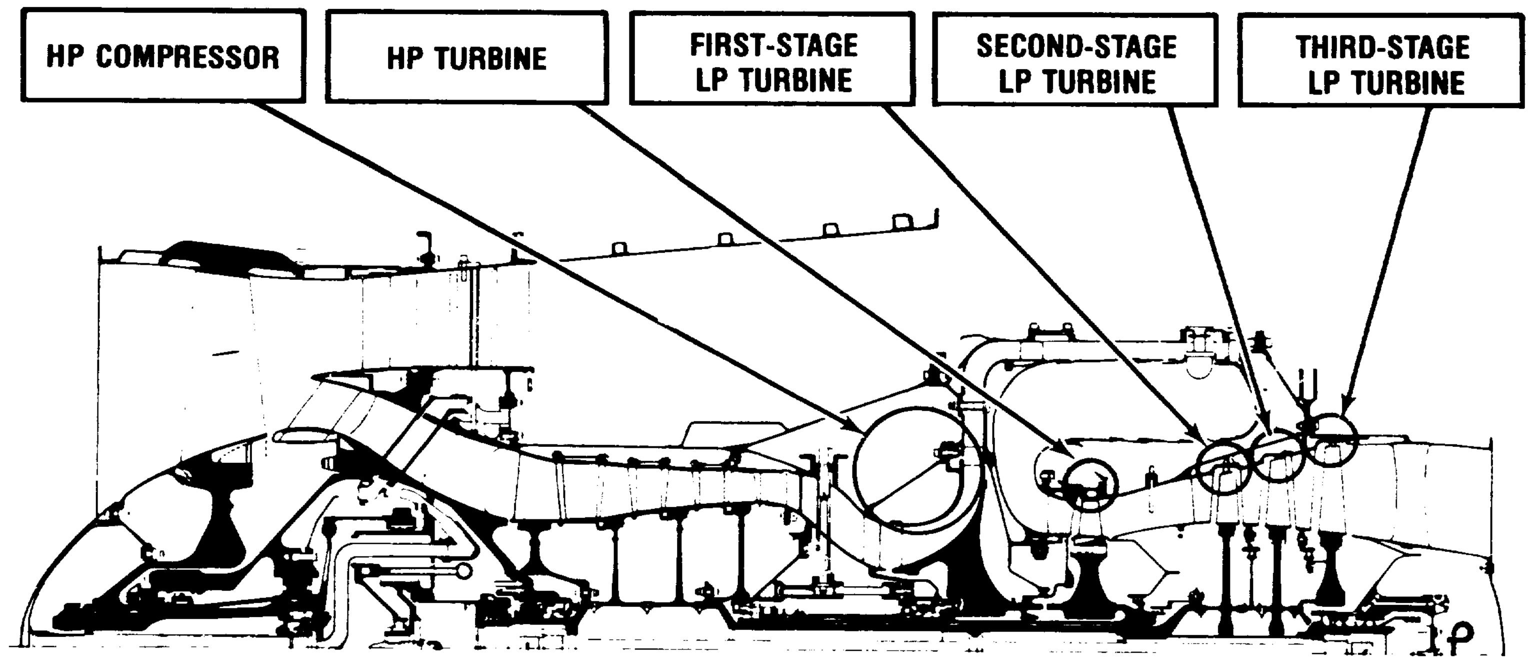

Figure 1. Location of the MATE Abradable Test Materials in the TFE731-3 Engine

Task IV - Manufacturing Process Development
Task V - Component Fabrication
Task VI - Engine Testing
Task VII - Post-Test Analysis

In Task I, the initial selection of candidate materials for Interim Full-Scale Engine Testing was accomplished. During Task II, Interim Engine Testing of the initially selected materials was conducted, and then additional candidate materials were screened and engine tested. In Task III, the component design required to adapt the TFE731-3 hardware to permit Full-Scale Engine Testing of the most promising materials was accomplished. In Task IV, the fabrication methods used in the manufacture of engine test hardware were finalized, and in Task V, the hardware necessary to support the Final Full-Scale Engine Tests was manufactured.

The engine testing, performance comparisons, and post-test evaluations of the gas-path seals are described in Volume II of this report.

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.

Task I screened a number of potential candidate materials by review of available data and material properties testing. The most promising candidates, as described in Table I, were selected for further evaluation in the first Task II Interim Engine Test.

Task II included the assembly of a test engine with build-up clearances calculated to ensure seal rubs, and the subsequent testing of the selected materials in a full-scale experimental engine test. In an expansion of the initial program, a second group of candidate materials, as described in Table II, was selected and subjected to a similar engine test. Based on the evaluation of the test results of the two sets of shrouds, material availability, cost, and other factors, the group of tested materials listed in Table III was selected for more extensive, endurance-type engine testing in Task VI.

Task III included the redesign, where required, of TFE731-3 Engine components to accommodate the specific abradable materials selected in Task II. The redesign was based on the Task II engine assembly data, modified as necessary by Task II test results. The redesign was accomplished to accommodate the desired abradable material thickness and ensure proper engine build-up clearances.

In Task IV, the processes used to fabricate the abradable test hardware and the method of attachment were finalized and documented for those materials selected for the final engine test.

In Task V, two complete sets of test hardware were fabricated to support the final engine test of Task VI. The test hardware was fabricated using the techniques developed in Task II and finalized in Task IV. The program cost goal of applying the selected abradable coatings for less than a 10-percent increase in component cost was achieved.

The Full-Scale Engine Testing (Task VI) and the Post-Test Analysis (Task VII) are reported separately in Volume II of this report.

TABLE I. CANDIDATE ABRADABLE MATERIALS SELECTED FOR THE FIRST TASK II INTERIM ENGINE TEST

Engine Component	Material Identification	Material Composition	Strength Level, MPa	(psi)	Attachment Method	Material Source	Engine Build Number
High-Pressure Compressor: Test Item: Abradable Plug (replaceable shoe) Installed in Shroud. Impeller surface Speed - 548.6 m/sec (1800 ft/sec); 700°K (800°F).	UCAR AB-1[a]	Nickel-Chromium	8.27	(1200)	Direct Sinter	Union Carbide	1
	UCAR AB-1	Nickel-Chromium	8.27	(1200)	Direct Sinter	Union Carbide	1
	UCAR AB-3	Nickel-Chromium	7.58	(1100)	Direct Sinter	Union Carbide	1
	UCAR AB-3	Nickel-Chromium	5.52	(800)	Direct Sinter	Union Carbide	1
	Feltmetal 501	Haynes 25	---	----	Braze	Brunswick	1
	Metco SF	Aluminum-Silicon		----	Thermospray	AiResearch	1
	Metco CE 2019	Bronze/Boron Nitride		----	Thermospray	Metco	1
High-Pressure Turbine: Test Item: Complete Shroud. Rotor Tip Speed (RTS) - 427 m/sec (1400 ft/sec); 1311°K (1900°F).	UCAR AB-4	Nickel-Chromium-Aluminum	11.03	(1600)	Braze	Union Carbide	1
	UCAR AB-4	Nickel-Chromium-Aluminum	13.79	(2000)	Braze	Union Carbide	1
	UCAR AB-4	Nickel-Chromium-Aluminum	16.35	(2400)	Braze	Union Carbide	1
	UCAR AB-4[b]	Nickel-Chromium-Aluminum	13.79	(2000)	Braze	Union Carbide	2
	Bradelloy 500[c]	----	24.32	(3600)	Braze and Sinter	Howmet-G.E.	2
Low-Pressure Turbine: Test Item: Complete Shroud (each stage).							
First-Stage: RTS - 380 m/sec (1250 ft/sec); 1144°K (1600°F).	UCAR AB-2	Nickel-Chromium	8.96	(1300)	Braze	Union Carbide	1
	UCAR AB-2[d]	Nickel-Chromium	8.96	(1300)	Braze	Union Carbide	2
	Honeycomb[d]	Hastelloy-X		----	Braze	AiResearch	2
Second-Stage: RTS - 412 m/sec (1350 ft/sec); 1033°K (1400°F).	UCAR AB-2	Nickel-Chromium	8.96	(1300)	Braze	Union Carbide	1
	Solabrade[c]	Hastelloy-X		----	Braze	Kelsey-Hayes	2
Third-Stage: RTS - 436 m/sec (1430 ft/sec); 922°K (1200°F).	UCAR AB-2[d]	Nickel-Chromium	8.96	(1300)	Braze	Union Carbide	1
	UCAR AB-2[d]	Nickel-Chromium	5.52	(800)	Braze	Union Carbide	1
	Feltmetal 522[c]	HS-188		----	Braze	Brunswick	2

[a] High-Strength Material Preoxidized Down to ~8.27 MPa (~1200 psi)
[b] Material Strength Level Based on Build 1 Results
[c] Build 2 Baseline Materials. Not Tested in Task I or Task II, Build 1
[d] Approximately 180° of Shroud

TABLE II. CANDIDATE ABRADABLE MATERIALS SELECTED FOR THE SECOND TASK II INTERIM ENGINE TEST

Engine Component	Material Identification	Material Composition	Attachment Method	Material Source	Engine Build Number
High-Pressure Compressor: Test Item: Abradable Plug (replaceable shoe) Installed in Shroud. Impeller Surface Speed - 548.6 m/sec (1800 ft/sec); 700°K (800°F).	Feltmetal 515B	Hastelloy-X	Braze	Brunswick	3
	Metco T310-10	Aluminum-Graphite-Silicon	Thermospray	Metco	3
	Metco T301-10	Boron-Nitride Cermet	Thermospray	Metco	3
	Metco P601-10	Aluminum-Polyester	Plasmaspray	Metco	3
High-Pressure Turbine: Test Item: Complete Shroud. Rotor Tip Speed (RTS)-427 m/sec (1400 ft/sec); 1311°K (1900°F).	Brunsbond Composite	Zirconium Oxide (Y_2O_3 Stabilized)	Braze	Brunswick	3
	Metco T201-10	Zirconium Oxide (CaO Stabilized)	Thermospray	Metco	3
	Metco P443-10 (Dense)	Nickel-Chromium-Aluminum	Plasmaspray	Metco	3
	Metco P443-10 (Open)	Nickel-Chromium-Aluminum	Plasmaspray	Metco	3
Low-Pressure Turbine: Test Items: Complete Shroud (each stage).					
First-stage: RTS-380 m/sec (1250 ft/sec); 1144°K (1600°F).	Honeycomb[a]	Hastelloy-X	Braze	Kelsey-Hayes	3
	Solabrade[a]	Hastelloy-X	Braze	Kelsey-Hayes	3
	Metco T450-14	Nickel-Aluminum	Thermospray	Metco	4
Second-stage: RTS-412 m/sec (1350 ft/sec); 1033°K (1400°F)	Metco T301-10	Boron-Nitride Cermet	Thermospray	Metco	3
	Feltmetal 537	Iron-Nickel-Chromium-Aluminum-Yttrium	Braze	Brunswick	4
Third-Stage: RTS-436 m/sec (1430 ft/sec); 922°K (1200°F)	Metco 304NS	Bronze/Boron-Nitride Composite	Thermospray	Metco	3
	Feltmetal 535	Iron-Chromium-Aluminum-Yttrium	Braze	Brunswick	4

[a] Approximately 180° of Shroud

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

Engine Component	Approximate Gas Temperature, °K	(°F)	Material Identification	Material Composition
High-Pressure Compressor	700	(800)	Metco P601-10	Aluminum-Polyester
High-Pressure Turbine	1311	(1900)	UCAR AB-4[a]	Nickel-Chromium-Aluminum
			Metco P443-10 (open)[a]	Nickel-Chromium-Aluminum
Low-Pressure Turbine				
First Stage	1144	(1600)	Honeycomb	Hastelloy-X
Second Stage	1033	(1400)	Metco T301-10	Boron Nitride Cermet
Third Stage	922	(1200)	Metco 304 NS	Bronze/Boron Nitride

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

TASK I - MANUFACTURING TECHNOLOGY

Scope

In Task I, Union Carbide Corporation (UCAR), the primary subcontractor, screened a number of abradable materials potentially suitable as gas-path seals on the high-pressure compressor, high-pressure turbine, and low-pressure turbine shrouds with the objective of choosing candidate materials for the interim engine testing scheduled for Task II. The screening effort included extensive physical- and mechanical-property tests of the abradable materials, and evaluation of methods of attachment of the abradable material to the substrate.

Screening Test Procedure

The screening tests and evaluations of the candidate materials included the following:

(a) Metallographic examination before and after selected tests.

(b) Room-temperature tensile tests to determine coating strength and coating-substrate bond strength (peel tests). Tensile tests were conducted prior to and following oxidation tests. The peel test consisted of measuring the force required to peel the foil backing from a 25-cm (10-inch) wide strip of abradable material.

(c) Oxidation tests were conducted at elevated temperatures for a period of 500 hours. High-pressure compressor candidate materials were tested at 811°K (1000°F), high-pressure turbine materials at 1311°K (1900°F), and low-pressure turbine materials at 1144°K (1600°F). The amount of oxidation was determined by the weight gain of the samples due to oxide formation as a function of time.

(d) Abradability tests were conducted at room temperature on flat specimens using a rotating titanium alloy blade to rub the high-pressure compressor seal materials, an INCONEL 600* knife edge and blade for the low-pressure turbine rubs, and an INCONEL 600 blade for the high-pressure turbine rubs. All rubs were made at a blade tip speed of 55 m/sec (180 ft/sec), and an interaction rate of 0.025 mm/sec (0.001 inch/sec) to produce a rub depth of approximately 0.76 mm (0.03 inch).

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*INCONEL 600 is a registered trademark of Huntington Alloys Division of the International Nickel Company.

(e) Erosion testing (grit-blasting) was accomplished by directing a measured quantity of No. 30 silicon carbide (SiC) shot against the abradable sample at an impingement angle of 30 degrees. The grit blast gun used a 3.175-mm (0.125-inch) nozzle operating at 0.28-MPa (40-psi) air pressure. Erosion depth and sample weight loss measurements were made at prescribed intervals.

Screening Test Results

High-Pressure Compressor Shroud - A summary of the measured properties of the UCAR high-pressure compressor candidate shroud materials and the baseline material (Metco SF) is presented in Table IV.

1. UCAR AB-1 and AB-3*. Three strength levels each of direct-sinter UCAR AB-1 and AB-3 were evaluated. Both basic structures are of a nominal 80-percent nickel and 20-percent chromium alloy composition with UCAR AB-1 having the coarser structure as shown in Figure 2.

Evaluation of both UCAR structures after the 500-hour oxidation test at 811°K (1000°F) showed small weight gains over the test period. Figure 3 illustrates the data and also presents data previously obtained by UCAR at 922°K (1200°F). Based on examination of photomicrographs of the oxidized samples, it was apparent that oxide formation at 811°K (1000°F) was minimal. The oxidation occurred exclusively at the particle surfaces. Typical photomicrographs of the two oxidized materials are shown in Figure 4.

The tensile-strength values of the UCAR materials did not decrease substantially as a function of the 500-hour oxidation test. Figure 5 presents this data and illustrates other data previously obtained by UCAR. Failure of all samples subjected to tensile testing occurred in the porous metal, indicating the stability of the direct-sinter bond.

A total of 15 grams (0.529 ounce) of silicon carbide shot was used for each erosion test, with erosion data being taken after each 5-gram (0.176-ounce) increment. The weight loss and surface erosion data is tabulated in Table IV and presented graphically in Figure 6. This figure clearly depicts the expected trend of increasing erosion resistance with increasing material strength levels.

*UCAR AB-1 and AB-3 are trade names for products produced by the Union Carbide Corporation.

TABLE IV. SUMMARY OF THE MEASURED PROPERTIES OF THE TASK I CANDIDATE ABRADABLE MATERIALS FOR THE HIGH-PRESSURE COMPRESSOR SHROUD

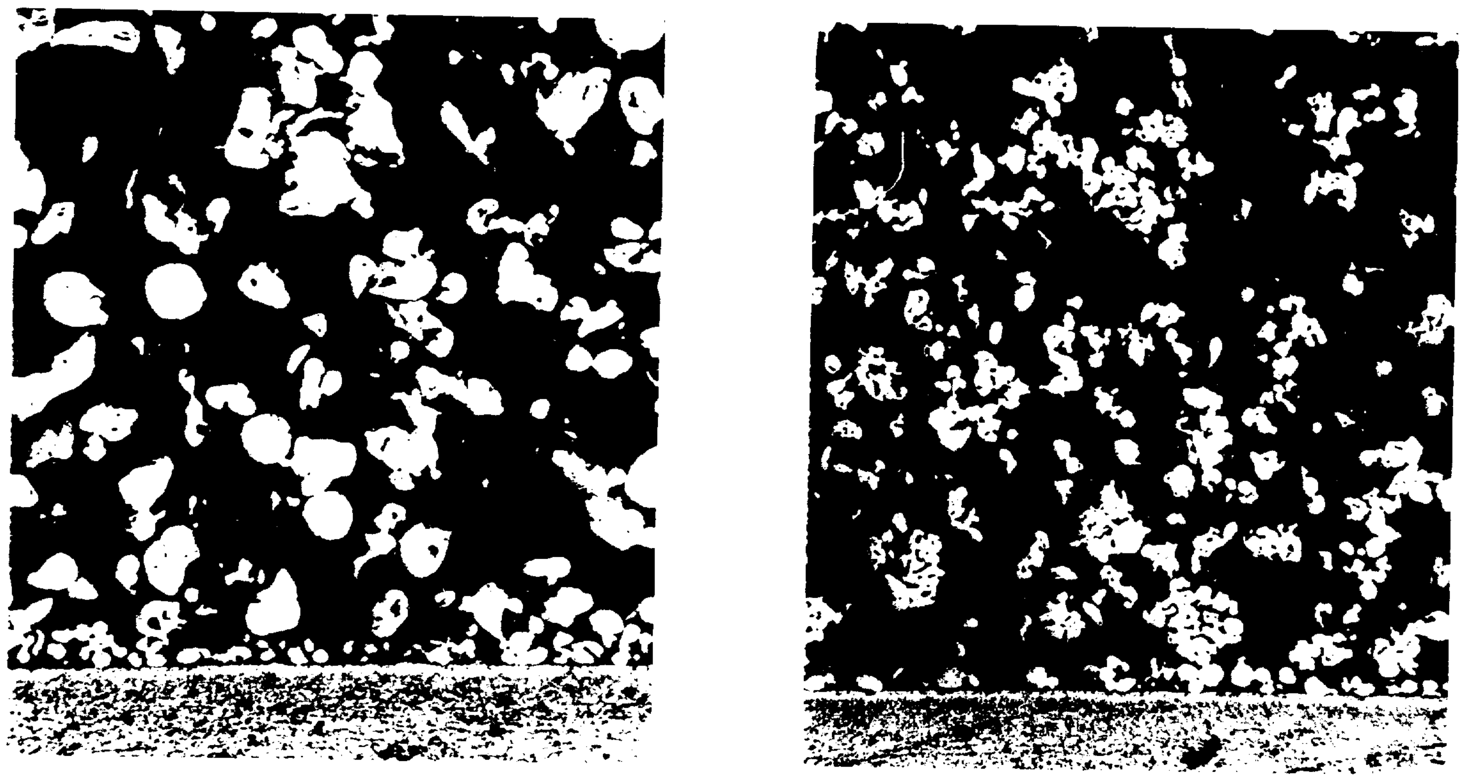
Task I Candidate Material	Nonoxidized Test Specimens					Oxidized Test Specimens [a]		
	Ultimate Tensile Strength, MPa (psi)	Density, g/cm^3 ($lb/in.^3$)	Peel Strength, kN/m (lb/in.) [b]	Erosion Weight Loss, g (grains) [c]	Erosion Depth, mm (in.)	Ultimate Tensile Strength, MPa (psi)	Weight Gain, Percent	Peel Strength, kN/m (lb/in.) [b]
UCAR AB-1	4.8 (700)	2.5 (0.0903)	3.2 (18)	0.181 (2.79)	0.22 (0.0087)	3.9 (560)	0.5	2.8 (16)
UCAR AB-1	6.9 (1000)	2.7 (0.0975)	6.3 (36)	0.060 (0.926)	0.12 (0.0047)	6.9 (1000)	0.3	6.1 (35)
UCAR AB-1	9.6 (1400)	2.5 (0.0903)	>7.0 (>40)	0.026 (0.401)	0.11 (0.0043)	8.6 (1250)	0.6	>7.0 (>40)
UCAR AB-3	4.8 (700)	2.5 (0.0903)	3.0 (17)	0.107 (1.651)	0.15 (0.0059)	4.8 (700)	0.7	1.6 (9)
UCAR AB-3	6.9 (1000)	2.5 (0.0903)	3.3 (19)	0.058 (0.895)	0.15 (0.0059)	6.9 (1000)	0.7	3.0 (17)
UCAR AB-3	9.6 (1400)	2.5 (0.0903)	5.3 (30)	0.015 (0.232)	0.12 (0.0047)	9.2 (133)	0.3	4.7 (27)
Metco SF	3.4 (490)	2.0 (0.0723)	0.35 (2.0)	0.015 (0.232)	0.05 (0.0020)	d	1.7	d

a Test specimens subjected to oxidation exposure at 811°K (1000°F) for 500 hours

b "Peel strength" represents the measured force required to peel the foil backing from a 2.5-cm (1.0-inch) wide strip of abradable material

c Test Conditions: 15 g[illegible] (232 grains) of No. 30 SiC shot at 30° angle and 0.028 MPa (40 psi) pressure

d Not tested



(a) UCAR AB-1

(b) UCAR AB-3

Figure 2. Typical Microstructure of Union Carbide Abradable Materials (Direct-Sinter Attachment) for the High-Pressure Compressor Shroud (Nonoxidized) (Mag.: 100X)

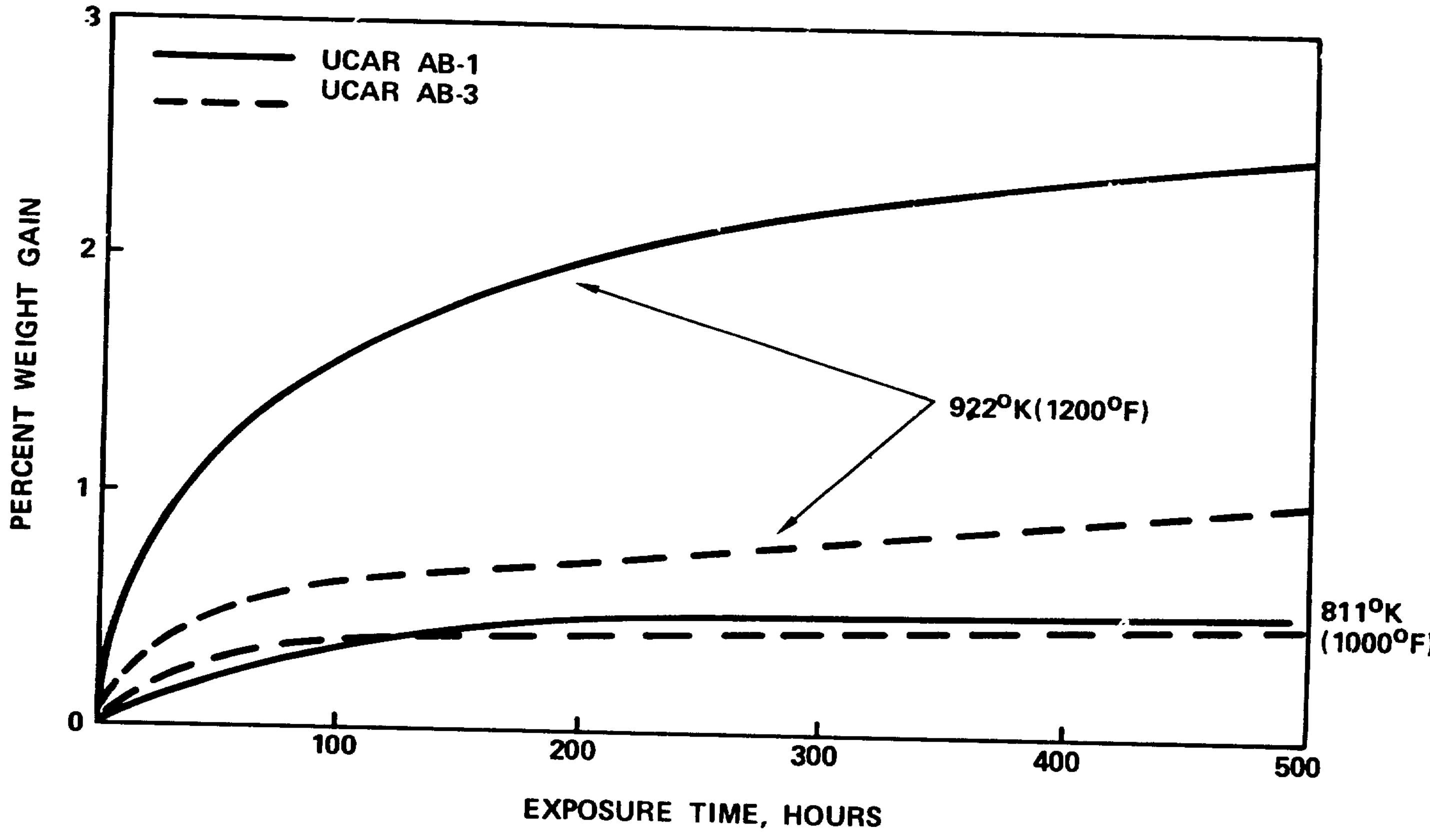
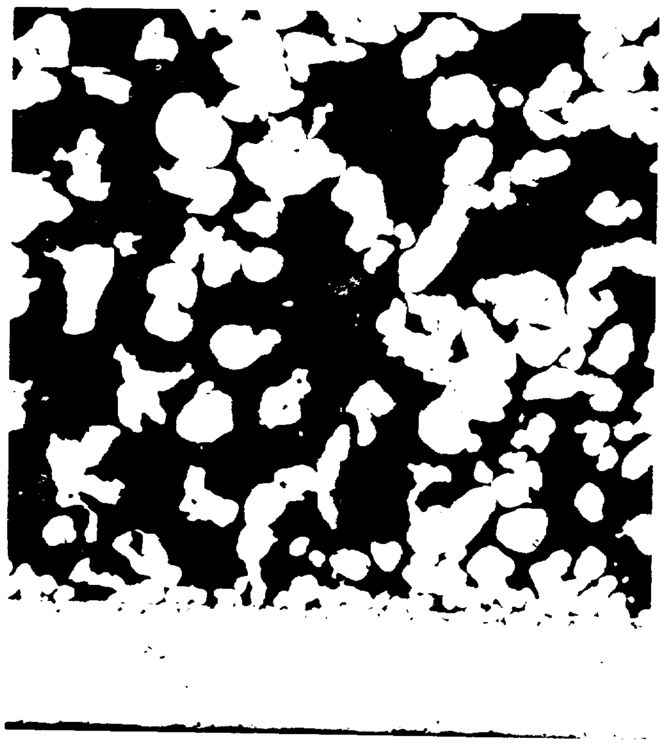
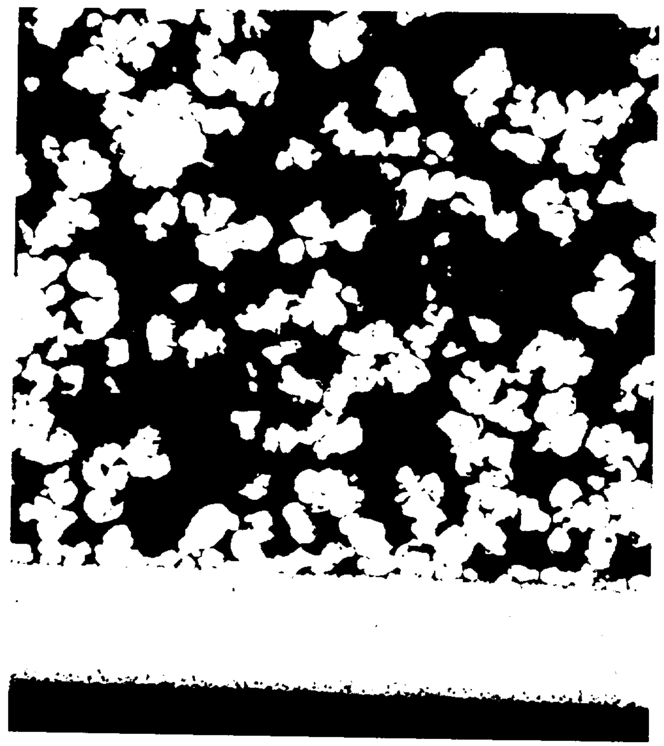


Figure 3. Oxidation Behavior of Union Carbide Abradable Materials (Direct-Sinter Attachment) for the High-Pressure Compressor Shroud



(a) UCAR AB-1



(b) UCAR AB-3

Figure 4. Typical Microstructure of Union Carbide Abradable Materials (Direct-Sinter Attachment) for the High-Pressure Compressor Shroud (After 500-Hours Oxidation at 811°K (1000°F) (Mag.: 100X)

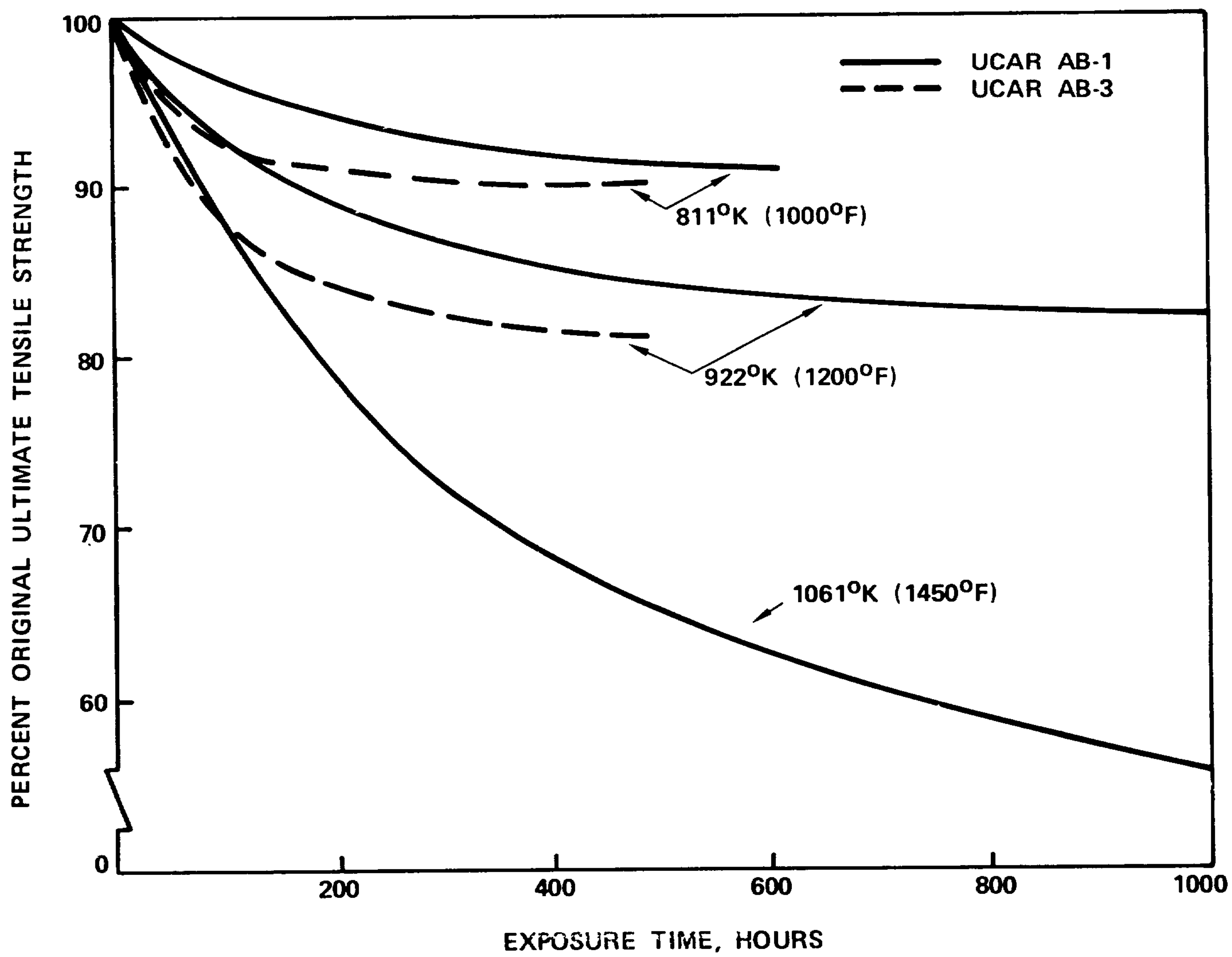


Figure 5. Effect of Oxidation Time on Ultimate Tensile Strength of Union Carbide Abradable Materials (Direct-Sinter Attachment) for the High-Pressure Compressor Shroud

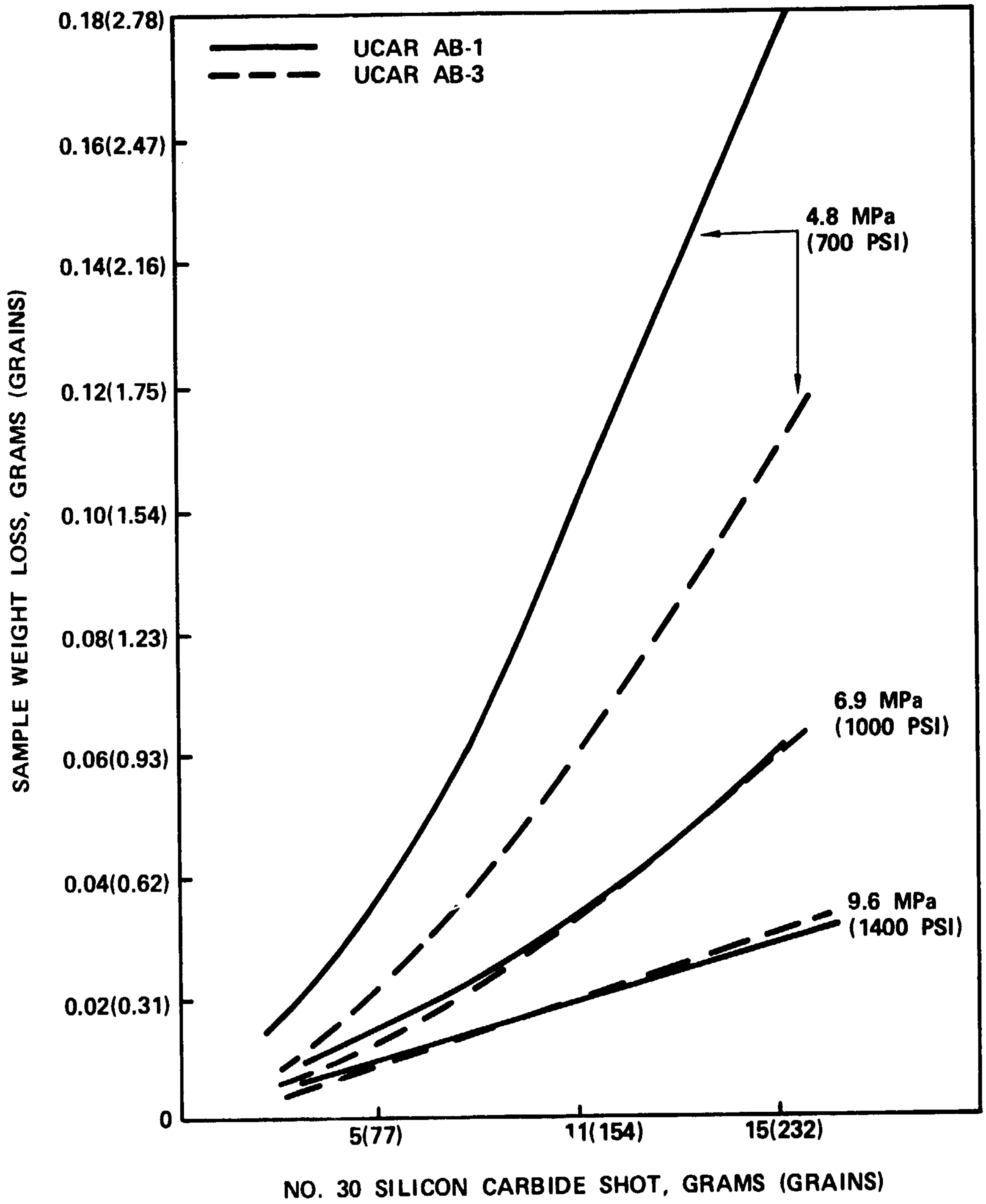


Figure 6. Erosion Behavior of Union Carbide Abradable Materials (Direct-Sinter Attachment) for the High-Pressure Compressor Shroud

Peel tests were conducted both before and after the 500-hour oxidation test with the results tabulated in Table IV. These tests showed that the bond was stronger than the abradable material. There was no significant decrease in the strength of the bond as a function of the oxidation test.

The abradability tests on UCAR materials illustrated that abradability is inversely proportional to tensile strength. Both AB-1 and AB-3 smeared at the 9.6-MPa (1400-psi) tensile strength and sufficient heat was generated to discolor the test blade tips. Previous testing by UCAR on materials of similar strength levels showed comparable results. Preoxidized 6.89 MPa (1000 psi) AB-3 proved to be more abradable than nonoxidized material of the same strength. Preoxidized 9.6-MPa (1400-psi) AB-1 smeared and caused measurable blade wear, while nonoxidized AB-1 material of equivalent strength smeared but did not produce any blade wear. Photographs of rub surfaces of tested UCAR materials are presented in Figure 7.

2. Metco SF*. Metco SF spray is currently used in the high-pressure compressor section of the production TFE731-3 Turbofan Engine. Samples of this aluminum-silicon coating on three thicknesses of INCONEL 718** backing were provided to UCAR by AiResearch for screening tests using the same procedures as those used to test the UCAR AB-1 and AB-3. Measured properties determined in these tests are included in Table IV.

Both tensile strength and peel strength for the Metco SF samples were significantly lower than those for the UCAR abradables. The low tensile strength was a result of failure at the SF-INCONEL 718 interface (bond area) rather than failure in the coating. This poor bonding was probably caused by the process modifications required to metal spray a flat plate rather than a contoured shroud. Based on the field experience of this coating in the AiResearch TFE731 Engine, it was concluded that the strength and bond properties of the test specimens were not representative of Metco SF coatings.

During oxidation tests, a much larger weight increase was observed for the Metco SF spray than for the UCAR abradables, as noted in Table IV. The bond interface had expanded due to oxide formation, and contained a high percentage of voids as shown in Figure 8. The sprayed structure also appeared to expand upon oxidation, and the number of voids within the structure was appreciably greater following the oxidation exposure (as shown in Figure 9).

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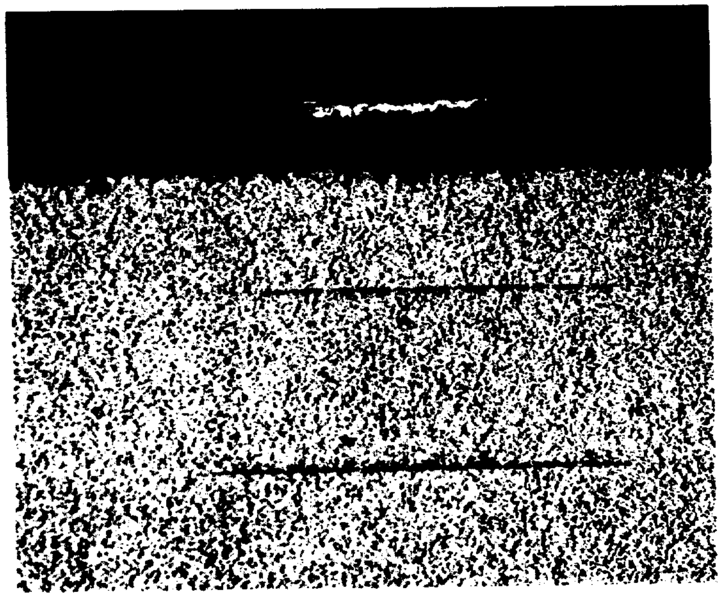
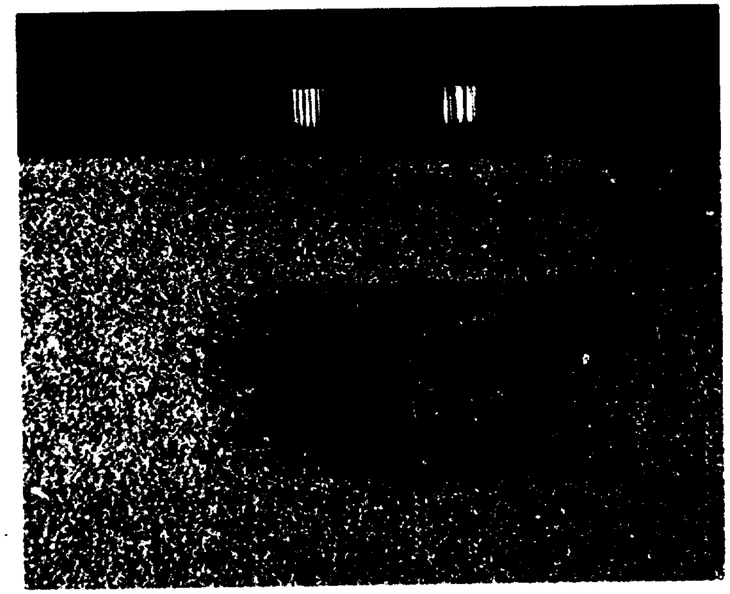
*Metco SF is a trade name of Metco, Inc.

