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Materials for Advanced Turbine Engines

Project Completion Report
Project 2

René 150 Directionally Solidified Superalloy Turbine Blades

Volume I

by

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16 Abstract

A four-year cooperative Government/Industry project, performed within the overall Materials for Advanced Turbine Engines (MATE) program, was conducted to produce and engine test directionally solidified (DS) rotating parts from the nickel-base superalloy René 150 using refined casting and manufacturing methods. The parts produced were the Stage 1 high pressure turbine blades for the CF6-50 engine The goals of the project were (1) to demonstrate the increased operational-temperature capability of DS René 150 turbine blades to achieve at least 1.45% sfc improvement in a variable-payload, advanced, commercial CF6-50 engine and (2) to refine a blade-casting process which would allow such blades to be fabricated in production quantities at a cost not greater than 1.5 times the cost of conventionally cast René 80 turbine blades

The project was divided into eight principal tasks. Task I included turbine blade design and analysis. Task II included alloy procurement and evaluation, mold/core selection, and development of preliminary casting parameters Task III involved the adaptation and evaluation of an external coating system for the René 150 turbine blades Task IV finalized the process for producing the René 150 turbine blade castings and included a preproduction demonstration casting run and a projected cost analysis. Task V covered the production of finished turbine blades which were subsequently tested and analyzed in order to qualify them for factory engine testing Task VI involved the manufacture of finished turbine blades for engine test. Task VII covered the testing of the finished René 150 turbine blades in a ground-based fan engine. The results of the fan engine test were analyzed in Task VIII. Volume II documents the results of the core engine test in Task V and the results of the last two tasks.

HPT blades were successfully manufactured from DS castings made from a production-size heat of René 150 Mechanical and physical properties of the blades met design requirements in both the coated and the uncoated condition, and the blades were tested in an accelerated endurance engine test, the results of which are given under separate cover in Volume II

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PREFACE

This report was prepared for the National Aeronautics and Space Administration, Lewis Research Center, under Contract NAS3-20074. It presents the results of a four-year project to refine methods for producing directionally solidified René 150 blades for the first stage of the CF6-50 high pressure turbine. The objectives were to demonstrate the increased operating-temperature capability of directionally solidified René 150 turbine blades and to refine a blade-casting process which would allow such blades to be fabricated in production quantities at an effective cost.

Appreciation is expressed for the contributions of D.B. Arnold, R.E. Allen, L.G. Wilbers, E.J. Kerzicnik, and T.K. Redden who were involved in Program Management of Project 2.

Appreciation is also expressed to C.M. Scheuermann, C.P. Blankenship, and S.J. Grisaffe of NASA Research Center; their guidance and counsel were invaluable to the overall successful completion of Project 2.

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NOMENCLATURE

A-A	Axial-Axial
A-B	Axial-Bending
BOM	Bill of Material
CC	Conventionally Cast
CSF	Combined Stress/Fatigue
DBTT	Ductile/Brittle Transition Temperature
DOC	Direct Operating Cost
DS	Directionally Solidified
EA	Electroplate Aluminide
ECM	Electrochemical Machining
EDAX	Energy-Dispersive Analysis of X-Ray
El	Elongation
FOD	Foreign-Object Damage
FPI	Fluorescent-Penetrant Inspection
HCF	High Cycle Fatigue
HPT	High Pressure Turbine
L	Longitudinal
LCF	Low Cycle Fatigue
MATE	Materials for Advanced Turbine Engines
RA	Reduction in Area
RAM-DS	Rapid, Automated, Multistation, Directional Solidification
ROI	Return on Investment
RT	Room Temperature
sfc	Specific Fuel Consumption

NOMENCLATURE (Concluded)

SETS	Simulated Engine Thermal Shock
SPLCF	Sustained-Peak-Loading Cyclic Fatigue
UTS	Ultimate Tensile Strength
YS	Yield Strength

1.0 SUMMARY

The objective of this Project was to scale-up René 150, an advanced directional solidified (DS) turbine blade alloy, for application to first-stage high pressure turbine (HPT) blades in the CF6-50 engine. This scale-up would permit an increased operating temperature capability of René 150 over René 80 that would result in a 1.45% specific fuel consumption (sfc) saving in an advanced, variable-payload, commercial CF6-50 engine. In this program, the casting process was refined to show that such blades could be fabricated in production quantities at a cost not greater than 1.5 times the cost of conventionally cast (CC) René 80 turbine blades.

Using the property data available for René 150 at the initiation of the project in September 1977, shown in Table I, a preliminary design analysis was conducted to determine the CF6-50 blade temperatures, loads, and stresses versus material capabilities. This analysis indicated the acceptability of René 150 to the CF6-50 Stage 1 HPT blade design. Cooling-air modification studies were then performed to determine the effects on blade temperatures, stresses, and life and to define the blade-cooling configuration necessary to accomplish the engine test demonstration. The René 150 blade-cooling configuration selected produced a bulk average temperature approximately 56° C (100° F) higher than that of the current CC René 80 blade. This was accomplished by removing one row of leading-edge cooling holes, as shown in Figure 1, and by the use of a metering plate on the bottom of the blade to control the amount of air entering the blade.

Concurrent with the preliminary design activities was the procurement and qualification of sufficient René 150 alloy to satisfy the needs of the overall project. A production-sized heat of René 150, 1.6 Mg (3500 lbm), was procured. The heat was subsequently qualified using General Electric's standard acceptance tests including chemistry-verification, castability, tensile, and stress rupture tests.

Four ceramic core materials and four face-coat/stucco ceramic shell combinations were evaluated for use in producing blade castings. The Sherwood SR-731 core body was ultimately selected based on fabricability and stability in contact with molten René 150 alloy. The alumina face-coat/mullite-stucco shell system was selected, based on the surface finish produced and temperature capability, for use in General Electric's Rapid Automated, Multistation, Directional-Solidification (RAM-DS) casting process.

The ceramic tooling necessary for blade production was procured, and preliminary casting trials were performed. A tooling modification was required in the shank area of the blade, shown in Figure 2, to provide additional metal thickness to prevent cracking during the casting operation. This additional material was subsequently removed by an electrochemical machining (ECM) operation to produce the desired configuration. Using the modified casting tooling, 20 final-design casting trials were conducted and fully evaluated in terms

Table I. Available René 150 Data at Project Initiation.

Test	Temperature, ° C (° F) Room Temperature	650 (1200)	760 (1400)	870 (1600)	980 (1800)	1100 (2000)
Tensile						
Ultimate Tensile Strength (UTS)	X	X	X	X	X	X
0.2% Yield Strength (YS)	X	X	X	X	X	X
Elongation (El)	X	X	X	X	X	X
Reduction in Area (RA)	X	X	X	X	X	X
Stress Rupture, 100 hr			X	X	X	X
Stress Rupture, 1000 hr			X	X	X	
Creep, 0.5%			X	X	X	
Low Cycle Fatigue (LCF)						
Strain Control (K_t = 1)			←	—	—	→
Load Control K_t = 1.4		←	→			
Load Control K_t = 2.8			X			
Load Control K_t = 8.0				X		
Comnbined Stress Fatigue (CSF); A = ∞, 1.0, 0.67; Axial-Axial and Axial-Bending			←	—	→	
Simulated Engine Thermal Shock (SETS)				←	—	→
Stability (1000-hr exposure)*				←	→	
Elastic Modulus	←	—	—	—	→	
Coefficient of Thermal Expansion	←	—	—	—	→	
Oxidation*				←	—	→
Hot Corrosion*				←	—	→

*Those properties marked with an asterisk were determined in the longitudinal direction only; all other properties were determined both in longitudinal and transverse directions.

←→ Range of temperature over which testing was conducted.

1.0 SUMMARY

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Stress Rupture, 100 hr			X	X	X	X
Stress Rupture, 1000 hr			X	X	X	
Creep, 0.5%			X	X	X	
Low Cycle Fatigue (LCF)						
Strain Control (K_t = 1)			◄	—	—	►
Load Control K_t = 1.4		◄	►			
Load Control K_t = 2.8			X			
Load Control K_t = 8.0				X		
Comnbined Stress Fatigue (CSF); A = ∞, 1.0, 0.67; Axial-Axial and Axial-Bending			◄	—	►	
Simulated Engine Thermal Shock (SETS)				◄	—	►
Stability (1000-hr exposure)*				◄	►	
Elastic Modulus	◄	—	—	—	►	
Coefficient of Thermal Expansion	◄	—	—	—	►	
Oxidation*				◄	—	►
Hot Corrosion*				◄	—	►

*Those properties marked with an asterisk were determined in the longitudinal direction only; all other properties were determined both in longitudinal and transverse directions.