**INCONEL 718 is a registered trademark of Huntington Alloys Division of the International Nickel Company.

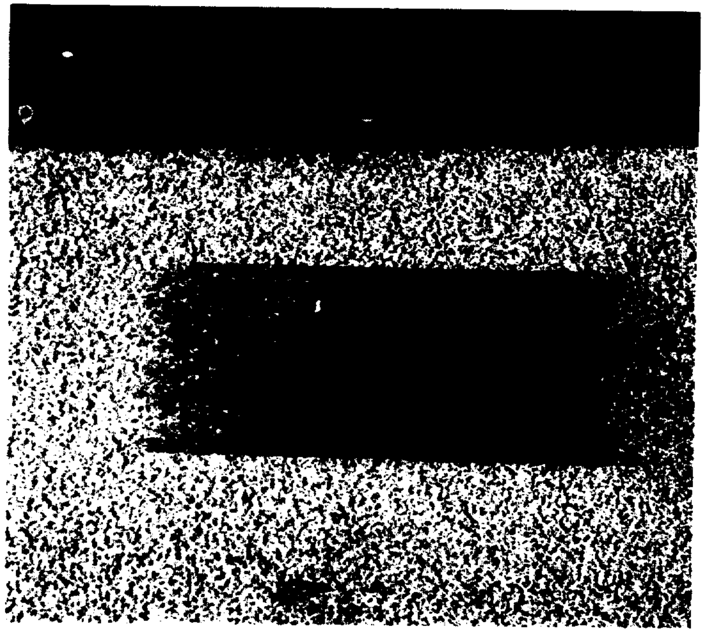


(a) UCAR AB-1 [4.8 MPa (700 psi)] (Clean Rub with Slight Metal Transfer Onto the Blade)

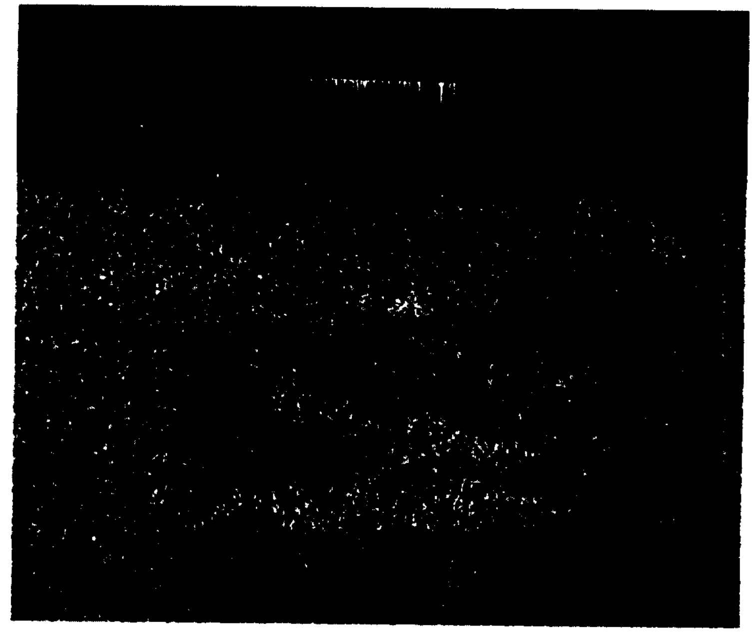


(b) UCAR AB-1 [6.9 MPa (1000 psi)] (Some Slight Smear -- Surface Effect Only -- Along with Some Blade Wear)

Figure 7. Abradability Test Rub Surface of Union Carbide Abradable Materials (Direct-Sinter Attachment) for the High-Pressure Compressor Shroud. Titanium Blade-Tip Speed of 54.9 m/sec (180 ft/sec), and an Interaction Rate of 0.025-mm/sec (0.001 inch/sec) for 0.76-mm (0.030-inch) Rub Depth (Mag.: 2X)

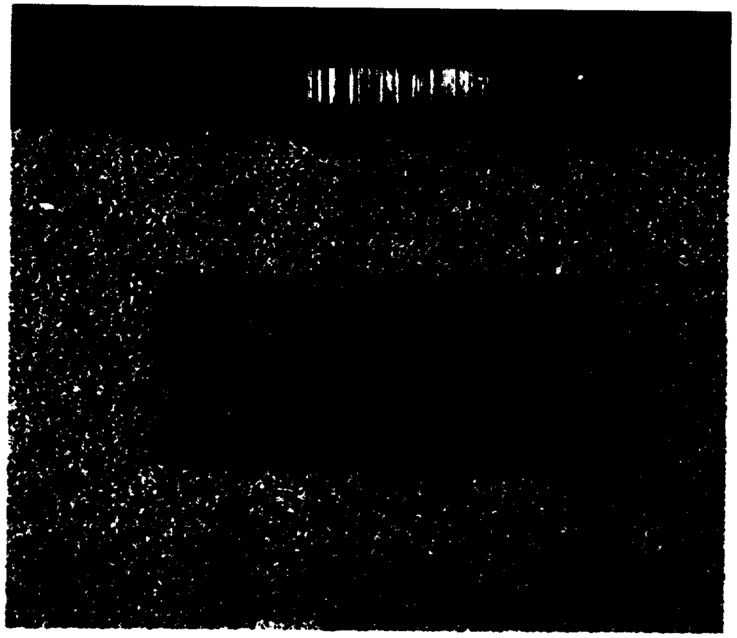


(c) UCAR AB-1 [9.6 MPa (1400 psi)] (Smeared Surface of Rub with Some Blade Wear)

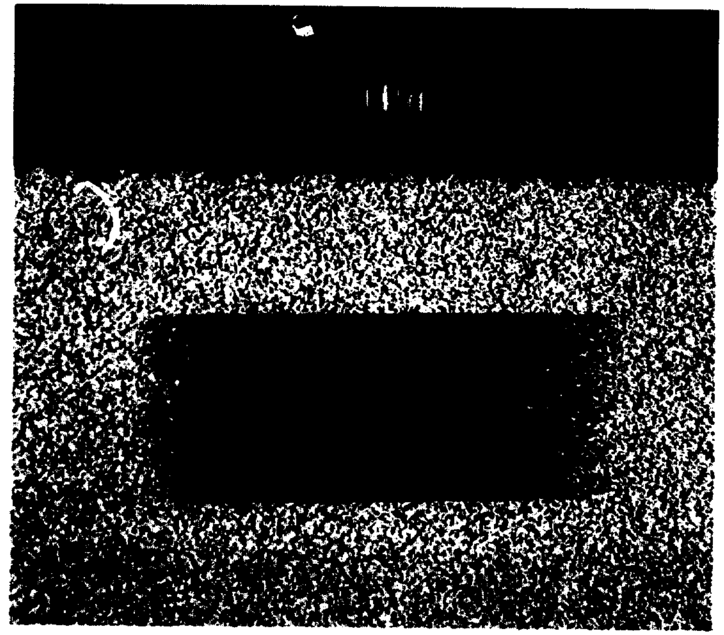


(d) UCAR AB-3 [4.8 MPa (700 psi)] (Very Slight Smearing of Rub with Some Slight Blade Wear)

Figure 7. (Continued) (Mag.: 2X)

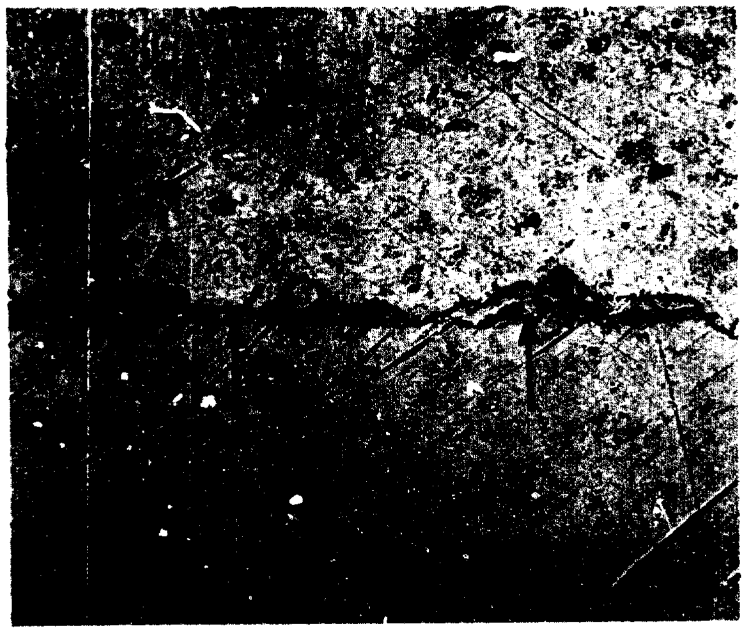


(e) UCAR AB-3 [6.9 MPa (1000 psi)]
(Partial Smearing of Rub
Surface with Some Blade Wear)



(f) UCAR AB-3 [9.6 MPa (1400 psi)]
(Smeared Rub Surface with
Some Blade Wear)

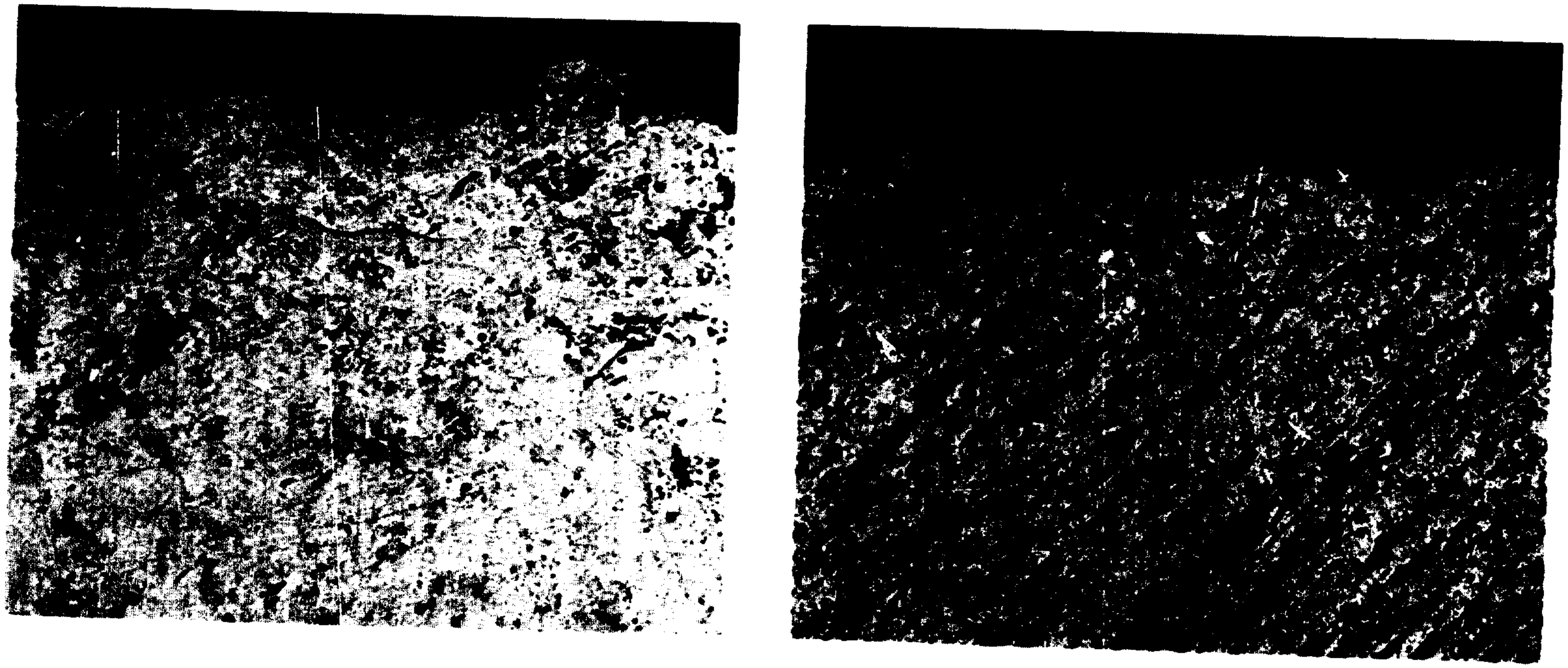
Figure 7. (Continued) (Mag.: 2X)



(a) Before Oxidation

(b) After 500-Hours Oxidation at 811°K (1000°F)

Figure 8. Bond Interface of Metco SF Abradable Material (Thermospray Attachment) for the High-Pressure Compressor Shroud (Arrows Denote the Interface) (Mag.: 100X)



(a) Before Oxidation

(b) After 500-Hours Oxidation at 811°K (1000°F)

Figure 9. Microstructure of Metco SF Abradable Material (Thermospray Attachment) for the High-Pressure Compressor Shroud (Mag.: 100X)

In the abradability tests, the Metco SF test samples did not abrade as readily as the UCAR material. A greater amount of energy was required to attain an equivalent rub depth, flakes of the spray peeled off, some material transferred to the blade tip, and partial separation of the spray from the INCONEL 718 backing was observed. Illustrations of the Metco SF tests are presented in Figure 10.

The erosion test data, tabulated in Table IV, indicates that the Metco SF resistance to erosion is equal to or better than the resistance of the UCAR materials.

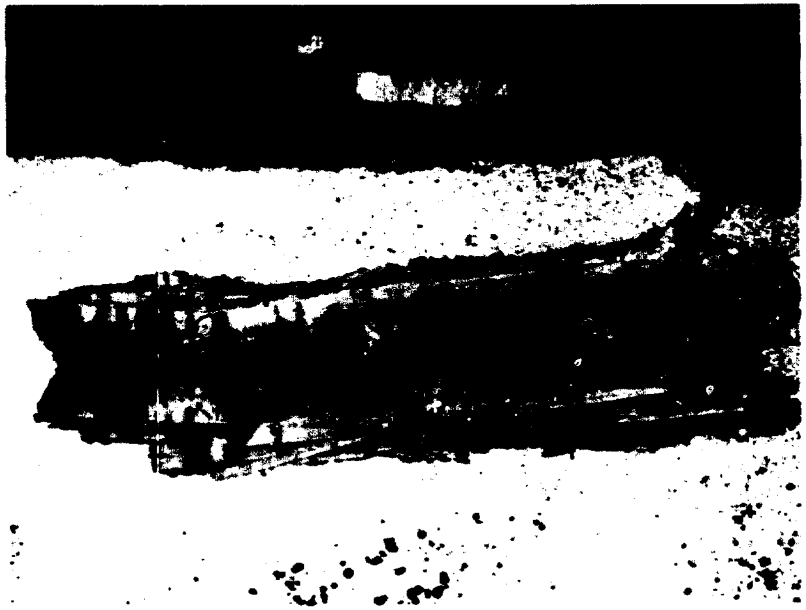
3. Simulated Direct-Sinter Thermal Test. A finished INCONEL 718 high-pressure compressor shroud was subjected to approximately 1450°K (2150°F) for 24 hours to simulate the most severe thermal treatment expected in direct sintering of UCAR AB-1 or UCAR AB-3 to the shroud. Inspection after the 24-hour exposure, and after the subsequent solution and age heat treatments showed minor changes in shroud-flange flatness and bolt-circle diameter. Therefore, to avoid any dimensional problems, procedures were established to ensure that the final machining operations were accomplished after completion of all heat-treatment operations.

High-Pressure Turbine Shroud - Two strength levels of UCAR AB-4* were evaluated for use in the 1311°K (1900°F) high-pressure turbine section. Typical properties for the two strength levels are given in Table V.

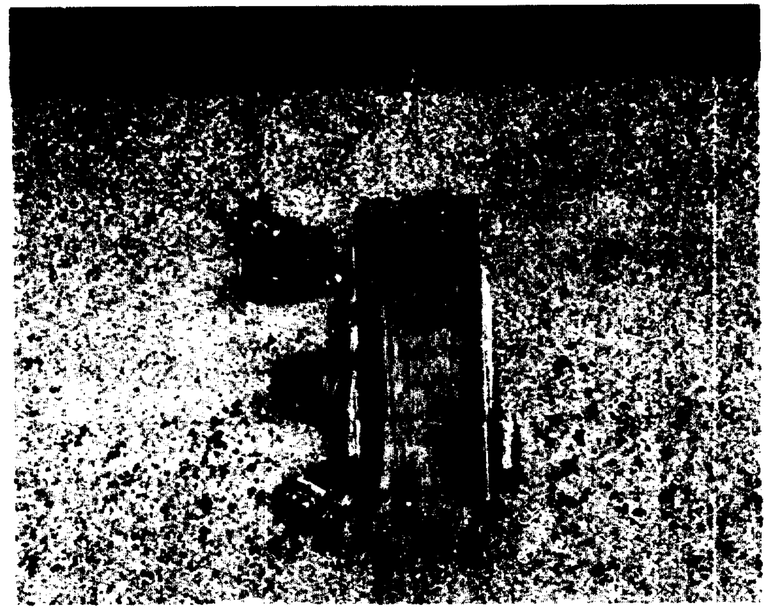
1. UCAR AB-4. This structure is a nominal 70-percent nickel, 20-percent chromium, and 10-percent aluminum composition that provides increased oxidation protection at high-temperature levels as compared to 80-percent nickel, and 20-percent chromium material.

The oxidation behavior of UCAR AB-4 at 1311°K (1900°F) is shown in Figure 11. This figure illustrates that there was a rapid increase in weight gain and volume growth, due to oxidation, during the first 100 hours at temperature. During this interval, a tightly-adhering aluminum-oxide shell formed around the individual samples. Once a shell of sufficient thickness was attained, the oxidation rate decreased, as shown in Figure 11. Typical microstructures of nonoxidized and oxidized AB-4 material are shown in Figure 12. In the oxidized specimen, thick oxide-shells surround the particles, but no significant internal oxidation has occurred.

*UCAR AB-4 is a trade name of the Union Carbide Corporation.



(a) First Sample (Smeared Rub Surface with Material Transfer to the Blade Tip. The Sample Twisted During Test and Separated from the INCONEL 718 Backing)



(b) Second Sample (Large Flakes of Material Pulled Off. Smeared Rub Surface with Material Transfer to the Blade Tip)

Figure 10. Abradability Test Rub Surface of Metco SF Abradable Material (Thermospray Attachment) for the High-Pressure Compressor Shroud. Titanium Blade-Tip Speed of 54.9 m/sec (180 ft/sec), and an Interaction Rate of 0.025-mm/sec (0.001 inch/sec) for 0.76-mm (0.030-inch) Rub Depth (Mag.: 2X)

TABLE V. SUMMARY OF THE MEASURED PROPERTIES OF TASK I CANDIDATE ABRADABLE MATERIALS FOR THE HIGH-PRESSURE TURBINE SHROUD

	Nonoxidized Test Specimens			Oxidized[a] Test Specimens		
Material	Ultimate Tensile Strength, MPa (psi)	Density, g/cm^3 ($lb/in.^3$)	Erosion Weight Loss, g (grains)	Erosion Depth, mm (in.)	Ultimate Tensile Strength, MPa (psi)	Weight Gain, Percent
UCAR AB-4	11.4 (1650	2.7 (0.0975)	b	b	7.8 (1140)	9.5
UCAR AB-4	13.1 (1900)	2.7 (0.0975)	0.48 (7.45)	0.060 (0.0024)	12.4 (1200)	9.0

a Test specimens subjected to oxidation exposure at 1311°K (1900°F) for 500 hours

b Not tested

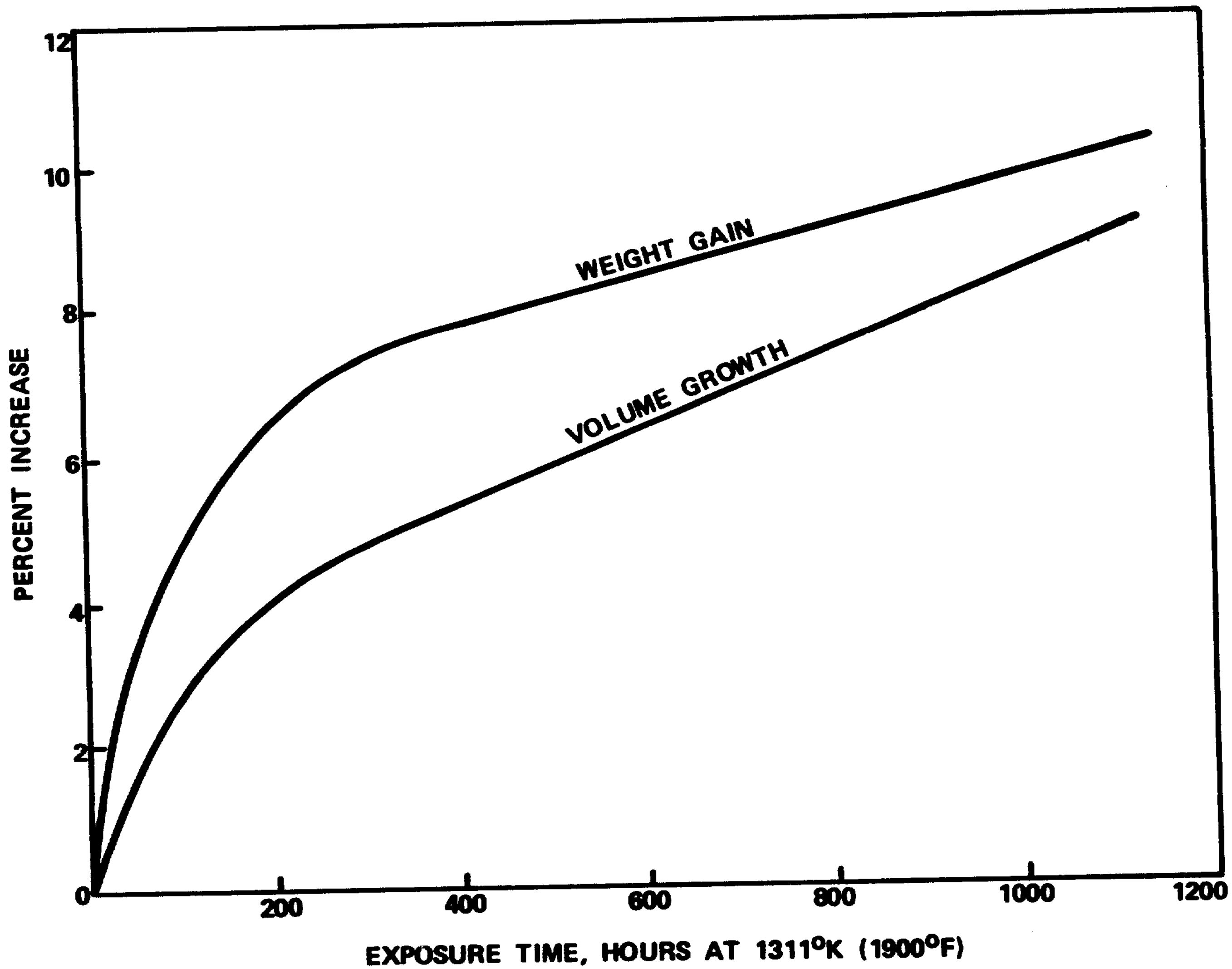
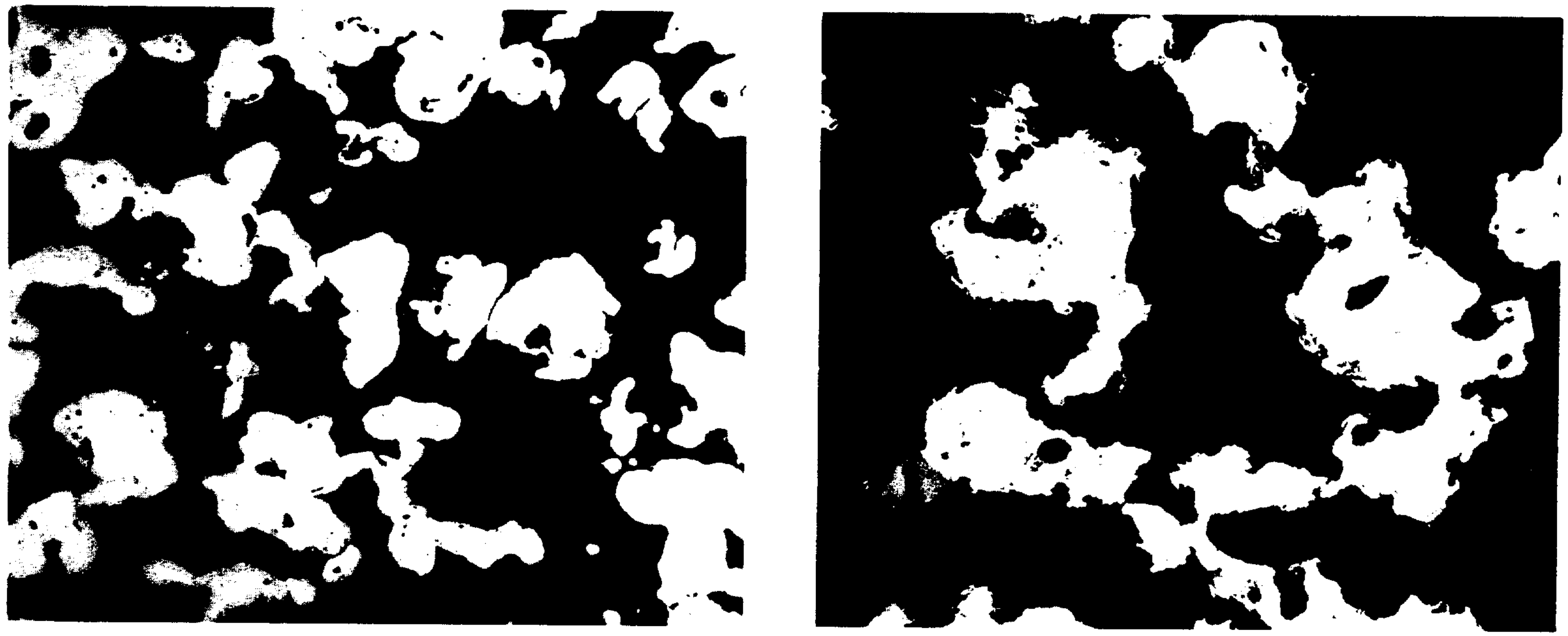


Figure 11. Oxidation Behavior of UCAR AB-4 Abradable Material (Braze Attachment) for the High-Pressure Turbine Shroud



(a) Before Oxidation (Mag.: 100X)

(b) After 500 Hours Oxidation at 1311°K (1900°F) (Mag.: 200X)

Figure 12. Typical Microstructure of UCAR AB-4 Abradable Material (Braze Attachment) for the High-Pressure Turbine Shroud

The ability of this structure to sustain long-term usage after 500 hours of exposure at 1311°K (1900°F) is shown in Figure 13. The retention, of only 70 percent of the original strength may lead to increased erosion during service. Considerable data, previously-generated by UCAR, exists showing the effects of oxidation time at 1273°K (1832°F) on the tensile strength of UCAR AB-4. As shown in Figure 14, the tensile strength increases during the first 250 hours of exposure, followed by a gradual decrease with additional exposure time. The strength retention at 1273°K (1832°F) is considered excellent.

Clean rub surfaces resulting from the abradability tests on both strength levels of AB-4 materials are shown in Figure 15.

An erosion test was conducted only on the high-strength AB-4 material. The sample tended to pit in areas rather than uniformly erode in the blast area (as shown in Figure 16). The weight loss was greater than that observed for the other UCAR abradable structures, partially due to the coarser particle size of the AB-4.

2. Braze Evaluation for UCAR AB-4. Three braze alloys were evaluated: LM Nicrobraz* (AMS 4777 Type), Nicrobraz 150*, and Nicrobraz 210*. Using these braze alloys, UCAR AB-4 coupons were brazed to INCONEL 600 substrates, and then subjected to long-term static oxidation at 1273°K (1832°F). After 500 hours of oxidation, cross-sections of each brazed coupon were examined. Based on these evaluations, Nicrobraz 150 was eliminated because of its lower oxidation resistance. Microstructures for each braze composition, before and after oxidation, are presented in Figures 17 through 19.

Additional braze evaluations were made with LM Nicrobraz and Nicrobraz 210 using L-605 alloy (Haynes 25**) as a substrate material. Typical microstructures before and after oxidation, for 500 hours at 1275°K (1832°F), are shown in Figures 20 and 21. The oxide formation was greater on the L-605 alloy than on the INCONEL 600 alloy; however, both joints remained sound.

Full-size high-pressure turbine shroud segments were fabricated using UCAR AB-4 abradable material brazed with LM Nicrobraz. A view of the brazed assembly is shown in Figure 22. X-ray examination did not reveal any disbonded areas following the completion of the 500-hour oxidation testing at 1273°K (1832°F). Further oxidation testing was conducted at the higher temperature

*Nicrobraz LM, 150, and 210 are registered trade names of Wall-Colmonoy Corp.

**L-605 (Haynes 25) is a registered trademark of Union Carbide Corp.

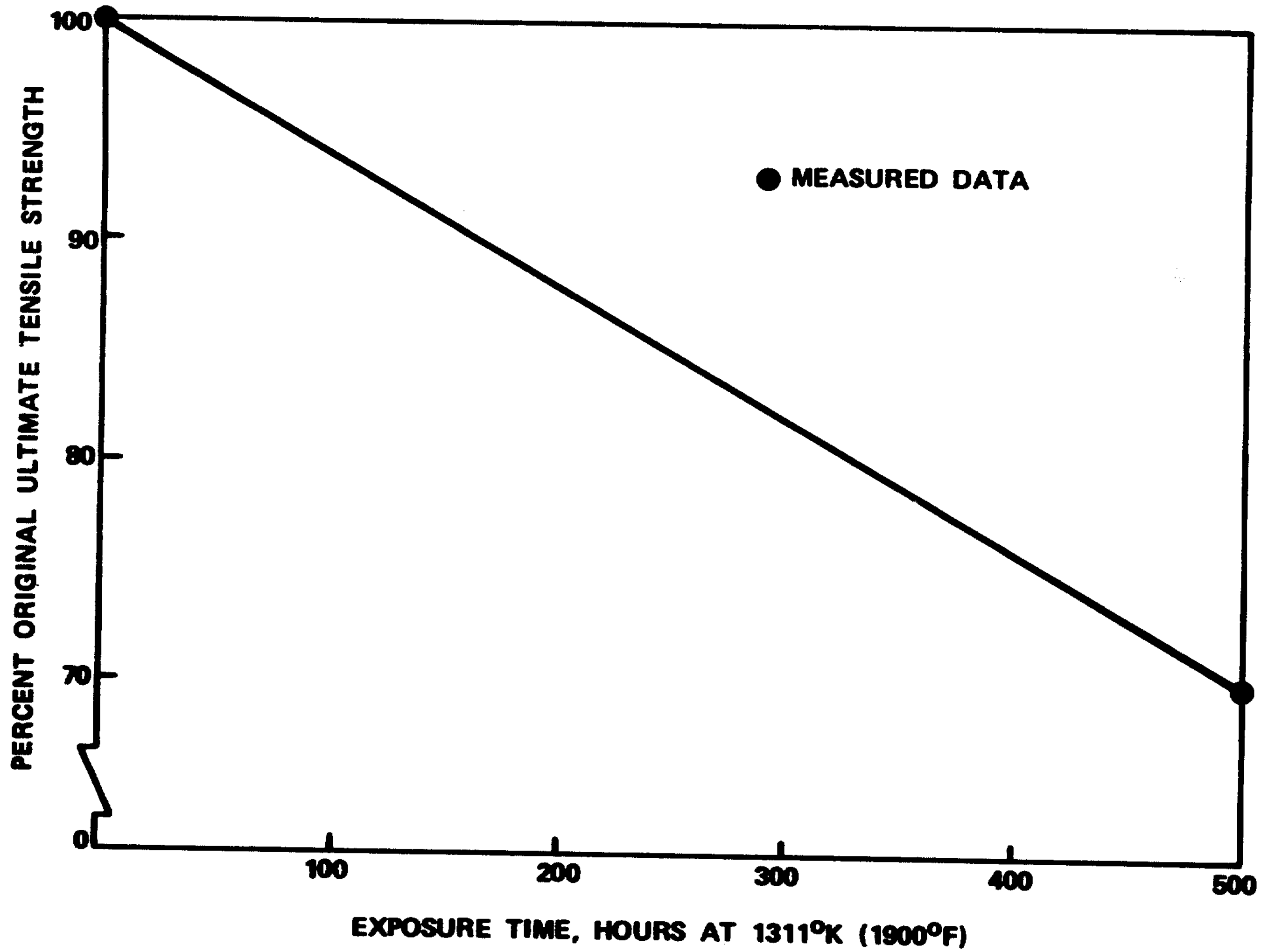


Figure 13. Effect of Oxidation Time on Ultimate Tensile Strength of UCAR AB-4 Abradable Material (Braze Attachment) for the High-Pressure Turbine Shroud

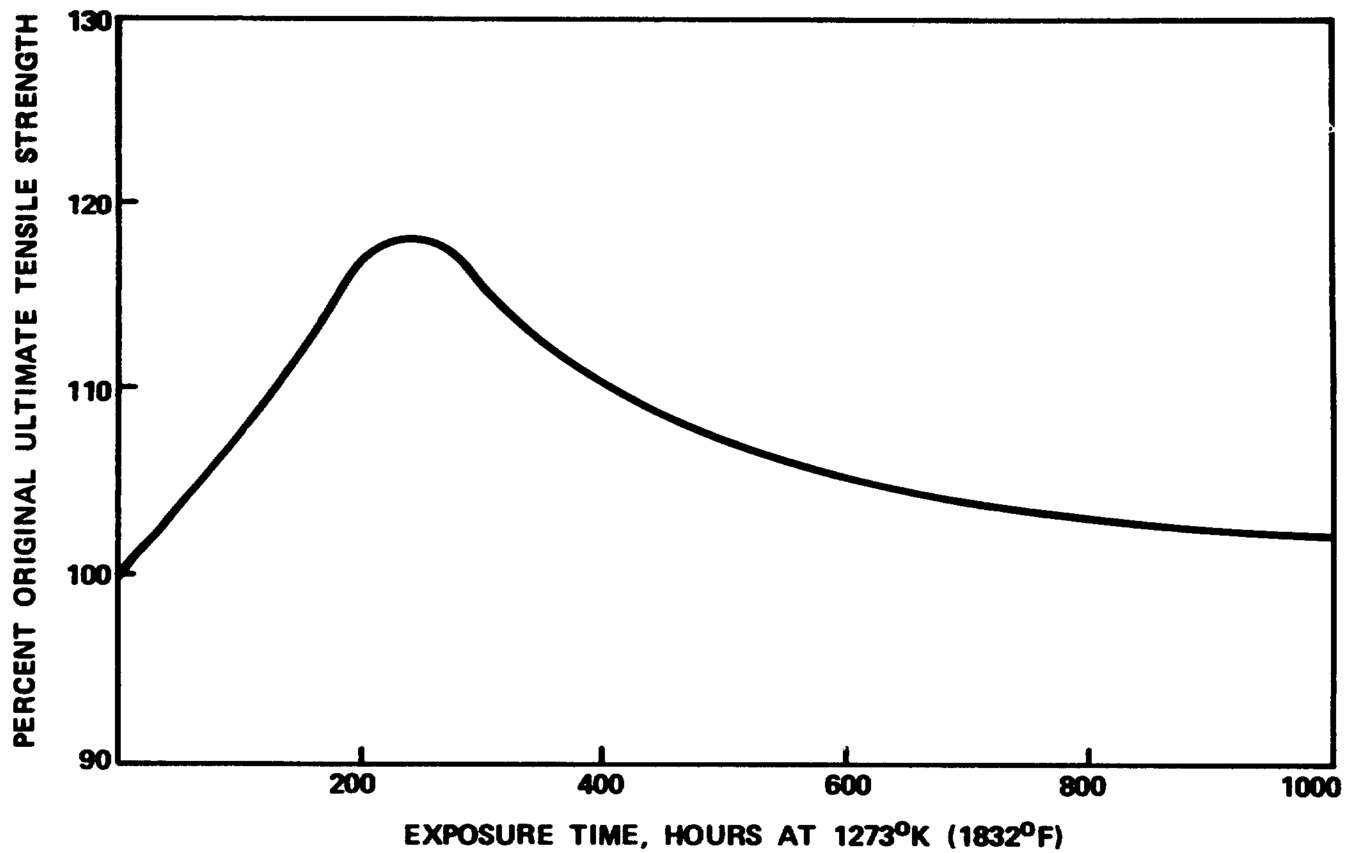
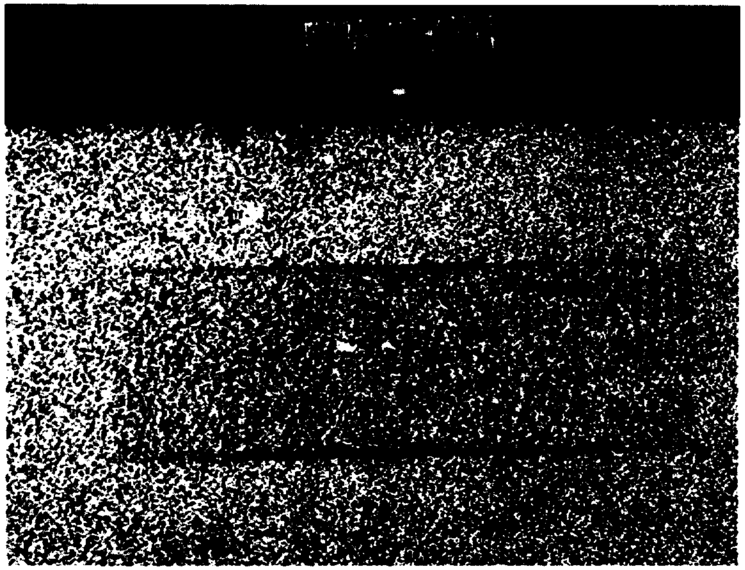
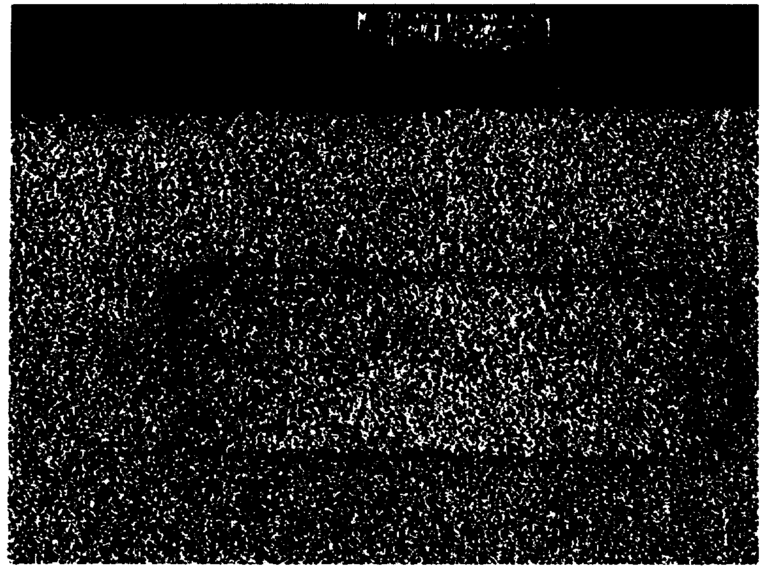


Figure 14. Effect of Oxidation Time on Ultimate Tensile Strength of UCAR AB-4 Abradable Material (Braze Attachment) for the High-Pressure Turbine Shroud



(a) UCAR AB-4 [11.4 MPa (1650 psi)] (Clean Rub with Slight Metal Transfer to the Blade)



(b) UCAR AB-4 [13.1 MPa (1900 psi)] (Clean Rub with Slight Metal Transfer to the Blade)

Figure 15. Abradability Test Rub Surface of UCAR AB-4 Abradable Material (Braze Attachment) for the High-Pressure Turbine Shroud. INCONEL 600 Blade-Tip Speed of 54.9 m/sec (180 ft/sec), and an Interaction Rate of 0.025 mm/sec (0.001 inch/sec) for 0.76-mm (0.030-inch) Rub Depth (Mag.: 2X)

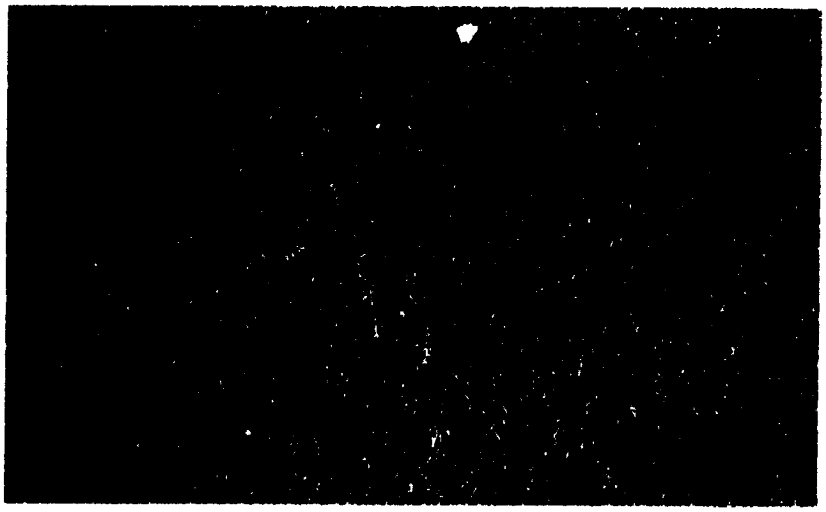
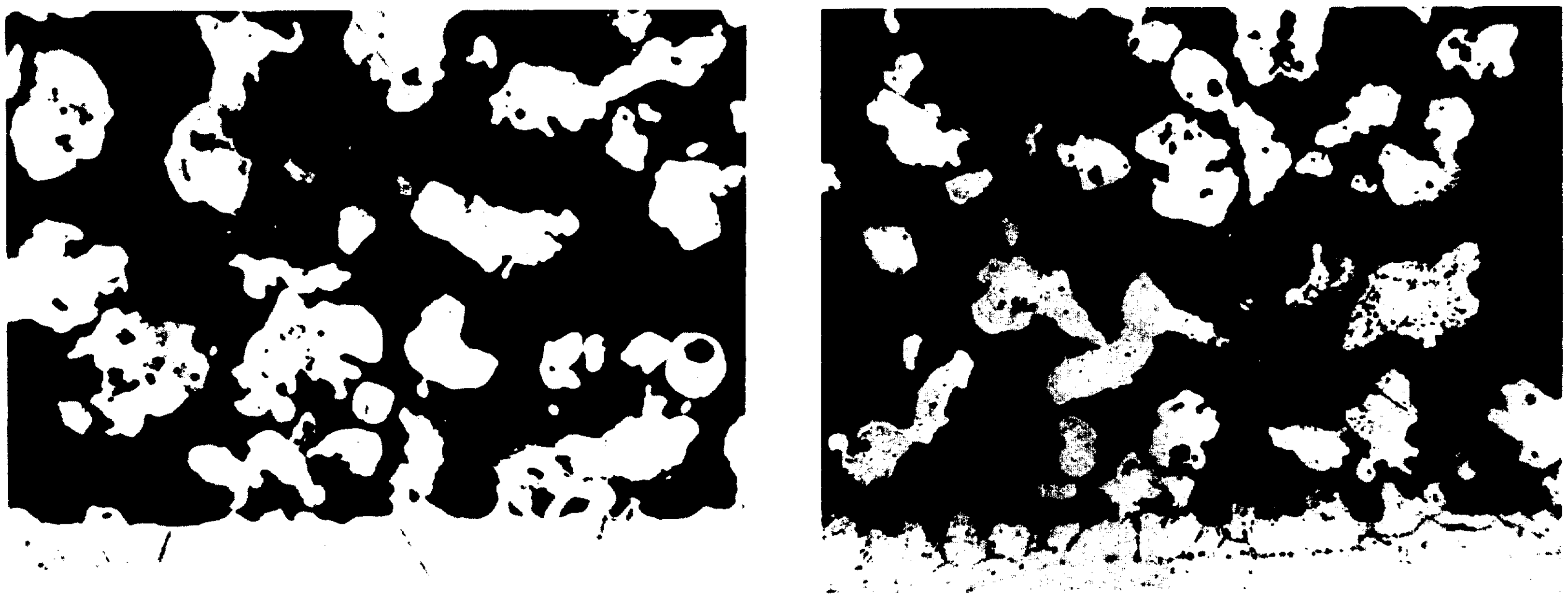


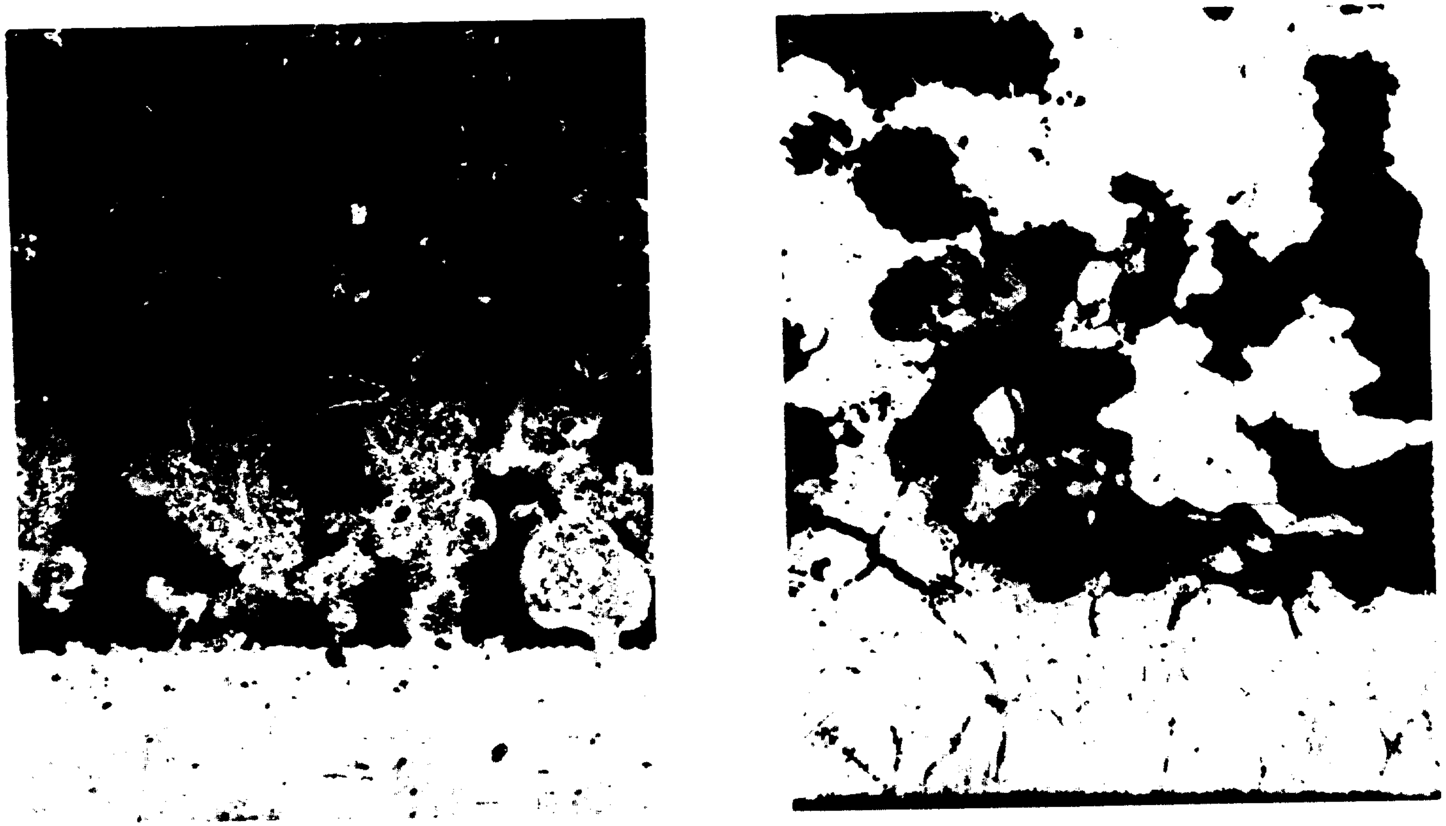
Figure 16. Erosion Test Surface of UCAR AB-4 Abradable Material (Braze Attachment) for the High-Pressure Turbine Shroud (Mag.: Approx. 5X)



(a) Before Oxidation

(b) After 500-Hours Oxidation at 1273°K (1832°F)

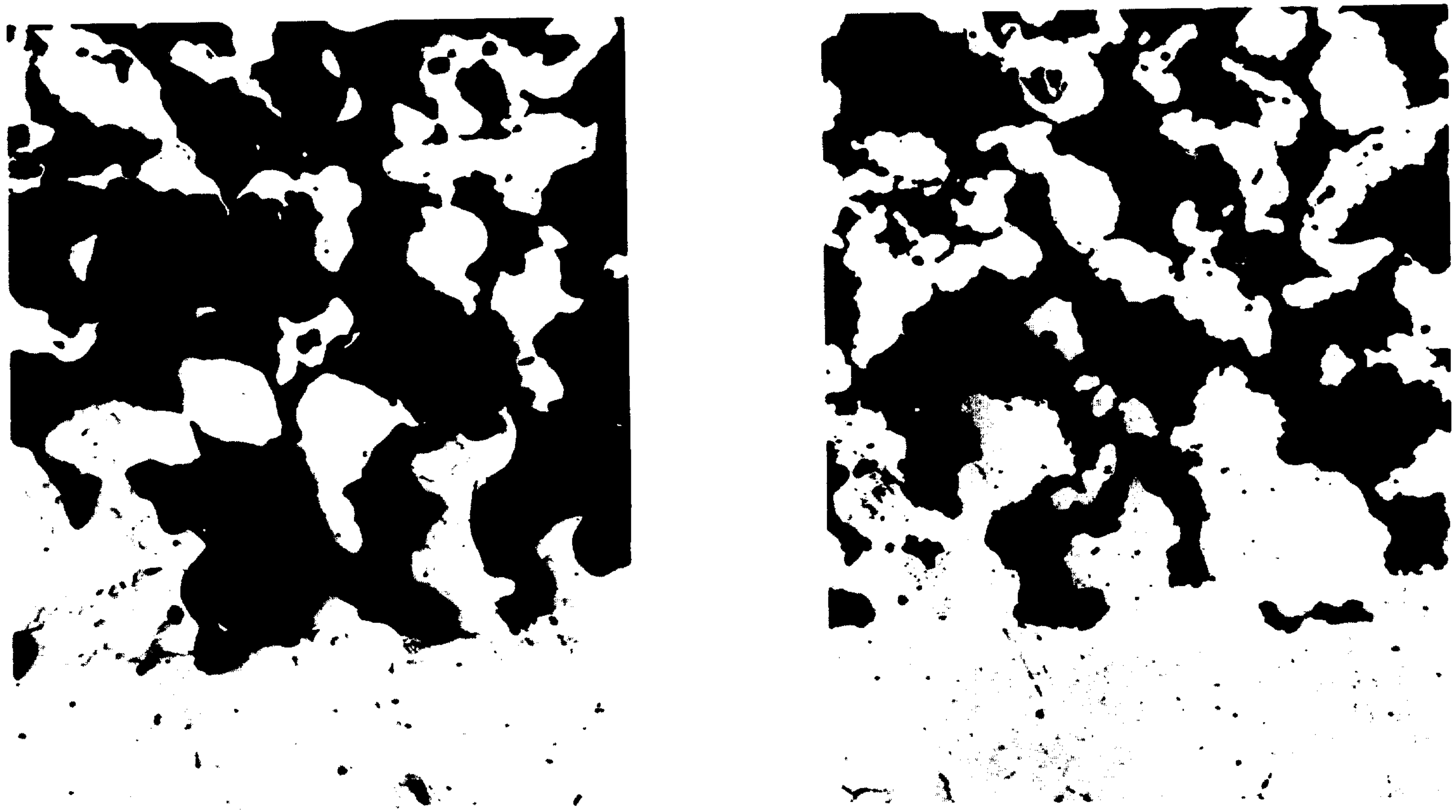
Figure 17. Cross Section of the Braze Interface UCAR AB-4/LM Nicrobraz INCONEL 600 (Mag.: 100X)