◄——► Range of temperature over which testing was conducted.

	Bulk Average Temperature	Cooling Air Required	LCF Life	Stress Rupture Life
René 80	Baseline	Baseline	Baseline	Baseline
René 150	+56° C (100° F)	-0.23% W_{2c}	10X	2X

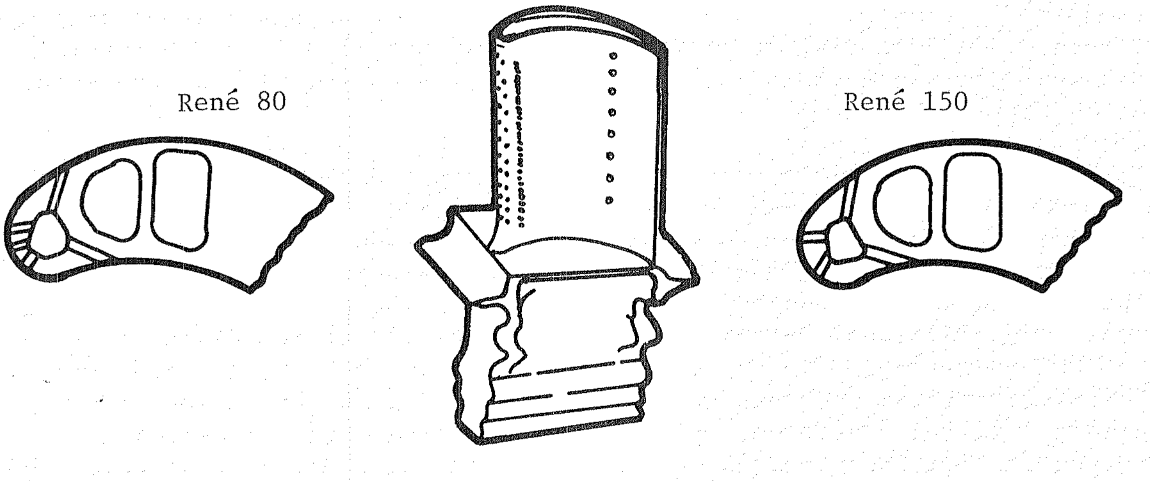


Figure 1. Improvements in Current CF6-50 Engine with René 150 Turbine Blades.

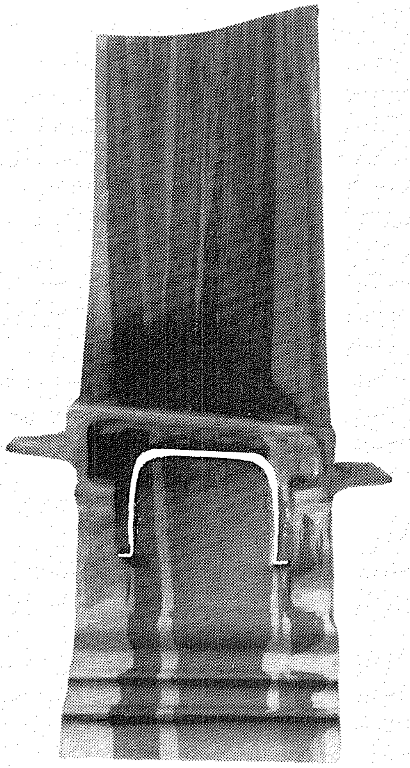


Figure 2. Final Design Casting Trials, CF6-50 Blade.

of grain structure, fluorescent penetrant inspection, visual inspection and X-ray inspection. No major problems were encountered; therefore, a preproduction run of castings was performed. Based on an overall yield of 80% through the initial foundry inspections, the final casting process specification was selected for use in the production of the component- and engine-test blades.

A cost analysis was performed to project the manufacturing cost for a production-size quantity of René 150 HPT blades produced to the final process specification and acceptance criteria. At a reasonably attainable yield for such blade hardware, it was estimated the cost of a René 150 turbine blade would be approximately 1.5 times that of a comparable equiaxed-grain René 80 turbine blade.

The René 150 blade castings for use in component and engine testing were produced using the RAM-DS process established in the project. These castings were serialized, processed through the foundry operations, had the cooling-hole pattern drilled, had the tip caps brazed in, were finish machined, and were inspected in accordance with engineering drawing requirements. The additional material in the shank region of the blade was removed by an ECM operation. The casting yield was found to be acceptable, and no major manufacturing problems were encountered with the exception of one cooling-hole drilling operation. Significant losses due to mislocated holes were experienced there because of the soft tooling that was utilized. These losses would not be expected in full production.

The electroplate aluminide (EA) NiCrAlHf coating process was initially selected to externally coat the René 150 blades. The selected coating contained three successive electroplated layers of chromium and nickel and a single pack-cementation process to add hafnium and aluminum to the coating. This coating was successfully adapted to the René 150 blade and evaluated with regard to protective capability on René 150; however, based on the results of a parallel, on-going program at General Electric, an alternate coating was selected and utilized on the component- and engine-test blades.

Concurrent with this blade manufacturing, mechanical-property and component tests were performed to provide maximum assurance that a safe and successful engine test could be run with René 150 HPT blades. These tests formed the basis for life and reliability predictions for the engine test. High cycle fatigue (HCF) tests were performed to provide a data base for setting limits on blade component tests and for comparison with blade data. The Goodman diagrams generated were used to establish HCF capability in relation to turbine blade design and performance. Blade component tests included:

- Strain distribution, frequency, and nodal-pattern tests to determine turbine blade reponse to various modes of excitation.

- Component HCF tests to establish blade fatigue strength relative to test-bar data and to determine the stress/strain capability of René 150 in the CF6-50 blade configuration.

- An instrumented core engine test to confirm the blade performance predictions based on laboratory tests.

- Impact tests to establish the relative foreign-object damage (FOD) resistance of the René 150 blades.

- Simulated Engine Thermal Shock (SETS) testing to provide information on the basic thermal-fatigue properties of René 150.

These tests confirmed that the René 150 CF6-50 Stage 1 HPT blade was satisfactory for the planned fan engine endurance test.

The completely finished and coated René 150 HPT blades were then installed in a CF6-50 rotor as shown in Figure 3. Engine assembly was completed, and the blades were endurance tested in a factory engine; the test results are presented in Volume II.

The results of Project 2 demonstrated the increased operating-temperature capability of René 150 and indicated that such blades could be produced at a cost within the target goal. The work served to advance the state of the art significantly for nickel-base, DS superalloys; the understanding gained concerning the behavior of such alloys was particularly valuable.