(a) Before Oxidation

(b) After 500 Hours Oxidation at 1273°K (1832°F)

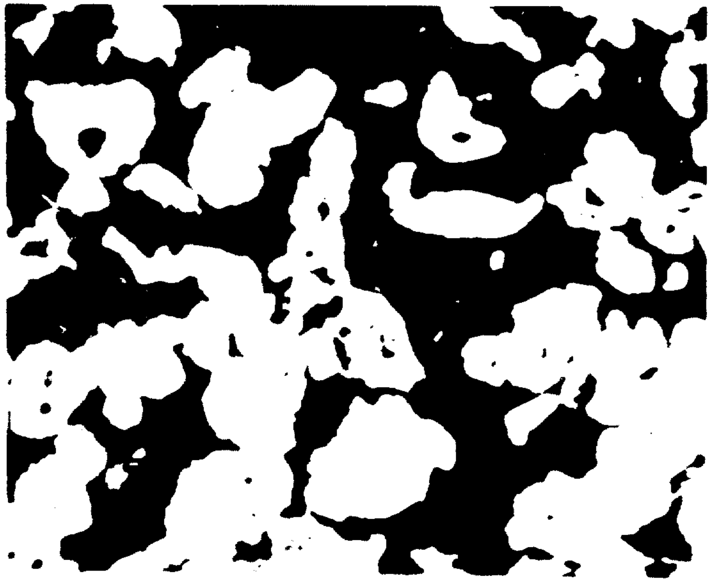
Figure 18. Cross Section of the Braze Interface of the UCAR AB-4/Nicrobraz 150/ INCONEL 600 (Mag.: 100X)



(a) Before Oxidation

(b) After 500 Hours Oxidation at 1273°K (1832°F)

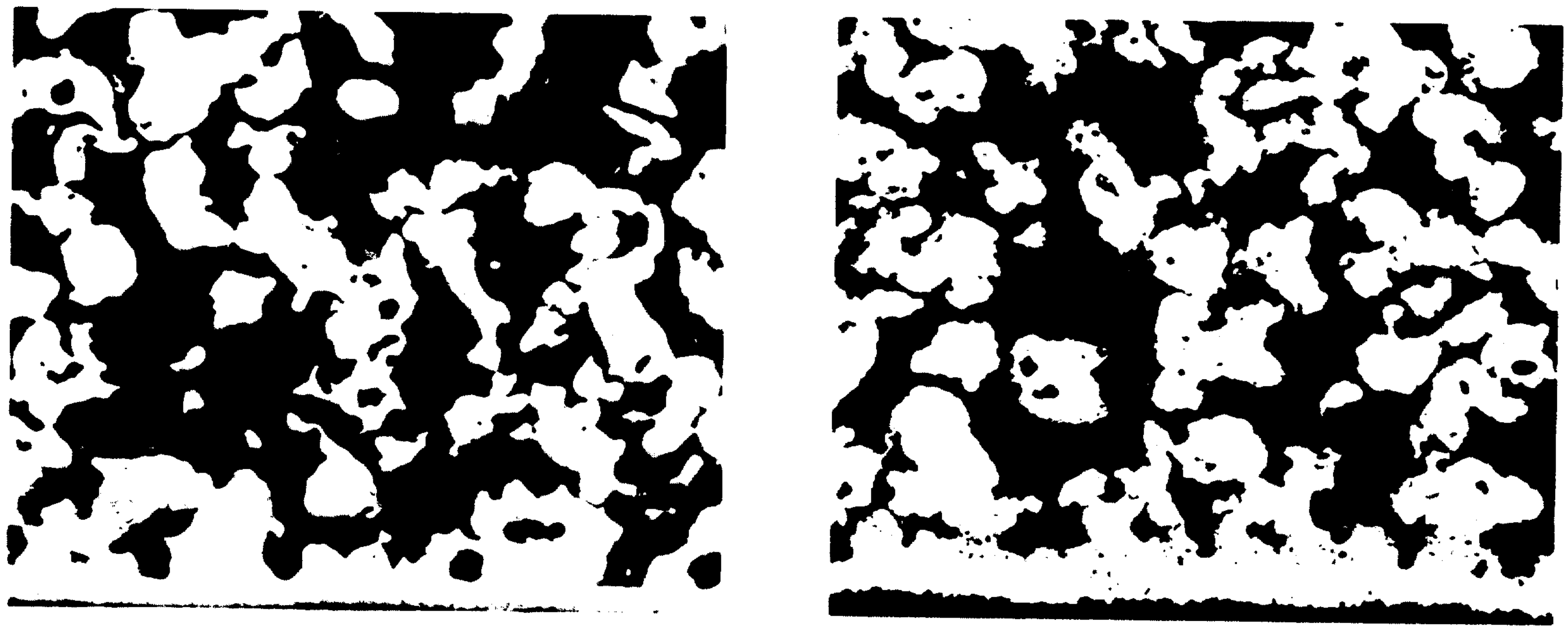
Figure 19. Cross Section of the Braze Interface of the UCAR AB-4/Nicrobraz 210/ INCONEL 600 (Mag.: 100X)



(a) Before Oxidation

(b) After 500 Hours Oxidation at 1273°K (1832°F)

Figure 20. Cross Section of the Braze Interface of the UCAR AB-4/LM Nicrobraz/L605 Alloy (Mag.: 100X)



(a) Before Oxidation

(b) After 500 Hours Oxidation at 1273°K (1832°F)

Figure 21. Cross Section of the Braze Interface of the UCAR AB-4/Nicrobraz 210/L605 Alloy (Mag.: 100X)

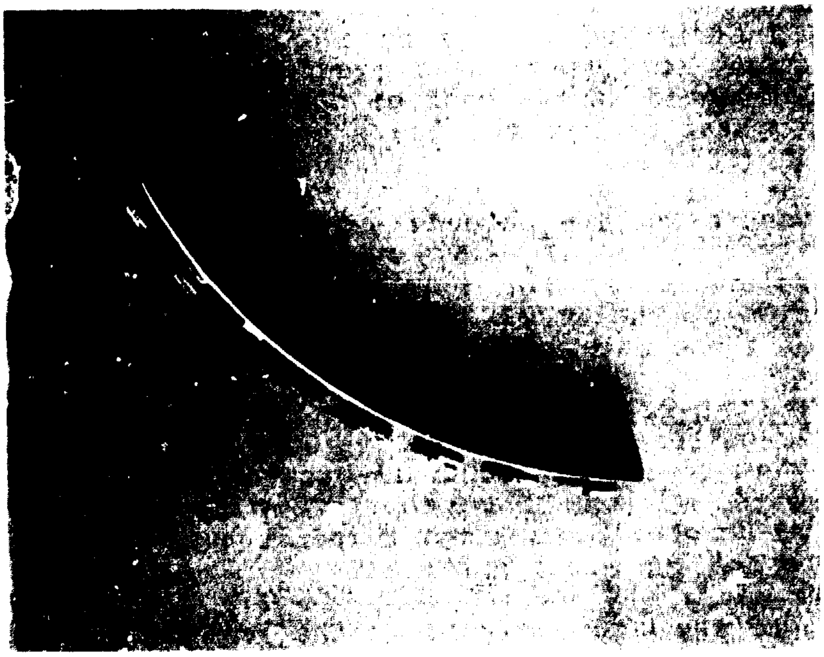


Figure 22. Brazed High-Pressure Turbine Shroud Segment of the UCAR AB-4 Abradable Material Brazed with LM Nicrobraz (Mag.: 1/2X)

of 1323°K (1922°F) where failure occurred at the abradable-substrate interface (bond joint) after 370 hours (as shown in Figure 23). The braze became completely oxidized at these conditions and the weight gain of the brazed piece is illustrated in Figure 24.

Excessive braze wicking was encountered when brazing UCAR AB-4 with Nicrobraz 210. Therefore, the LM Nicrobraz (AMS4777 Type) was selected for brazing the AB-4 to the shroud segments for the Task II Interim Engine Testing even though oxidation of the joint can occur if temperatures exceed 1311°K (1900°F). With cooling air directed at the back of the shroud segment retaining hardware, temperatures at the braze joint were not expected to exceed 1283°K (1850°F).

Low-Pressure Turbine Shrouds - Two strength levels of foil-backed UCAR AB-2* material -- 5.5 MPa (800 psi) and 9.0 MPa (1300 psi) -- were evaluated for potential use in the low-pressure turbine section of the TFE731 Engine. A summary of the measured properties of these materials is given in Table VI.

1. UCAR AB-2. This structure is a nominal 80-percent nickel and 20-percent chromium (80Ni-20Cr) alloy powder that has been brazed onto an INCONEL 600 foil-backing strip. The structure has been treated with a UCAR proprietary coating for oxidation protection at higher operating temperatures than is normally possible with the 80Ni-20Cr material.

Testing of the UCAR material in the low-pressure turbine was the same as for the high-pressure compressor materials testing except that oxidation studies were conducted at 1144°K (1600°F). This temperature is typical of the operating environment in the first-stage low-pressure turbine of the TFE731-3 Engine. Results indicate that this structure is capable of long-term operation at this temperature level. Weight gains as a function of time are depicted in Figure 25 (this curve includes data previously generated by UCAR). Strength retention during long-term oxidation exposure is shown in Figure 26, and is considered sufficient to minimize erosion in service with a shrouded blade. Typical microstructures of the nonoxidized and oxidized UCAR AB-2 material are presented in Figure 27. Oxidation occurred primarily at the surface of the particles.

The erosion test results indicated that the higher strength structure was slightly more erosion resistant. The blast surfaces of both strength-level materials eroded uniformly with no evidence of excessive particle pullout.

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*UCAR AB-2 is a trade name of the Union Carbide Corporation.

Figure 23. Microstructure Showing Failure Region of the Brazed Joint in a High-Pressure Turbine Shroud Segment After 370 Hours at 1323°K (1922°F) (Mag.: 100X)

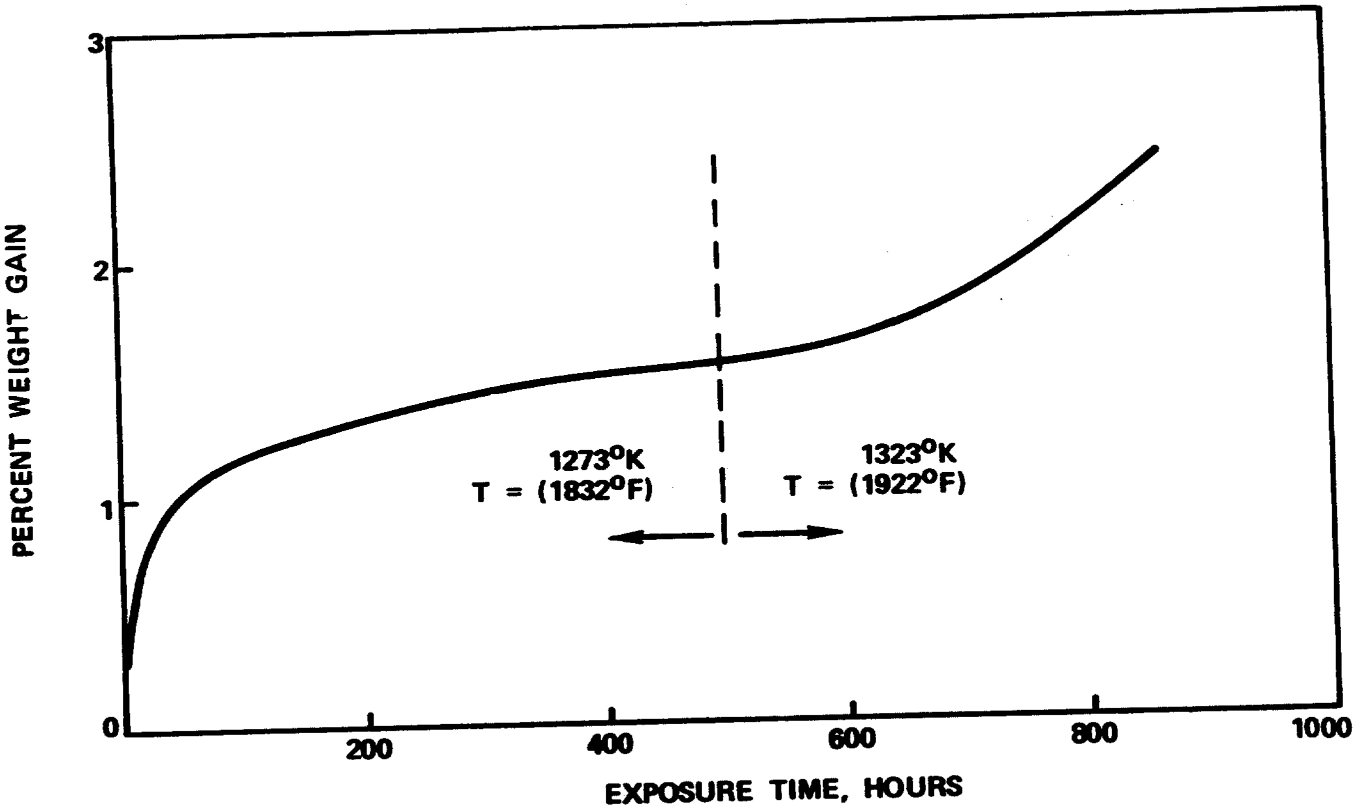


Figure 24. Oxidation Behavior of a Brazed High-Pressure Turbine Shroud Segment of the UCAR AB-4 Abradable Material Brazed with LM Nicrobraz

TABLE VI. SUMMARY OF THE MEASURED PROPERTIES OF TASK I CANDIDATE ABRADABLE MATERIALS FOR THE LOW-PRESSURE TURBINE SHROUDS.

	Nonoxidized test specimens					Oxidized test specimens [a]		
Material	Ultimate Tensile Strength, MPa (psi)	Density, g/cm^3 ($lb/in.^3$)	Peel [b] Strength, kN/m (lb/in.)	Erosion Weight Loss, g (grains)	Erosion Depth, mm (in.)	Ultimate Tensile Strength, MPa (psi)	Weight Gain, Percent	Peel [b] Strength, kN/m (lb/in.)
UCAR Type AB-2	5.5 (800)	2.7 (0.0975)	3.0 (17)	0.044 (0.68)	0.11 (0.0043)	3.3 (480)	2.0	2.5 (14)
UCAR Type AB-2	9.0 (1300)	2.7 (0.0975)	5.1 (29)	0.022 (0.34)	0.08 (0.0038)	7.9 (1150)	1.9	3.5 (20)

a Test specimens subjected to oxidation exposure at 1144°K (1600°F) for 500 hours

b "Peel strength" represents the measured force required to peel the foil backing from a 2.54-cm (1-inch) wide strip of abradable material

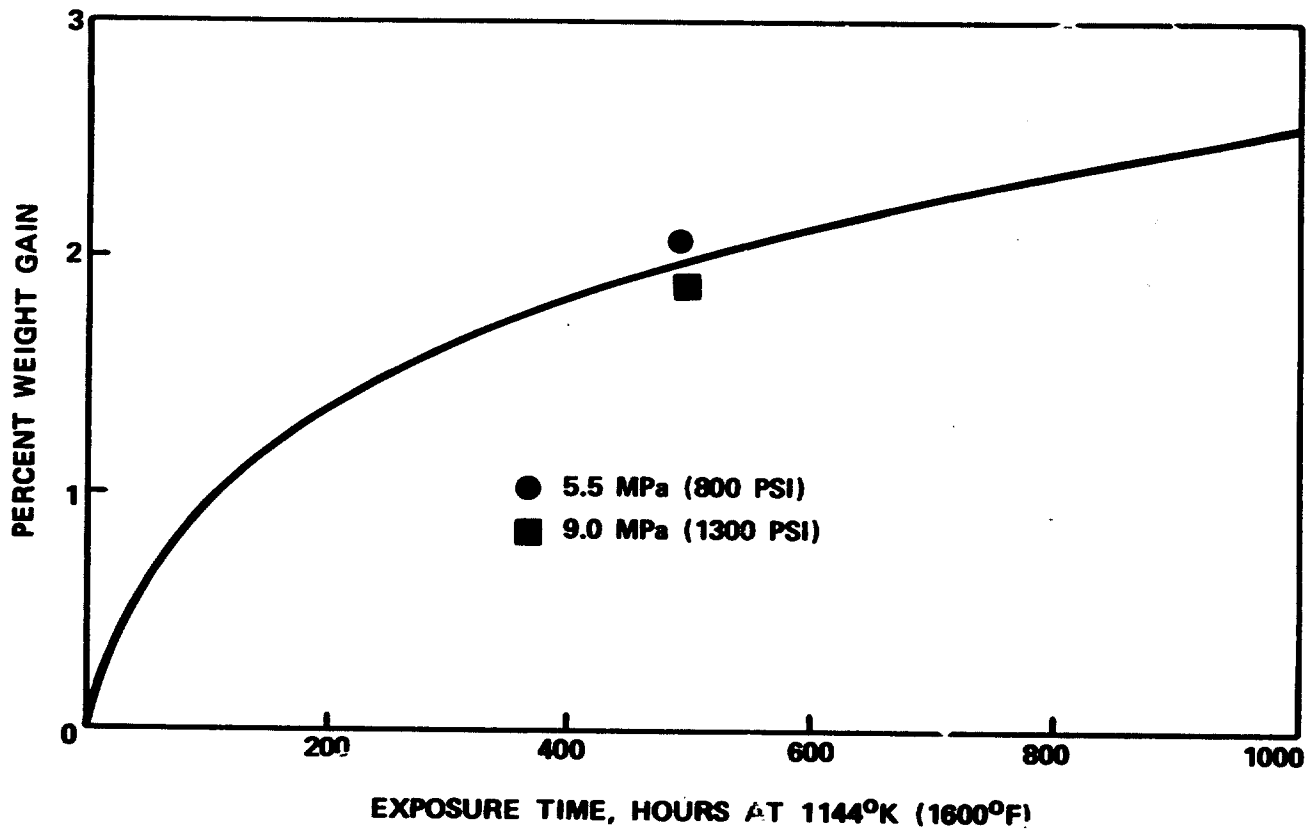


Figure 25. Oxidation Behavior of UCAR AB-2 Abradable Material (Braze Attachment) for the Low-Pressure Turbine Shroud

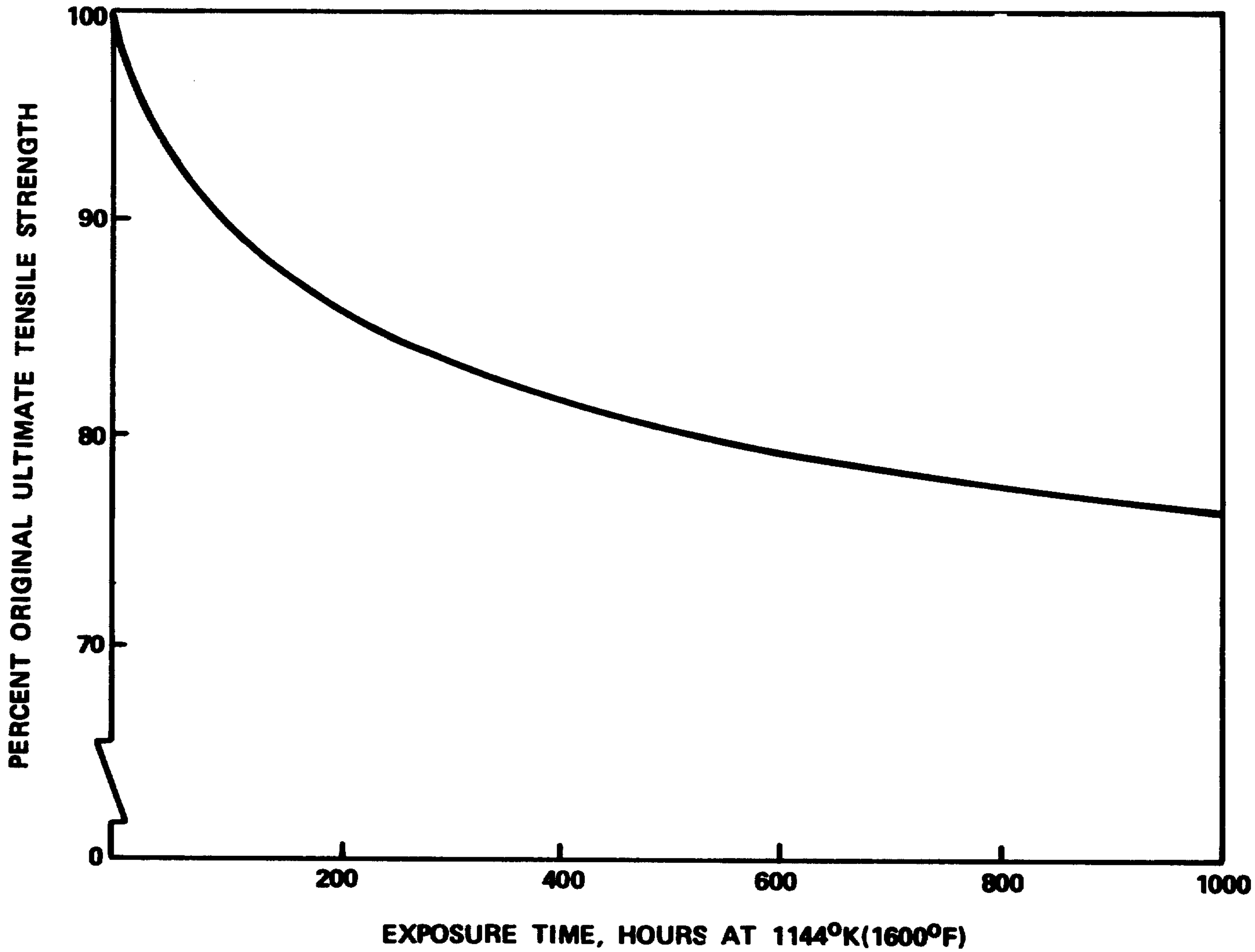
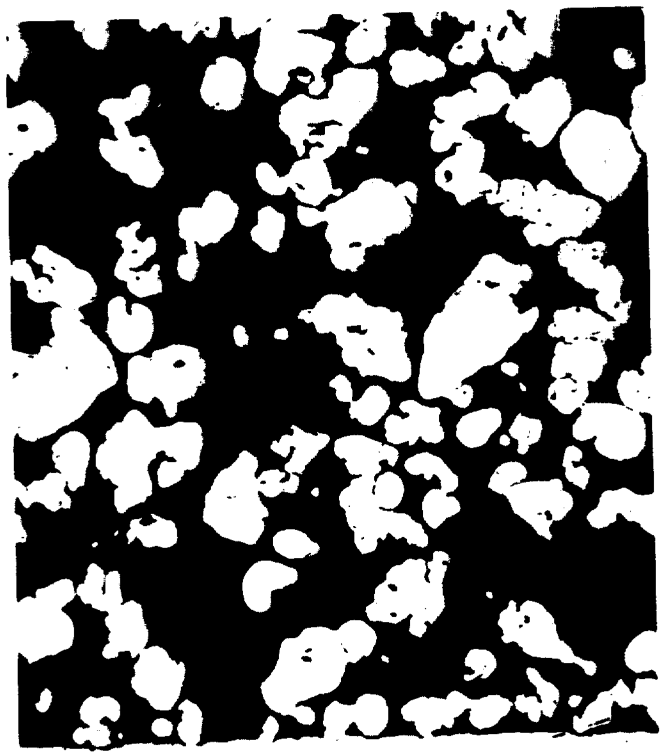
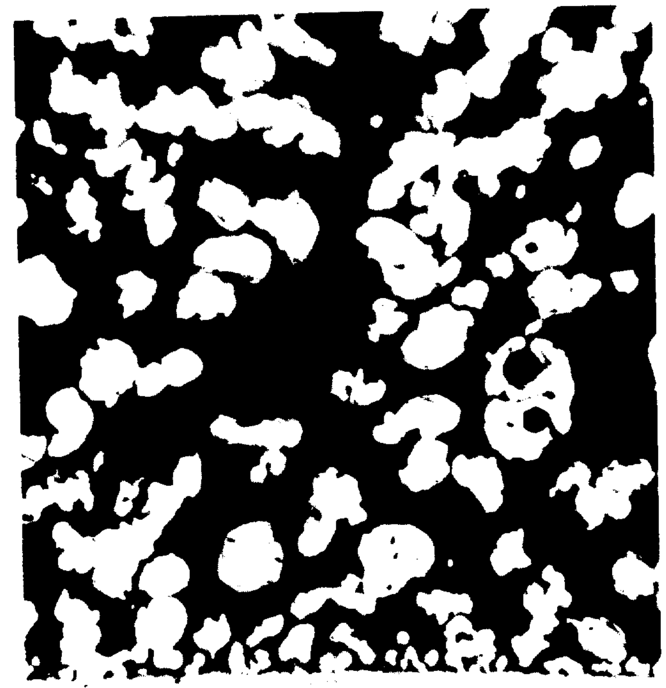


Figure 26. Effect of Oxidation Time on the Ultimate Tensile Strength of UCAR AB-2 Abradable Material (Braze Attachment) for the Low-Pressure Turbine Shroud



(a) Before Oxidation



(b) After 500 Hours Oxidation at 1144°K (1600°F)

Figure 27. Microstructure of UCAR AB-2 Abradable Material (Braze Attachment) for the Low-Pressure Turbine Shrouds (Mag.: 100X)

Separate samples of the two strength levels were tested for abradability using both INCONEL 600 knife edges and blades. Figure 28 presents the rub surface after the blade test. In this test, the higher strength structure smeared heavily over the rub area, and the test blade was discolored to a blue tint. The 5.5-MPa (800-psi) structure contained only a few areas of slight galling. [Again, in the knife-edge test, slight galling was experienced on the 5.5-MPa (800-psi) structure, whereas the 9.0 MPa (1300 psi) structure smeared excessively.]

2. <u>Abradability Tests of UCAR AB-2 Solvent-Cleaned Specimens</u>. Since it might have been necessary to use electrical discharge machining (EDM) for cutting the foil-backed material, tests were conducted to evaluate the effects of EDM fluid and subsequent cleaning procedures on abradability. Abradability tests were run on UCAR AB-2 [5.52 MPa (800 psi)] in both the as-bonded condition, and the as-cleaned condition following saturation in EDM fluid, and subsequent ultrasonic cleaning in trichlorethylene or benzene. Based on appearance and the abradability test results, both solvents were effective in removing the EDM fluid. All of the samples were similar in appearance after testing indicating comparable abradability.

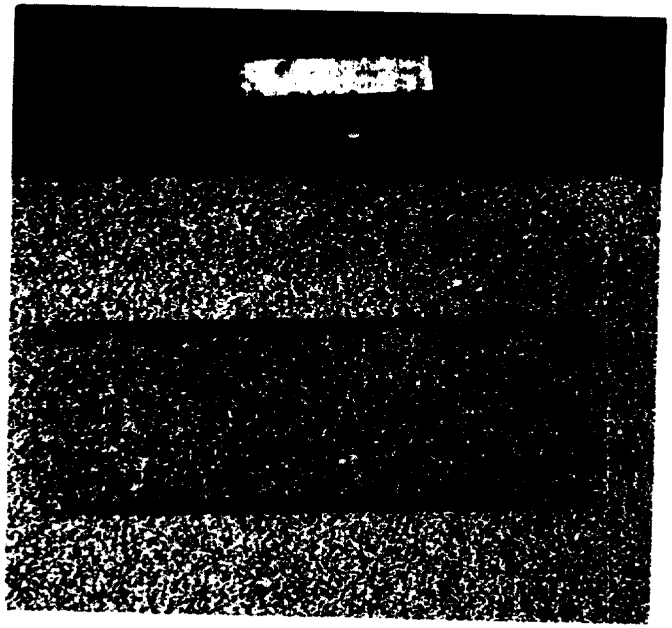
Summary of Task I

The following candidate material systems and material strength levels were selected for the Interim Engine Testing based on the extensive screening tests performed at Union Carbide.

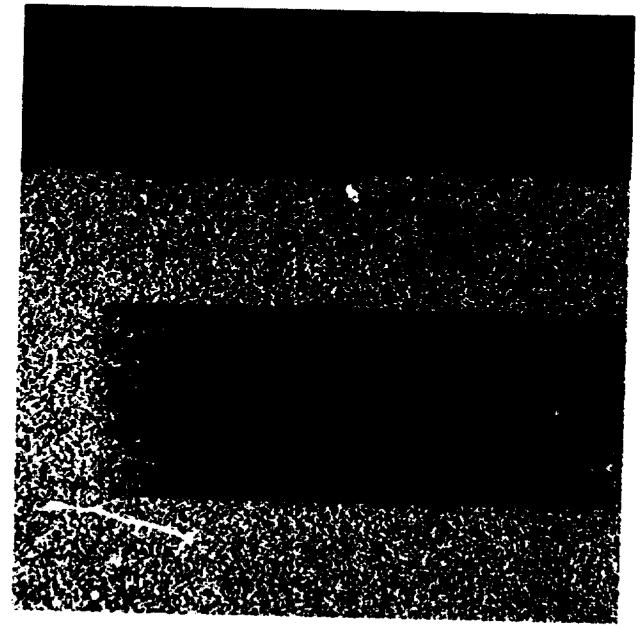
High-Pressure Compressor: Virgin and Pre-oxidized
- UCAR AB-1 [8.27 MPa (1200 psi)]
- UCAR AB-3 [7.58 MPa (1100 psi)]
- UCAR AB-3 [5.52 MPa (800 psi)]

High-Pressure Turbine:
- UCAR AB-4 [11.03 MPa (1600 psi)]
- UCAR AB-4 [13.79 MPa (2000 psi)]
- UCAR AB-4 [16.35 MPa (2400 psi)]

Low-Pressure Turbine:
- UCAR AB-2 [8.96 MPa (1300 psi)]
- UCAR AB-2 [5.52 MPa (800 psi)]



(a) UCAR AB-2 [5.5 MPa (800 psi)] (Slight Wear on Blade with Slight Galling of the Rub Surface)



(b) UCAR AB-2 [9.0 MPa (1300 psi)] (Smeared Rub Surface with Some Blade Wear)

Figure 28. Abradability Test Rub Surface of Union Carbide Abradable Material (Braze Attachment) for the Low-Pressure Turbine Shrouds. INCONEL 600 Blade-Tip Speed of 54.9 m/sec (180 ft/sec), and an Interaction Rate of 0.025 mm/sec (0.001 inch/sec) for 0.76-mm (0.030-inch) Rub Depth (Mag.: 2X)

TASK II - MATERIAL AND PROCESS SELECTION

Scope

This task was designed to evaluate candidate abradable materials and attachment methods by means of full-scale Interim Engine Tests. The results of the Task II testing and evaluation were utilized as a basis for selection of the most promising candidates for evaluation under the more extensive full-scale engine endurance test of Task VI.

Task II included two 50-hour Interim Engine Tests. The first Interim Engine Test, in two builds, used components fabricated with the candidate materials listed in Table VII (same as Table I). This table lists those candidate materials subjected to properties testing in Task I plus several materials of known characteristics selected either as baseline materials for comparison purposes, or because their properties suggested a potential application for this program.

The Second Interim Engine Test, also in two builds, used engine components fabricated with the materials listed in Table VIII (same as Table II). This second series of testing was added after the completion of the first test when Union Carbide announced that they planned to discontinue their metallic-abradable seal business. This announcement was cause for concern in the MATE Program since the primary emphasis of both Task I, and the First Interim Engine Test in Task II had been based on UCAR materials. Therefore, working closely with NASA, a Second Interim Engine Test was added to this Project based on available industry materials including low-cost spray coatings where available. Union Carbide has since sold their abradable business to the Chromalloy American Corporation.

The Garrett-AiResearch TFE731-3 Turbofan Engine was selected as the test vehicle (see Figure 29) for all Interim Engine Testing. Candidate abradable materials were tested in the single-stage radial high-pressure compressor (HPC), the single-stage axial high-pressure turbine (HPT), and in each of the three axial stages of the low-pressure turbine (LPT). The standard engine hardware was modified only where necessary to accommodate the candidate abradable materials in their test configuration, provide assembly clearances to ensure rubs, and to accommodate any special instrumentation selected for use during the tests.

The design modifications required to incorporate the MATE abradables are described in detail in Task III. The major change was made in the HP compressor section where an insertable plug was designed to minimize engine assembly/disassembly, and yet maximize the number of abradable materials that could be tested. The plugs, with the abradable material mounted on one end, could then

Engine Component	Material Identification	Material Composition	Strength Level, MPa	(psi)	Attachment Method	Material Source	Engine Build Number
TABLE VII. CANDIDATE ABRADABLE MATERIALS SELECTED FOR THE FIRST TASK II INTERIM ENGINE TEST							
High-Pressure Compressor: Test Item: Abradable Plug (replaceable shoe) Installed in Shroud. Impeller surface Speed - 548.6 m/sec (1800 ft/sec); 700°K (800°F).	UCAR AB-1[a]	Nickel-Chromium	8.27	(1200)	Direct Sinter	Union Carbide	1
	UCAR AB-1	Nickel-Chromium	8.27	(1200)	Direct Sinter	Union Carbide	1
	UCAR AB-3	Nickel-Chromium	7.58	(1100)	Direct Sinter	Union Carbide	1
	UCAR AB-3	Nickel-Chromium	5.52	(800)	Direct Sinter	Union Carbide	1
	Feltmetal 501	Haynes 25	---	----	Braze	Brunswick	1
	Metco SF	Aluminum-Silicon		----	Thermospray	AiResearch	1
	Metco CE 2019	Bronze/Boron Nitride		----	Thermospray	Metco	1
High-Pressure Turbine: Test Item: Complete Shroud. Rotor Tip Speed (RTS) - 427 m/sec (1400 ft/sec); 1311°K (1900°F).	UCAR AB-4	Nickel-Chromium-Aluminum	11.03	(1600)	Braze	Union Carbide	1
	UCAR AB-4	Nickel-Chromium-Aluminum	13.79	(2000)	Braze	Union Carbide	1
	UCAR AB-4	Nickel-Chromium-Aluminum	16.35	(2400)	Braze	Union Carbide	1
	UCAR AB-4[b]	Nickel-Chromium-Aluminum	13.79	(2000)	Braze	Union Carbide	2
	Bradelloy 500[c]	----	24.32	(3600)	Braze and Sinter	Howmet-G.E.	2
Low-Pressure Turbine: Test Item: Complete Shroud (each stage). First-Stage: RTS - 380 m/sec (1250 ft/sec); 1144°K (1600°F).	UCAR AB-2	Nickel-Chromium	8.96	(1300)	Braze	Union Carbide	1
	UCAR AB-2[d]	Nickel-Chromium	8.96	(1300)	Braze	Union Carbide	2
	Honeycomb[d]	Hastelloy-X		----	Braze	AiResearch	2
Second-Stage: RTS - 412 m/sec (1350 ft/sec); 1033°K (1400°F).	UCAR AB-2	Nickel-Chromium	8.96	(1300)	Braze	Union Carbide	1
	Solabrade[c]	Hastelloy-X		----	Braze	Kelsey-Hayes	2
Third-Stage: RTS - 436 m/sec (1430 ft/sec); 992°K (1200°F).	UCAR AB-2[d]	Nickel-Chromium	8.96	(1300)	Braze	Union Carbide	1
	UCAR AB-2[d]	Nickel-Chromium	5.52	(800)	Braze	Union Carbide	1
	Feltmetal 522[c]	HS-188		----	Braze	Brunswick	2

[a] High-Strength Material Preoxidized Down to ~8.27 MPa (~1200 psi)
[b] Material Strength Level Based on Build 1 Results
[c] Build 2 Baseline Materials. Not Tested in Task I or Task II, Build I
[d] Approximately 180° of Shroud

TABLE VIII. CANDIDATE ABRADABLE MATERIALS SELECTED FOR THE SECOND TASK II INTERIM ENGINE TEST

Engine Component	Material Identification	Material Composition	Attachment Method	Material Source	Engine Build Number
High-Pressure Compressor: Test Item: Abradable Plug (replaceable shoe) Installed in Shroud. Impeller Surface Speed - 548.6 m/sec (1800 ft/sec); 700°K (800°F).	Feltmetal 515B	Hastelloy-X	Braze	Brunswick	3
	Metco T310-10	Aluminum-Graphite-Silicon	Thermospray	Metco	3
	Metco T301-10	Boron-Nitride Cermet	Thermospray	Metco	3
	Metco P601-10	Aluminum-Polyester	Plasmaspray	Metco	3
High-Pressure Turbine: Test Item: Complete Shroud. Rotor Tip Speed (RTS)-427 m/sec (1400 ft/sec); 1311°K (1900°F).	Brunsbond Composite	Zirconium Oxide (Y_2O_3 Stabilized)	Braze	Brunswick	3
	Metco T201-10	Zirconium Oxide (CaO Stabilized)	Thermospray	Metco	3
	Metco P443-10 (Dense)	Nickel-Chromium-Aluminum	Plasmaspray	Metco	3
	Metco P443-10 (Open)	Nickel-Chromium-Aluminum	Plasmaspray	Metco	3
Low-Pressure Turbine: Test Items: Complete Shroud (each stage). First-stage: RTS-380 m/sec (1250 ft/sec); 1144°K (1600°F).	Honeycomb[a]	Hastelloy-X	Braze	Kelsey-Hayes	3
	Solabrade[a]	Hastelloy-X	Braze	Kelsey-Hayes	3
	Metco T450-14	Nickel-Aluminum	Thermospray	Metco	4
Second-stage: RTS-412 m/sec (1350 ft/sec); 1033°K (1400°F)	Metco T301-10	Boron-Nitride Cermet	Thermospray	Metco	3
	Feltmetal 537	Iron-Nickel-Chromium-Aluminum-Yttrium	Braze	Brunswick	4
Third-Stage: RTS-436 m/sec (1430 ft/sec); 922°K (1200°F)	Metco 304NS	Bronze/Boron-Nitride Composite	Thermospray	Metco	3
	Feltmetal 535	Iron-Chromium-Aluminum-Yttrium	Braze	Brunswick	4

[a] Approximately 180° of Shroud

Figure 29. The TFE731-3 Engine Utilized in the Interim Engine Screening Tests (Installed in the Test Cell)

be installed and removed without disturbing the "cold" end of the engine. The details of this plug or shoe are included in Task III.

First Interim Engine Test--Task II

The first 50-hour Interim Engine Test was divided into two engine builds to provide minimum operating time on the various abradables. The components and abradable materials tested in each build are listed in Table VII. Normal engine build clearances were reduced based on operating experience and calculated rotor and shroud growths to ensure rubs on the test abradables during engine operation. Each engine build was run for approximately 25 hours.

Engine Build 1

1. High-Pressure Compressor Shroud Tests. During the first engine build, shoes (plugs) having abradable coatings (as listed in Table VII) were individually inserted into the high-pressure compressor shroud and tested for approximately one hour to the test cycle depicted in Figure 30. The shoe was rubbed by the titanium alloy (Ti-6Al-2Sn-4Zr-2Mo) impeller at takeoff conditions, approximately 700°K (800°F) and 548.6 m/sec (1800 ft/sec) at a measured interaction rate of 0.025 mm/minute (0.001 inch/minute). A second one-hour test was run on a duplicate shoe for each material to provide additional data. A typical rubbed shoe is presented in Figure 31. The tapered rub surface is due to the differential deflection of the high-pressure compressor rotor and shroud. For engine operation, other than abradable shoe testing, a dummy shoe with a recessed face was installed to prevent gas leakage.

a. UCAR AB-1 - A layer of nickel was deposited on four INCONEL 718 shoes as a diffusion barrier, and then UCAR AB-1 was direct-sintered to the shoe. Two of the shoes were coated with 8.27-MPa (1200-psi) tensile strength material while the other two were coated with a higher strength material that was then oxidized in air at 1005°K (1350°F) for 24 hours down to approximately 8.27-MPa (1200-psi) strength. This pretest oxidation was meant to simulate long-time engine tested parts. The shoes were tested as described above. X-ray analysis of the rubbed surfaces in a scanning electron microscope (SEM) did not show evidence of titanium-alloy blade transfer, and the impeller blades did not exhibit wear. All four shoes had similar rub surfaces with no apparent difference between oxidized and non-oxidized material. The abradability of the AB-1 material was judged "good" based on the appearance of the rubbed surface and the absence of titanium-alloy blade-metal transfer. The typical appearance of the AB-1 shoes after testing is shown in Figure 32.

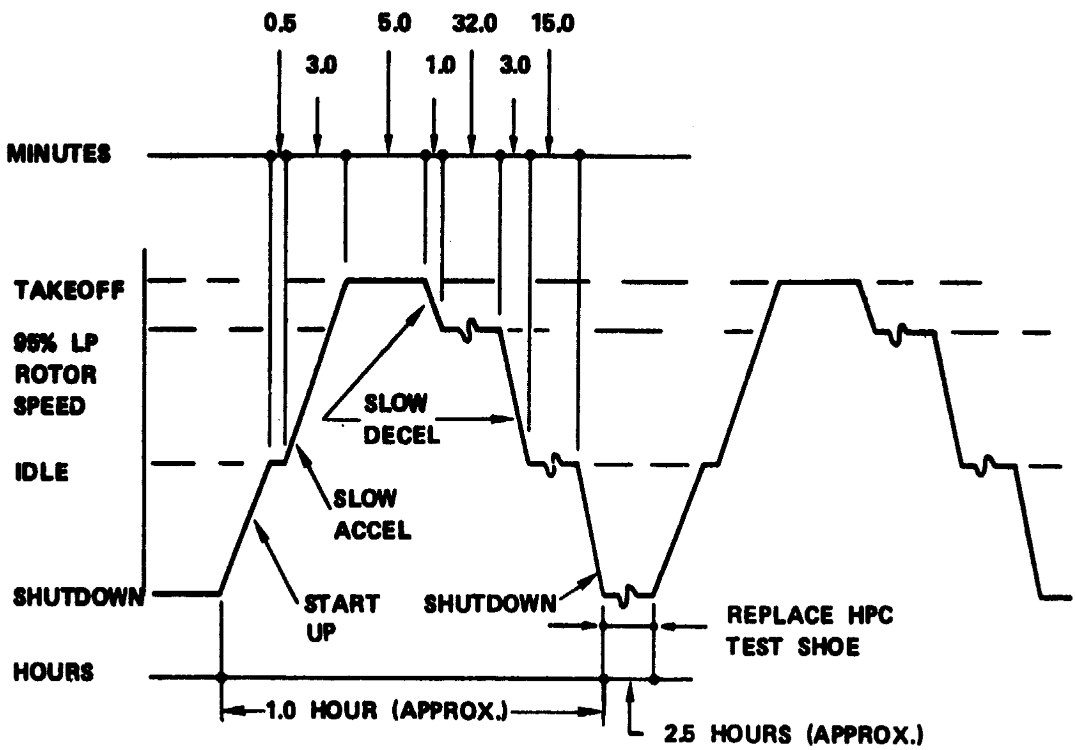


Figure 30. Typical Engine Test Cycle for the First Task II Interim Engine Test (Build 1)

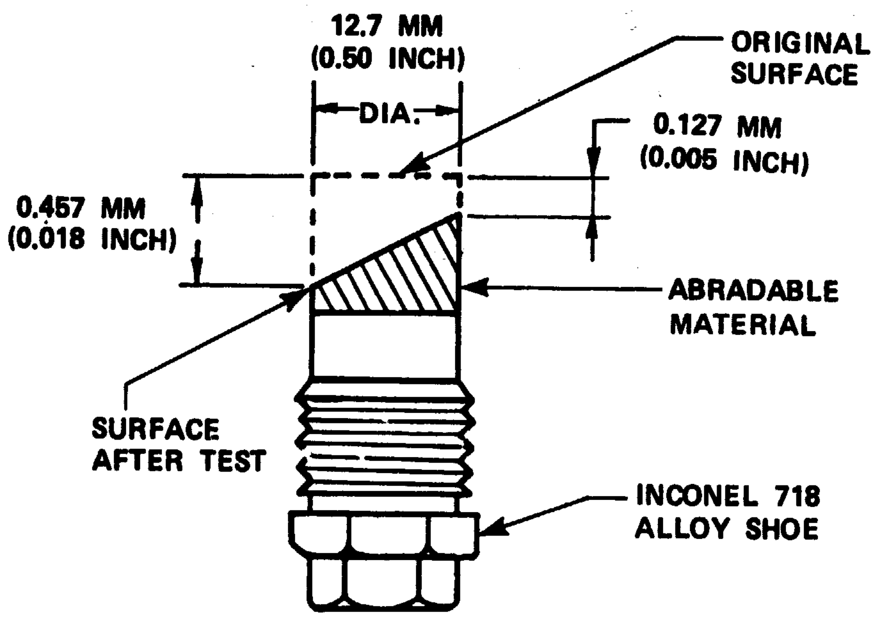
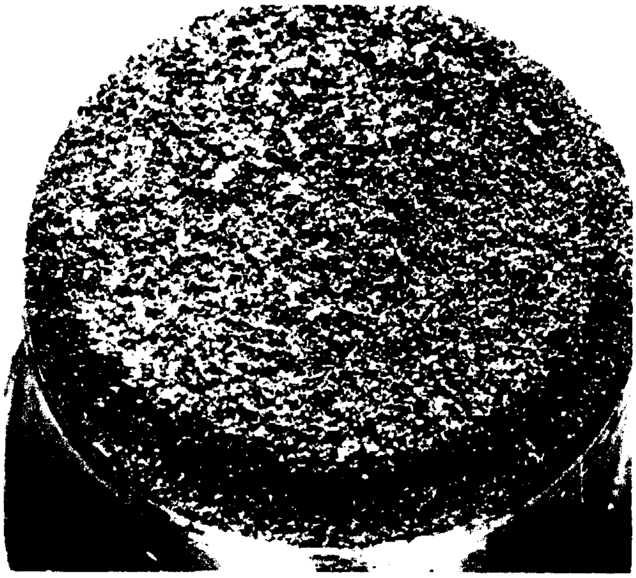
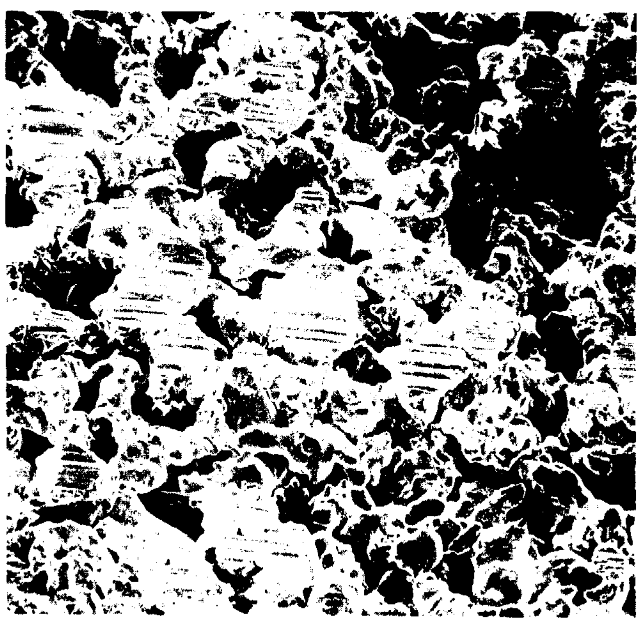


Figure 31. Typical Wear Contour on High-Pressure Compressor Test Shoes after One Hour of Engine Testing



(a) Optical View (Mag.: 7X)



(b) SEM Image of Rub Area (Mag.: 100X)

Figure 32. Typical Appearance of the UCAR AB-1 [8.27-MPa (1200-psi)] High-Pressure Compressor Test Shoes After One Hour of Engine Testing

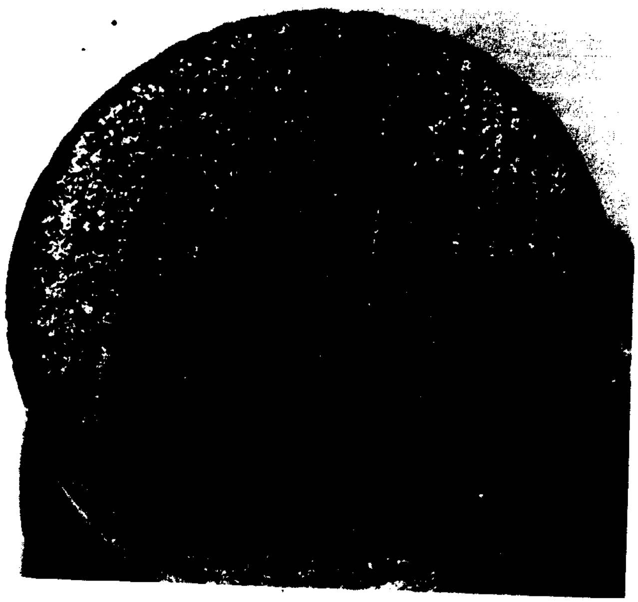
b. UCAR AB-3 - Two strength levels of UCAR AB-3--5.52 MPa (800 psi) and 7.58 MPa (1100 psi)--were applied by direct-sintering in a manner similar to AB-1, and then engine tested as described previously. Examination of the rubbed test shoes showed that some titanium-alloy had been transferred from the impeller blades, although the impeller did not show measurable wear. The two strength levels of AB-3 gave comparable results. The appearance of the rub surface was similar to that of AB-1, but due to the titanium pickup, the overall abradability of AB-3 was rated below AB-1. Optical and SEM photographs of the rubbed surfaces of the two strength-level materials are shown in Figures 33 and 34.

c. Feltmetal 501 - This material was brazed to the test shoe surface using LM Nicrobraz (AMS 4777 Type) alloy. The braze material "wicked" approximately 0.38 mm (0.015 inch) into the fiber-metal structure, but this was not considered detrimental to the test. Evaluation after the standard test of the shoe in the engine showed a slight amount of "pull-out" on the surface. X-ray examination of the rub surface did not disclose the presence of titanium, and impeller wear was not detected. The abradability of this material was down-graded to a "fair" rating due to the pull-outs. Optical and SEM photographs of the rub surface of the Feltmetal 501 are shown in Figure 35.

d. Metco SF - The Metco SF coated shoes were fabricated by first applying a base coat of Metco 405*, then a flash coat of Metcoloy No. 2*, and finally, the flame-spray coating of Metco SF. This material is the standard high-pressure compressor clearance-control coating applied to the production TFE731 HP compressor shroud. This coating is not classified as a true "abradable" coating, but was tested as the baseline high-pressure compressor coating for comparison purposes.