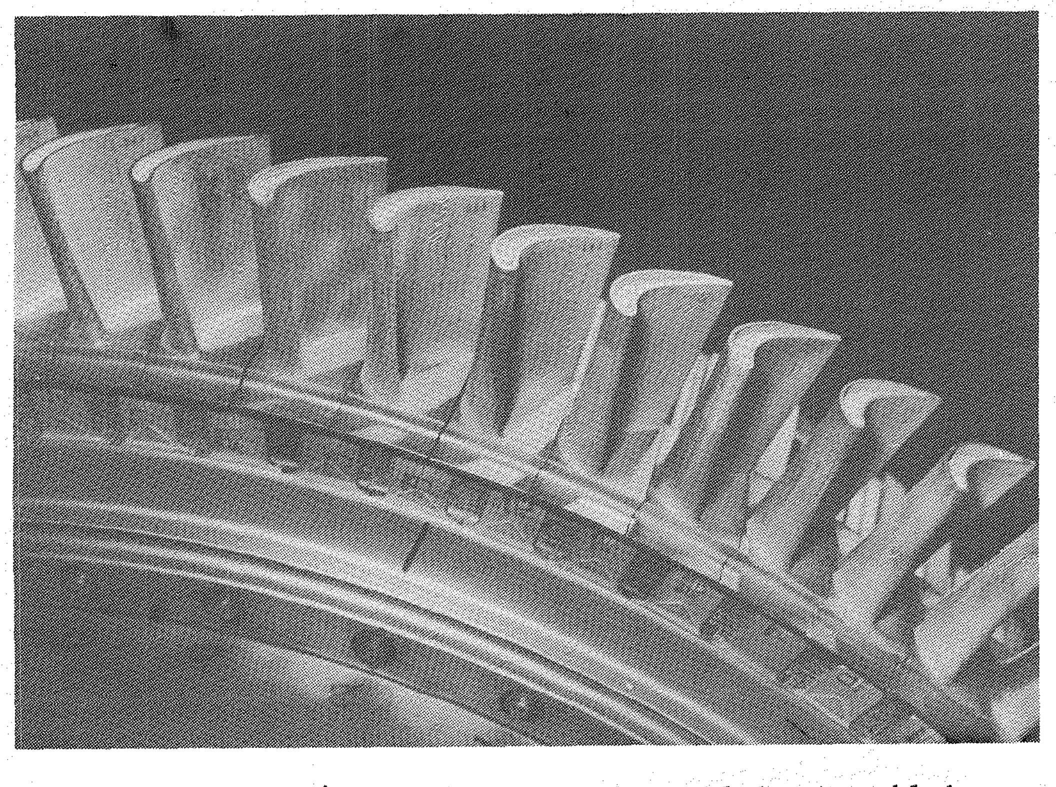


Figure 3. René 150 CF6-50 Stage 1 HPT Blades Assembled in Rotor.

2.0 INTRODUCTION

2.1 BACKGROUND

The NASA MATE Program has as the primary objective the accelerated introduction of new materials technologies into advanced aircraft gas turbine engines to achieve economic and performance advantages. The program encompasses the accelerated transfer of selected materials technologies, by scaling them up from the feasibility stage to engine demonstration, as well as the performance of cost/benefit analyses to provide guidance in the selection of the candidate material technologies.

General Electric's second MATE Project, described in this report, involved the scale-up of an advanced, directionally solidified, turbine blade alloy (René 150) for application to first-stage HPT blades in the CF6-50 engine. The following paragraphs describe the objectives of this MATE project effort together with some of the characteristics of René 150.

From the earliest days of jet engine technology, improved turbine blade materials have been desired. The result has been the development of a new class of superalloys. The growth in temperature capability has been about 8° C (15° F) per year. Since the early 1950's this growth in capability has depended on improvements of gamma prime (γ') strengthened, nickel-base superalloys. Significant improvements in equiaxed, vacuum-cast superalloys beyond the best alloy in use today (René 125) were considered unlikely.

Directional solidification of superalloys provides at least three important advantages over conventional, randomly oriented microstructures:

- Virtual elimination of strength-limiting grain boundaries perpendicular to the solidification direction; in turbine blades this is also the major stress axis. This elimination enhances rupture strength.

- A substantial reduction in elastic modulus in the solidification direction greatly reduces stresses generated by thermal gradients, thus increasing resistance to thermal fatigue.

- A large increase in ductility in the growth direction allows substantially greater amounts of alloying elements to be added for strength improvements while adequate ductility is maintained.

As a result, an alloy goal (René 150) was established by General Electric. The alloy was targeted to provide a substantial gain over René 125. René 150 is directionally solidified and gamma-prime strengthened, but it is more heavily alloyed than René 125 to take advantage of the benefits of directional solidification. The specified composition for René 150 is tabulated in Appendix A.

Alloys designed originally as conventionally cast (CC) materials historically offer only minimal temperature capability improvement when directionally solidified. René 150 was specifically developed to take full advantage of the benefits derived from the DS process and thereby provide an additional 28 to 33° C (50 to 60° F) rupture-strength margin over current DS alloys. This translates to a 64° C (115° F) margin over General Electric's production alloy, René 80, and a 33° C (60° F) margin over René 125.

Preliminary data on René 150 stress rupture strength indicated that it was 64 to 67° C (115 to 120° F) higher in temperature capability than CC René 80. The rupture strength of René 150 is compared with René 80 and René 125 in Figure 4. Other data on René 150 available prior to the initiation of this project are given in Appendix A: composition, density, tensile properties, modulus of elasticity, oxidation resistance, hot corrosion resistance, thermal expansion, LCF, and thermal conductivity.

The following estimated payoffs for René 150 were derived using a comparison of René 150 versus René 80 in an advanced version of General Electric's CF6-50 engine under variable payload conditions:

Parameter	Δ
Specific Fuel Consumption	- 1.45%
Fuel Usage	- 3.23%
Direct Operating Cost (DOC)	- 1.85%
Return on Investment (ROI)	+ 0.64%

A unique DS process was employed in this project; it is termed Rapid Automated Multistation DS (RAM-DS). The process is a significant departure from the traditional investment foundry practices and employs casting of blades separately in single molds within individual heating, cooling, and withdrawal systems rather than the conventional cluster mold approach.

Although General Electric had made excellent technical progress on René 150 development, a major scale-up effort was required to permit accelerated introduction of this alloy into commercial service.