The first of the two shoes tested in the engine sheared off at the bond joint between the INCONEL 718 substrate and the Metco 405 base coat. The amount of interference between the shoe and the impeller was reduced for the second test, and the resulting rub depth was 0.025 mm (0.001 inch) with no evidence of shear. Shearing of the first shoe occurred because a satisfactory bond to the INCONEL 718 substrate could not be achieved on such a small area. A view of both tested shoes is presented in Figure 36. A highly-magnified image of the rub surface of the second shoe is shown in Figure 37. It is evident that continuous smearing occurred,

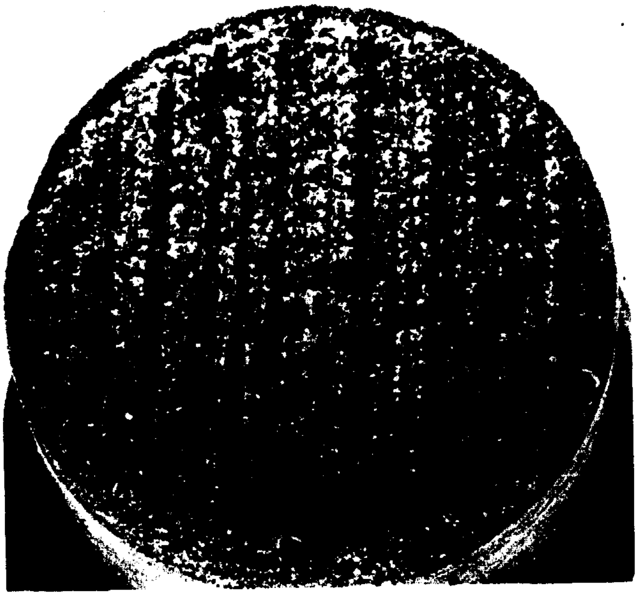
*Metco 405 and Metcoloy No. 2 are trade names of Metco, Inc.



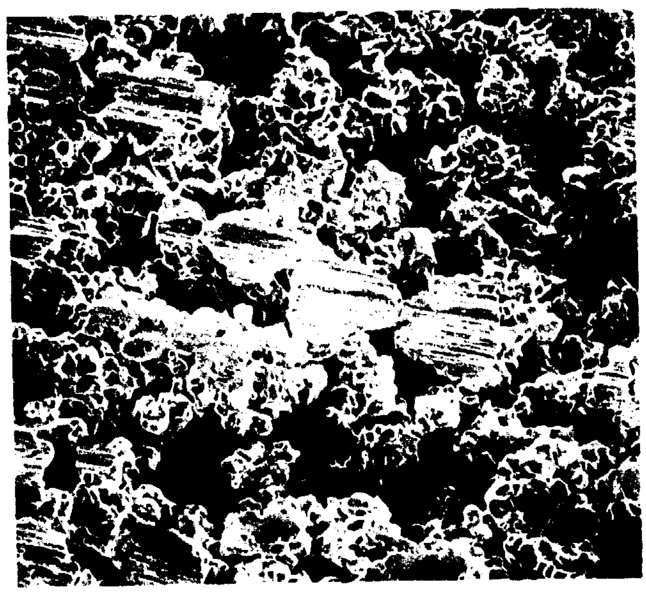
(a) Optical View (Mag.: 7X)

(b) SEM Image of Rub Area (Mag.: 100X)

Figure 33. Typical Appearance of the UCAR AB-3 [5.52-MPa (800-psi)] High-Pressure Compressor Test Shoes After One Hour of Engine Testing

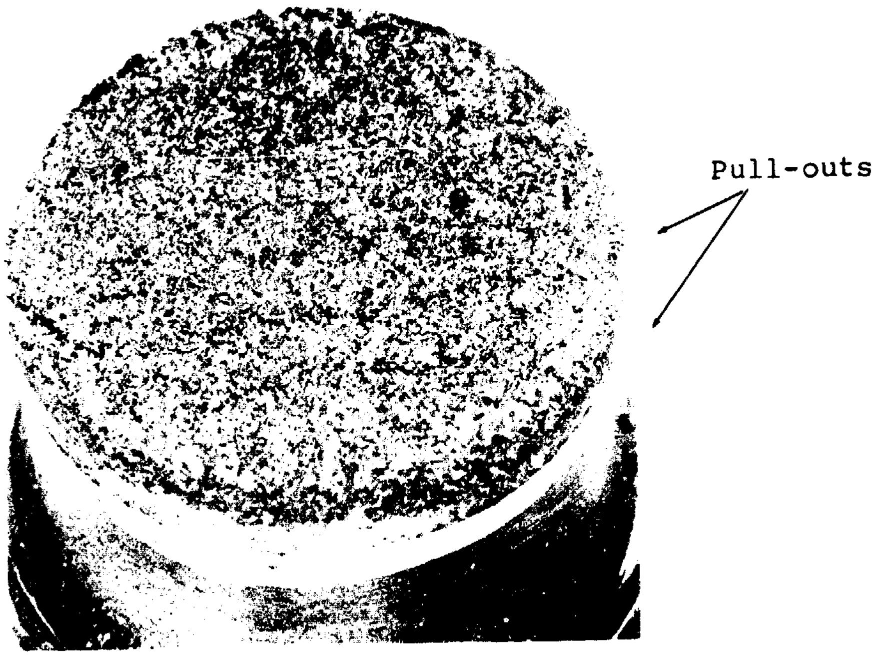


(a) Optical View (Mag.: 7X)



(b) SEM Image of Rub Area (Mag.: 100X)

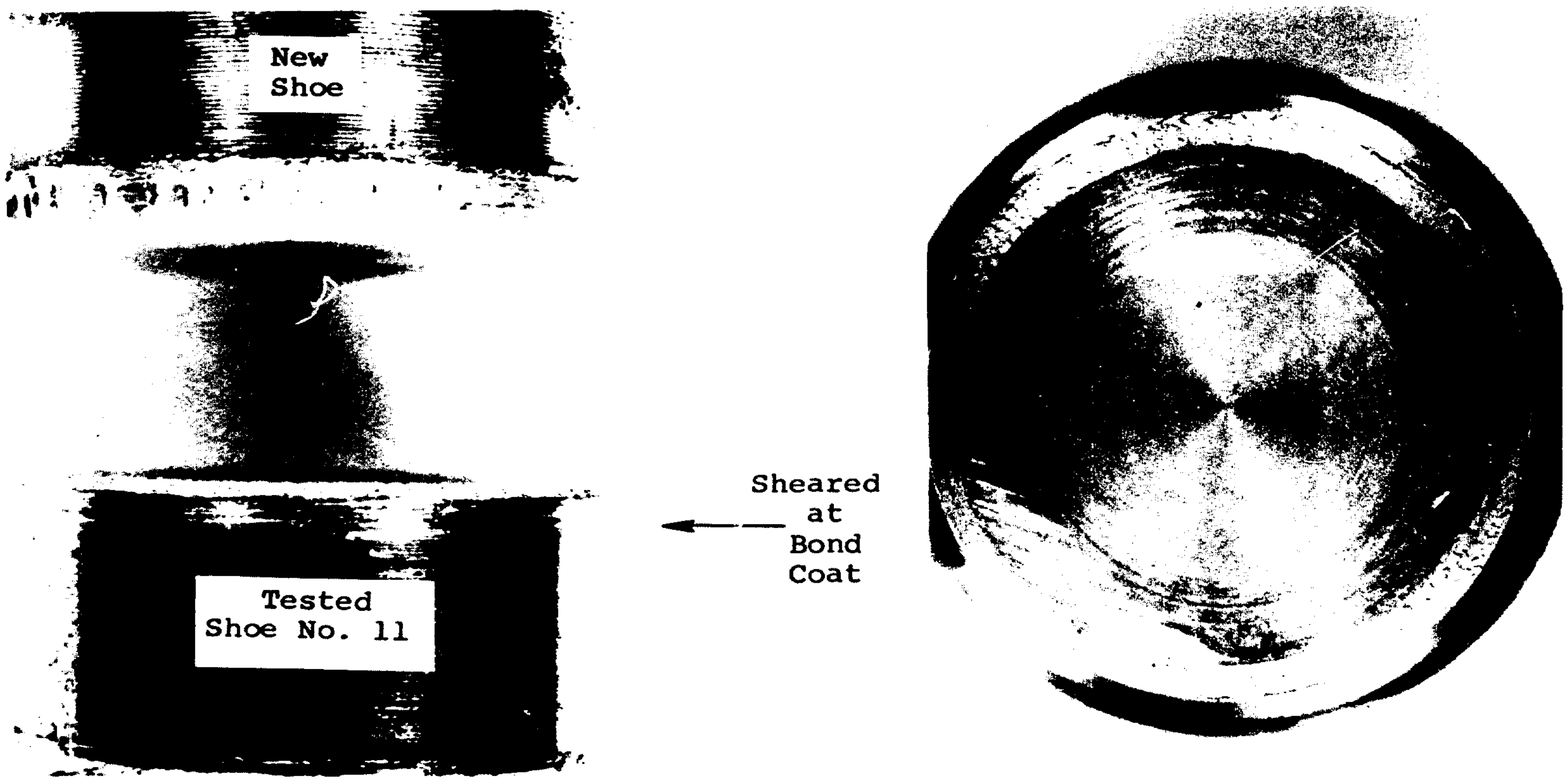
Figure 34. Typical Appearance of UCAR AB-3 [7.59-MPa (1100-psi)] High-Pressure Compressor Test Shoes After One Hour of Engine Testing



(a) Optical View (Mag.: 7X)

(b) SEM Image of Rub Area (Mag.: 100X)

Figure 35. Typical Appearance of the Feltmetal 501 High-Pressure Compressor Test Shoes after One Hour of Engine Testing



(a) Tested Shoe No. 11
Compared to New Shoe

(b) Tested Shoe No. 12

Figure 36. Appearance of Metco SF Test Shoes After One Hour of Engine Testing
(Mag.: 6X)

Figure 37. Scanning Electron Microscope Image of a Metco SF Rub Surface After One Hour of Engine Testing (Mag.: 500X)

indicating poor abradability. Titanium-alloy pickup was not detected, although previous experience with this material in the engine indicates that excessive heat generation and blade-metal transfer occurs under more severe rub conditions.

Based on these results and prior AiResearch experience, the abradability of Metco SF was rated "poor". Although bond integrity was only fair for these small test shoe samples, the bond integrity of large components coated with Metco SF is considered good (based on AiResearch production engine experience).

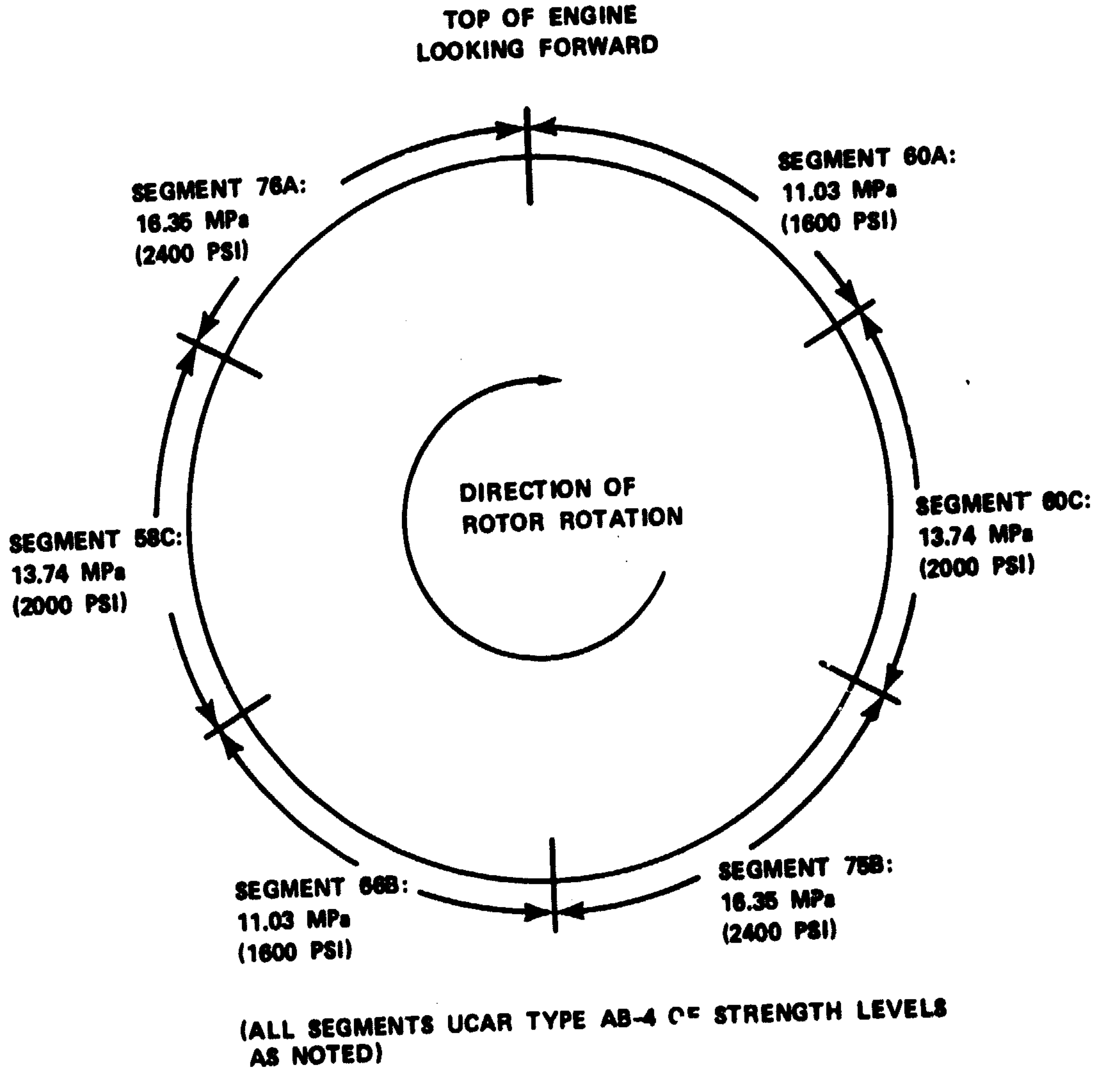
e. Metco CE2019* - This material was tested in addition to the Task I materials because it was being evaluated as an abradable coating for commerical air carriers. Prior to the completion of testing it was learned that this coating is not recommended where contact with titanium occurs. As with Metco SF, one of the two shoes sheared at the bond joint while the second shoe completed the test without shearing. Titanium was present on the rub surface indicating blade-metal transfer. The abradability and the bond integrity were rated "fair".

2. High-Pressure Turbine Shroud Segment Tests. The TFE731-3 single-stage high-pressure turbine shroud (seal) consists of six segments (60-degrees each), assembled into a ring and supported by a shroud retaining sleeve and flange. For the Interim Engine Tests, the supporting hardware was modified to accomodate shroud segments having an abradable coating thickness of 2.54 mm (0.100 inch), and a test-instrumentation clearance-measurement probe in each segment. A view of a coated segment is shown in Figure 22.

For Engine Build 1, all six high-pressure turbine shroud segments were coated with UCAR AB-4--two each of 11.03-MPa (1600-psi), 13.74-MPa (2000-psi), and 16.35-MPa (2400-psi) tensile-strength-level materials. The abradable materials were brazed to the segments with LM Nicrobraz (AMS 4777 Type) alloy. A schematic of the installation positions of the segments and a listing of the depth of the wear grooves after 23.5 hours of testing is presented in Figure 38. The incursion rate (blade-to-shroud) was measured by the clearance probes at 0.1016 mm/min (0.004 in/min).

Segments 75B and 66B, at the 5:00 and 7:00 o'clock positions, respectively, exhibited the deepest wear, with 75B [16.35 MPa (2400 psi)] the only segment showing excessive smearing. The different strength levels of the segments within the same shroud

*Metco CE2019 is a trade name of Metco, Inc.



POSITION	SEGMENT AND GROOVE DEPTH-OF-WEAR [mm (INCHES)]					
	58C	60C	66B	60A	75B	76A
LEADING EDGE	NOT MEASURED	0.203 (0.008)	0.305 (0.012)	0.076 (0.003)	0.457 (0.018)	0.000 (0.000)
TRAILING EDGE	NOT MEASURED	0.432 (0.017)	0.432 (0.017)	0.305 (0.012)	0.432 (0.017)	0.102 (0.004)

Figure 38. Schematic of the First Interim Engine Test, Build 1, High-Pressure Turbine Shroud Segment Location Showing Material Strength Level and Groove Depth-of-Wear

assembly did not affect the abradability evaluation, and heat generation and carryover from one segment to the next was not detected. The ratio of the maximum amount of material removed from the shroud assembly (maximum inside diameter) to the diameter reduction in the rotor was calculated as 4:1. This defined the wear ratio for the 16.35-MPa (2400-psi) strength-level material in the Build 1 test since this hard material removed blade-tip material during smearing. No other wear ratios were determined. The pretest and post-test appearance of the rotor blade tips are shown in Figure 39.

. six segments showed a tendency for the braze joints to separ e at the segment ends during the test. This was apparently due t lack of braze flow as shown in Figure 40. Refinements in the brazing process were made to avoid recurrence of this problem. Portions of the rubbed surfaces on three segments (one of each strength level) were examined in the SEM.

a. <u>UCAR AB-4, 11.03-MPa (1600-psi) strength level-</u> Segment 66B, 11.03-MPa (1600-psi) material, exhibited very little evidence of wear considering the depth of the grooves, 0.305 to 0.432 mm (0.012 to 0.017 inch). These grooves may have been caused by gas erosion or the material may have behaved in a truly abradable manner. The former is the most likely conclusion based on the rounded corners noted at the edges of the segment. Minor traces of blade alloy were found in the wear regions using SEM X-ray analysis. Based on the overall appearance of the rubs, the material was rated "good" from an abradability standpoint, but unsatisfactory from a gas-erosion standpoint.

b. <u>UCAR AB-4, 13.74-MPa (2000-psi) strength level-</u> Segment 60C, 13.74-MPa (2000-psi) material, was worn to a depth of between 0.203 and 0.432 mm (0.008 and 0.017 inch). Examination of these areas under the SEM disclosed the typical abrading shown in Figure 41 with traces of blade alloy found in the wear regions. Also shown in Figure 41 is the etched microstructure from a cross section taken in the segment center. Note the braze alloy flow, and that the bond integrity between the L-605 alloy substrate, and the AB-4 abradable was maintained during testing. Based on the appearance of the rub areas and the absence of heat generation, the material was given a "good" rating for abradability, and there was no evidence of gas erosion.

c. <u>UCAR AB-4, 16.35 MPa (2400-psi) strength level-</u> Segment 75B, 16.35 MPa (2400 psi) material, exhibited 0.457 mm (0.018 inch) of wear in the deepest groove and a large smear area. Figure 42 presents the smeared surface as examined under the optical microscope and the SEM. X-ray analysis disclosed that the surface of the smear region was

(a) Pretest

(b) Post-Test

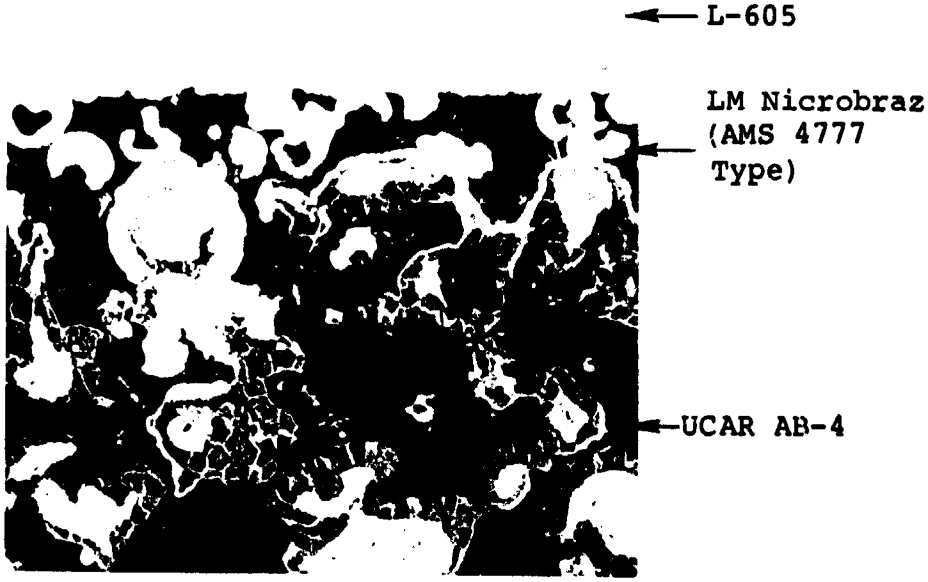
Figure 39. High-Pressure Turbine Rotor Blade Tips Before and After 23.5 Hours of the First Interim Engine Test, Build 1

(a) End View (Mag.: 6X)

(b) Kallings Etch (Mag.: 100X)

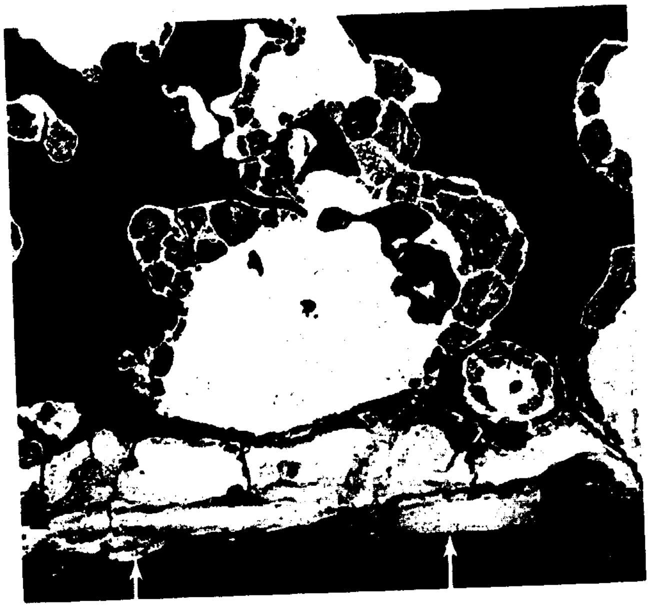
Figure 40. High-Pressure Turbine Shroud Segment 66B [UCAR AB-4, 11.03 MPa (1600 psi)] After 23.5 Hours of the First Interim Engine Test, Build 1. (Braze Failure is Shown in Left View. Separation is Typical of All Segments Tested in Build 1)

(a) SEM Image of Rub Area

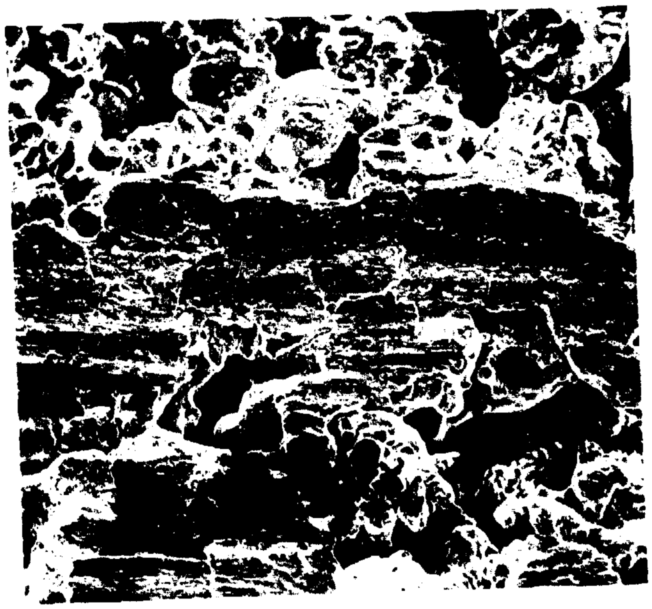


(b) Kallings Etch

Figure 41. High-Pressure Turbine Shroud Segment 60c [UCAR AB-4, 13.74 MPa (2000 psi)] After 23.5 Hours of the First Interim Engine Test, Build 1. Typical Wear Region and Cross-Section Microstructure are Shown (Mag.: 100X)



(a) Kallings Etch (Mag.: 200X)



(b) SEM Image of Rub Area (Mag.: 100X)

Figure 42. High-Pressure Turbine Shroud Segment 75B [UCAR AB-4, 16.35 MPa (2400 psi)] After 23.5 Hours of the First Interim Engine Test, Build 1

almost entirely blade alloy. Based on the smearing and heat generation, abradability was rated "poor", and there was no evidence of gas erosion.

3. Low-Pressure Turbine Shroud Tests. The TFE731-3 Engine low-pressure turbine contains three stages--each stage includes an upstream nozzle plus an integral blade-tip shroud. Each nozzle assembly was modified only to install the candidate test abradables as listed in Table I. The materials shown were run for the entire operating time of the engine build. The interaction rates were not determined for the low-pressure turbine, but are generally comparable to the rates determined for the high-pressure compressor and high-pressure turbine [0.0254 to 0.1016 mm/minute (0.001 to 0.004 inch/minute)]. All three stages of LP turbine blades are shrouded, and thus, any rub is produced by contact with the knife edges of the shrouded blade.

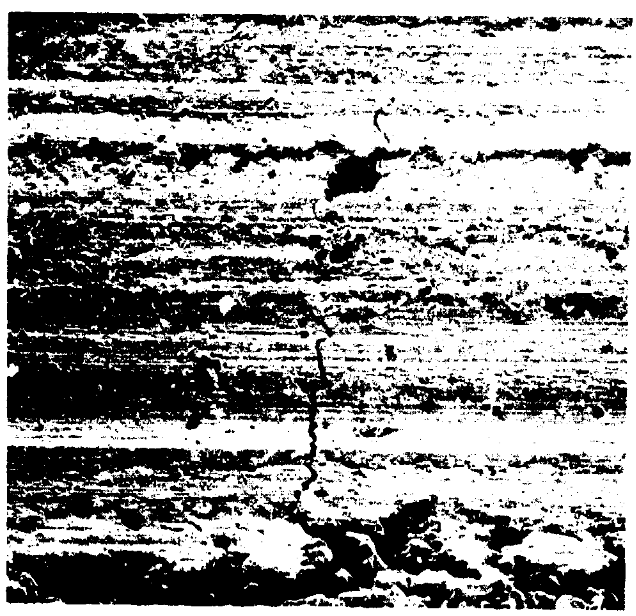
a. First-stage shroud - The first-stage shroud tested in Build 1 utilized UCAR AB-2 [8.96-MPa (1300-psi) tensile strength-level] material over the entire circumference of the shroud. The foil-backed abradable material was brazed to the Alloy 713LC* shroud using LM Nicrobraz braze alloy. The shrouded turbine blades are IN100**, and the first stage operates at a temeprature of approximately 1144°K (1600°F) and a blade-tip speed of 381 m/sec (1250 ft/sec) at the engine takeoff condition.

Visual observations after completion of 23.5 hours of testing on Build 1 indicated that the material had a tendency to smear and crush instead of fracture at particle boundaries. The depth of the grooves produced by the turbine blade knife edges ranged from zero (no contact) at the 12:00 o'clock position to 0.229 mm (0.009 inch) near the 6:00 o'clock position. The appearance of the rubbed surfaces as compared to the non-rubbed surfaces, as seen on photomicrographs from the scanning electron microscope, are shown in Figure 43. A typical cross-section microstructure, shown in Figure 44, illustrates the good braze quality, and the thin UCAR coating (proprietary) surrounding the abradable particles. The calculated wear ratio for the UCAR AB-2 in the first-stage turbine is approximately 1:1. The abradability was rated "fair" because of the materials crushing (instead of fracture) characteristic.

b. Second-stage shroud - The second-stage shroud tested in Build 1 also used foil-backed UCAR AB-2, 8.96-MPa

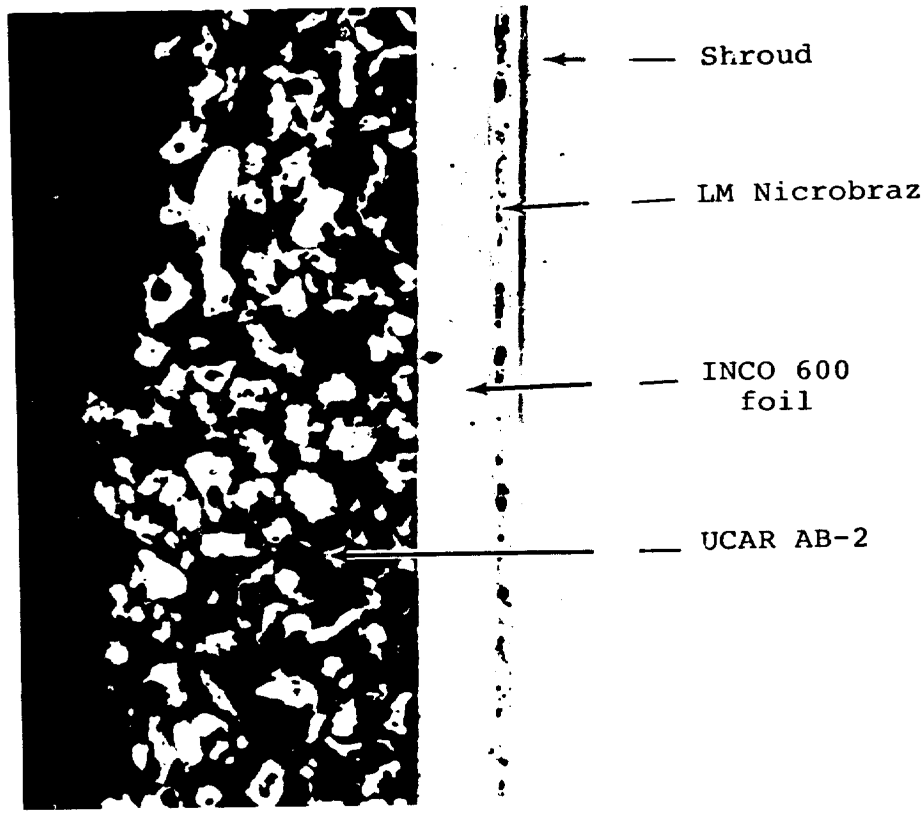
*Alloy 713LC is a registered trademark of the International Nickel Company.
**IN100 is a registered trade name of the International Nickel Company.

(a) SEM Image of No-Contact Area

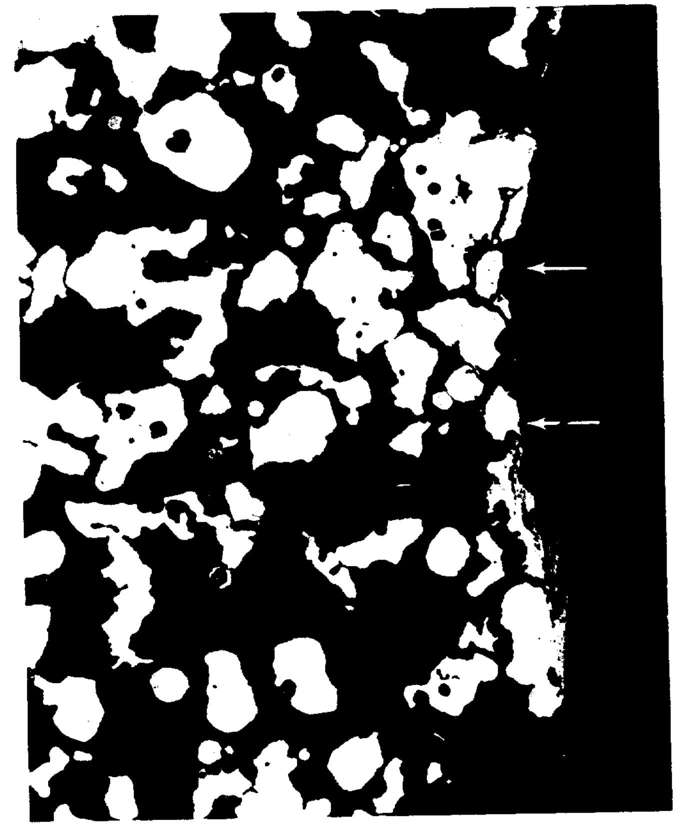


(b) SEM Image of Contact Area

Figure 43. First-Stage Low-Pressure Turbine Abradable Shroud [UCAR AB-2, 8.96 MPa (1300 psi)] After 23.5 Hours of the First Interim Engine Test, Build 1 (Mag.: 50X)



(a) As-Brazed, Unetched (Mag.: 50X)



(b) After 23.5 Hours of the First Interim Engine Test, Build 1. (Smeared, Unetched) (Mag.: 100X)

Figure 44. Typical Microstructure of the First-Stage Low-Pressure Turbine Shroud [UCAR AB-2, 8.96 MPa (1300 psi)]

(1300-psi) strength level material over the entire circumference of the shroud. The second-stage shrouded turbine blades are Alloy 713LC, and the stage operates at a maximum temperature of 1033°K (1400°F), and an approximate blade-tip speed of 412 m/sec (1350 ft/sec) at the engine takeoff condition.

Some difficulty was experienced in achieving a consistent braze over the entire shroud with the LM Nicrobraz braze alloy, and the test nozzle was rebrazed with Palniro 7* braze alloy. The cause of the braze difficulty with LM Nicrobraz on this part was not determined, but may have been due to the heavy nickel plating on the Alloy 713LC nozzle. The problem is not considered typical since other nozzles have been successfully brazed with this alloy.

During the Build 1 test (23.5 hours), a 360-degree rub was produced in the UCAR AB-2 material on the second-stage shroud with the wear depth ranging from 0.127 to 0.254 mm (0.005 to 0.010 inch). The appearance of the rub was similar to that observed in the first-stage except that only a portion of the wear grooves were smeared as shown by the SEM examination (see Figure 45). The surface condition of the lightly smeared region is also shown in this figure. Traces of blade alloy were detected on the rubbed surfaces. The wear ratio was calculated to be 10:1, considerably better than the 1:1 observed for the same material on the first-stage. This improvement was the result of very little blade material being removed due to the lower temperature, and therefore higher strength of the blade alloy. The overall abradability in this application was rated "fair-to-good".

c. <u>Third-stage shroud</u> - Two strength levels of UCAR AB-2--5.52 MPa (800 psi) and 8.96 MPa (1300 psi)--were tested in the third-stage turbine shroud in Build 1. Approximately two-thirds of the shroud contained the higher strength material, with the lower strength material in the remaining one-third. The foil-backed abradable material was brazed onto the HS-31** alloy shroud casting with LM Nicrobraz braze alloy. The shrouded turbine blades were Alloy 713LC. The stage operates at a temperature of 922°K (1200°F) and a blade-tip speed of approximately 436 m/sec (1430 ft/sec) at the takeoff condition.

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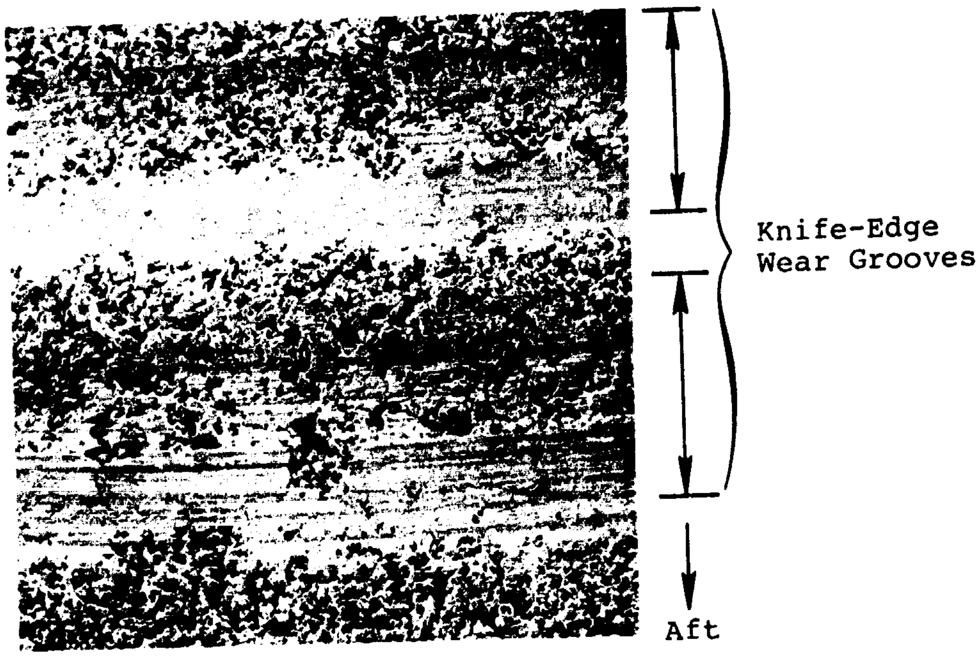
*Palniro 7 is a registered trade name of Western Gold and Platinum Company.

**HS-31 is a registered trade name of the Union Carbide Corporation.



(a) SEM Image of Rub Area (Mag.: 10X)

(b) SEM Image of Rub Area (Mag.: 100X)
(Lightly Smeared Region)

Figure 45. Second-Stage Low-Pressure Turbine Abradable Shroud [UCAR AB-2, 8.96 MPa (1300 psi)] After 23.5 Hours of the First Interim Engine Test, Build 1

A 360-degree rub was produced on the two abradable coatings during Build 1 testing. Figure 46 presents the appearance of the rubs on both materials. Note that the lower strength material had less tendency to smear than the higher strength material. The wear depths ranged from 0.1016 to 0.2032 mm (0.004 to 0.008 inch) in the 8.96-MPa (1300-psi) material, and from 0.0762 to 0.254 mm (0.003 to 0.010 inch) in the 5.52-MPa (800-psi) material. The calculated wear ratio of the two materials combined was 7:1, slightly below the ratio measured on the second stage. Since the wear of the blades will be determined by the hardest abradable, this is not an acceptable method to determine the wear ratio of the softer material.

The appearance of the rub on the 8.96-MPa (1300-psi) strength material was similar to that observed on the first and second stages. The heavy smear was again predominant with small regions of light rub. The wear regions of the 5.52-MPa (800-psi) strength material are shown in Figure 47 where typical areas of heavy and light smearing are shown. These are similar to comparable regions of the 8.96-MPa (1300-psi) strength material on the first and second stages. X-ray analysis of both strength levels of AB-2 detected traces of blade metal in the heavily rubbed regions. The overall abradability of the 8.96-MPa (1300-psi) strength AB-2 was rated "fair" to "good" while the 5.52-MPa (800-psi) material was rated good.

Engine Build 2

The same TFE731-3 Engine used in Build 1 was reassembled using the abradables selected for the Build 2 testing. The assembly techniques duplicated those of Build 1. The engine was installed in the same test cell and subjected to 27 test cycles of 1 hour each. The Build 2 test cycle, Figure 48, was similiar to the Build 1 cycle except for an increase of 10 minutes in the cruise test point (95-percent low-pressure rotor speed), and a decrease of 10 minutes at final idle. The routine 2.5-hour shutdown after each cycle was not required since the high-pressure compressor abradable test shoes were not tested in Build 2, and the required changeover time was eliminated.

1. High-pressure Turbine Shroud Tests. The high-pressure turbine test shroud for Build 2 included three segments (180 degrees) of UCAR AB-4 13.74-MPa (2000-psi) strength-level material and three segments (180 degrees) of Bradelloy 500* material. Two of the AB-4 segments were new with the remaining one a segment

*Bradelloy is a registered trade name of The General Electric Co.