2.2 PROGRAM OUTLINE

The overall objective of General Electric's MATE Project 2 was to scale-up and engine test René 150, an advanced DS turbine blade alloy. The turbine engine component selected to demonstrate this technology was the first-stage HPT blade of the CF6-50 engine. The target goals of this project were (1) to demonstrate an increased operating-temperature capability, by using DS René 150 turbine blades, which would achieve at least 1.45% sfc savings in an advanced, variable-payload, commercial CF6-50 engine and (2) to refine a

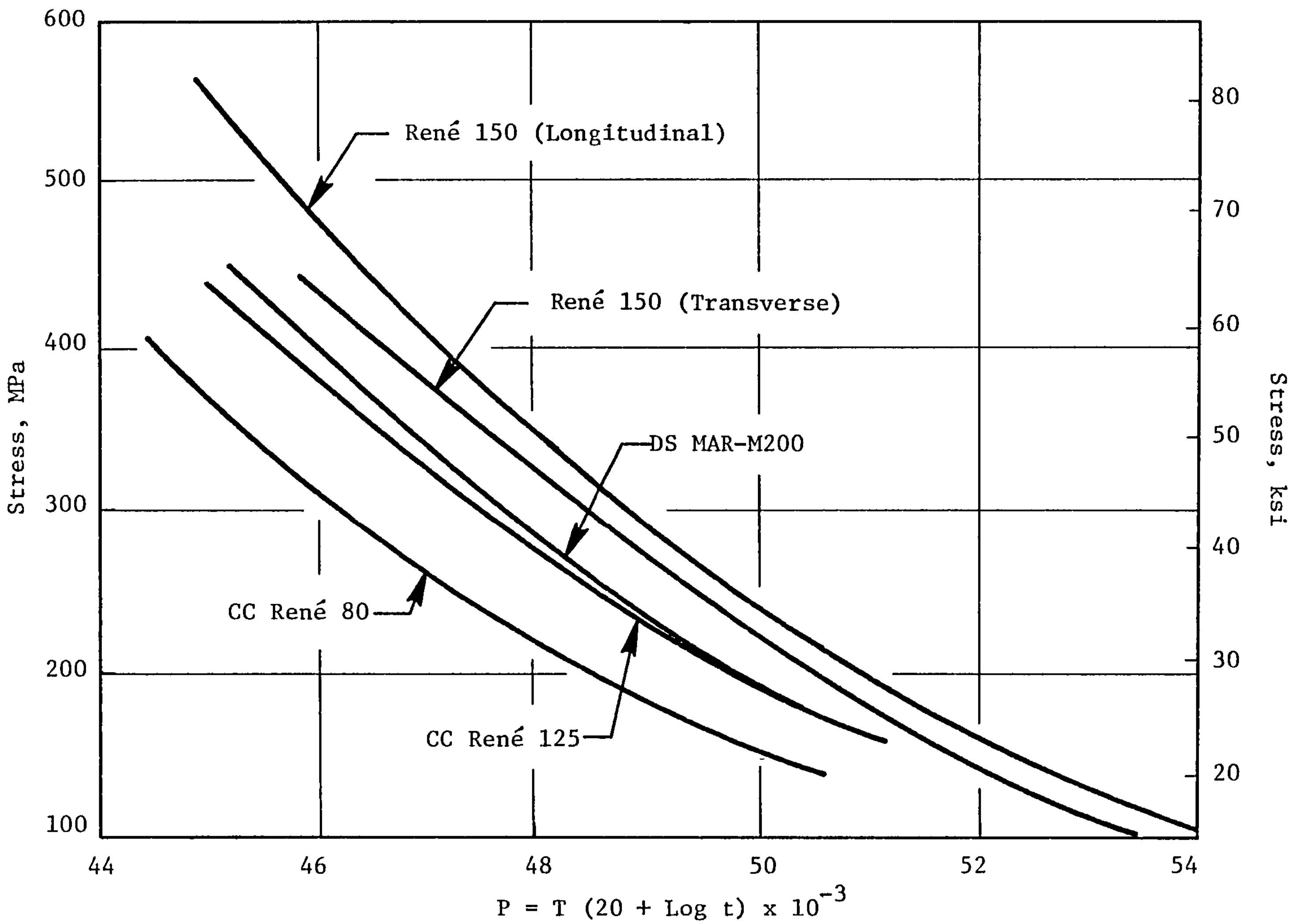


Figure 4. Stress Rupture of Turbine Blade Alloys.

blade-casting process that would allow such blades to be produced in production quantities at a cost not greater than 1.5 times the cost of CC René 80 turbine blades.