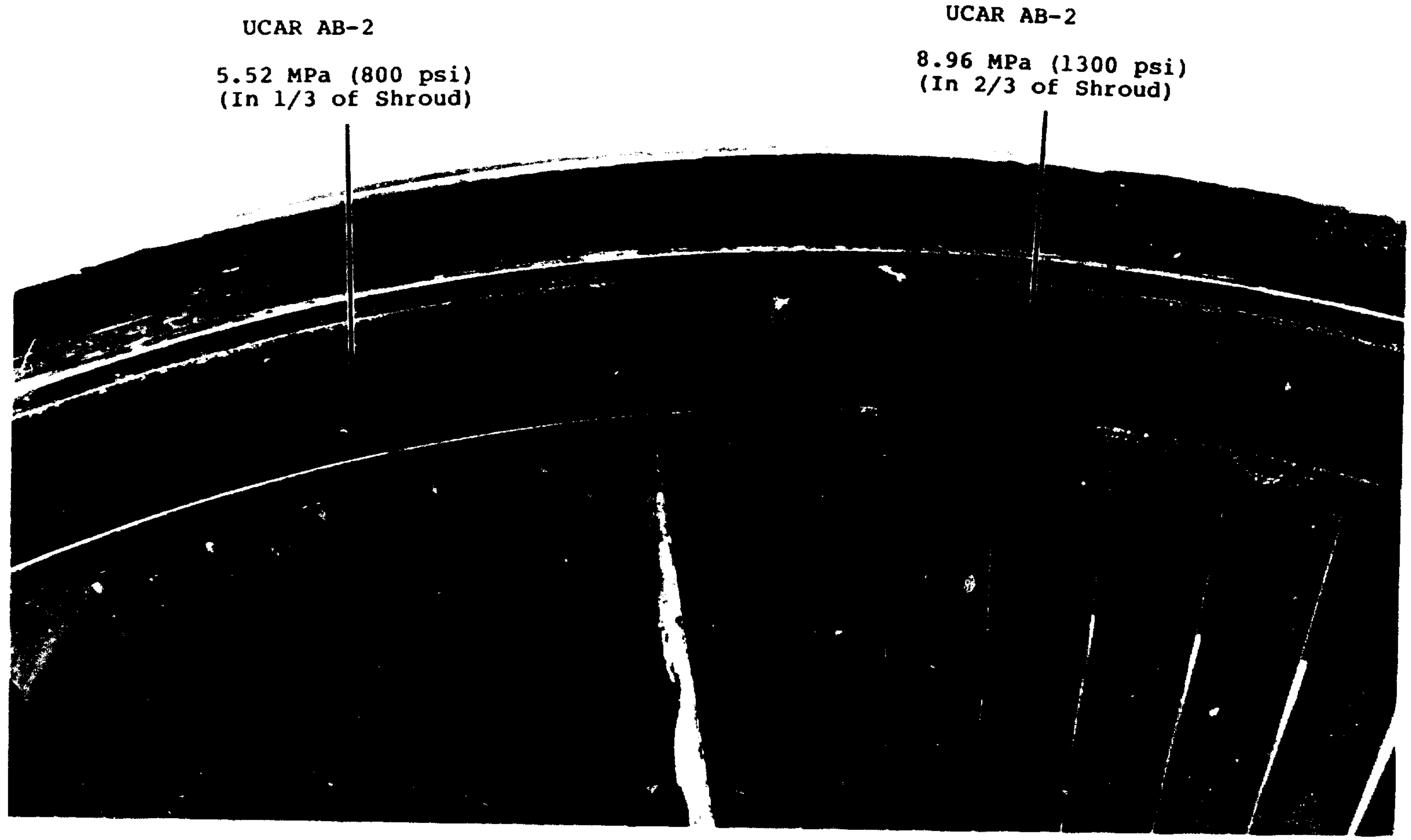


Figure 46. Third-Stage Low-Pressure Turbine Abradable Shroud After 23.5 Hours of the First Interim Engine Test, Build 1

(a) SEM Image of Rub Area (Mag.: 100X)
(Light Smear Region)

(b) SEM Image of Rub Area (Mag.: 50X)
(Heavy Smear Region)

Figure 47. Third-Stage Low-Pressure Turbine Abradable Shroud [UCAR AB-1, 5.52 MPa (800 psi)] After 23.5 Hours of the First Interim Engine Test, Build 1

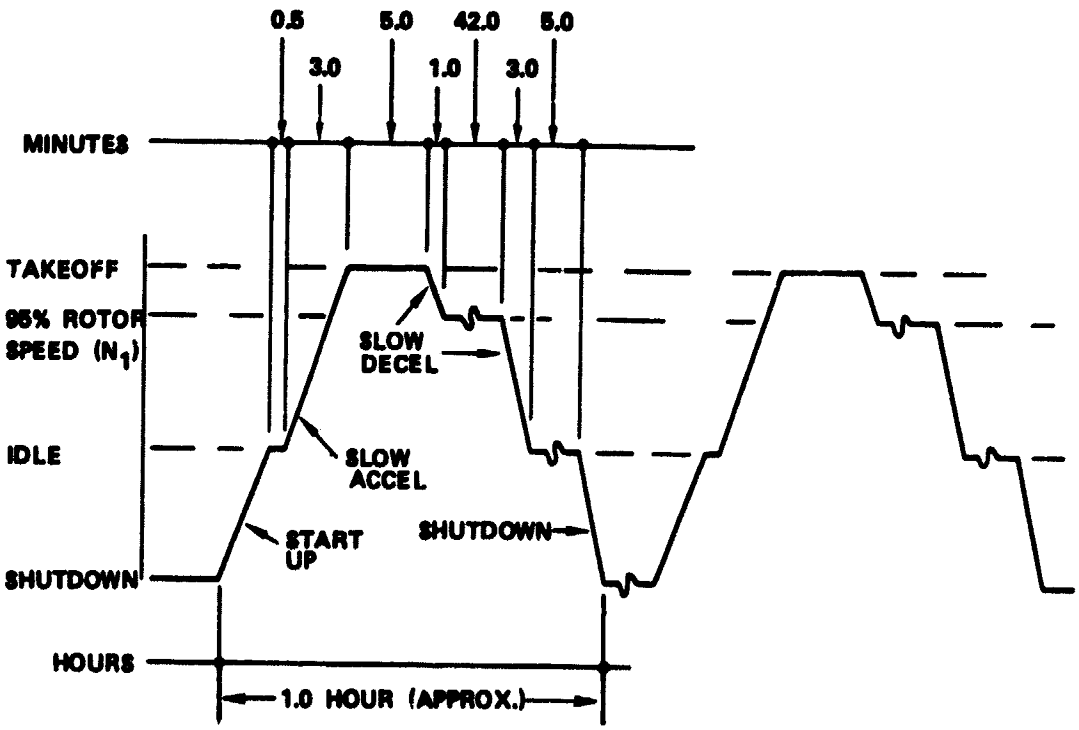


Figure 48. Typical Test Cycle for the First Task II Interim Engine Test (Build 2)

previously tested in Build 1 (58C). This segment was included to produce a component that could be tested for 50 hours. Bradelloy 500 was identified by the Program Plan as the baseline, high-temperature, turbine abradable material. Bradelloy segments were procured from Howmet Corporation and were fabricated by processes proprietary to Howmet and the General Electric Company. Figure 49 presents a schematic of the installation positions of the six segments and the wear produced during the Build 2 testing. A rub was experienced on all shrouds except the used UCAR AB-4 shroud.

Results of the evaluation of the UCAR AB-4 were similar to those obtained from Build 1. The lack of braze flow was again evident. Figure 50 shows the extent to which the end of Segment 67A lifted during the engine run. Of significance was the amount of wear on the lifted portion of the AB-4 (it had not chipped or spalled) which indicated the good abradability characteristics of the material. Transfer of blade alloy to the wear regions of Segment 67A was not detected. Wear did not occur on the used Segment 58C, as the diameter of this segment was approximately 0.254-mm (0.010-inch) larger than the other segments. This used segment did not exhibit any sign of gas erosion despite 50.5 hours of engine testing.

The abradability of Bradelloy 500 was rated poor compared to UCAR AB-4. There was no measurable shroud wear after the engine test, even though the turbine blade squealer tips were nearly worn off [up to 0.279-mm (0.0112-inch) blade-tip wear]. The smeared regions of the abradable material showed a slight build-up of material due to blade-alloy transfer. Figure 51 shows the appearance of a smeared area both optically and, as examined under the SEM. Figure 52 presents the cross-section microstructure of the Bradelloy material in an unrubbed region and in a region of smearing. Evidence of heat generation is present in the view presenting the smeared region.

2. Low-Pressure Turbine Shroud Tests.

a. First-stage shroud - The first-stage low-pressure turbine shroud tested in Build 2 consisted of 180 degrees of 8.96-MPa (1300-psi) UCAR AB-2 and 180 degrees of Hastelloy-X* honeycomb [1.587-mm (0.0625-inch) cell size, and 0.0762- to 0.1016-mm (0.003- to 0.004-inch) foil thickness]. These materials were brazed to the shroud with LM Nicrobraz braze alloy.

Evaluation of UCAR AB-2, after Build 2 testing, showed results entirely representative of those obtained in Build 1, where this

*Hastelloy-X is a registered trade name of the Union Carbide Corporation.

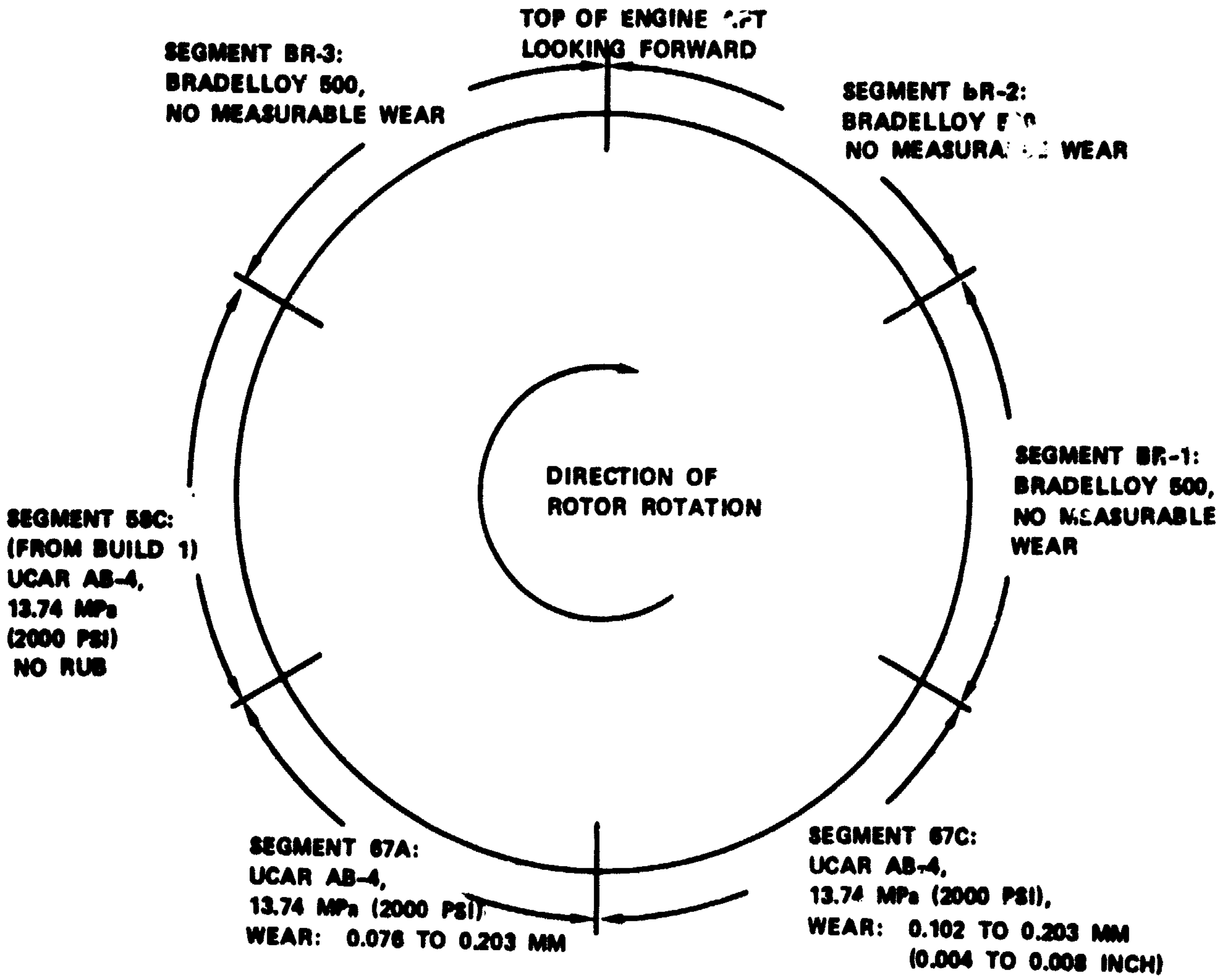
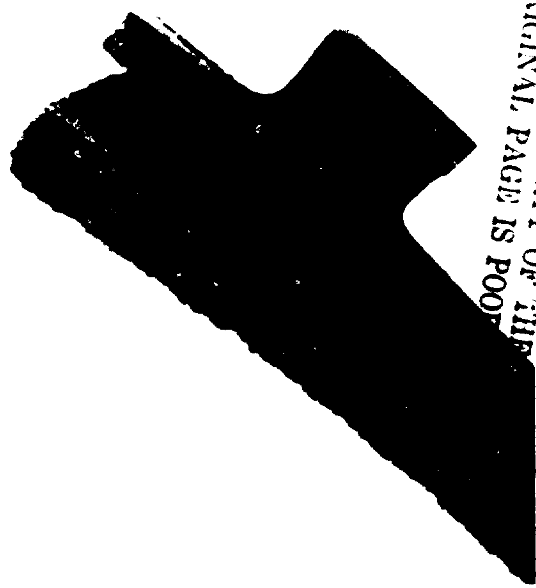
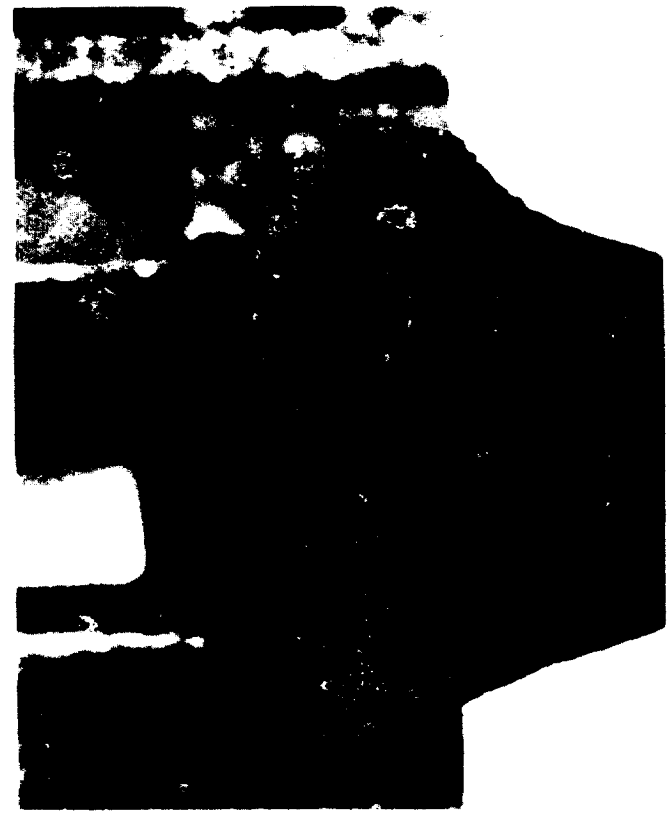


Figure 49. Schematic of the First Interim Engine Test (Build 2) High-Pressure Turbine Shroud Segment Locations Showing Material Identification and Measured Groove Depth-of-Wear



(a) Side View



(b) End View

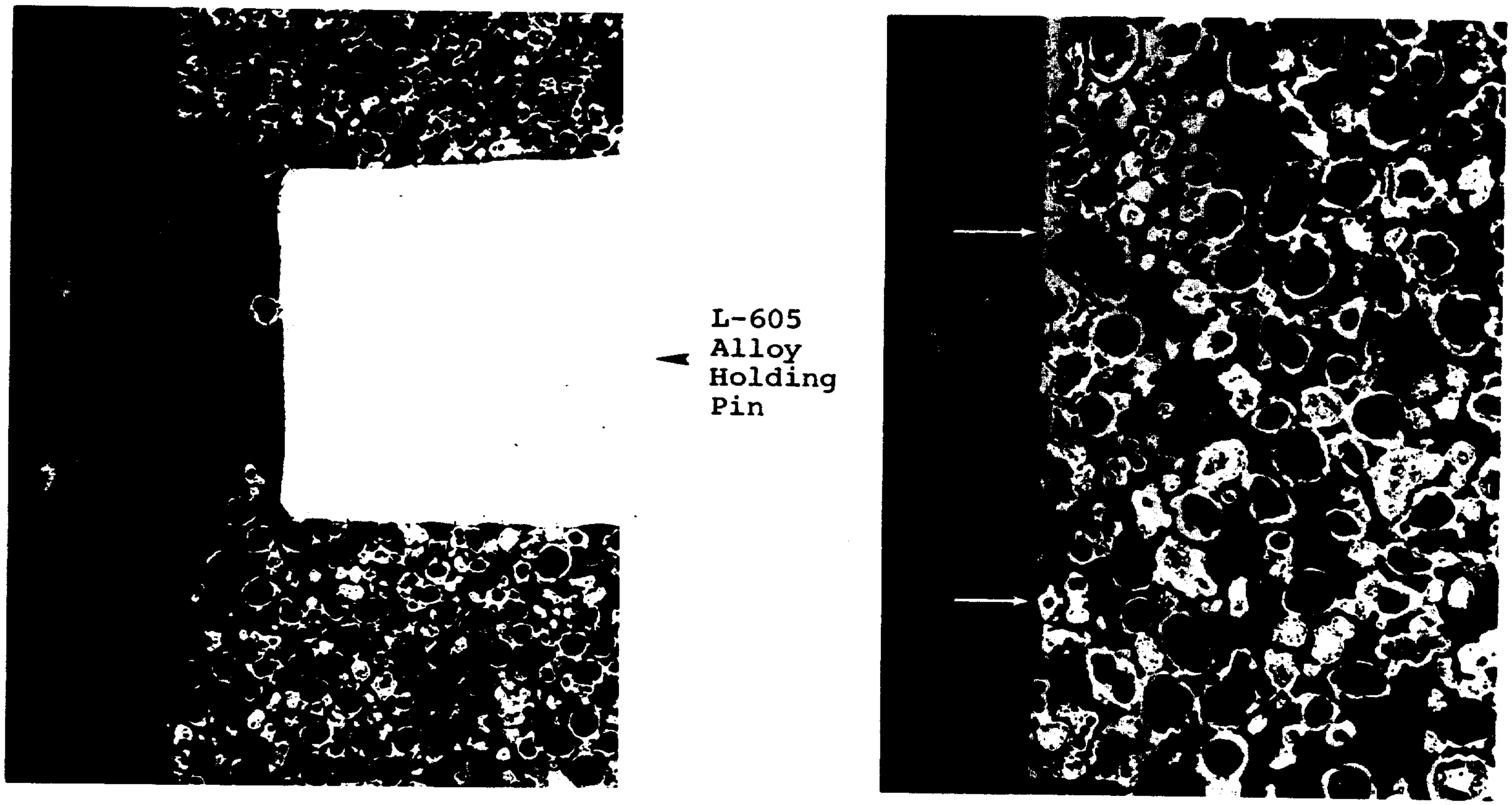
Figure 50. High-Pressure Turbine Shroud Segment 67A From the First Interim Engine Test, Build 2, Showing the Opening of the Braze Joint that Occurred During Testing (Mag.: 2X)

(a) Optical View of Rub Area (Mag.: 4X)
(Arrows Show Pins That Held the Material in Place)

(b) SEM Image of Rub Area (Mag.: 100X)

Figure 51. High-Pressure Turbine Shroud Segment BR-1 (Bradelloy 500) Showing One of the Smeared Regions Present After the First Interim Engine Test, Build 2

C-2



(a) Unrubbed Region (Mag.: 50X)

(b) Rubbed Region (Mag.: 100X)
(See Arrows)

Figure 52. High-Pressure Turbine Shroud Segment BR-1 (Bradelloy 500) Showing Microstructures Near the Surfaces of an Unrubbed and a Rubbed Region After the First Interim Engine Test, Build 2

material was used on the complete shroud (360 degrees). Evaluation of the Build 2 results confirmed the "fair" abradability rating and the 1:1 wear ratio established in Build 1.

The wear depths of the Hastelloy-X Honeycomb ranged from no contact to 0.1778 mm (0.007 inch) near the AB-2/Honeycomb joint. Optical and SEM views of the Honeycomb after engine testing are shown in Figure 53. It is evident from this figure that excessive braze alloy was utilized (note the unflowed braze powder and wicking on the foil). The knife-edge rub produced smearing and folding of the foils, which can also be seen in Figure 53. A wear ratio for the honeycomb could not be calculated, since the rotor-blade wear was influenced by the harder UCAR AB-2. Blade-alloy transfer was not evident on the honeycomb. The overall abradability of the Hastelloy-X Honeycomb was rated "good".

b. Second-stage shroud - For Build 2, Solabrade* was used for the entire (360 degrees) second-stage low-pressure turbine shroud. Solabrade is a foil-type, corrugated abradable material designed to avoid the braze wicking which is sometimes encountered at the nodes when brazing honeycomb. The type selected for evaluation was fabricated from 0.0508- to 0.0762-mm (0.002-to 0.003-inch) thick Hastelloy-X foil corrugated with a pitch of 7.87 per cm (20 per inch), and brazed to a perforated 0.127-mm (0.005-inch) thick INCONEL 600 backing strip. This assembly was then brazed to the turbine shroud with an AMS 4777 type braze alloy.

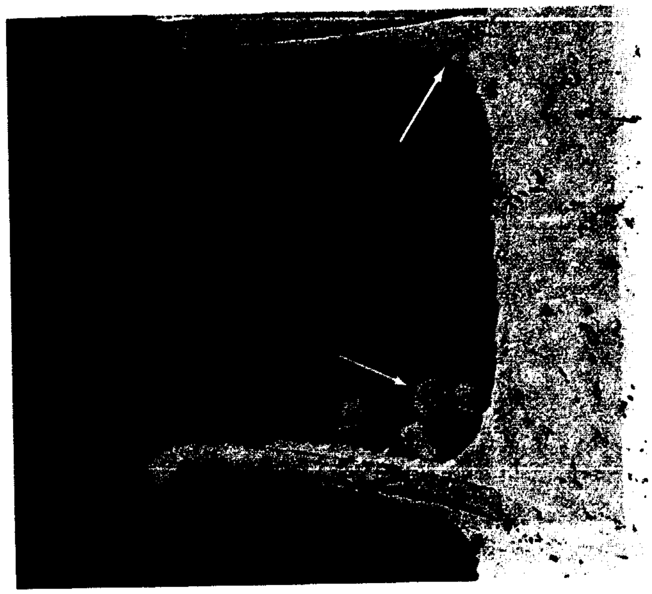
Approximately 180 degrees of this shroud was rubbed by the rotor-blade knife edges during the Build 2 test. The wear depth was measured at 0.3048 mm (0.012 inch) on the aft groove, and 0.2794 mm (0.011 inch) on the forward groove at the point of severest rub. Enlarged views of this material after testing are shown in Figure 54. It appeared that crushing and smearing occurred with very little heat generation. SEM examination disclosed a trace of the Alloy 713LC blade alloy in the smeared regions. The wear ratio was calculated at 23:1, which is considered excellent, and the overall abradability was rated "good".

c. Third-stage shroud - Feltmetal 522** was used for coating the entire (360 degrees) third-stage low-pressure turbine shroud in Build 2. This material, which has the composition of HS-188*** alloy and a tensile strength of approximately 13.1 MPa (1900 psi), was brazed directly to the shroud without any backing strip.

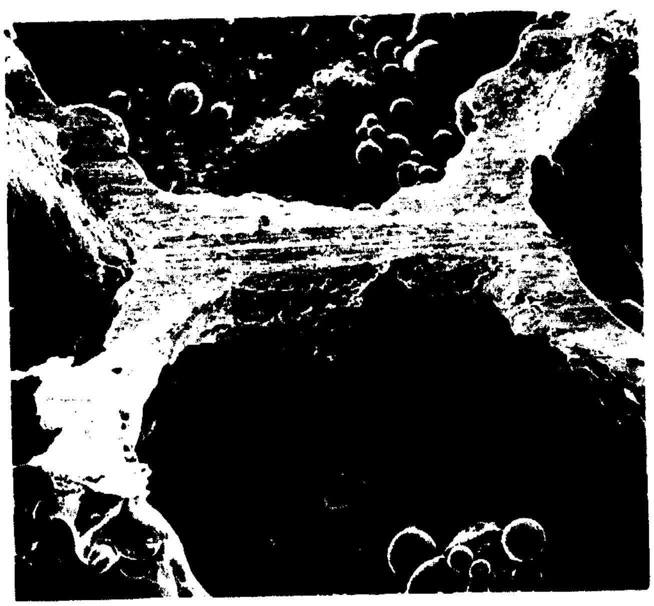
*Solabrade is the trade name of a material developed by the Solar Division of International Harvester and marketed by Kelsey-Hayes Company.

**Feltmetal 522 and 501 are trade names of materials supplied by the Technetics Division of the Brunswick Corporation.

***HS-188 is a registered trade name of the Cabot Corporation.



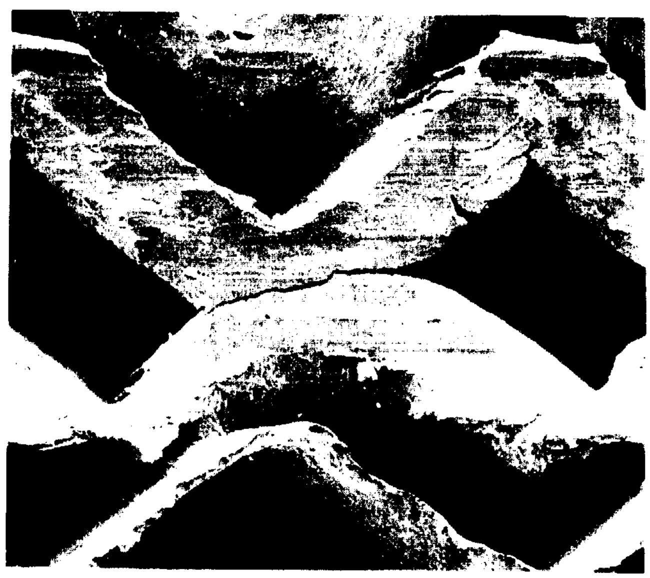
(a) Optical Cross-Section View
(Note Braze Wicking, Excess Braze, and Folding of Foils)



(b) SEM Image of Rub Area

Figure 53. Appearance of the Hastelloy-X Honeycomb First-Stage Low-Pressure Turbine Shroud After the First Interim Engine Test, Build 2 (Mag.: 50X)

(a) Optical Cross-Section View



(b) SEM Image of Rub Area

Figure 54. Appearance of the Solabrade Second-Stage Low-Pressure Turbine Shroud After the First Interim Engine Test, Build 2 (Mag.: 50X)

Approximately 300 degrees of rub was produced on this component during Build 2 testing. The rub generated excessive heat, and 0.5588 mm (0.022 inch) was removed from the rotor diameter, resulting in a wear ratio less than 1:1. Blade-metal pickup was evident on the rubbed surfaces. The wear grooves and the appearance of a severely smeared region are shown in Figure 55. This figure also illustrates the tendency for the material to crack and pull-out when excessive heat is generated. The overall abradability of Feltmetal 522 was rated "poor".

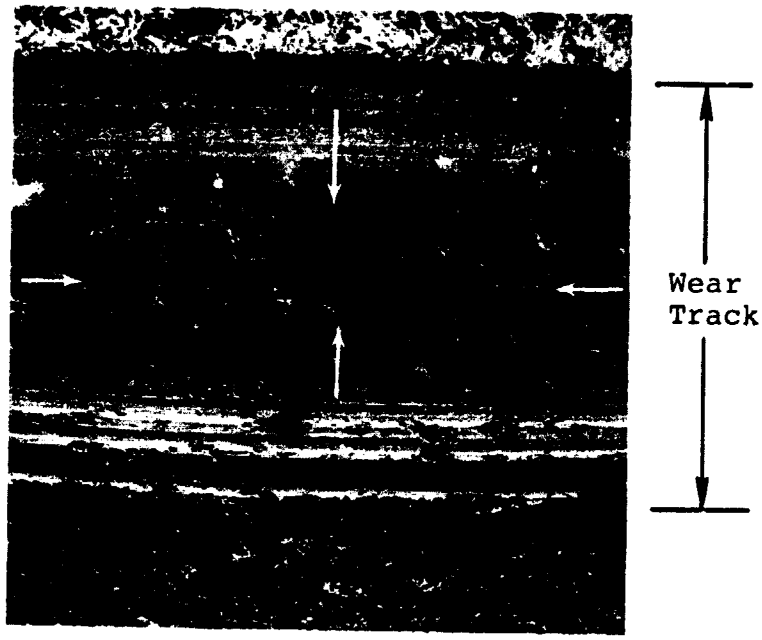
Summary of the First Interim Engine Test Results

A summary of the evaluations of the high-pressure compressor abradable materials is presented in Table IX. The 8.27-MPa (1200-psi) strength level UCAR AB-1 appeared to be the best material tested. Feltmetal 501 was considered acceptable, but the tendency for metal-fiber pull-out may limit its service life.

A summary of the evaluations of the high-pressure turbine abradable materials is given in Table X. The 13.74-MPa (2000-psi) strength level UCAR AB-4 was considered the best material from this testing.

A summary of the evaluations of the low-pressure turbine abradables is given in Table XI. The following candidates are considered acceptable for the designated LPT stages:

First-Stage:	Honeycomb, UCAR AB-2 [8.96 MPa (1300 psi)]
Second-Stage:	Solabrade, UCAR AB-2 [8.96 MPa (1300 psi)]
Third-Stage:	UCAR AB-2 [5.52 MPa (800 psi)]



(a) SEM Image of Aft Track Rub Area (Mag.: 20X)
(Arrows Show Pull-Out Region)

(b) SEM Image of Aft Track Rub Area (Mag.: 100X)
(Heavy Smearing)

Figure 55. Appearance of the Feltmetal 522 Third-Stage Low-Pressure Turbine Shroud After the First Interim Engine Test, Build 2

TABLE IX. SUMMARY OF HIGH-PRESSURE COMPRESSOR ABRADABLE SEAL MATERIAL EVALUATIONS FROM THE FIRST INTERIM ENGINE TEST, BUILD 1

Material	Strength, MPa (psi)	Attachment Method	Abradability [a]	Blade-Metal Pick-Up	Bond Integrity	Remarks
UCAR AB-1	8.27 (1200)	Direct sinter	Good	No	Good	--
UCAR AB-1 (Oxidized)	~8.27 (~1200)	Direct sinter	Good	No	Good	Similar to non-oxidized
UCAR AB-3	7.58 (1100)	Direct sinter	Fair	Yes	Good	--
UCAR AB-3	5.52 (800)	Direct sinter	Fair	Yes	Good	--
Feltmetal 501	--	Braze	Fair	No	Good	--
Metco SF	--	Thermospray	Poor	Questionable	Fair	--
METCO CE2019	--	Thermospray	Fair	Yes	Fair	--

[a] Impeller surface speed equals 548.6 m/sec (1800 ft/sec) at test shoe contact point; interaction rate of approximately 0.0254 mm/minute (0.001 inch/minute); approximately 700°K (800°F)

TABLE X. SUMMARY OF HIGH-PRESSURE TURBINE SHROUD ABRADABLE SEAL MATERIALS FROM THE FIRST INTERIM ENGINE TEST, BUILDS 1 AND 2

Material	Engine Build	Strength MPa (psi)	Attachment Method	Abradability [a]	Blade-Metal Pick-Up	Bond Integrity	Wear Ratio [b]	Remarks
UCAR AB-4	1	11.03 (1600)	Braze	Good	Trace	Poor	4:1	Gas erosion
UCAR AB-4	1 & 2	13.74 (2000)	Braze	Good	Trace	Good	4:1	--
UCAR AB-4	1	16.35 (2400)	Braze	Poor	Yes	Poor	4:1	Heat generation
Bradelloy 500	2	24.32 (3600)	Braze & sinter	Very poor	Yes	Good	c	Heat generation

[a] 427 m/sec (1400 ft/sec) rotor tip speed; 0.0508 mm/minute (0.002 inch/minute) interaction rate; 1311°K (1900°F)

[b] Maximum amount of shroud material removed (diameter inside wear track)/reduction of rotor diameter

[c] Not determined; blade squealer tip was completely lost with no measurable depth-of-rub in the abradable material

TABLE XI. SUMMARY OF LOW-PRESSURE TURBINE ABRADABLE SEAL MATERIAL EVALUATIONS FROM THE FIRST INTERIM ENGINE TEST, BUILDS 1 AND 2

Material	Engine Build	Turbine Stage	Strength, MPa (psi) or Alloy	Attachment Method	Abradability [a]	Blade-Metal Pick-Up	Bond Integrity	Wear Ratio [b]	Remarks
UCAR AB-2	1 & 2	1	8.96 (1300)	Braze	Fair	Yes	Good	~1:1	--
Honeycomb	2	1	Hastelloy-X	Braze	Fair-to-Good	Yes	Good	d	--
UCAR AB-2	1	2	8.96 (1300)	Braze	Fair-to-Good	Yes	Good	10:1	--
Solabrade	2	2	Hastelloy-X	Braze	Good	Trace	Good	23:1	--
UCAR AB-2	1	3	5.52 (800)	Braze	Good	Yes	Good	7:1 [c]	--
UCAR AB-2	1	3	8.96 (1300)	Braze	Fair-to-Good	Yes	Good	7:1 [c]	--
Feltmetal 522	2	3	HS-188	Braze	Poor	Yes	Good	0.6:1	Heat Generation

[a] Operating conditions:

First-Stage - 380 m/sec (1250 ft/sec) rotor tip speed; 1144°K (1600°F)
Second-Stage - 412 m/sec (1350 ft/sec) rotor tip speed; 1033°K (1400°F)
Third-Stage - 436 m/sec (1430 ft/sec) rotor tip speed; 922°K (1200°F)
Interaction rate not determined. Estimated at 0.0254 to 0.1016 mm/min (0.001 to 0.004 inch/min)

[b] Maximum amount of shroud material removed (diameter inside wear track)/reduction of rotor diameter

[c] On same third-stage shroud. Wear ratio determined by hardest material

[d] Wear ratio could not be determined. On same shroud with UCAR AB-2

Second Interim Engine Test -- Task IIA

Before the Interim Engine Test of Task II was completed, Union Carbide notified AiResearch that they had decided to drop metallic abradable coatings from their future business plans. They planned to sell that phase of their business, if a suitable buyer could be found, but there was no guarantee of the future availability of their products. Since Union Carbide was the prime subcontractor on both Task I and II, this unexpected decision jeopordized the completion of the MATE Project 2.

After discussing this development with the NASA-MATE management team, it was decided to continue the project with the addition of a second 50-hour Interim Engine Test as a new task, Task IIA. For this second engine screening test, abradable candidates were to be selected from those currently available with proven laboratory feasibility within the coating industry--no effort was made to invent a new abradable. Thermal-spray coatings were emphasized for this test due to the economics of both application and refurbishment, and the sensitivity of business jets to front-end costs.

Similar to the First Interim Engine Test, the second 50-hour test was divided into two engine builds to provide operating time for all the various abradable candidates. The build criteria for each of the two builds was as similar to the first test as practicable for comparison purposes.

A listing of the candidate materials for the Second Interim Engine Test is given in Table VIII. The majority of the materials tested were thermospray coatings which were emphasized in the candidate selection process.

After the Second Interim Engine Test was completed, Union Carbide announed that they had found a buyer for their abradable activity. The Turbine Support Division (TSD) of Chromalloy American Corporation purchased all rights to both metallic and ceramic abradables from UCAR. They plan to develop and market abradables through a newly formed branch of TSD called Chromalloy-Porous Materials Technology located in Dallas, Texas.

Engine Build 3

1. High-Pressure Compressor Shroud Tests. High-pressure compressor gas-path seal tests were conducted on four candidate materials in Build 3 of the Second Interim Engine Test. The test setup and procedure (using replaceable shoes installed in the high-pressure compressor shroud) were similar to the First Interim Test. Eight INCONEL 718 shoes were coated with the four abradable materials (two shoes per material), and tested for one hour each

to the schedule shown in Figure 48. When an abradable coated shoe was not being tested, a dummy shoe with a recessed face was installed to maintain compressor performance.

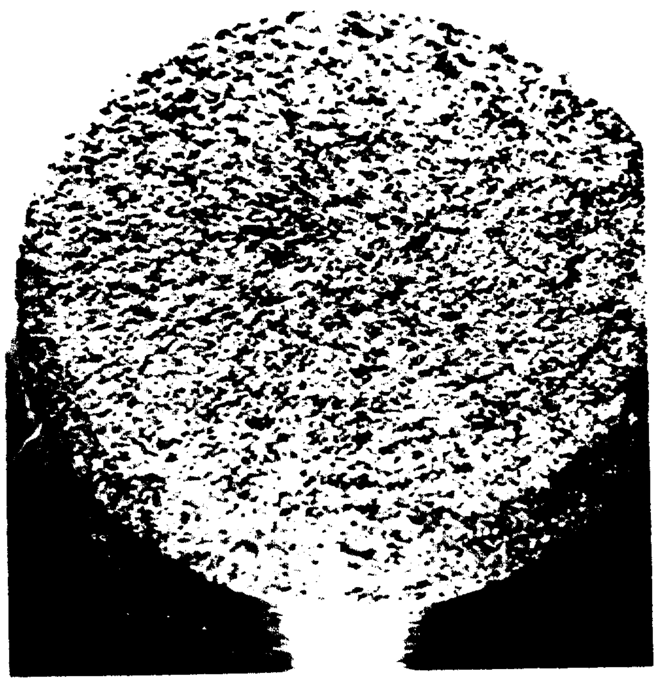
a. Brunswick Feltmetal 515B* - This metal-fiber material has the nominal composition of Hastelloy-X for the fibers and a density of approximately 19 percent of solid Hastelloy-X. The test material was brazed to the shoe with LM Nicrobraz braze alloy. The appearance of the material before and after the [illegible]our test is shown in Figure 56 (Note the roughness of [illegible] tested surface with regions of pull-out.) Figure 57 presents views of the material microstructure and the rubbed surface. X-ray analysis in the SEM of the rubbed surface showed evidence of blade-metal transfer, but no measureable wear was found on the blades. The abradability of Feltmetal 515B was judged "poor" due to the blade-metal transfer and the tendency for fiber pull-out.

b. Metco T310-10** - This abradable material has a nominal composition of 57-percent aluminum, 35-percent graphite, and 8-percent silicon. After applying a 0.127-mm (0.005-inch) bond coat to the test shoes, the abradable material was thermosprayed to a thickness of 2.032 mm (0.080 inch), followed by machining to the proper dimension for engine testing. Figure 58 shows the appearances of one of the shoes before and after testing. The coating sheared off below the rub surface at the bond joint on both shoes tested, even though the bond joint was recessed below the shear-loading plane to avoid this problem (see Figure 59), and no measurable wear was detected on the impeller blades. Additional analysis was not performed on the Metco T310-10 material which was rated "poor" due to its lack of shear strength.

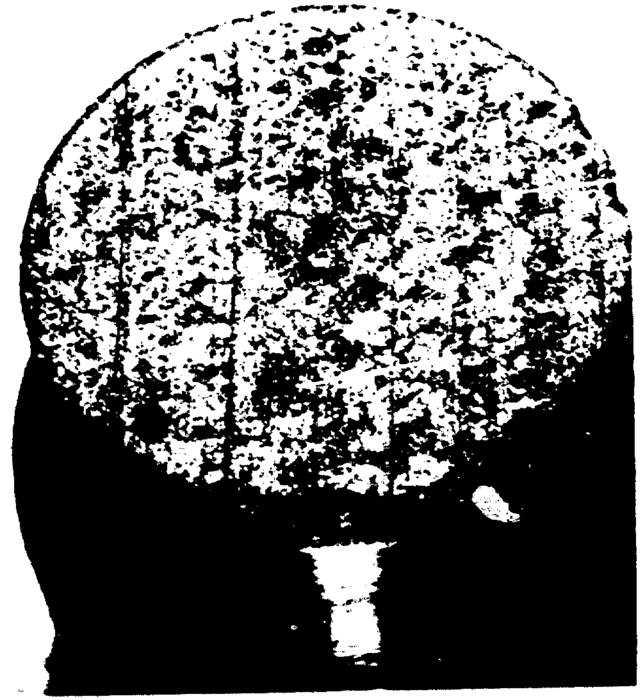
c. Metco T301-10 - The nominal composition of this material is 14-percent chromium, 8-percent iron, 5.5-percent boron nitride, 3.5-percent aluminum, and 69-percent nickel. The abradable was thermal-sprayed directly onto the test shoe, and machined to the proper height prior to testing. One of the shoes is shown before and after testing in Figure 60. The appearance of the rub is good with little evidence of smearing or heat generation. The microstructure and the SEM image of the rubbed surface are presented in Figure 61. X-ray analysis of the rubbed surface in the SEM showed just a trace of blade metal, although there was no measurable wear of the impeller blade. The abradability of

*Feltmetal 515B is a trade name of the Technetics Division of Brunswick Corporation.

**Metco T301-10 is a trade name of Metco, Inc.

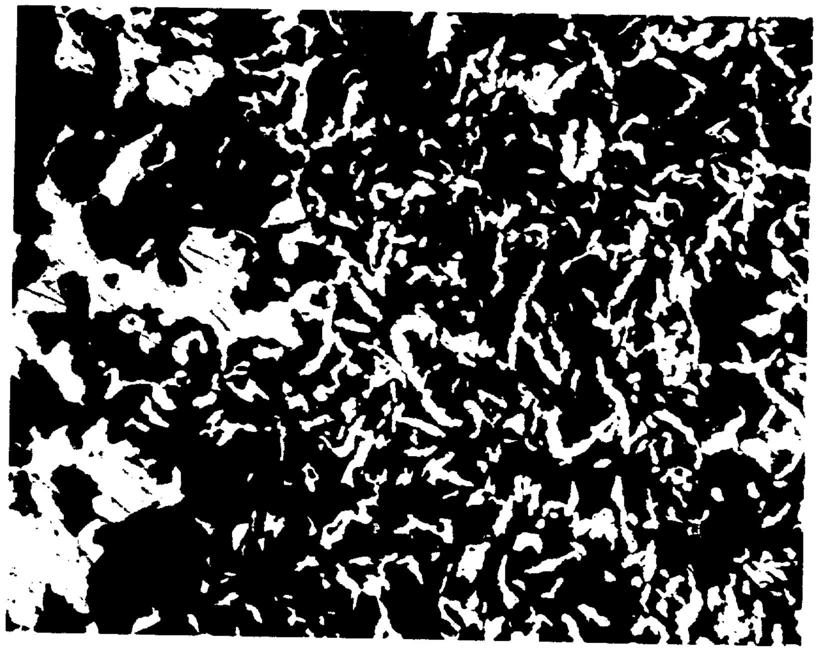


Optical View Before Testing



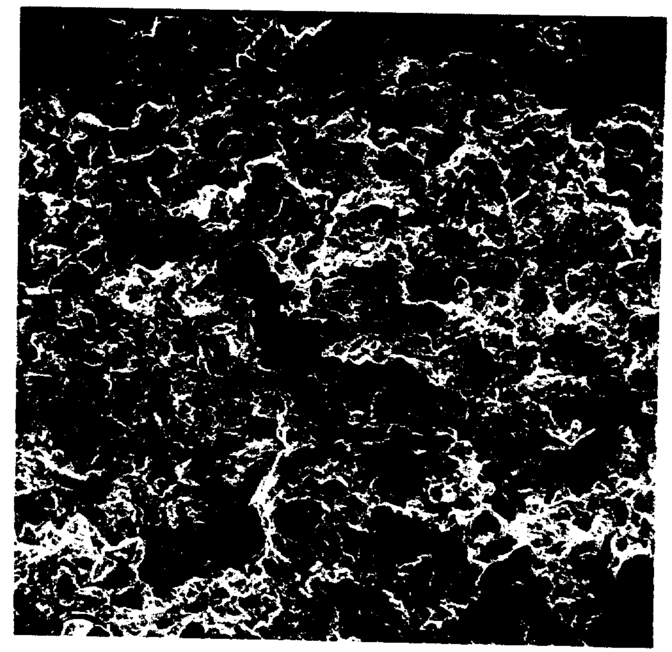
Optical View After Testing
(Arrows Indicate Pull-Outs)

Figure 56. Typical Appearance of a Feltmetal 515B High-Pressure Compressor Test Shoe Before and After One Hour of Engine Testing in the Second Interim Engine Test, Build 3 (Mag.: 7X)



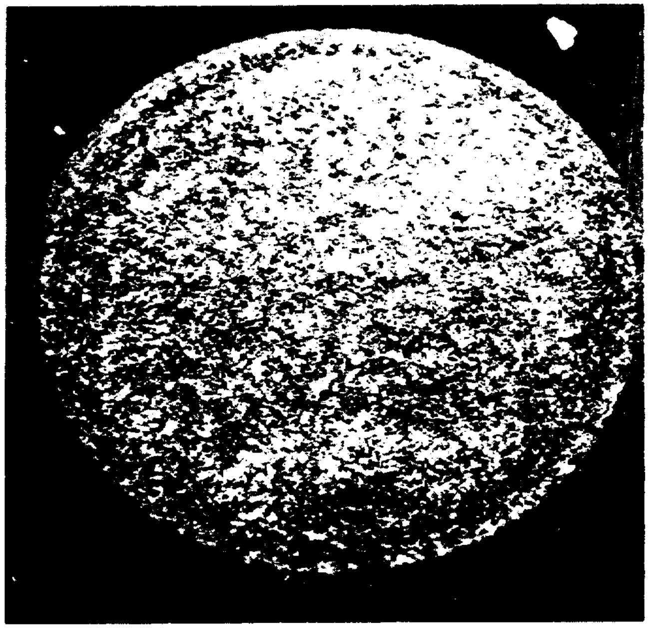
Braze Wicking | Feltmetal 515B

Microstructure



SEM Image of Rub Area

Figure 57. Microstructure and Appearance of a Feltmetal 515B High-Pressure Compressor Test Shoe After One Hour of Engine Testing in the Second Interim Engine Test, Build 3 (Mag.: 100X)



Optical View Before Testing

Optical View After Testing

Figure 58. Appearance of a Metco T310-10 High-Pressure Compressor Test Shoe Before and After One Hour of Engine Testing in the Second Interim Engine Test, Build 3 (Mag.: 7X)

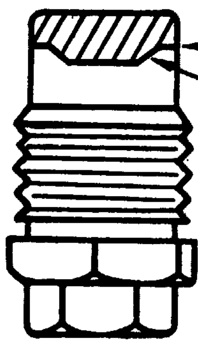
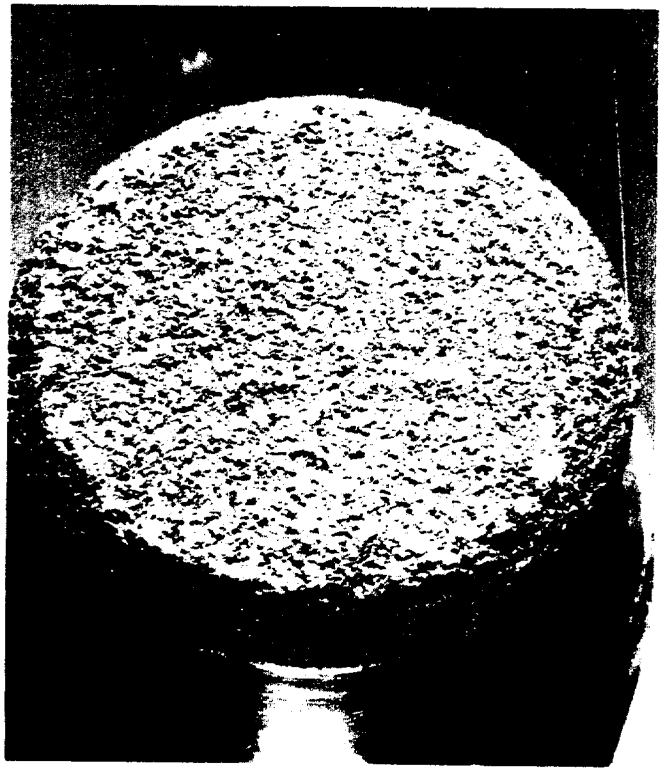
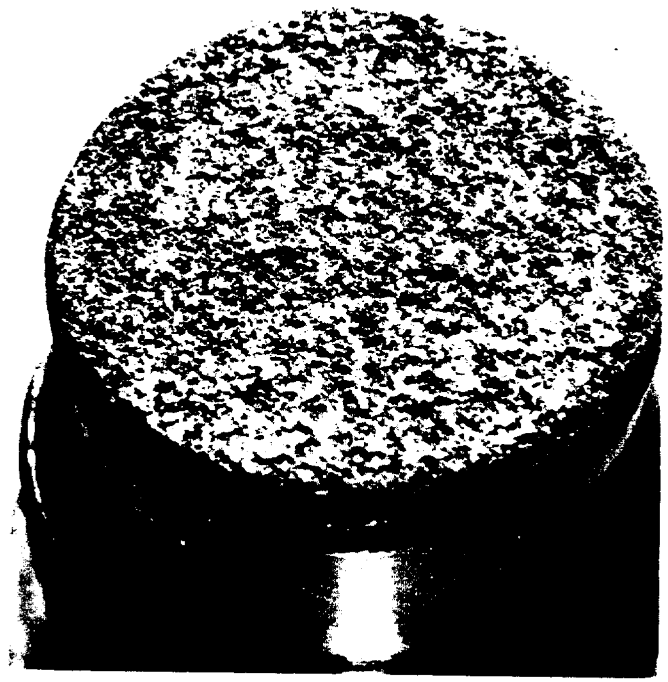