The Program Task structure of Project 2 was as follows:

Task I - Turbine Blade Design and Analysis

Task II - Preliminary René 150 System Refinement

Task III - Coating Adaptation and Evaluation

Task IV - Final René 150 System Refinement

Task V - Component-Test Blade Production and Evaluation

Task VI - Engine-Test Blade Production

Task VII - Engine Test

Task VIII - Posttest Analysis

A flow chart showing the overall program structure is shown in Figure 5.

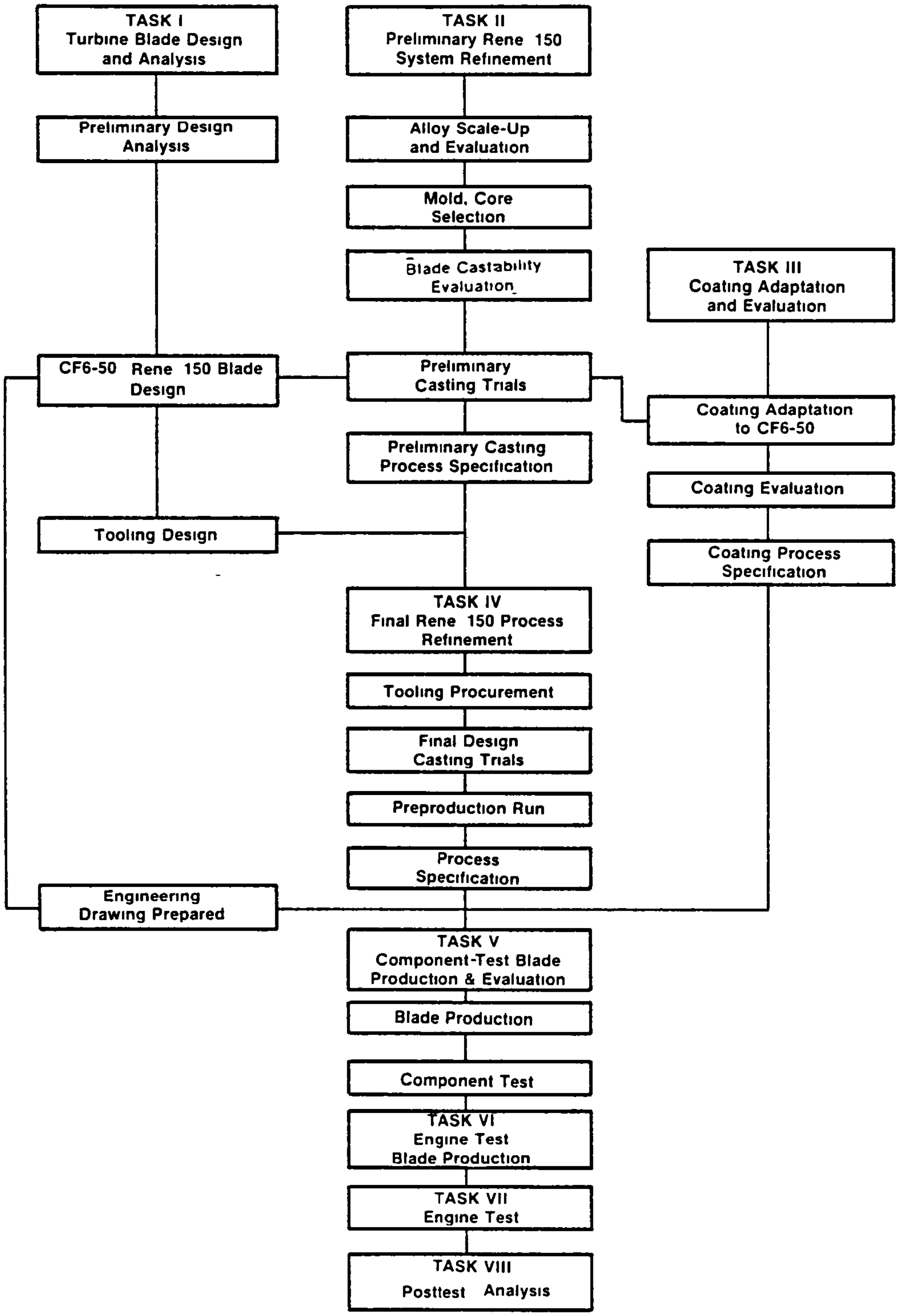


Figure 5. René 150 Directionally Solidified Superalloy Turbine Blade Project Plan.