Figure 59. High-Pressure Compressor Test Shoe Showing Recessed Bond Joint

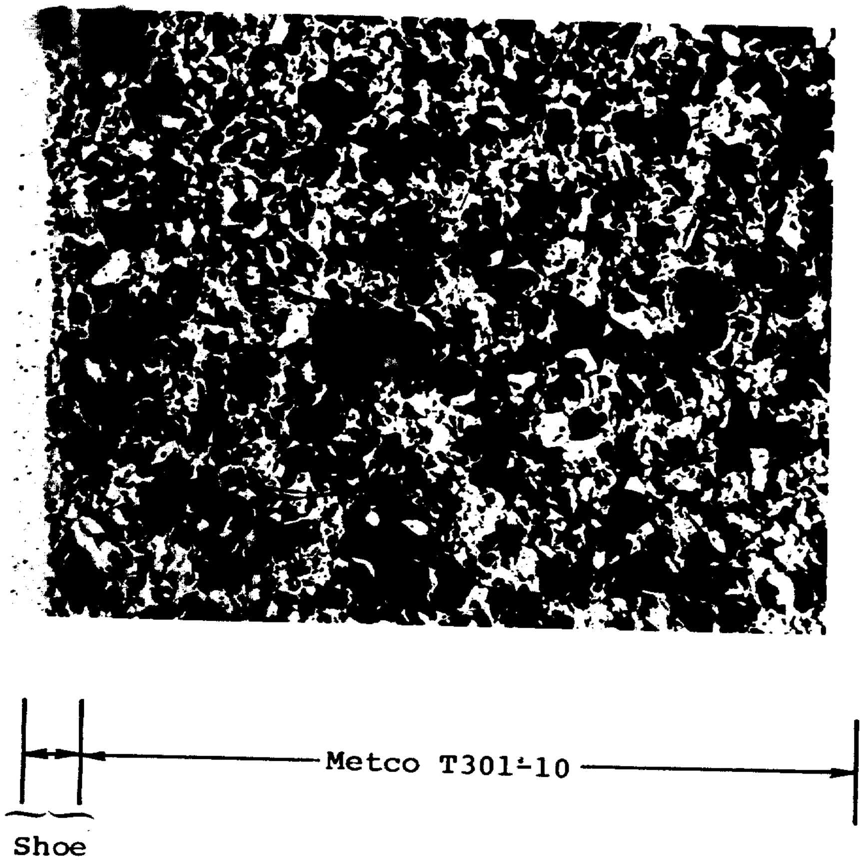


Optical View Before Testing

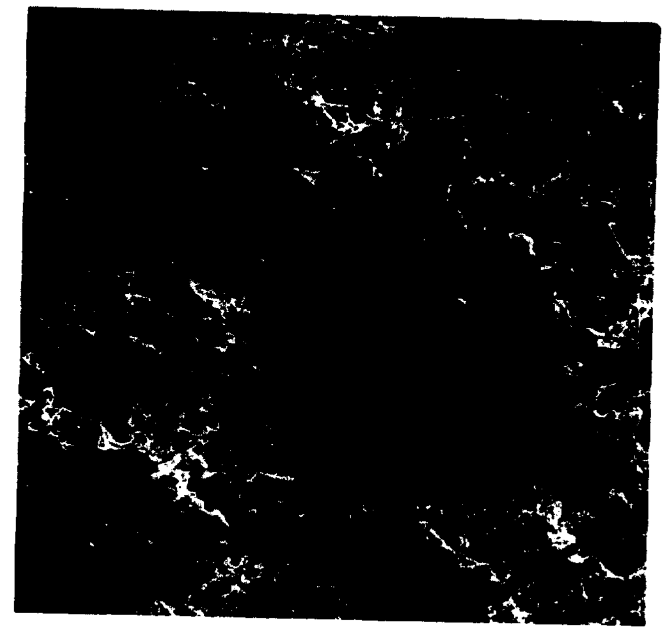


Optical View After Testing

Figure 60. Appearance of a Metco T301-10 High-Pressure Compressor Test Shoe Before and After One Hour of Engine Testing in the Second Interim Engine Test, Build 3 (Mag.: 7X)



(a) Microstructure (Mag.: 50X)



(b) SEM Image of Rub Surface (Mag.: 100X)

Figure 61. Microstructure and Appearance of Metco T301-10 High-Pressure Compressor Test Shoe After One Hour of Engine Testing in the Second Interim Engine Test, Build 3

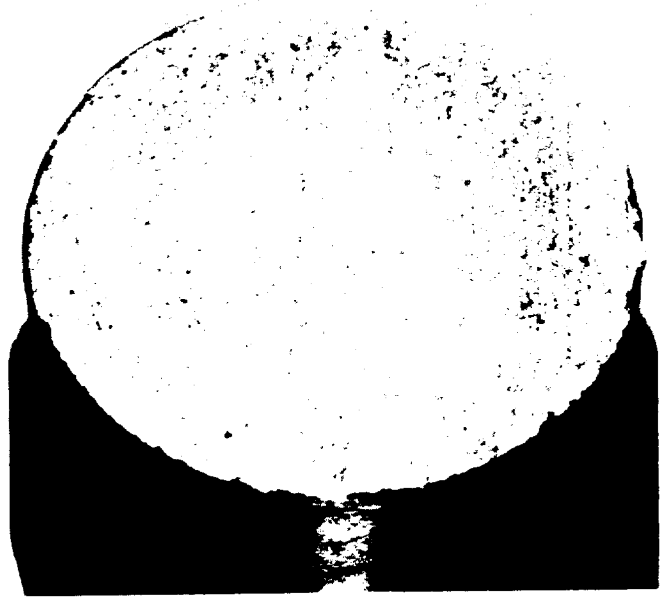
Metco T301-10 was rated "fair-to-good". This material would have been rated higher except for the trace of blade-metal transfer.

d. Metco P601-10* - The nominal composition of this powder material is 60-percent alloy (containing 88-percent aluminum and 12-percent silicon) and 40-percent Metco 600* polyester. Approximately 2.00 mm (0.080 inch) was plasma-sprayed onto the two test shoes over a bond coat of Metco P443-10* and then machined to proper height for engine testing. Figure 62 presents the rubbed surfaces of both tested shoes. Note that the streaks across one of the test shoe samples is not evident on the other. These streaks were found to contain traces of the titanium blade-metal alloy, while the adjacent rubbed area outside the streak did not. Figure 63 shows SEM images in and out of a rub streak. No measurable wear was detected on the impeller blades. The abradability of Metco P601-10 was rated "fair to good". This material would have been rated higher had the isolated blade-metal transfer not occurred.

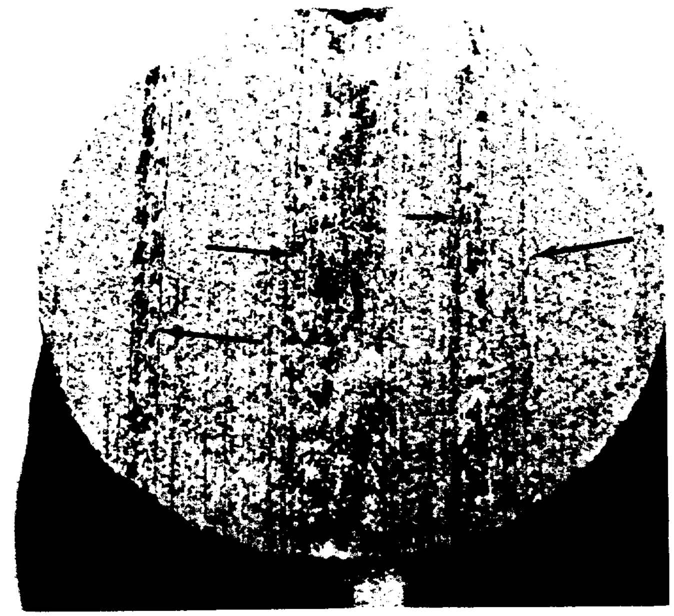
e. Metco P601-10 static-oxidation tests - Metco recommended a maximum operating temperature of 616°K (650°F) for the Metco P610-10 abradable to avoid excessive oxidation of the polyester. Due to the previous history of this coating at AiResearch with its reputation as a "good" abradable, and in recognition of the approximate 700°K (800°F) operating environment of the high-pressure compressor, constant-temperature static-oxidation tests were run for 100 hours on test specimens at several temperatures between 579°K and 755°K (600°F and 900°F). Following this exposure, the specimens were examined for loss of polyester. Figure 64 shows microstructures of the material as applied, and after 100 hours at 700°K (800°F). Note the similarity of appearance and the presence of the polyester material after the exposure. This test provided a preliminary indication that Metco P601-10 can be used up to temperatures of 700°K (800°F) and above without degradation of the microstructure.

2. High-Pressure Turbine Shroud Segment Tests. Four candidate abradable high-pressure turbine shroud materials, as listed in Table II, were assembled and tested in the Second Interim Engine Test, Build 3. The test shroud segments were positioned for this testing as shown in Figure 65. It was intended that all of these candidate materials be tested for the full 50 hours scheduled for the Second Interim Engine Test. However, as discussed below, inspection after the 25 hours of testing of Build 3 showed that several pieces of the Brunsbond ceramic and Metco

*Metco P601-10, Metco 600, and Metco P443-10 are trade names of Metco, Inc.

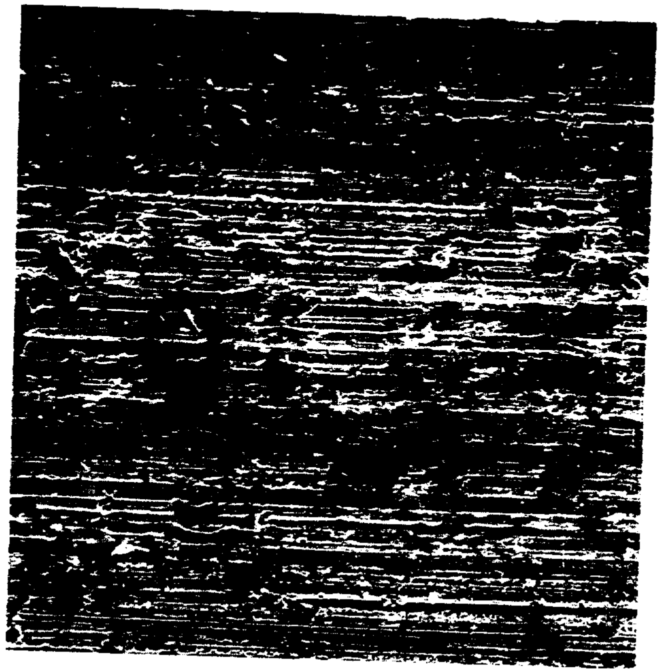


(a) Optical View of Test Shoe Sample No. 4

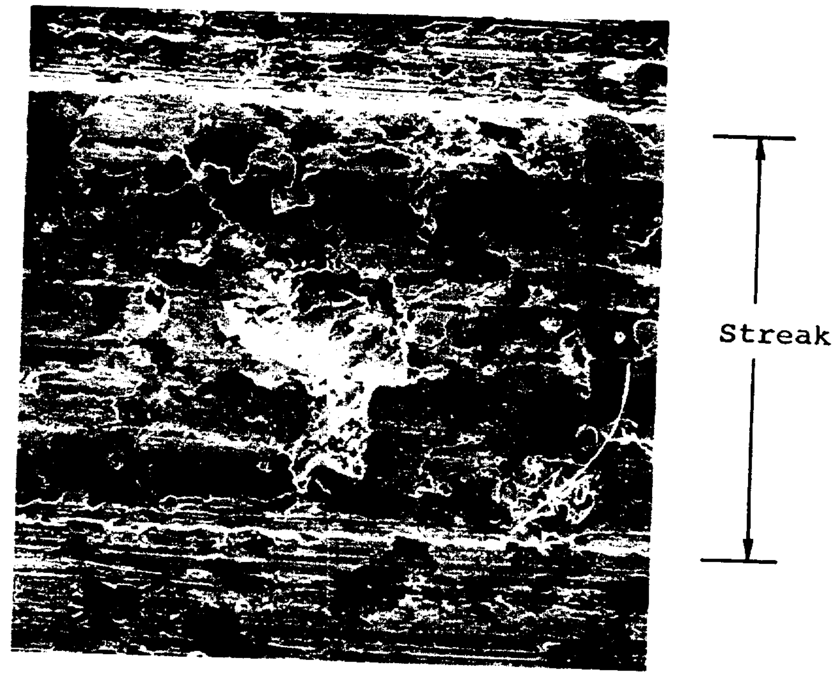


(b) Optical View of Test Shoe Sample No. 5 (Arrows Show Streaks Which Contain Traces of Blade-Metal)

Figure 62. Appearance of Metco P601-10 High-Pressure Compressor Test Shoes After One Hour of Engine Testing in the Second Interim Engine Test, Build 3 (Mag.: 7X)

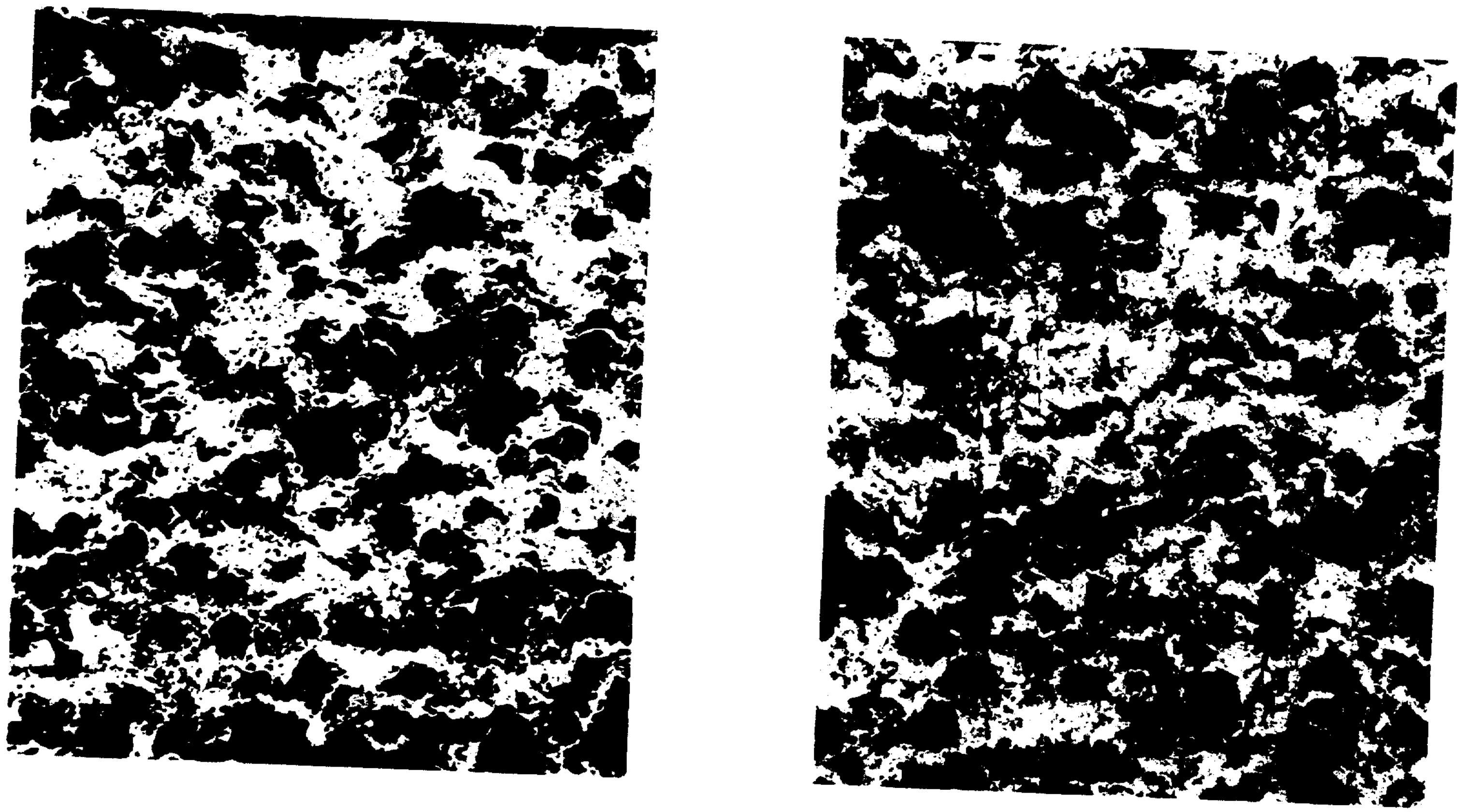


(a) SEM Image of Rubbed Region Outside Streak



(b) SEM Image of Streak

Figure 63. SEM Images of Metco P601-10 High-Pressure Compressor Test Shoes After One Hour of Engine Testing in Build 3 (The "Streak" Contains Blade-Metal While the Adjacent Regions Do Not) (Mag.: 100X)



(a) As-Applied

(b) After 100 Hours at 700° K (800° F)

Figure 64. Microstructures of Metco P601-10 As-Applied and After 100-Hours Static Oxidation (The Dark Regions are Polyester) (Mag.: 100X)

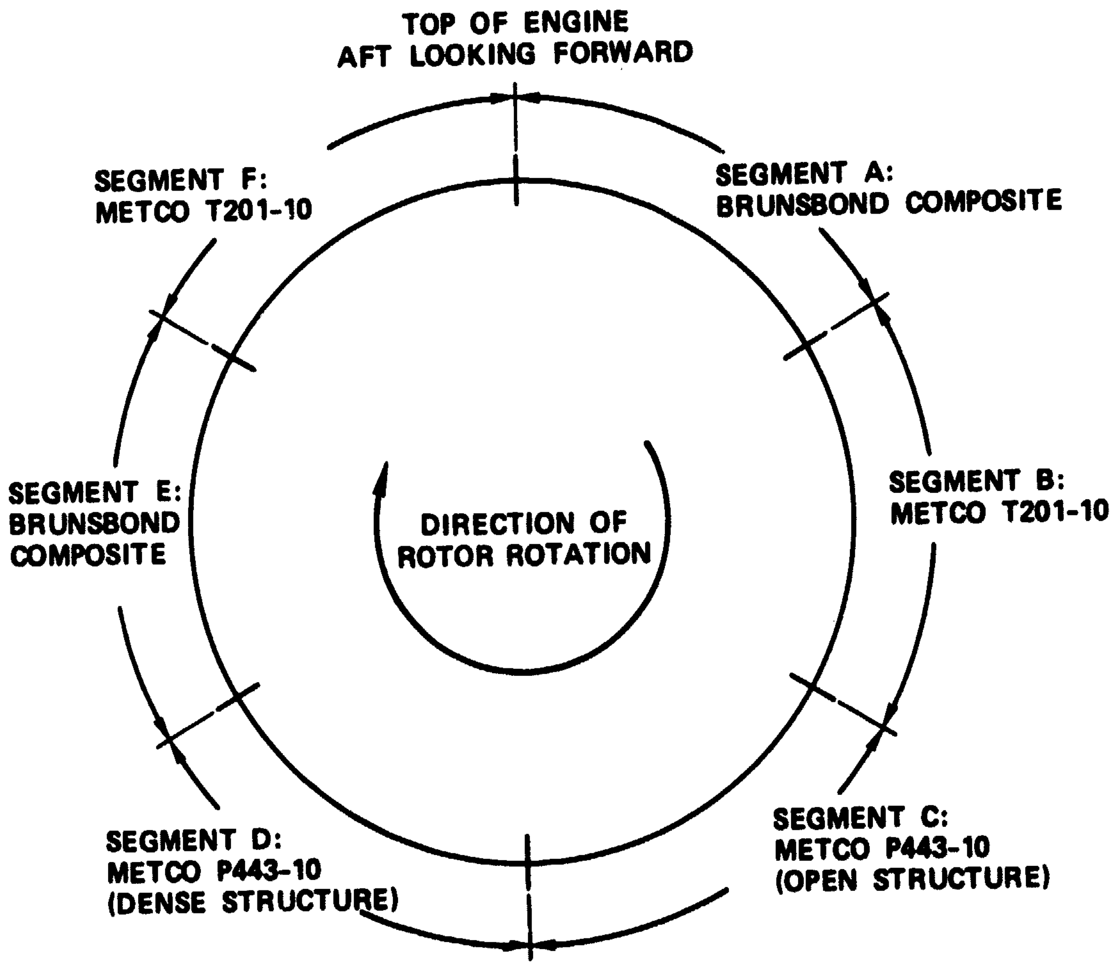


Figure 65. Schematic of Second Interim Engine Test, Build 3, High-Pressure Turbine Shroud Segment Location

201-10* had come loose and were ingested by the low-pressure turbine. While damage to the downstream hardware did not preclude its use in further testing, the entire high-pressure turbine test shroud was replaced with production hardware for Build 4 to avoid further damage. The production shroud segments, and the abradable test shroud segments are not interchangeable due to the special shroud retaining hardware; therefore, continued testing of the remaining high-pressure turbine abradable candidates in Build 4 was not possible.

A meaningful wear ratio for the Build 3 high-pressure turbine assembly could not be determined due to problems with the ceramic material that caused an overall decrease in the shroud inside diameter instead of the normal increase associated with rubs.

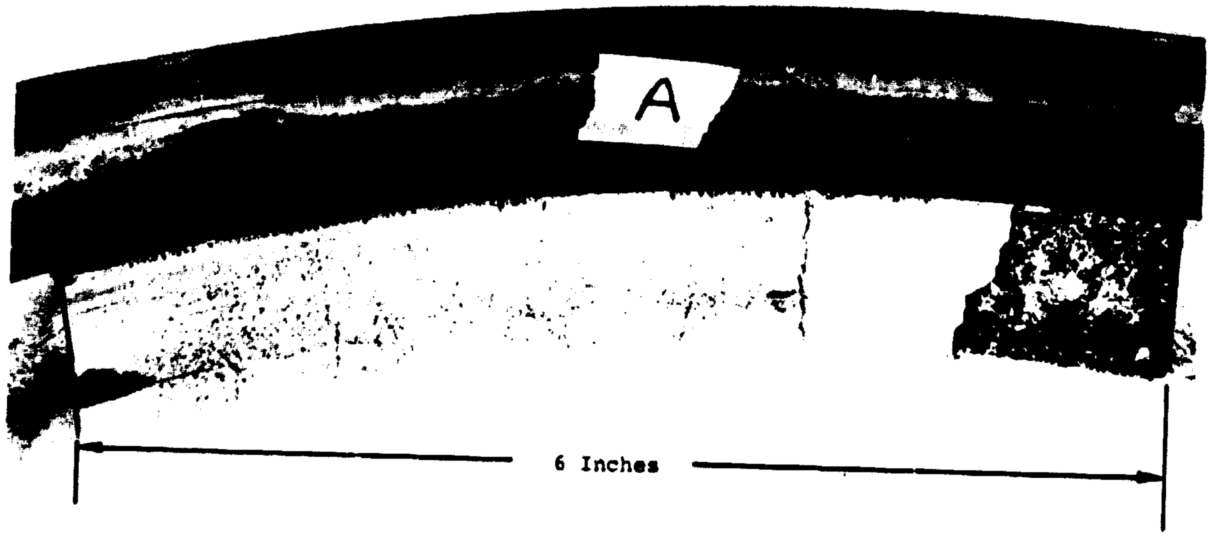
a. Brunsbond Composite** - Brunsbond composite consists of a layer [approximately 1.524-mm (0.060-inch) thick] of low-modulus fiber-metal brazed to the L-605 shroud segment, and a layer [approximately 1.778-mm (0.070-inch) thick] of plasma-sprayed, yttria-stabilized zirconia (ceramic) to act as the high-temperature abradable material. The bond between the metal fibers and the ceramic is mechanical, relying on the irregular surface of the fibers to "lock in" the ceramic layer.

The 25-hour Build 3 test produced cracking and spalling in both of these tested shroud segments (with large pieces missing as shown in Figure 66). The cross-section microstructure presented in Figure 67 shows the layers in the sprayed composite, as well as the separation between the ceramic and fiber-metal layers after testing. This separation was believed to be caused by thermal fatigue or a difference in thermal expansion between the two material layers. The turbine rotor blade rubbed both test segments. Two magnifications of the rub surface are shown in Figure 68. X-ray analysis (in the SEM) confirmed a definite blade-metal pickup on the ceramic abradable surface. The abradability of Brunsbond composite was rated "poor" due to lack of integrity within the material and evidence of blade-metal transfer.

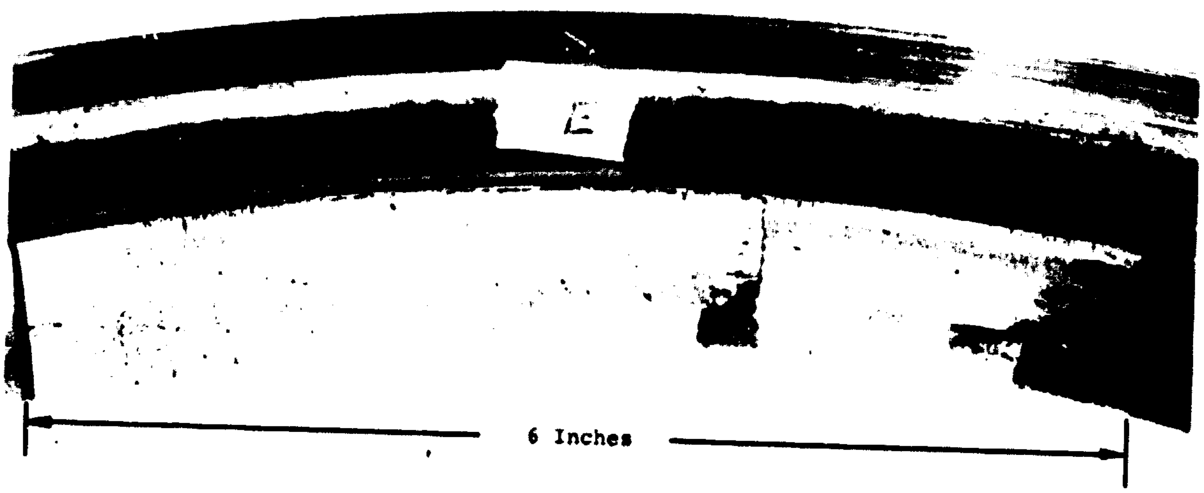
b. Metco T201-10 - Two L-605 alloy shroud segments were thermosprayed with the following layers of materials to produce the abradable candidate identified as Metco T201-10:

Layer 1 - 100-percent Metco P443-10 bond coat (approximately 0.008-inch thick)

*Metco 201-10 is a trade name of Metco, Inc.
**Brunsbond Composite is a trade name of the Technetics Division of Brunswick Corp.



(a) Shroud Segment A



(b) Shroud Segment E

Figure 66. Appearance of Brunsbond Composite High-Pressure Turbine Shroud Segments After 25 Hours of the Second Interim Engine Test, Build 3

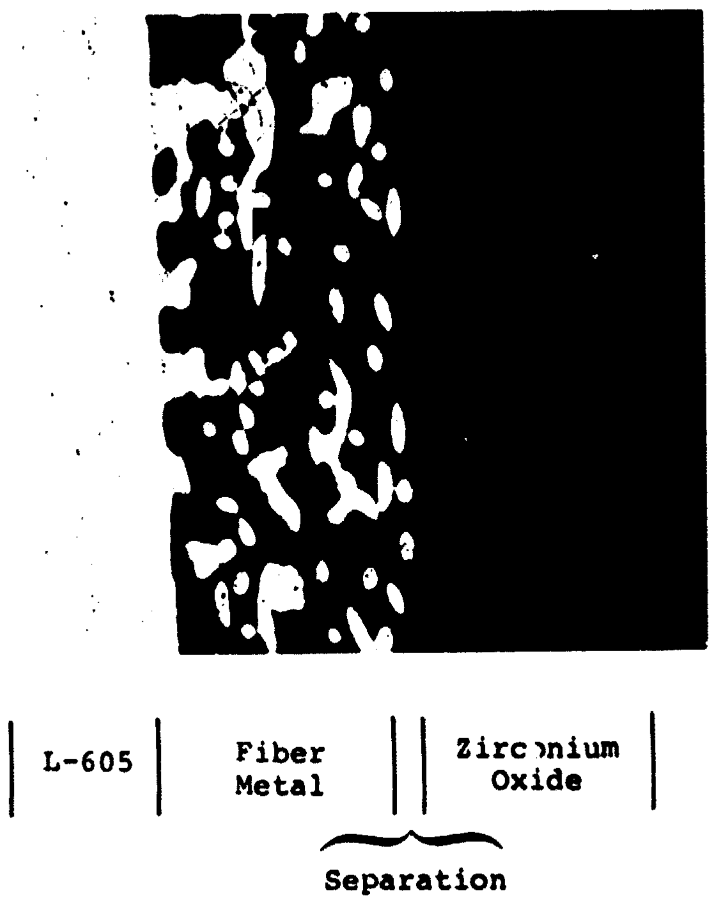
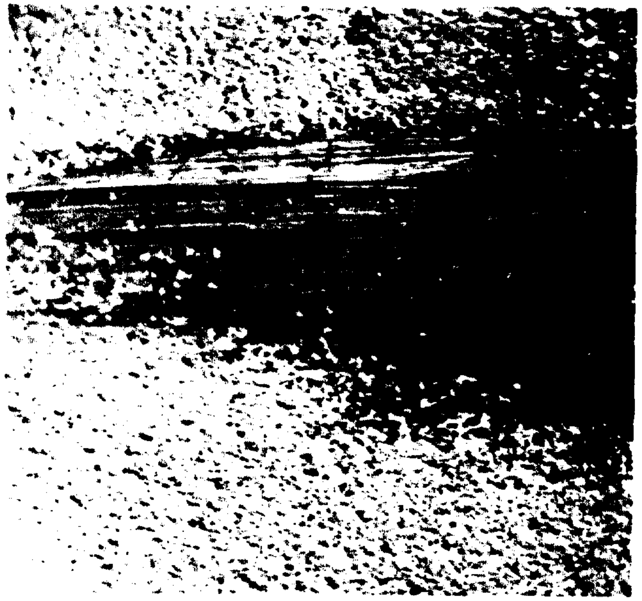


Figure 67. Cross-Section Microstructure of Brunsbond Composite After 25 Hours of the Second Interim Engine Test, Build 3 (Mag.: 20X)



(Mag.: 10X)

(Mag.: 50X)

Figure 68. SEM Images of the Rubbed Surface of Brunsbond Composite After 25 Hours of the Second Interim Engine Test, Build 3

Layer 2 - 60-percent Metco P443-10 and 40-precent Metco 201B-NS-1 (approximately 0.020-inch thick)

Layer 3 - 30-percent Metco P443-10 and 70-percent Metco 201B-NS-1* (approximately 0.018-inch thick)

Layer 4 - 100-percent Metco 201B-NS-1 (approximately 0.060-inch thick)

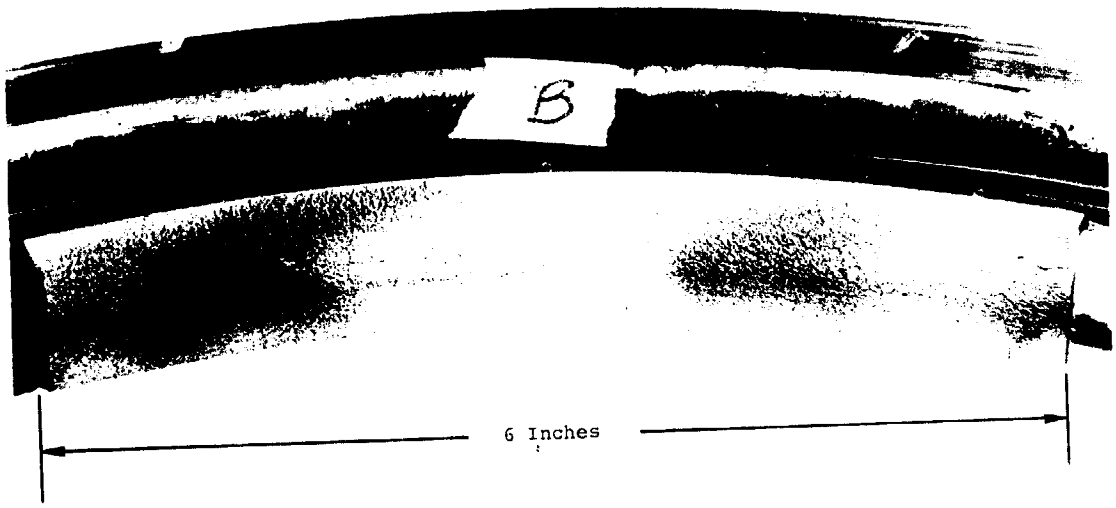
The composition of Metco P443-10 is 94-percent nickel-chromium (80-percent nickel and 20-percent chromium), and 6-percent aluminum. The composition of Metco 201B-NS-1 is 92-percent zirconium oxide and 8-percent calcium carbonate.

The 25 hours of testing in Build 3 of the Second Interim Engine Test produced cracking and spalling of both segments of Metco T201-10, as shown in Figure 69, similar to but not as severe as the yttria-stabilized zirconia (Brunsbond Composite). A cross-section microstructure is shown in Figure 70, which illustrates the four layers of the coating. The surface of the segments contained many small cracks, probably due to thermal fatigue. Details of these cracks can be seen on the SEM images presented in Figure 71. A rub region was not detected on the segment selected for metallurgical evaluation, so X-ray analysis in the SEM was not accomplished. However, it is anticipated that blade-metal would be transferred to this zirconia material during a rub, as it was on the yttria-stabilized zirconia. Metco T201-10 abradable material was rated "poor" due to the cracking and spalling experienced in the engine testing.

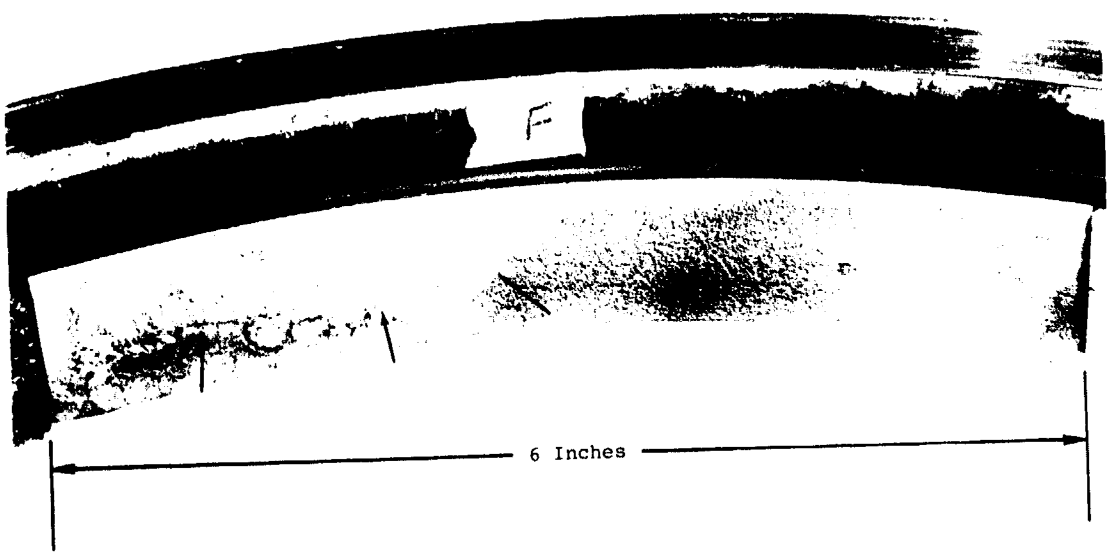
c. <u>Metco P443-10 (dense structure)**</u> - Metco P443-10 powder, having the nominal composition of 6-percent aluminum and 94-percent nickel-chromium (80-percent nickel and 20-percent chromium), was plasma-sprayed onto the test shroud segments. Two different sets of spray parameters were used: one to produce the standard very dense structure of Metco P443-10 coating, and one to produce a less dense "open" Metco P443-10 coating. This "open" structure is discussed in Section d.

Figure 72 shows the cross-section microstructure of Metco P443-10 (dense) after engine testing exhibiting a rubbed surface and Figure 73 shows two SEM images of the rubbed region. X-ray analysis (in the SEM) revealed a deposit of blade-metal on the rubbed surface indicating material transfer. The abradability of Metco P443-10 (dense) was rated "poor" due to evidence of heat generation and blade-metal transfer.

*Metco 201B-NS-1 is a trade name of Metco, Inc.
**Metco P443-10 is a trade name of Metco, Inc.

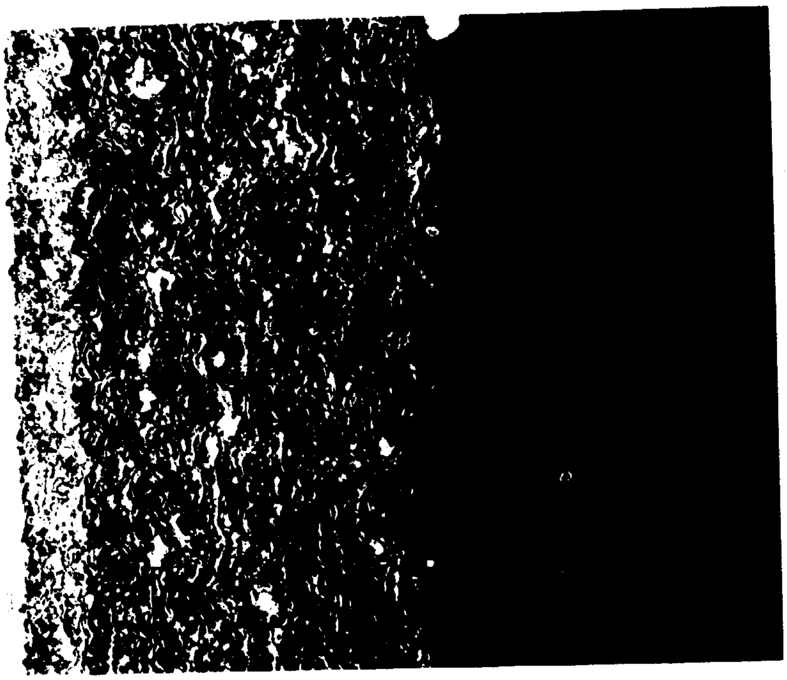


(a) Shroud Segment B



(b) Shroud Segment F

Figure 69. Appearance of Metco T201-10 High-Pressure Turbine Shroud Segments After 25 Hours of the Second Interim Engine Test, Build 3 (Arrows Show Spalled Regions)

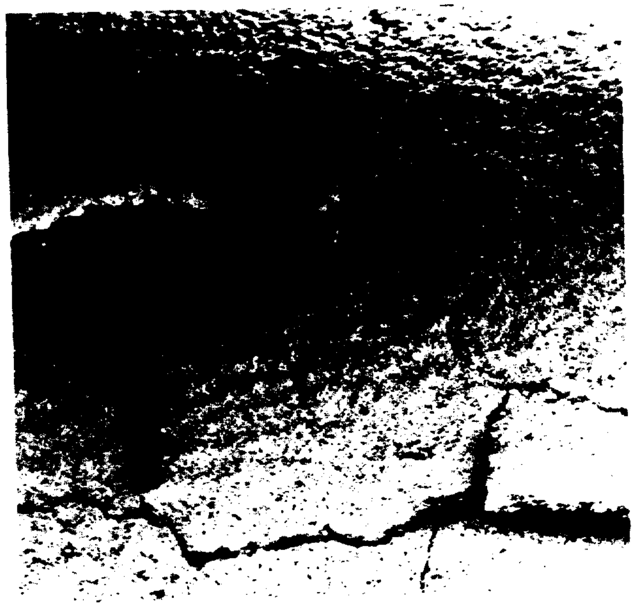


Layer 2 | Layer 3 | Layer 4

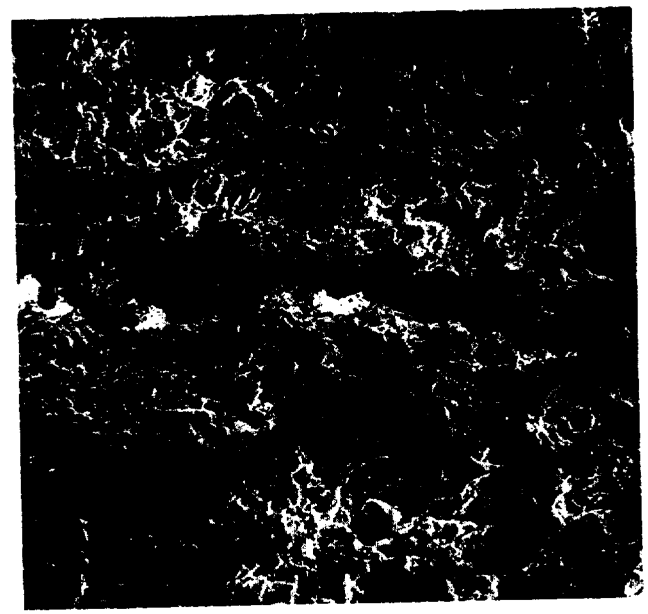
Layer 1

Layer 1 - 100-percent Metco 443 Bond Coat
Layer 2 - 60-percent Metco 443 and
40-percent Metco 201B-NS-1
Layer 3 - 30-percent Metco 443 and
70-percent Metco 201B-NS-1
Layer 4 - 100-percent Metco 201B-NS-1

Figure 70. Cross-Section Microstructure of Metco T201-10 After 25 Hours of the Second Interim Engine Test, Build 3 (Unetched.) (Mag.: 50X)



(Mag.: 10X)

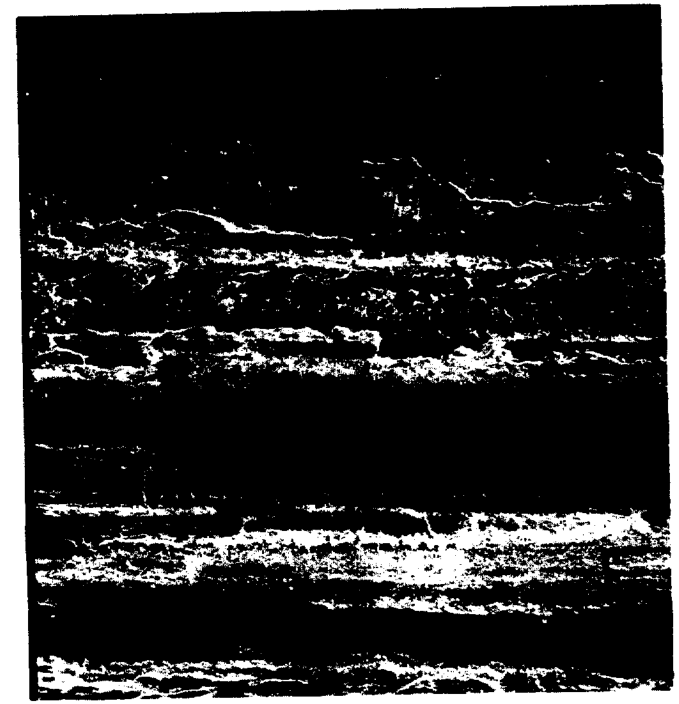


(Mag.: 100X)

Figure 71. SEM Images of Metco T201-10 Surface After 25 Hours of the Second Interim Engine Test, Build 3 (Note the Cracking)

Figure 72. Cross-Section of Metco P443-10 (Dense) After 25 Hours of the Second Interim Engine Test, Build 3 (Unetched.)(Mag.: 50X)

(Mag.: 20X)



(Mag.: 100X)

Figure 73. SEM Images of Two Rubbed Regions on Metco P443-10 After 25 Hours of the Second Interim Engine Test, Build 3

d. Metco P443-10 (open structure) - A view of the Metco P443-10 open structure segment after testing is shown in Figure 74. The dark edges of the segment were areas that did not clean up during the preassembly grinding, and were not a result of this test. Since the rotor blades did not rub this segment during the test, blade-metal transfer could not be determined, and the effects of rub on the surface could not be evaluated. Figure 75 shows the cross-section microstructure of the "open" structure material. It can be seen that the density of this material is considerably less than the standard (dense) Metco P443-10 material (Figure 72). The abradability of Metco P443-10 (open structure) could not be determined without a rub, but no evidence of either erosion or a tendency to separate was observed.

3. Low-Pressure Turbine Shroud Tests.

a. First-stage shroud - The first-stage low-pressure turbine shroud tested in Build 3 was assembled with 180 degrees of honeycomb, and 180 degrees of Solabrade (both made from Hastelloy-X foil). These two abradable structures were brazed into the shroud simultaneously using an AMS 4777 Type braze alloy, and then electrochemically machined to the desired diameter.

The honeycomb was fabricated from 0.0508- to 0.0762-mm (0.002- to 0.003-inch) thick Hastelloy-X foil into 1.587-mm (0.0625-inch) hexagonal cells. The radial wear measured after Build 3 testing ranged from no-contact to 0.1524 mm (0.006 inch). A view showing a section of the shroud containing both honeycomb and Solabrade is presented in Figure 76. Wear track images as observed by the SEM are shown in Figure 77. Braze wicking to the surface was not evident, but minor blade-metal transfer to the honeycomb was observed. The wear ratio could not be determined due to inaccurate rotor diameter measurements prior to testing. The abradability of the Hastelloy-X honeycomb was rated "good".

The Solabrade material tested was the same type tested in the second-stage low-pressure turbine shroud in Build 2 of the First Interim Engine Test. This abradable material is a corrugated structure fabricated from 0.0508- to 0.0762-mm (0.002- to 0.003-inch) thick Hastelloy-X foil with the corrugations having a pitch of 7.87 per cm (20 per inch), and brazed to a perforated 0.127-mm (0.005-inch) thick INCONEL 600 backing strip. This backing strip is then brazed directly to the shroud. As in the case of honeycomb, the radial wear depth varied from no-contact to 0.1524 mm (0.006 inch). Figure 78 shows a view of the rubbed surface as seen in the SEM, and a photomicrograph of the cross-section of one of the wear tracks. The abrading mechanism appears to be by crushing and smearing with very little heat generation.

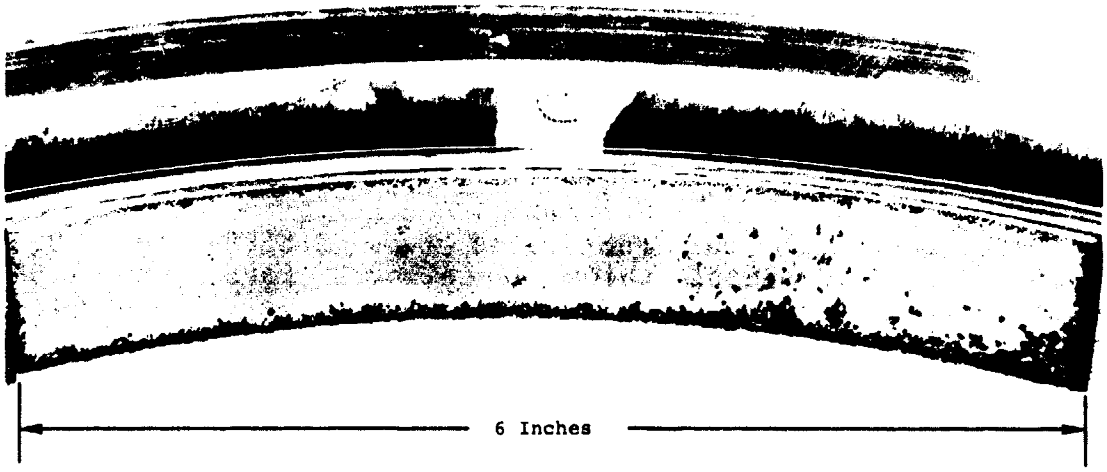


Figure 74. Appearance of the Metco P443-10 (Open Structure) High-Pressure Turbine Shroud Segment After 25 Hours of the Second Interim Engine Test, Build 3. (Turbine Rotor Blades Did Not Contact Shroud Surface)

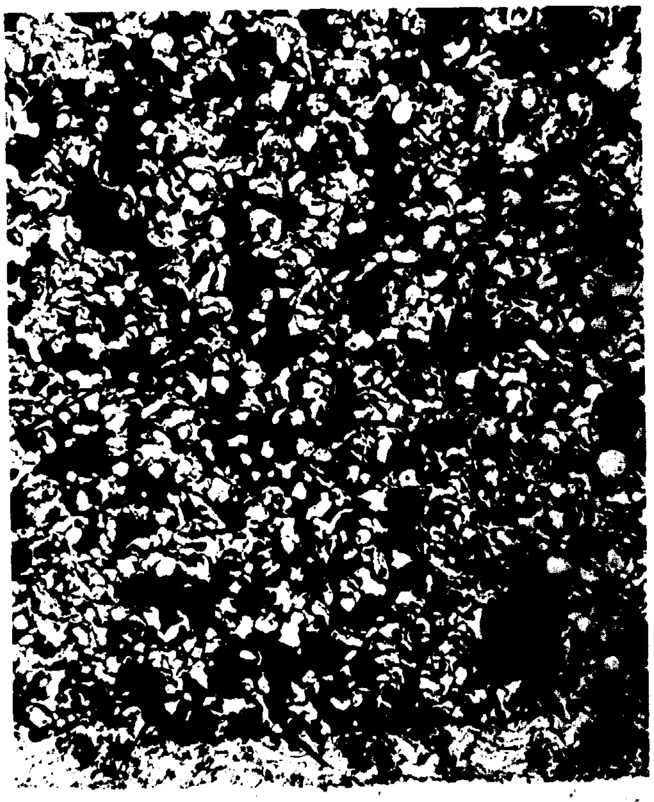


Figure 75. Cross-Section Microstructure of the Metco P433-10 (Open Structure) After 25 Hours of the Second Interim Engine Test, Build 3 (Dark Regions Indicate Porosity) (Mag.: 50X)

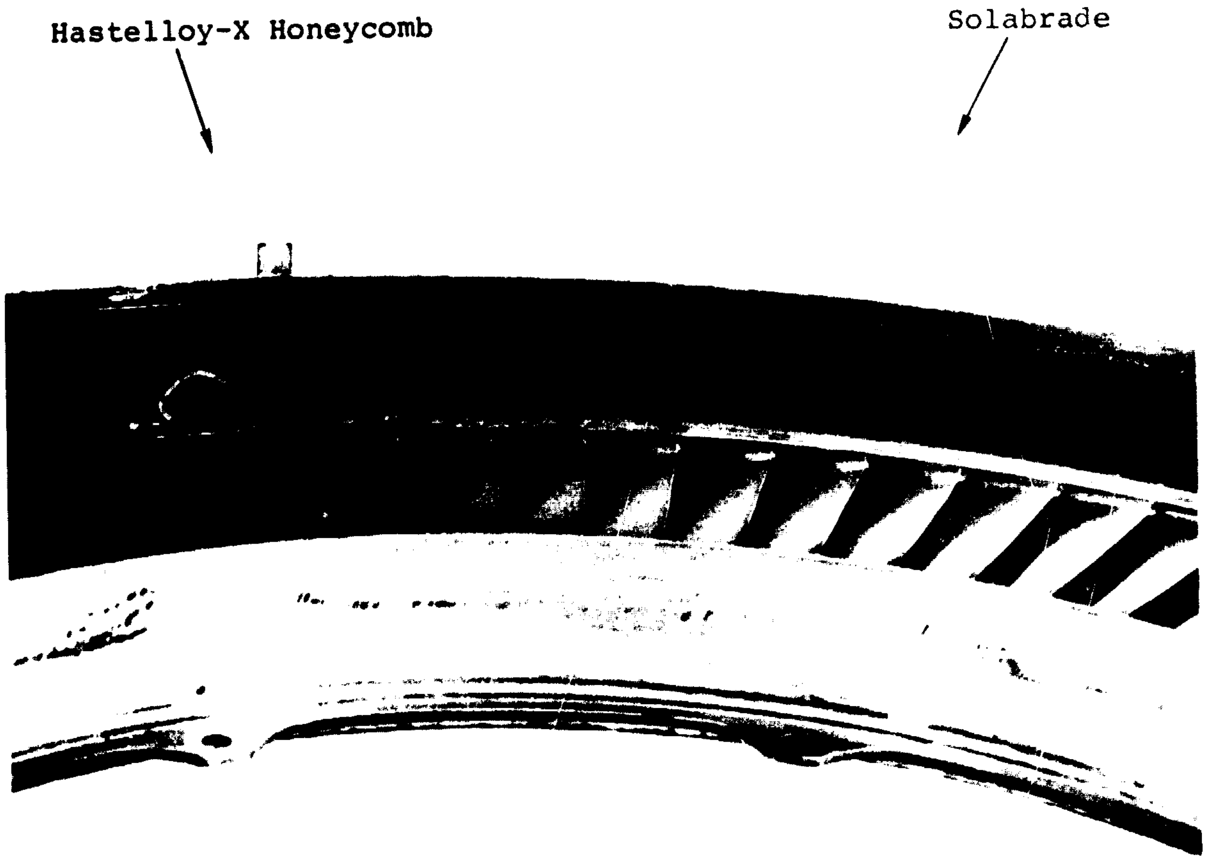
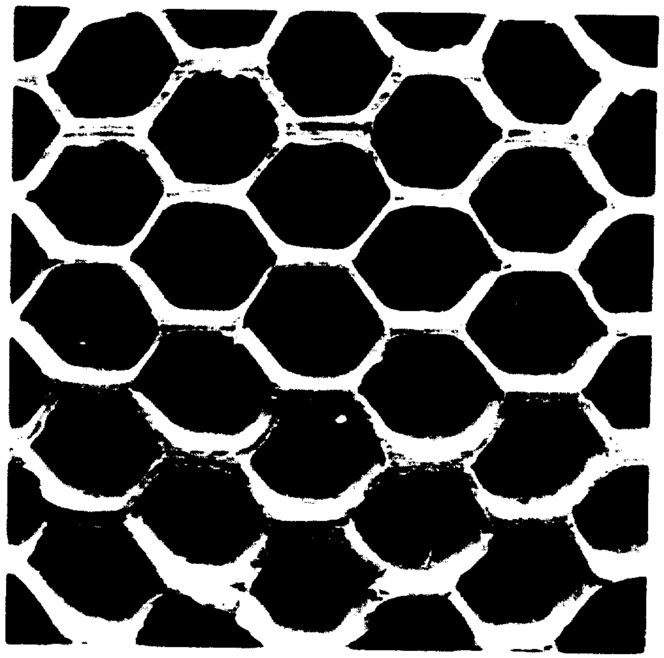
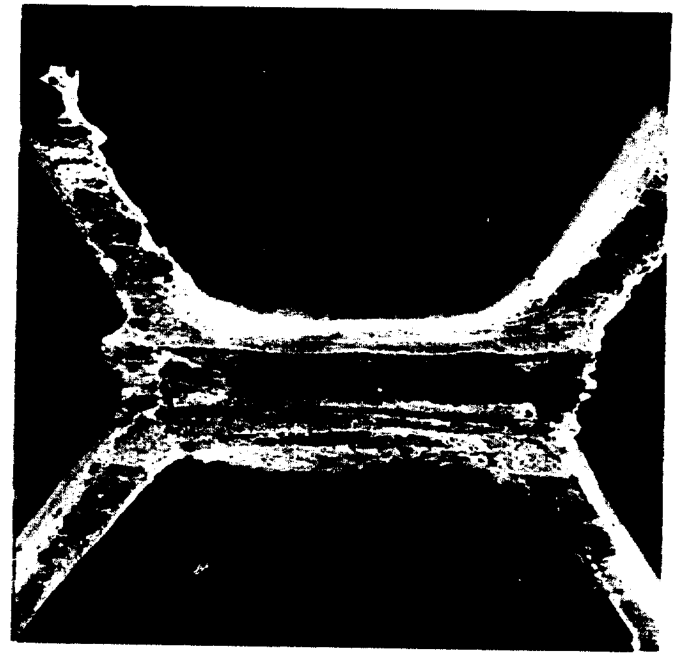


Figure 76. Appearance of First-Stage Low-Pressure Turbine Shroud Containing Hastelloy-X and Solabrade After 25 Hours of the Second Interim Engine Test, Build 3 (Mag.: 1/2X)

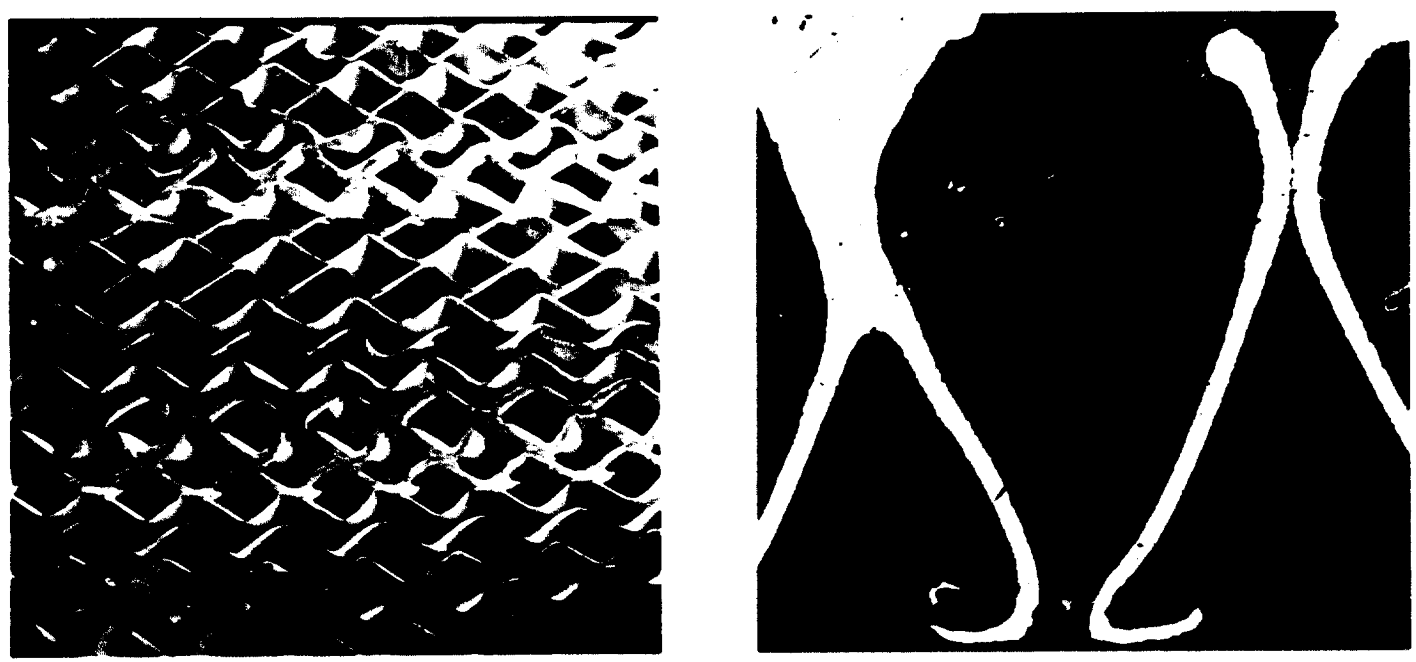


(a) SEM Image of Wear Track (Mag.: 10X)



(b) SEM Image of Wear Track (Mag.: 50X)

Figure 77. Appearance of Hastelloy-X First-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 3



(a) SEM Image of Rub Surface (Mag.: 10X)

Direction of Rub

(b) Photomicrograph of Cross-Section (Mag.: 50X)

Figure 78. Appearance of Solabrade First-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 3

A trace of blade-metal transfer to the Solabrade was detected by SEM analysis. Again, the wear ratio could not be determined due to inaccur.te pretest rotor measurements. The abradability of Solabrade was rated "good".

b. Second-stage shroud - The second-stage low-pressure turbine shroud tested in Build 3 was coated with Metco T301-10 abradable material. This material has a nominal composition of 14-percent chromium, 8-percent iron, 3.5-percent aluminum, and 5.5-percent boron nitride, and 69-percent nickel. The material was thermosprayed on the shroud using spray parameters formulated to produce an open, abradable coating. During the engine test of Build 3, a blade rub was experienced through approximately 300 degrees of shroud periphery with a maximum rub depth of 0.127 mm (0.005 inch). Figure 79 presents the region of deepest contact, and a minor pull-out under the wear track. Figure 80 shows a SEM view and the microstructure in the wear track region. Blade-metal transfer was detected by the SEM although the blades showed no evidence of overheating. As in the case of the first-stage rotor, wear ratios could not be determined due to pretest measuring errors. The abradability of Metco T301-10 was rated "fair-to-good". This material would be rated higher if pull-outs could be eliminated. Metco's evaluation of this coating plus their previous experience indicated that the tendency to pull-out could be reduced or eliminated through minor coating modifications.

c. Third-stage shroud - The third-stage low-pressure turbine shroud tested in Build 3 was coated with Metco 304NS*. This material is an aluminum bronze-boron nitride composite that was applied to the HS-31 cast shroud structure by thermospray. The Build 3 testing produced blade contact over the entire 360-degree circumference of the shroud with a depth of penetration ranging from 0.0254 to 0.3302 mm (0.001 to 0.013 inch). Figure 81 shows the double-wear track near the maximum depth of penetration. Figure 82 presents the appearance of the wear track in the SEM, and the cross-section microstructure under the track. The initial impression from the visual examination was that excessive heat generation occurred. However, this was not borne out by further study since the wear ratio was at least 7:1 (which is considered good), and the microstructure under the wear track did not show any evidence of heat generation. The SEM analysis detected some minor blade-metal transfer on the rub surfaces. The overall abradability of Metco 304NS was rated "good" considering the severity of the rub, and the high-wear ratio.

Engine Build 4.

Testing of candidate abradable materials for the high-pressure compressor, and the high-pressure turbine were completed

*Metco 304NS is a trade name of Metco, Inc.

Pull-out from under the wear track

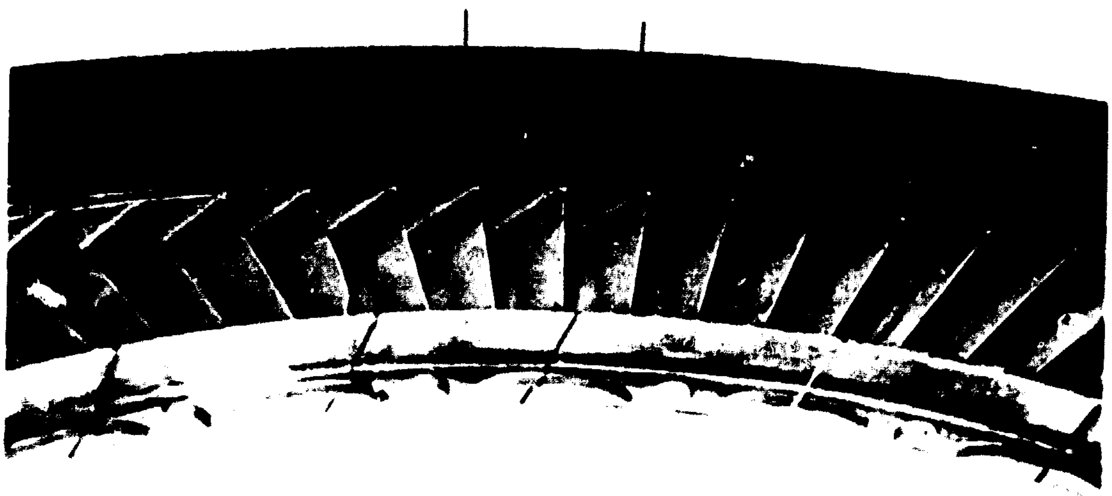
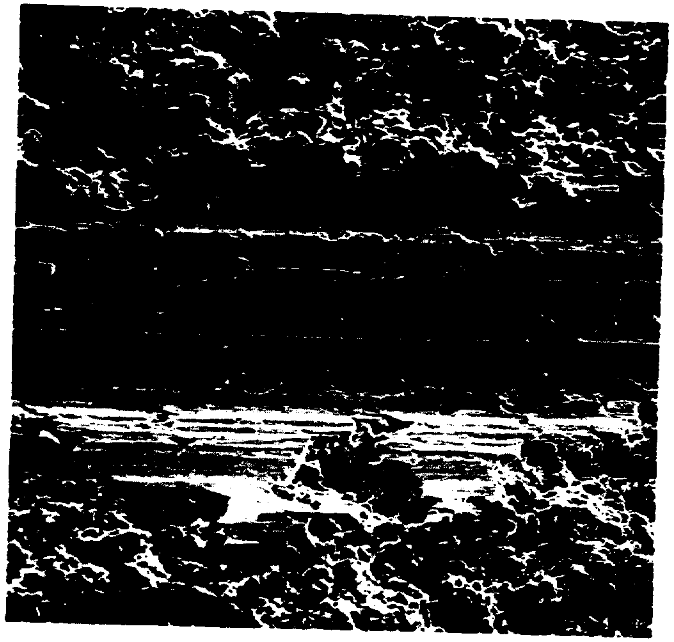
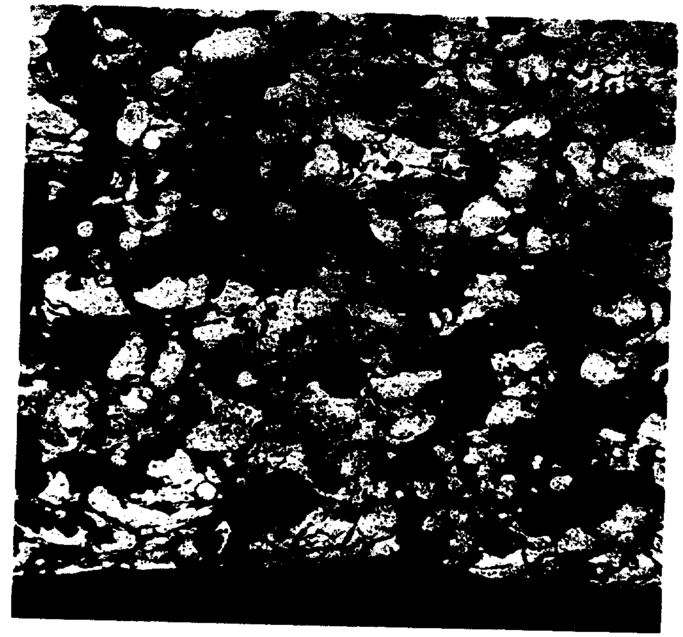


Figure 79. Appearance of Metco T301-10 Second-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 3 (Mag.: 1/2X)



(a) SEM Image of Wear Track (Mag.: 50X)



(b) Cross-Section Microstructure, Unetched (Mag.: 100X) (Arrows indicate wear track surface)

Figure 80. Metco T301-10 Second-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 3

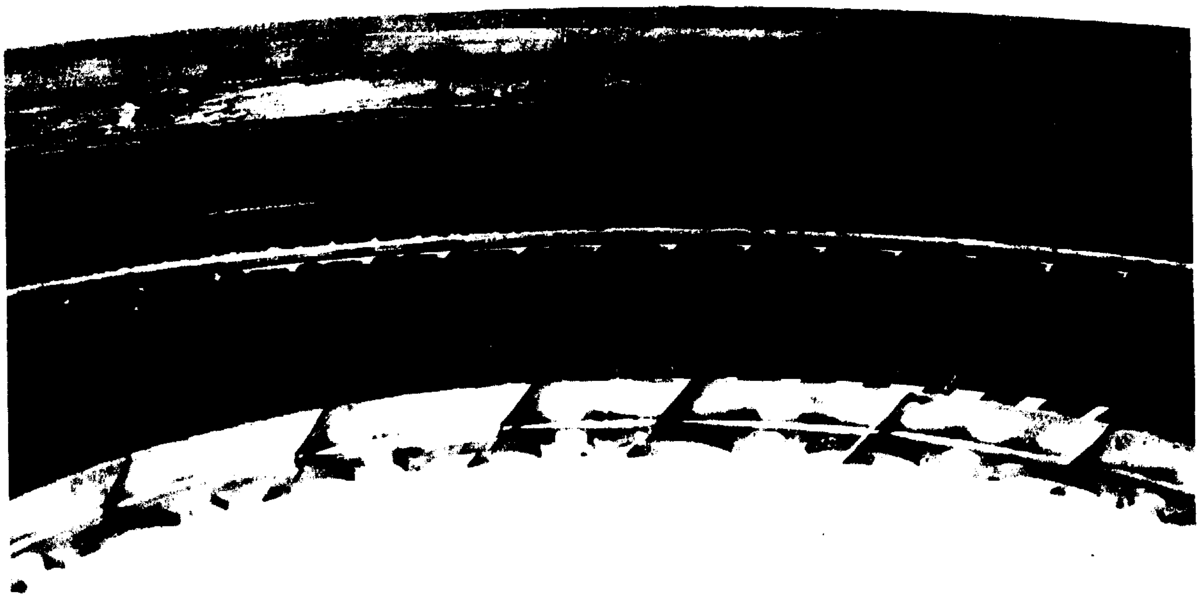
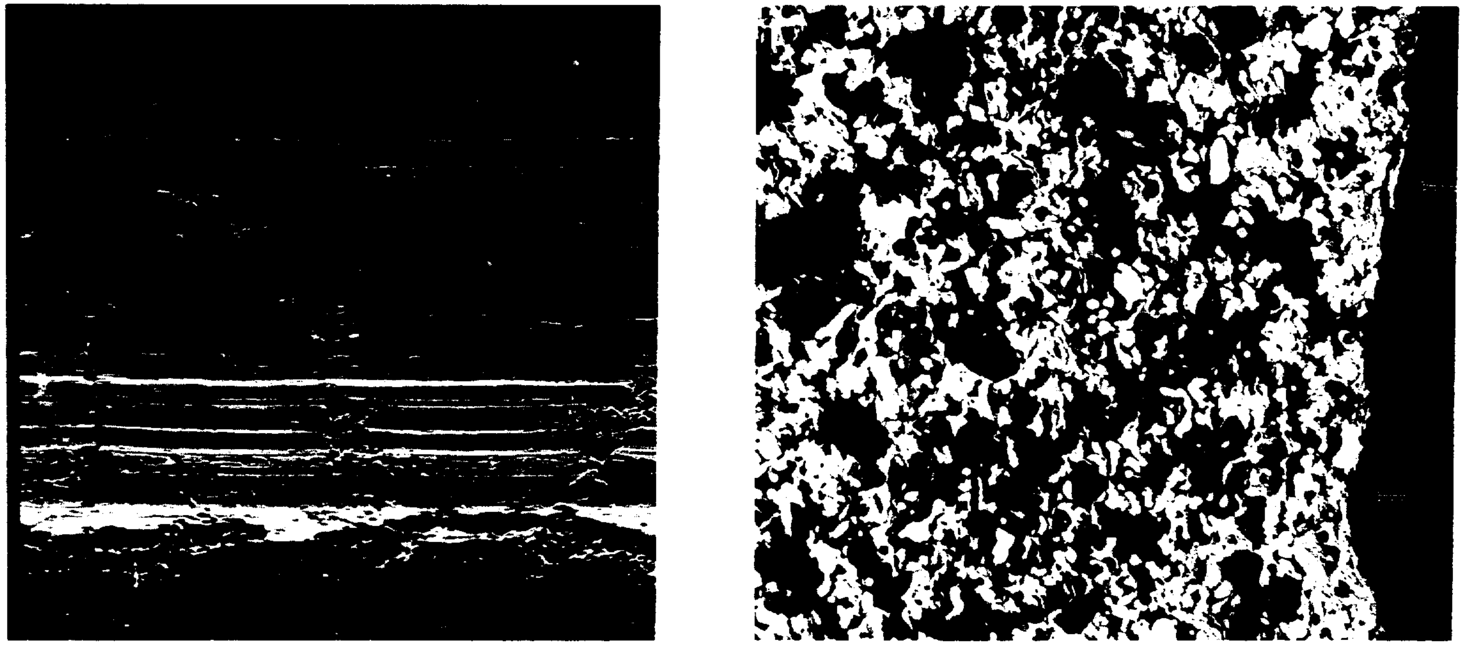


Figure 81. Appearance of Metco 304NS First-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 3 (Mag.: 1/3X)



(a) SEM Image of Wear Track (Mag.: 50X)

(b) Cross-Section Microstructure, Unetched (Mag.: 100X) (Arrows Indicate Wear Track Surface)

Figure 82. Metco 304NS Third-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 3

in Engine Builds 1, 2 and 3. Build 4 of the Second Interim Engine Test was conducted to evaluate the remaining candidate abradables for the low-pressure turbine.

1. First-Stage Low-Pressure Turbine Shroud. The abradable tested in the first-stage low-pressure turbine shroud in Build 4 of the Second Interim Engine Test was Metco T450-14* with a nominal composition of 4.5-percent aluminum and 95.5-percent nickel. This material was thermosprayed into the cast Alloy 713LC shroud structure using spray parameters designed to yield an open structure of moderate density. During the test of this material, blade contact occurred over approximately 180 degrees of the shroud up to a depth of 0.0762 mm (0.003 inch). Erosion of the material, however, was observed for the full 360 degrees as shown in Figure 83. The erosion appeared to be most severe between the two knife-blade edges which may indicate that particles of the coating were trapped between the knife edges, and acted as abrasives causing further erosion. Gas erosion is indicated in Figure 83 by the "rounded" corners, and the pulled-out areas of the coating outside the wear tracks. Figure 84 shows the appearance of the wear track and the cross-section microstructure. The wear track was smeared and a crushing of the abradable structure was noted. As determined by SEM analysis, blade-metal had been transferred to the surface of the coating. The microstructure showed large open regions that may explain the susceptibility of this material to erosion. With this type of structure, clusters of the abradable material may be held loosely together. These clusters are then easily broken loose during engine testing. The abradability of this material was rated "poor" based on the rub characteristics and the extensive erosion.

2. Second-Stage Low-Pressure Turbine Shroud. The abradable material tested in the second-stage low-pressure turbine shroud in Build 4 was Feltmetal 537** brazed to Alloy 713LC shroud structure prior to final machining. This abradable is fabricated from iron-nickel-chromium-aluminum-yttrium alloy fibers approximately 18 microns in diameter. Initially, some difficulty was experienced in brazing this fiber structure to the shroud even though limited success had been obtained in test coupon brazing trials. It was concluded that oxidation of the aluminum in the abradable was preventing complete wetting of the fibers. The shroud was then successfully brazed in a furnace capable of maintaining a good vacuum using LM Nicrobraz braze alloy.

The Build 4 engine test produced blade contact throughout the entire shroud (360 degrees) to a maximum depth of 0.1016 mm (0.004 inch). Figure 85 shows the dual knife-edge rub near the deepest penetration. Figure 86 presents the SEM appearance of the

*Metco T450-14 is a trade name of Metco, Inc.

**Feltmetal 537 is a trade name of Technetics Division of Brunswick Corp.

Region of most severe erosion

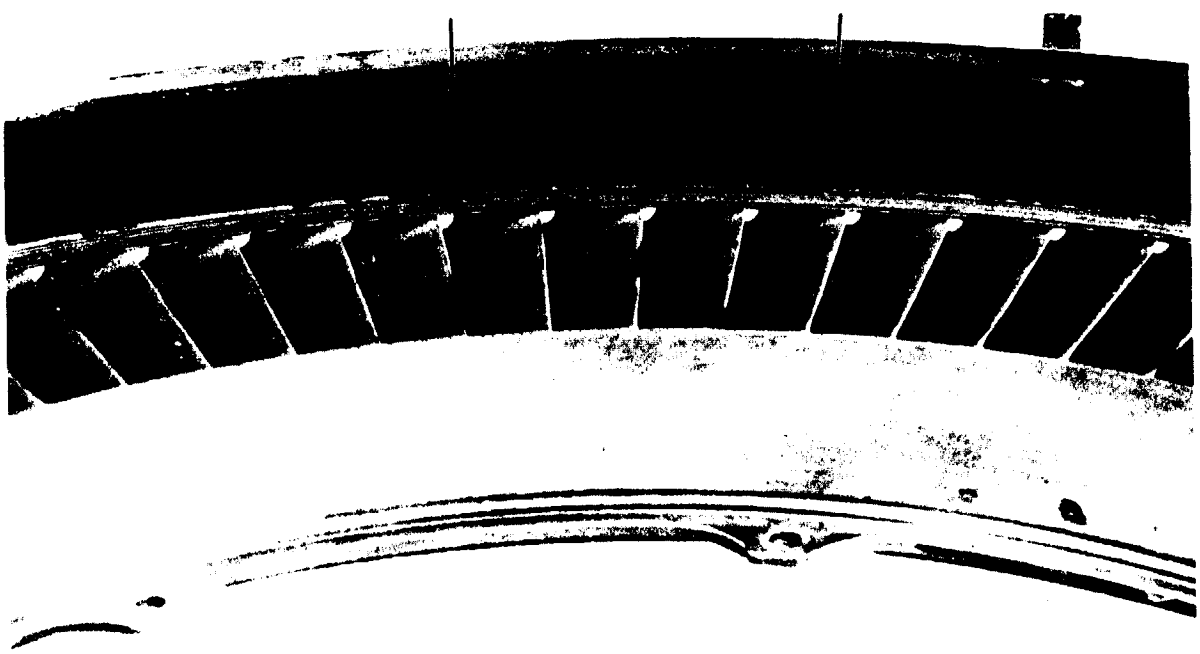
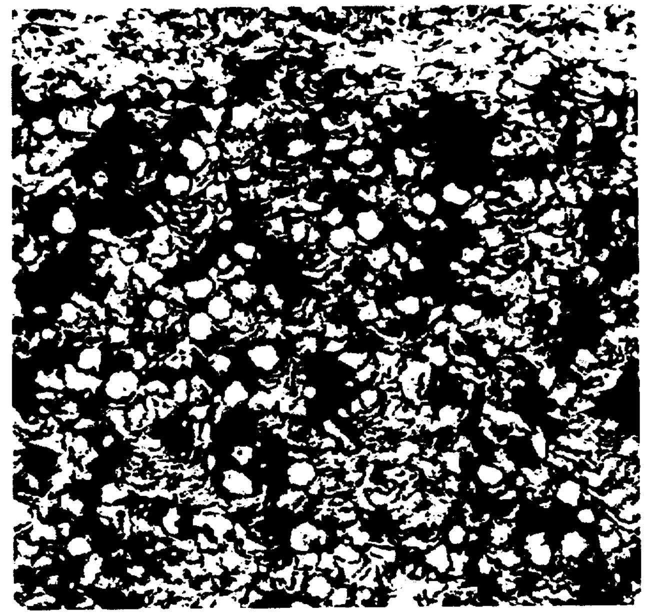


Figure 83. Appearance of Metco T450-14 First-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 4 (Mag.: Approx. 1/2X)

(a) SEM Image of Wear Track (Mag.: 50X)



(b) Cross-Section Microstructure, Unetched (Mag.: 100X)

Figure 84. Metco T450-14 First-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 4

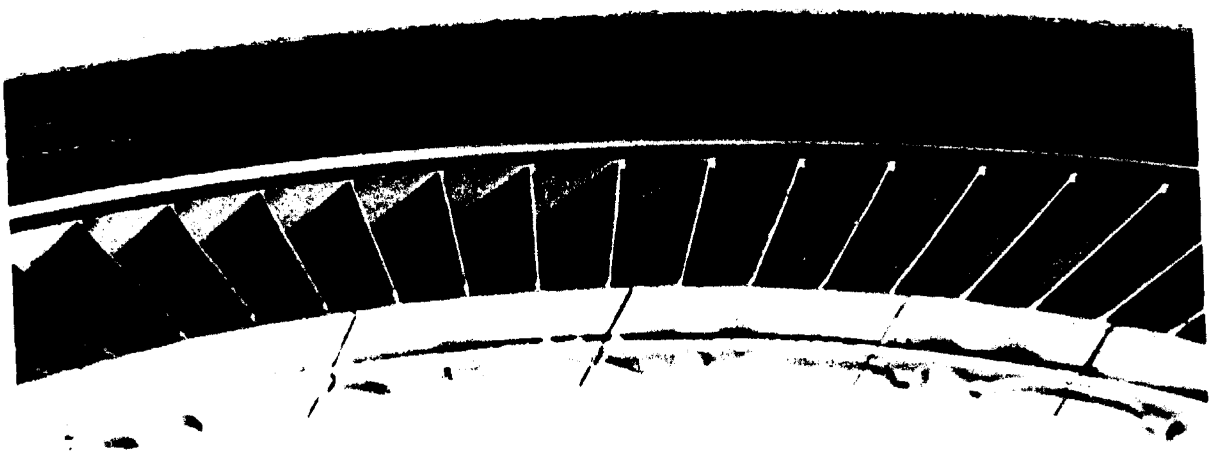
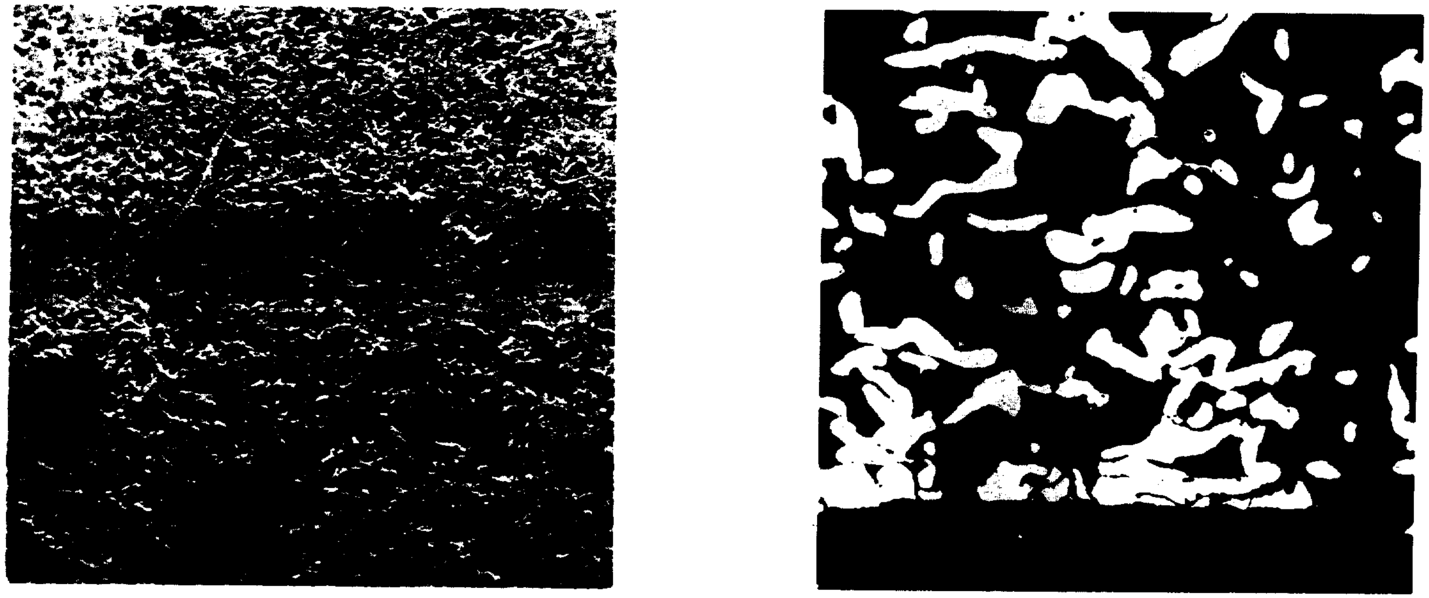


Figure 85. Appearance of Feltmetal 537 on the Second-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 4 (Mag.: 1/2X)



(a) SEM Image of Wear Track (Mag.: (20X)

(b) Cross-Section Microstructure, Unetched (Mag.: 100X) (Arrows Indicate Wear Track Surface)

Figure 86. Feltmetal 537 on the Second-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 4

wear track, and the cross-section microstructure under the rub groove. Blade-metal was detected by the SEM in the wear tracks, and the cross-section shows a slight crushing of the structure. The overall abradability rating of Feltmetal 537 was "fair-to-good".

3. Third-Stage Low-Pressure Turbine Shroud. Feltmetal 535* was the abradable shroud material tested in Build 4 in the third-stage low-pressure turbine. This material is fabricated from iron-chromium-aluminum-yttrium alloy fibers approximately 12 microns in diameter. As with the Feltmetal 537 material tested in the second-stage turbine shroud, brazing was a problem until an extremely good vacuum was maintained in the furnace. The braze was successfully accomplished using five preformed segments to complete the shroud.

The engine test produced blade contact on the abradable coating for the full 360 degrees of the shroud at depths ranging from 0.0508 to 0.2286 mm (0.002 to 0.009 inch). Figure 87 shows an inconsistency resulting from the test in that one of the presumably identical pieces of Feltmetal 535 exhibited severe gas erosion. Examination in the SEM of unrubbed areas in two adjacent shroud sections revealed an apparent difference in density as shown in Figure 88. Laboratory examination by the supplier indicated that the suspect segment contained regions of lower-tensile strength material that allowed the high-velocity gas to break down the structure.

The appearance of Feltmetal 535 in the SEM and the microstructure of the wear track in a noneroded area are presented after testing in Figure 89. The rub appeared to have generated considerable heat and cracked the surface. The wear ratio was very poor at 2:1 (another indication of heat generation), and blade-metal was detected in the wear tracks. The overall abradability of Feltmetal 535 was rated "poor".

Summary of the Second Interim Engine Test Results

A summary of the evaluations of abradable materials tested in the Second Interim Engine Test (Task IIA) is presented in the following discussion.

Table XII presents the summary of the high-pressure compressor abradable materials evaluations. Both Metco T301-10 and P601-10 are considered acceptable materials with P601-10 being the preferred material due to less blade-material pickup.

A summary of the high-pressure turbine abradable material evaluations is given in Table XIII. None of the candidates that

*Feltmetal 535 is the trade name of the Technetics Division of Brunswick Corp.

Severe gas erosion on one segment

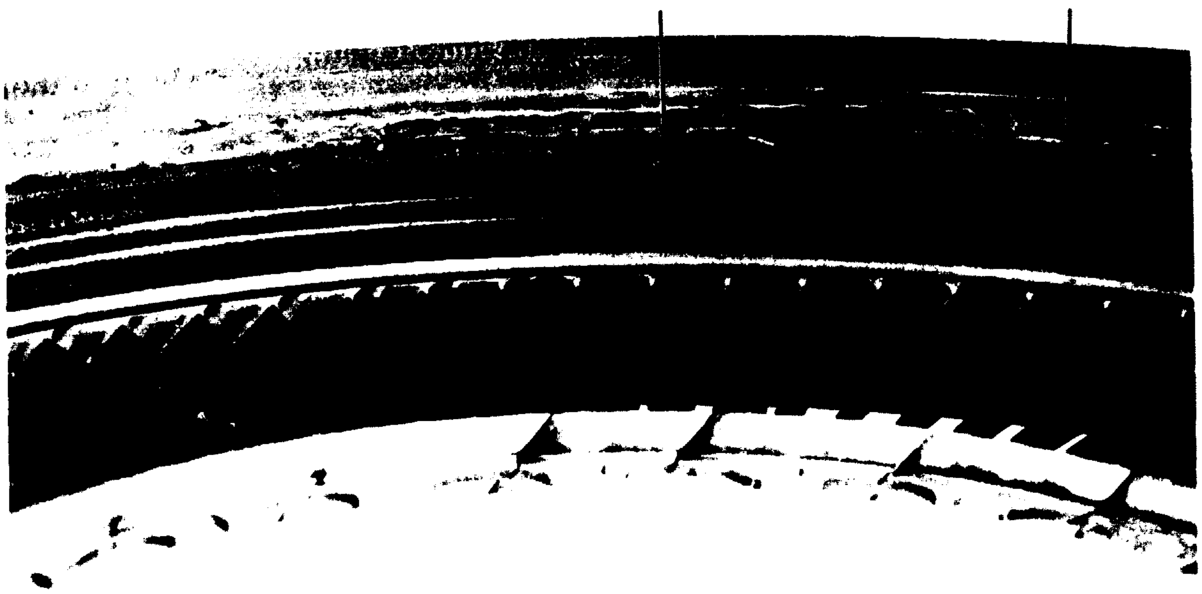
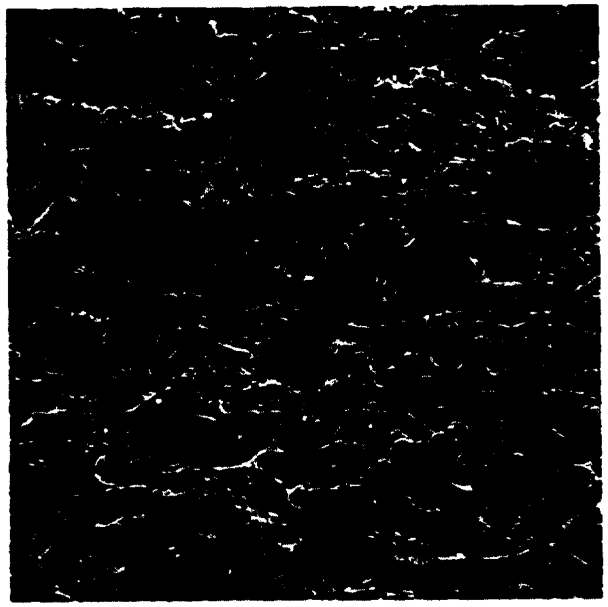


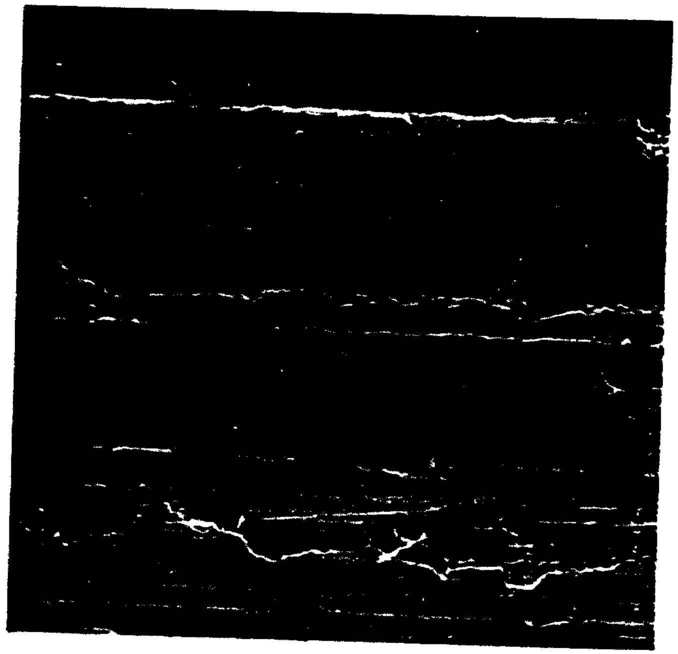
Figure 87. Appearance of Feltmetal 535 on the Third-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 4 (Mag.: 1/2X)



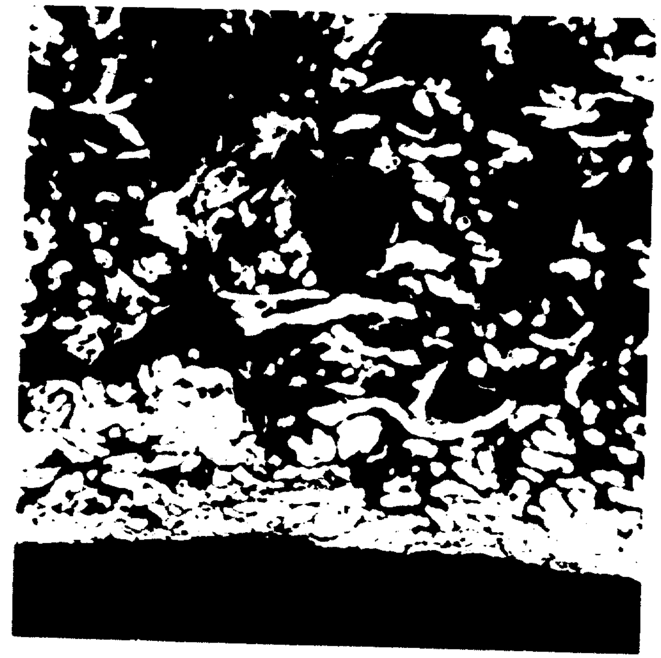
(a) SEM Image of Segment Not Showing Erosion

(b) SEM Image of Segment Showing Erosion

Figure 88. SEM Views of Two Different-Appearing Feltmetal 535 Third-Stage Low-Pressure Turbine Shroud Segments After 25 Hours of the Second Interim Engine Test, Build 4 (Mag.: 50X)



(a) SEM Image of Wear Track



(b) Cross-Section Microstructure, Unetched (Arrows Indicate Wear Track Surface)

Figure 89. Feltmetal 535 on the Third-Stage Low-Pressure Turbine Shroud After 25 Hours of the Second Interim Engine Test, Build 4 (Mag.: 100X)

TABLE XII. SUMMARY OF THE HIGH-PRESSURE COMPRESSOR SHROUD ABRADABLE SEAL MATERIAL EVALUATIONS FROM THE SECOND INTERIM ENGINE TEST, BUILD 3

Material	Attachment Method	Abradability [a]	Blade-Metal Pick-Up	Bond Integrity	Remarks
Feltmetal 515B	Braze	Poor	Yes	Good	Tendency to pull-out
Metco T310-10	Thermospray	Poor	Not Determined [b]	Poor	Sheared near bond joint
Metco T301-10	Thermospray	Fair-to-good	Trace	Good	--
Metco P601-10	Plasmaspray	Fair-to-good	Trace [c]	Good	--

[a] Impeller surface speed equals 548.6 m/sec (1800 ft/sec) at test shoe contact point; interaction rate of 0.1016 mm/minute (0.004 inch/minute); approximately 700°K (800°F)

[b] Blade-metal pick-up not determined

[c] Blade-metal present in local streaks

TABLE XIII. SUMMARY OF THE HIGH-PRESSURE TURBINE SHROUD ABRADABLE SEAL MATERIAL EVALUATIONS FROM THE SECOND INTERIM ENGINE TEST, BUILD 3

Material	Attachment Method	Abradability [a]	Blade-Metal Pick-Up	Bond Integrity	Wear Ratio [b]	Remarks
Brunsbond composite	Braze	Poor	Yes	Poor	c	Pieces pulled out
Metco P443-10 (Dense)	Plasmspray	Poor	Yes	Good	c	--
Metco P443-10 (Open)	Plasmspray	Did not rub	Did not rub	Good	Did not rub	--
Metco T201-10	Thermospray	Poor	Not Determined	Poor	c	Surface cracking

[a] 427 m/sec (1400 ft/sec) rotor tip speed; 0.0508 mm/minute (0.002 inch/minute) interaction rate; 1311°K (1900°F)

[b] Maximum amount of shroud material removed (inside wear track)/reduction of rotor diameter

[c] Not determined, but very poor

experienced a rub offered any real potential for this application. Further testing is recommended for the "open" structure Metco P443-10 since it did not rub, and may offer some potential for this application.

Table XIV presents a summary of the low-pressure turbine abradable material evaluations--all three stages. The following candidates are considered acceptable for the designated LPT Stages:

First Stage: Honeycomb (Hastelloy-X);Solabrade(Hastelloy-X)
Second Stage: Metco T301-10; Feltmetal 537
Third Stage: Metco 304NS

Selection of Candidates for Final Engine Testing

After completing the Second Interim Engine Test, the materials evaluated in both Interim Engine Tests, as summarized in Tables IX, X, XI, XII, XIII and XIV, were compared with the objective of selecting the most promising candidates for the Final Engine Testing of Task VI. The following criteria were used in the selection process:

- o Abradability
- o Cost
- o Inspectability
- o Ease of refurbishment

Along with these criteria, material availability was considered. At the time of the selection of Task VI test materials, the status of the Union Carbide materials was undetermined. Consequently, UCAR materials were selected for the Final Engine Test only if there were no other acceptable candidates, and if the hardware was already available from procurement earlier in the project.

A summary of the acceptable candidates from the First and Second Interim Engine Tests is presented in Table XV. After considering all factors as discussed above, the candidate materials listed in Table XVI were selected for the Final Engine Testing of Task VI and approved by the NASA Project Manager.

TABLE XIV. SUMMARY OF THE LOW-PRESSURE TURBINE SHROUD ABRADABLE SEAL MATERIAL EVALUATIONS FROM THE SECOND INTERIM ENGINE TEST, BUILDS 3 AND 4

Material	Engine Build	Turbine Stage	Attachment Method	Abradability[a]	Blade-Metal Pick-Up	Bond Integrity	Wear Ratio[b]	Remarks
Honeycomb	3	1	Braze	Good	Trace	Good	c	Same shroud
Solabrade	3	1	Braze	Good	Trace	Good	c	Same shroud
Metco T450-14	4	1	Thermospray	Poor	Yes	Good	c	Gas and particle erosion
Metco T301-10	3	2	Thermospray	Fair-to-good	Yes	Good	c	--
Feltmetal 537	4	2	Braze	Fair-to-good	Yes	Good	c	--
Metco 304 NS	3	3	Thermospray	Good	Yes	Good	7:1	--
Feltmetal 535	4	3	Braze	Poor	Yes	Good	2:1	Excessive blade wear

[a] Operating conditions:

First-Stage - 380 m/sec (1250 ft/sec) rotor tip speed; 1140°K (1600°F)
Second-Stage - 412 m/sec (1350 ft/sec) rotor tip speed; 1033°K (1400°F)
Third-Stage - 436 m/sec (1430 ft/sec) rotor tip speed; 922°K (1200°F)
Interaction rate not determined. Estimated at 0.0254 to 0.1016 mm/min (0.001 to 0.004 inch/min)

[b] Maximum amount of shroud material removed (diameter inside wear track)/reduction of rotor diameter

[c] Not determined

TABLE XV. ACCEPTABLE ABRADABLE MATERIAL CANDIDATES AS DETERMINED FROM THE FIRST AND SECOND INTERIM ENGINE TESTS

Engine Component	Material Identification	Material Composition	Attachment Method
High-Pressure Compressor	Metco P601-10	Aluminum-polyester	Plasmaspray
	Metco T301-10	Boron-nitride cermet	Thermospray
	UCAR AB-1 [827 MPa (1200 psi)]	Nickel-chromium	Direct sinter
High-Pressure Turbine	UCAR AB-4 [13.74 MPa (2000 psi)]	Nickel-chromium-aluminum	Braze
	Metco P443-10 (open)	Nickel-chromium-aluminum	Plasmaspray
Low-Pressure Turbine:			
First-Stage	Honeycomb	Hastelloy-X	Braze
	Solabrade	Hastelloy-X	Braze
Second-Stage	Metco T301-10	Boron-nitride cermet	Thermospray
	Feltmetal 537	Iron-nickel-chromium-aluminum-yttrium	Braze
	Solabrade	Hastelloy-X	Braze
	UCAR AB-2 [8.96 MPa (1300 psi)]	Nickel-chromium-aluminum	Braze
Third-Stage	Metco 304 NS	Bronze/boron nitride	Thermospray
	UCAR AB-2 [5.52 MPa (800 psi)]	Nickel-chromium-aluminum	Braze

TABLE XVI. CANDIDATE ABRADABLE MATERIALS SELECTED FOR THE TASK VI 150-HOUR ENGINE TEST*

Engine Component	Approximate Gas Temperature, °K	(°F)	Material Identification	Material Composition
High-Pressure Compressor	700	(800)	Metco P601-10	Aluminum-polyester
High-Pressure Turbine	1311	(1900)	UCAR AB-4	Nickel-chromium-aluminum
			Metco P443-10 (open)	Nickel-chromium-aluminum
Low-Pressure Turbine:				
First-Stage	1144	(1600)	Honeycomb	Hastelloy-X
Second-Stage	1033	(1400)	Metco T301-10	Boron-nitride cermet
Third-Stage	922	(1200)	Metco 304 NS	Bronze/boron nitride

*This data is also presented in Table III

TASK III - COMPONENT DESIGN

Scope

The objectives of this task were as follows:

- Identify the engine components and parts that had to be physically changed to accommodate the abradable test materials.
- Establish the engine build-up clearances necessary to achieve the desired rub on the candidate abradables during engine testing.
- Document these findings in appropriate engineering drawings and acceptance criteria to permit fabrication of engine test hardware.
- Make predictions of engine performance effects and component life of the shroud abradable seal systems based on Tasks I and II.

The Task III design was accomplished in two phases. The first phase was a preliminary design meant to define modified hardware and assembly criteria for the Task II and IIA Interim Engine Tests. The second phase was a modification of the abradable hardware for the final design based on both analysis and the Interim Engine Test results.

Design Modifications

1. <u>High-Pressure Compressor</u>. The principal parts comprising the high-pressure compressor system are the rotating radial-flow impeller and its companion stationary shroud. The shroud contour matches the contour of the outer edges of the adjacent impeller vanes, and forms the stationary boundary of the airflow path from the impeller inlet to its exit.

The face of the shroud adjacent to the impeller blades is the surface subject to blade rubs, and therefore, the place to use abradable coatings to minimize the clearance between the impeller and the shroud during engine operation. To change the HP compressor shroud requires extensive engine disassembly and assembly, adding considerable cost and downtime to the engine test program. Therefore, to minimize the engine disassembly and assembly operations, the standard impeller shroud was modified to provide for insertion of a 1.27-mm (0.5-inch) diameter abradable-coated plug (replaceable shoe) into the gas path (as shown in Figure 90). The

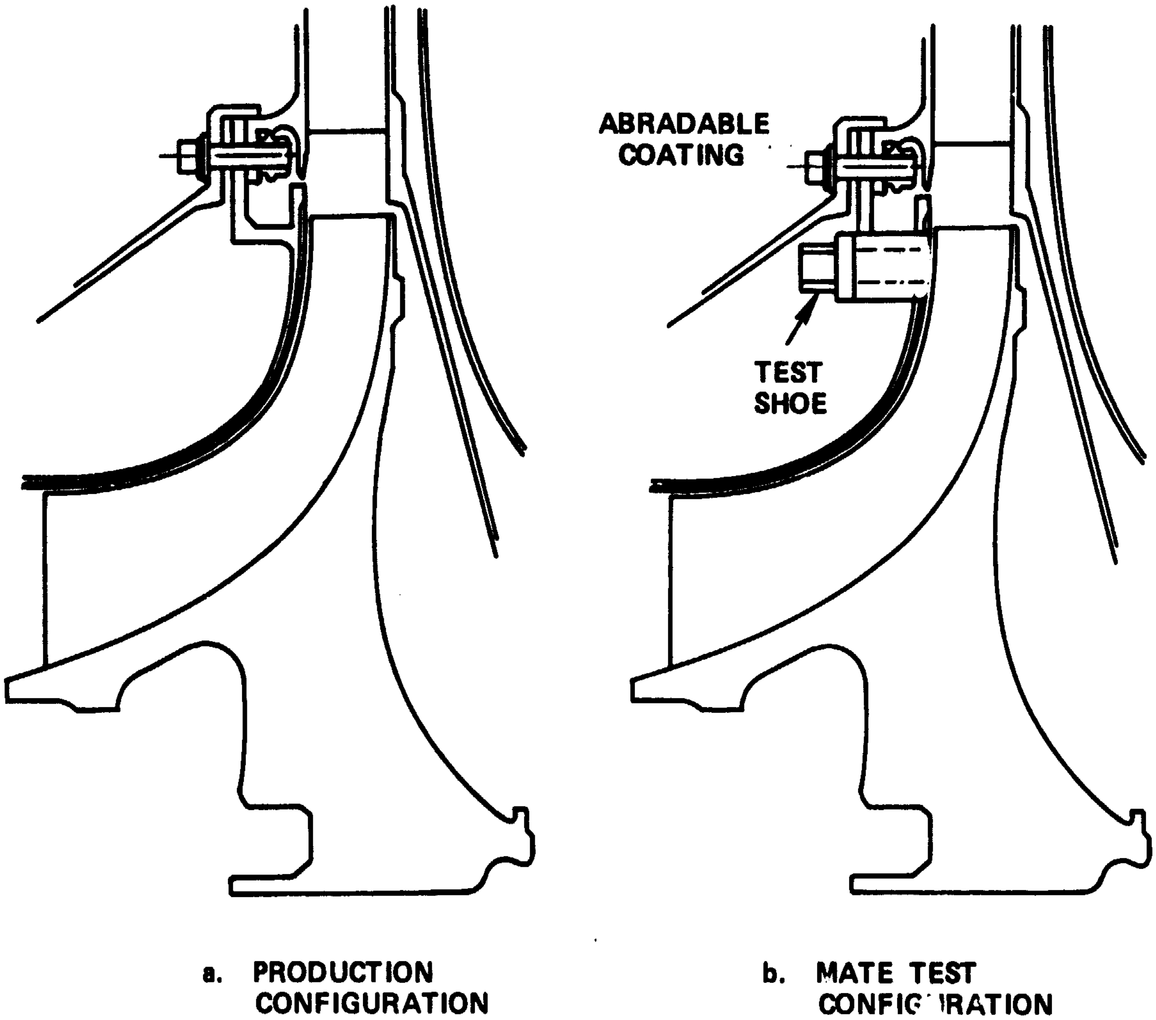


Figure 90. Schematic of the High-Pressure Compressor Shroud and the Impeller Showing both the Production Configuration and the Location of the Abradable-Coated Plug (Replaceable Shoe) for the MATE Test Configuration.

plug can be readily adjusted to provide the desired clearance contact with the impeller. In addition, the shroud was modified to provide for the installation of six proximity probes to monitor the impeller-abradable seal clearances, and to provide data for use in establishing impeller-to-shroud incursion rates. A view of the shroud showing the shoe and the proximity probe locations is presented in Figure 91. Figure 92 is a view of an uncoated INCONEL 718 alloy replaceable shoe.

The compressor case assembly and the interstage compressor diffuser were also modified to provide an access from the external surface of the case to permit replacement of the test shoe without engine disassembly.

2. High-Pressure Turbine. The high-pressure turbine shroud design consists of a stationary, essentially cylindrical ring attached to an upstream turbine nozzle assembly carrying the abradable-seal material on its inside diameter. In its installed position, the shroud is in the rotating plane of the turbine rotor, with the abradable material adjacent to the rotor-blade tips.

The standard high-pressure turbine shrouds are uncoated segments that are carried on circular support rings as shown in Figure 93. For the abradable testing, the shroud and shroud supports were modified as shown in Figure 94. The inside diameter of the shroud segments was moved radially outward to provide space for the abradable coating. The clearances were controlled by machining the I.D. of the abradable to provide a radial build-up clearance that was calculated to yield the desired blade-tip abradable rub. With this system, the clearances of different segments (i.e. different materials), machined on the same shroud support are the same, and no method is available for individual shroud adjustment. Six clearance-measurement probes were also installed in the shroud segments to provide information on the blade-to-shroud incursion and to monitor the operating clearances. A view of the high-pressure turbine shroud assembly with an abradable material applied, and the test instrumentation installed is presented in Figure 95.

3. Low-Pressure Turbine. The low-pressure turbine contains three stages. Each stage consists of an integral stator casting that contains stationary vanes which are located upstream from the rotor and a continuous ring shroud. The rotor blades are shrouded with two knife-edge projections at the tip. When assembled as a complete rotor, the knife edges form two parallel ridges that form two parallel wear tracks on the shroud I.D. during any contact. The production second-stage configuration is shown in Figure 96 as a typical LP stage with no coating on the shroud.

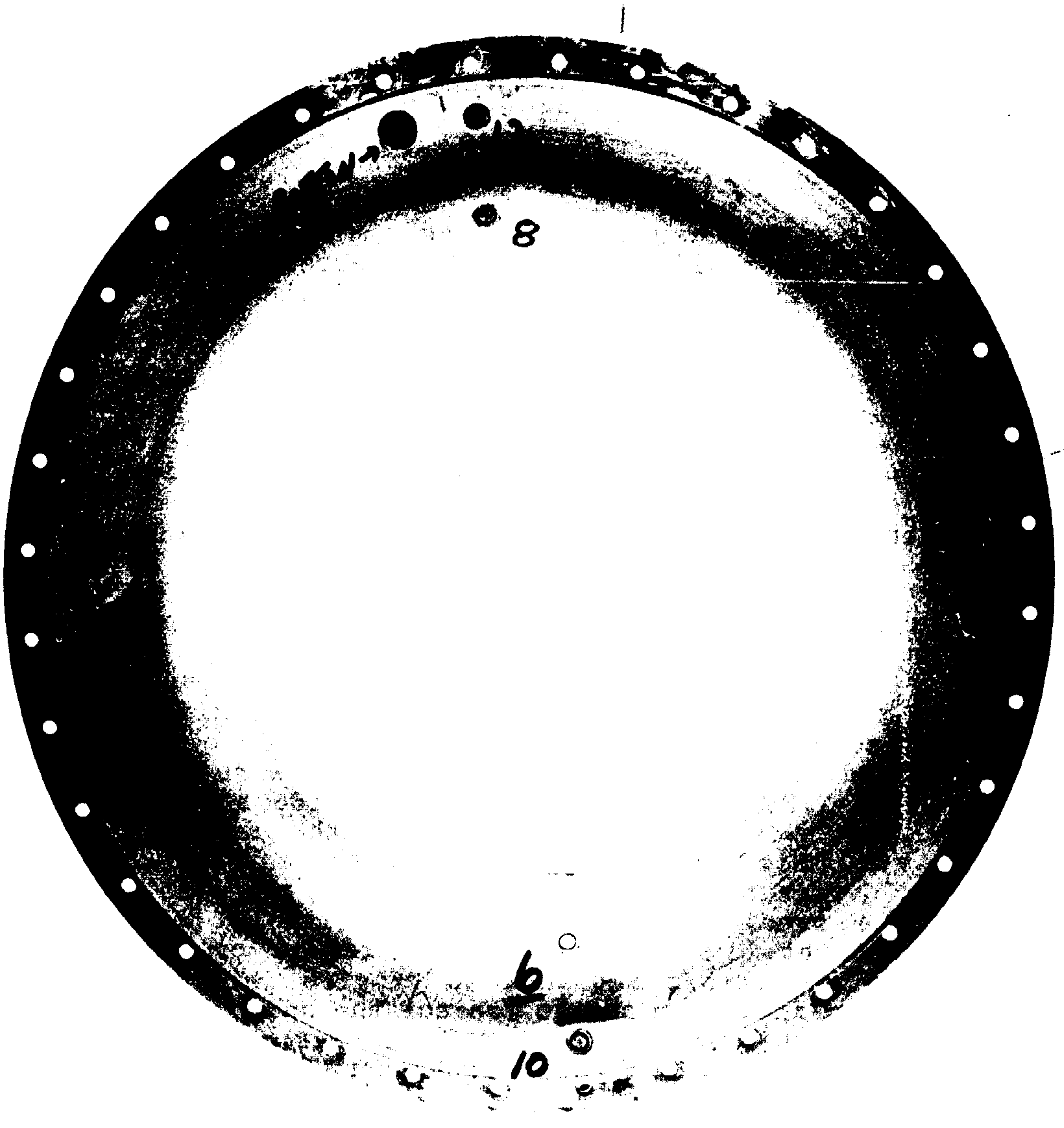


Figure 91. High-Pressure Compressor Shroud Showing the Location of the Replaceable Shoe and the Six Clearance-Measurement Probes

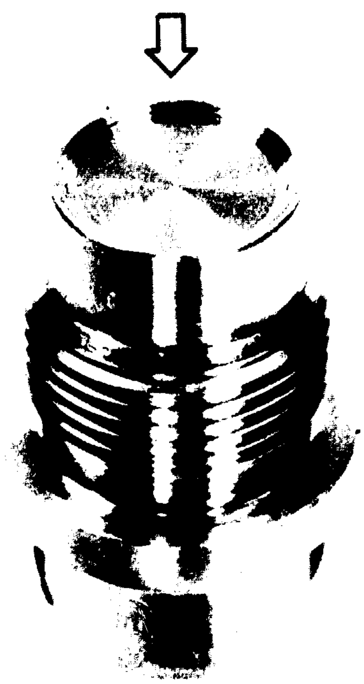


Figure 92. Replaceable Shoe for Testing Abradable Candidates in the High-Pressure Compressor (The Arrow Indicates the Surface for Attachment of the Material) (Mag.: Approximately 3X)

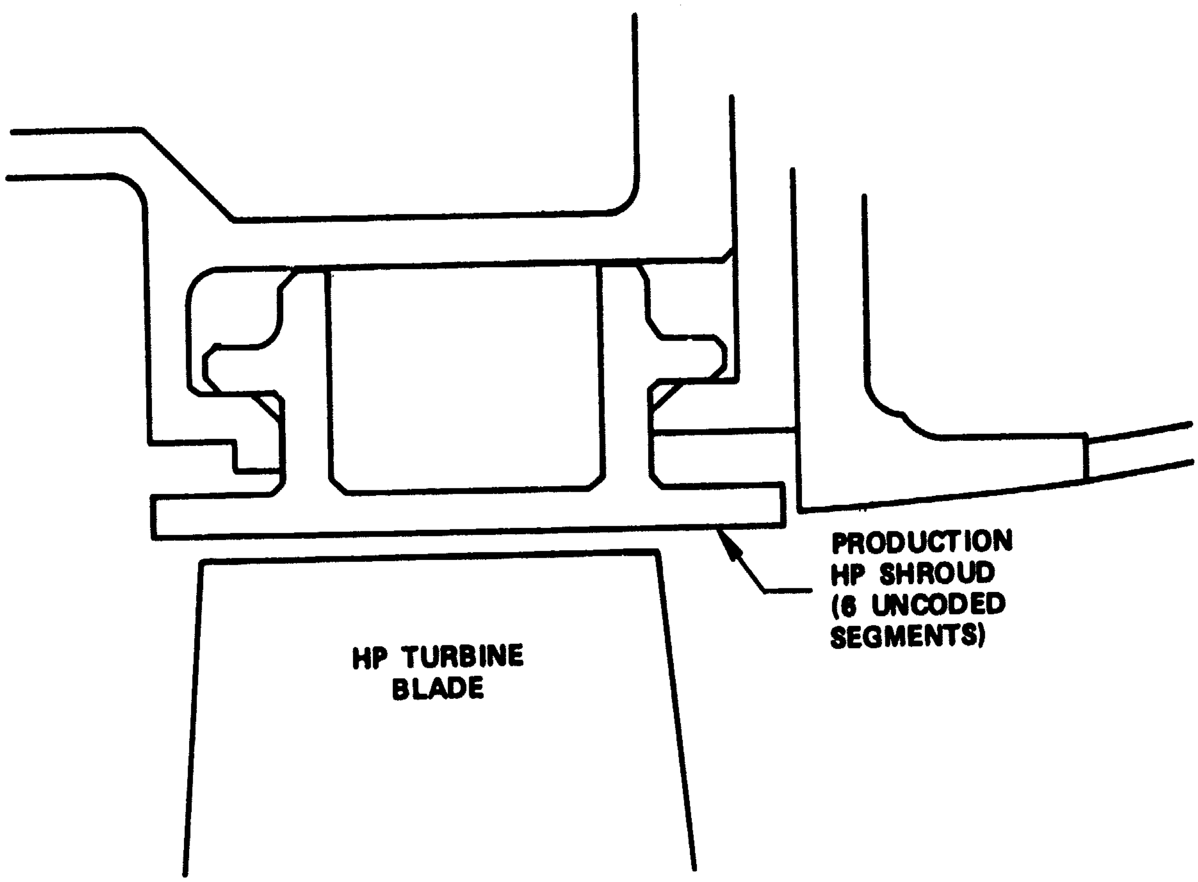


Figure 93. Production TFE731-3 High-Pressure Turbine Shroud Configuration

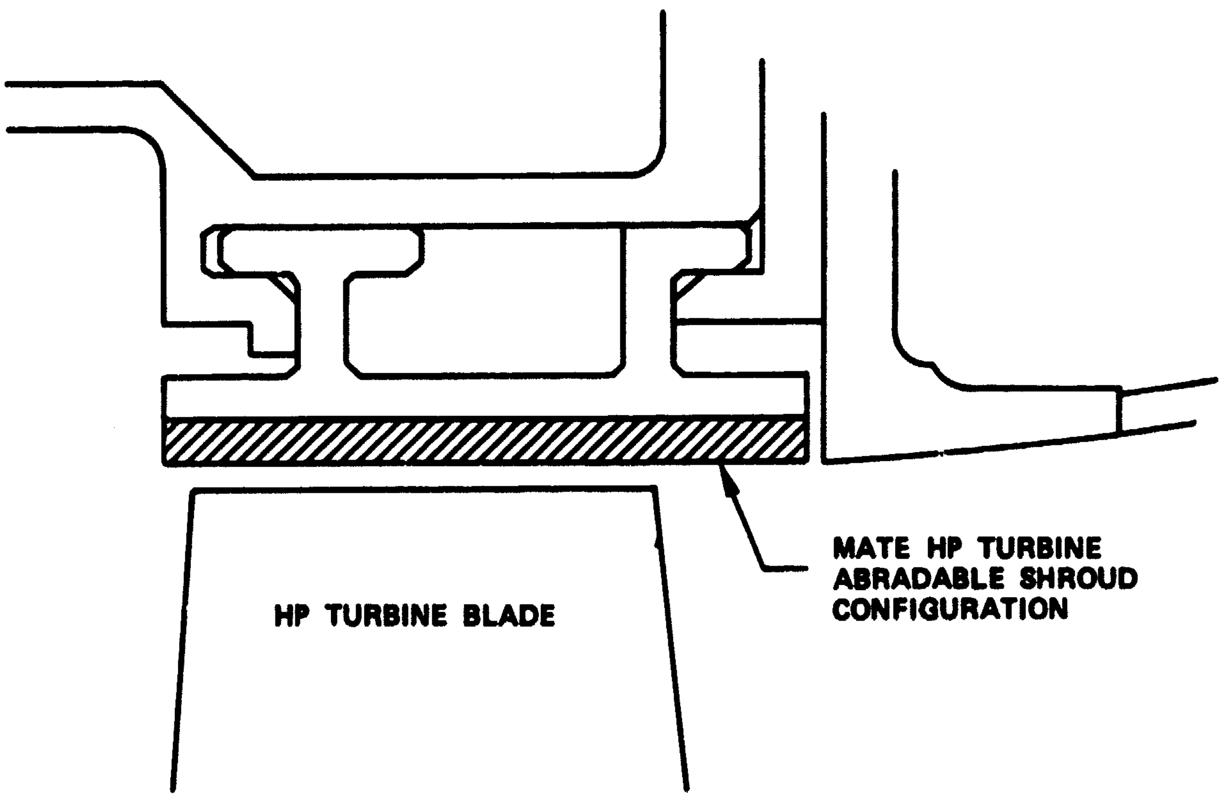


Figure 94. MATE High-Pressure Turbine Abradable Shroud Configuration

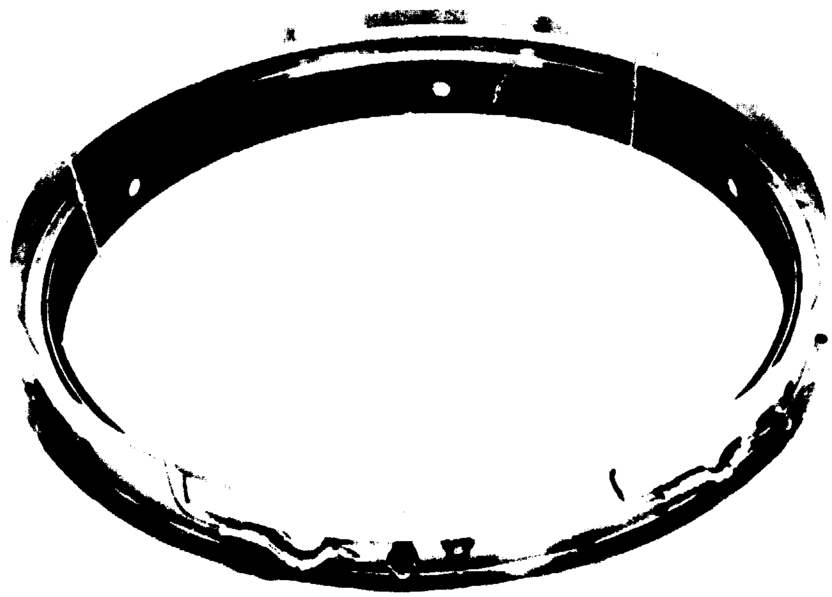


Figure 95. High-Pressure Turbine Shroud Assembly Showing the Location of the Six Clearance-Measurement Probes

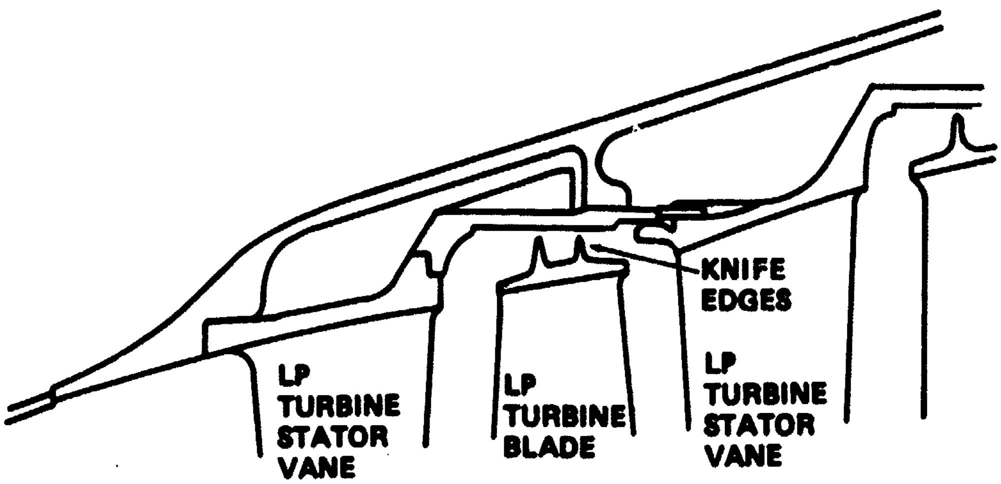


Figure 96. Production TFE731-3 Low-Pressure Turbine Shroud Configuration

Each low-pressure turbine nozzle assembly was modified the minimum amount to accommodate the abradable test materials, and to provide the proper clearances to achieve a rub at operating temperatures. No modifications were made to the turbine rotors. The modified second-stage configuration is shown in Figure 97. Photographs of the first-, second-, and third-stage nozzle assemblies are presented in Figures 98, 99, and 100, respectively.

Verification of Design Modifications

The results of the Interim Engine Testing (Tasks II and IIA indicated that the redesign of the shrouds to accept the abradable materials, and to provide clearance limits suitable for the MATE test purposes was satisfactory. Clearances were adjusted slightly in subsequent testing, but the basic design changes proved acceptable. Thus, the preliminary drawings employed for the Tasks II and IIA test configurations were finalized with only minor changes. In addition to the basic design definitions, the drawings include (either directly or by reference to appropriate specifications and/or other documents) the quality assurance requirements necessary to fabricate and accept hardware suitable for the Task VI Final Engine Testing.

Engine-Assembly Clearance Analysis

The cold (room temperature) engine build clearances were initally reduced to a level designed to ensure abradable rubs at the expected operating temperatures. This reduction was based on existing engine detail design, current production limits, and previous test and post-test critical examination experience. Each component was analyzed separately, but the average cold radial clearances applied in the First Interim Engine Test, Build 1, were approximately half of the normal production engine clearances. Evaluation of the blade-shroud contact following completion of the Build 1 testing verified the validity of the method utilized to determine build-up clearances. Thus, the assemblies for the subsequent Interim Engine Tests (Builds 2, 3 and 4) were accomplished with only minor changes to some clearances. The measured clearances and the resulting blade-shroud contact data from all of the Interim Engine Tests were used to establish the assembly clearances for the Task VI Final Engine Test.

The drawings produced for the Final Engine Test hardware are tabuled in Table XVII:

Without special instrumentation and/or expensive and time consuming component testing, it is virtually impossible to separate the improvements of the modified components during engine

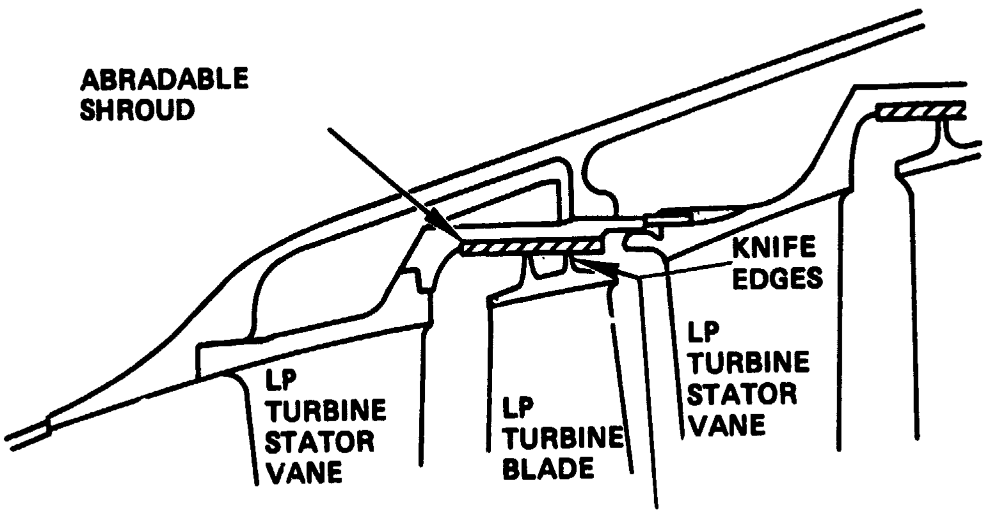


Figure 97. MATE Low-Pressure Turbine Abradable Shroud Configuration

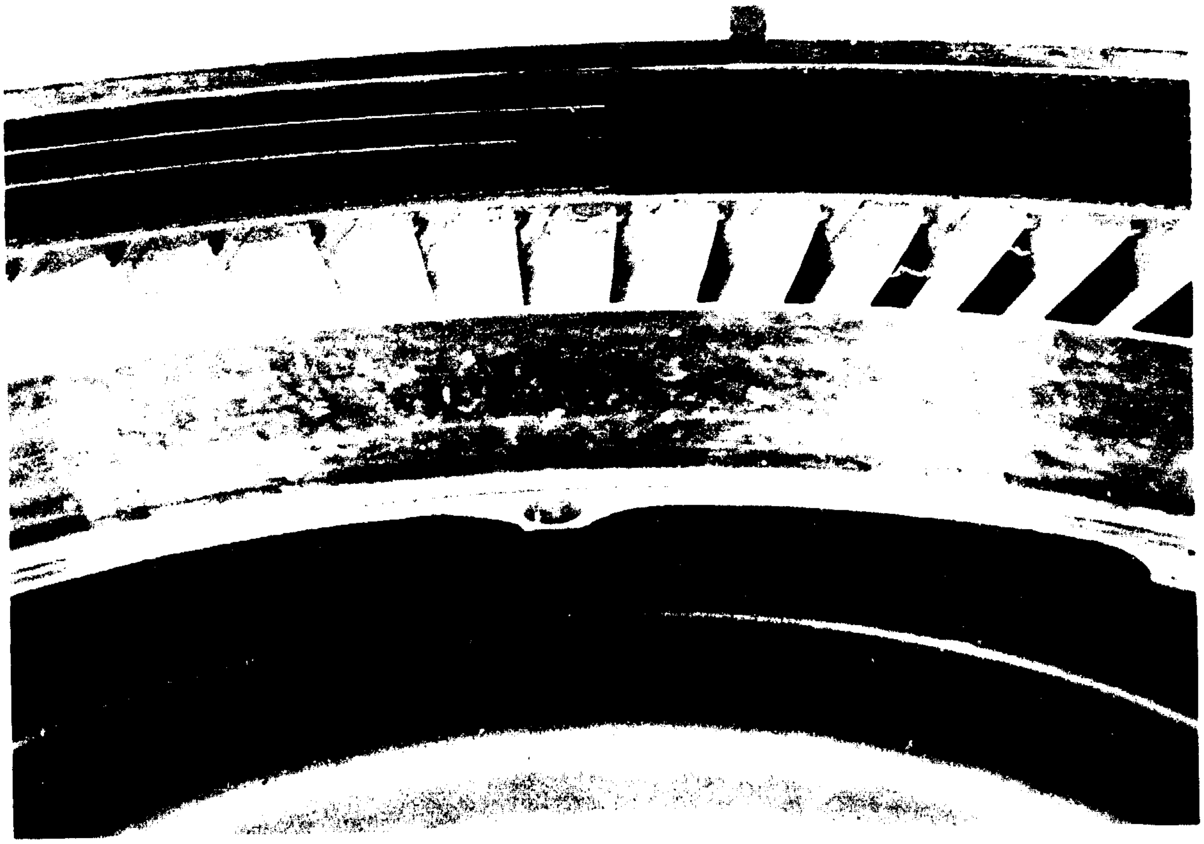


Figure 98. First-Stage Low-Pressure Turbine Nozzle Coated with UCAR AB-2 and Hastelloy-X Honeycomb Materials

Figure 99. Second-Stage Low-Pressure Turbine Nozzle
with Solabrade Applied

Figure 100. Third-Stage Low-Pressure Turbine Nozzle with Feltmetal FM-522 Applied

TABLE XVII. TABULATION OF THE DRAWINGS PRODUCED FOR THE FINAL ABRADABLE COMPRESSOR AND TURBINE HARDWARE

Component	Part No.	Comments
HP Compressor Shroud	3069978	METCO 601 coating applied
HP Turbine Shroud	PAP242545	UCAR AB-4 coating
LP Turbine Shroud		
First Stage	PAP242546	Hastelloy-X Honeycomb
Second Stage	PAP242547	METCO 301-10
Third Stage	PAP242548	METCO 304NS

testing. However, based on previous AiResearch experience in compressor and turbine rigs, the effects of component clearance reduction on engine efficiency can be estimated. Using this technique, the performance predictions for the Final Engine Test (Task VI) are tabulated in Table XVIII. The performance improvements are presented in terms of improvement in TSFC which is measured during engine testing with standard instrumentation.

TABLE XVIII. PERFORMANCE AND LIFE PREDICTIONS FOR THE TASK VI FINAL ENGINE TEST

Component	Predicted Performance Improvement (TSFC)	Predicted Life
HP Compressor	-0.3%	150 Hours
HP Turbine	-0.4%	a
First-Stage LP Turbine	-0.4%	150 hours
Second-Stage LP Turbine	-0.3%	150 hours
Third-Stage LP Turbine	-0.2%	150 hours
TOTAL	-1.6%	
GOAL	-1.5%	

[a] One of the HPT shroud materials, Metco 443 (open), did not rub in the Interim Engine Test; therefore, no prediction can be made

TASK IV - MANUFACTURING PROCESS DEVELOPMENT

The objective of Task IV was to finalize the component fabrication methods of the abradables selected for use in the manufacture of hardware in Task V for the Final Engine Testing (Task VI).

An on going evaluation of the fabrication methods was performed as part of Tasks I, II, IIA, and III, and the results of these evaluations are discussed in the respective sections of this report. The evaluation effort included review of supplier material specifications and production control documents, and the refinement of these documents, as necessary, to reflect the results of earlier tasks. This documentation consisted of AiResearch specifications, drawings, and other documents covering the procurement and installation of the selected abradable materials into the engine components required for the Task VI Engine Testing.

TASK V - COMPONENT FABRICATION

Two complete sets of hardware for the high-pressure compressor, the high-pressure turbine, and the low-pressure turbine were fabricated with the selected abradable gas-path seal coatings to support the Task VI Final Engine Testing. The abradable materials used in these components were selected following completion of the Interim Engine Testing (Tasks II and IIA), as listed in Table XV. This hardware was fabricated in accordance with the finalized specification defined in Task IV, and the drawing requirements established in Task III. The fabrication was accomplished by AiResearch or the supplier, as appropriate. Each component was subjected to detailed inspection and acceptance in accordance with the Reliability and Quality Assurance provisions of the contract. Photographs of each component and photomacrographs (Mag.: 5X) of each coated surface were made prior to testing. Test results will be covered in Volume II of this Project Completion Report.

COST OBJECTIVE

The Project 2 cost goal (contractual objective) is listed below. The other goals of this project will be discussed in Volume II of this report.

- Coating cost not to exceed 10 percent of the part cost.

Based on production-type quotes, and the design changes developed in this project, the cost goals were achieved as illustrated in Figure 101. This presents the abradable cost for the components where potentially acceptable coatings have been identified for future work. No cost comparison was prepared for the HP turbine segments since only the UCAR AB-4 has been successfully tested, and this material is not currently commercially available because of the marketing decision of Union Carbide as discussed earlier.

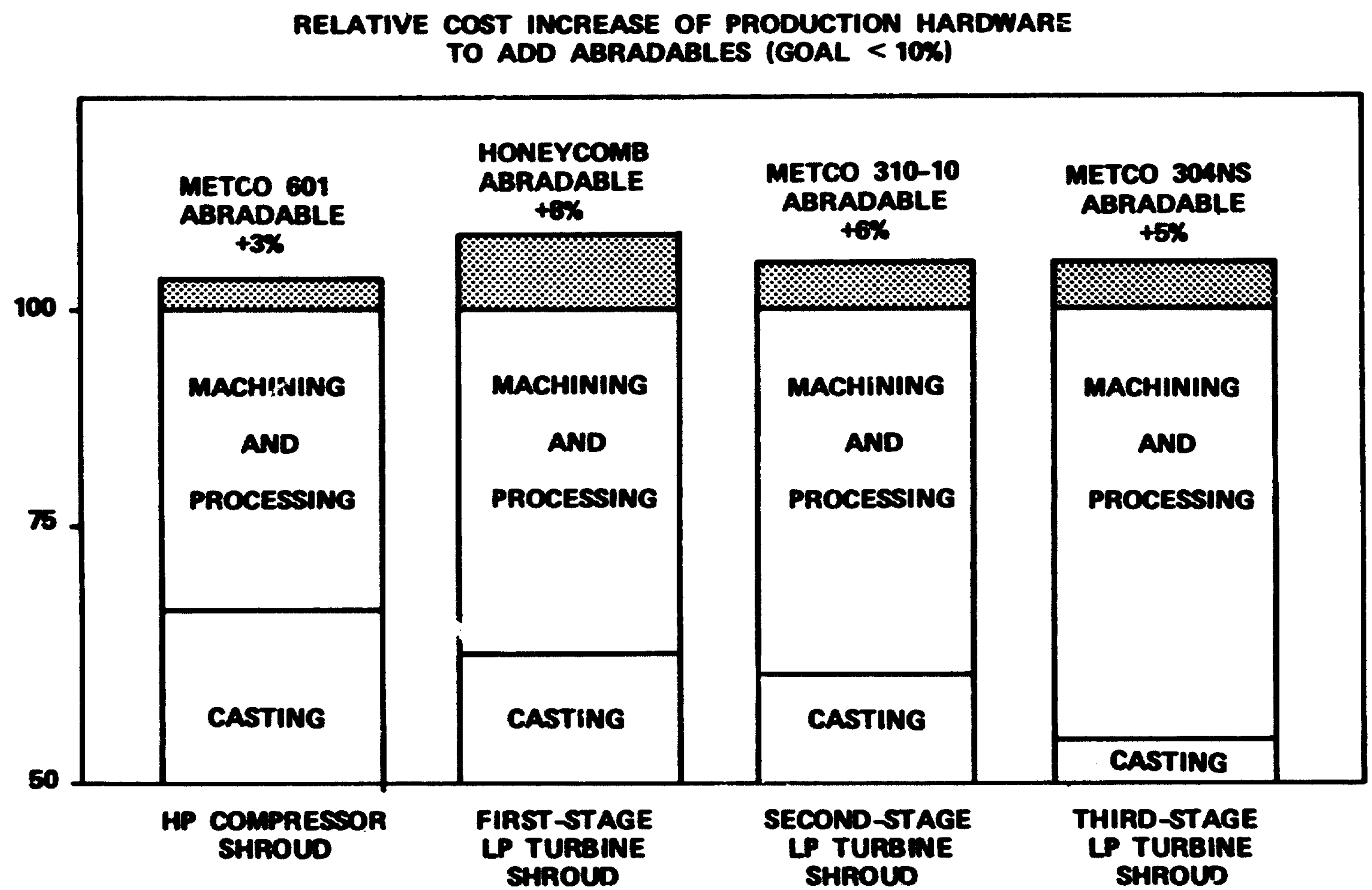


Figure 101. Cost Comparison for the Abradable Compressor and Turbine Components That Had Potentially Acceptable Coatings

CONCLUSIONS

Based upon the material properties evaluations, Interim Engine Tests, and the design and procurement considerations performed in this project (MATE Project 2), the materials in Table III offer the best potential of all materials considered for use as gas-path seals in the TFE731-3 Engine. The materials listed in Table XIV were selected for further evaluation in the Full-Scale Engine Test of Task VI.

The minimum cost increase goal of 10 percent has been achieved in all components except the HP turbine. Acceptable processes have been identified, and an abradable design has been selected prior to the scheduled 150-hour endurance test.

The Final Engine Test results and Post-Test Evaluations are described in Volume II of this report.

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(a) Optical View of Rub Area (Mag.: 4X)
(Arrows Show Pins That Held the Material in Place)

(b) SEM Image of Rub Area (Mag.: 100X)

Figure 51. High-Pressure Turbine Shroud Segment BR-1 (Bradelloy 500) Showing One of the Smeared Regions Present After the First Interim Engine Test, Build 2

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