3.0 TASK I - TURBINE BLADE DESIGN AND ANALYSIS

The objective of this task was to perform a design analysis to provide guidelines for the successful testing of René 150 turbine blades in an endurance factory engine test.

3.1 PRELIMINARY DESIGN ANALYSIS

A preliminary design analysis was conducted using the René 150 property data (Appendix A), available at the start of the project, to determine the CF6-50 blade temperatures, loads, and stresses.

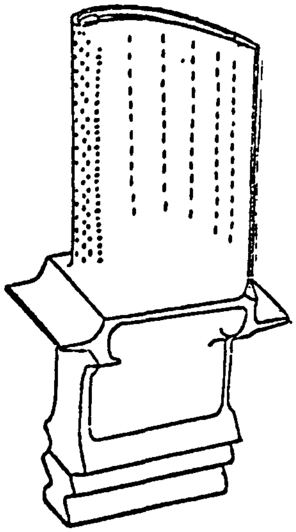
The pitch-line temperature analysis of the CF6-50M blade configuration (the current design and the one to be used in Project 2) was performed at CF6-50M engine temperature and speed conditions. The minimum life to rupture, based on a BUCKET CREEP III computer program analysis, was 4.2 times the rupture life of a comparably cooled, CC René 80 blade using the same assumptions as applicable. This analysis included thin-wall effects, a 10° grain misorientation factor, and a 0.7 safety factor.

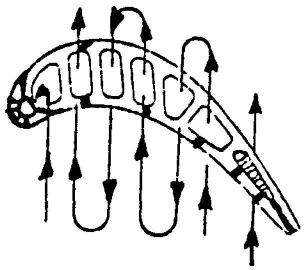
A similar analysis of low cycle fatigue (LCF) life revealed that the René 150 blade has a predicted life more than 16 times that of the CC René 80 blade under similar conditions and using average property data. Life is defined here as cycles to crack initiation on the airfoil leading edge. This preliminary analysis indicated the acceptability of René 150 to the CF6-50M Stage 1 HPT blade design.

3.2 René 150 CF6-50 BLADE DESIGN

The objective of this subtask was to conduct cooling-air modification studies to determine the effects on blade temperature, stress, and life analyses and to define the blade-cooling configuration necessary to accomplish the engine test demonstration. Since René 150 exhibits a higher temperature capability than the present production alloy, René 80, the method chosen to demonstrate the advantages of René 150 was to run blades of each alloy in the same engine such that René 80 blades would operate at normal temperatures and the René 150 blades would operate at representatively higher metal temperatures. The demonstrated increased temperature capability of René 150 over current superalloys, such as René 80, could then be translated into increased engine performance, engine life extension, or a combination of these. Specifically, the payoff options that René 150 would provide are:

Engine Performance - Higher temperature capability allows a reduction in cooling air for constant life and a corresponding improvement in fuel energy consumption. As an example, the potential sfc improvements in a current-production, fixed-payload, CF6-50 engine with René 150 turbine blades is shown in Figure 6. A more advanced CF6-50 variable-payload commercial engine application, which could most benefit by results of Project 2, could result in a 1.45% sfc improvement; this estimate is based on results of NASA's Study of Turbine Engines Designed for Low Energy Consumption (STEDLEC) program with General Electric. Higher allowable turbine inlet temperature also permits an increase in thrust at constant design stress levels and cooling flow-rates.





Material	Cooling Air	Cruise SFC	Takeoff SFC
René 80	3.5% W_{2c}	Base	Base
René 150	2.8% W_{2c}	-0.45%	-0.55%
	0.7% W_{2c} Reduction		

Figure 6. Potential SFC Improvements in a Production CF6-50 Engine with René 150 Stage 1 Turbine Blades.

Engine Life - Improved material properties allow an increase in turbine blade design life at constant stress, turbine inlet temperature, and cooling-airflow rates.

Based on this approach, the René 150 HPT blade-cooling configuration was designed to produce a bulk average temperature approximately 56° C (100° F) higher than that of the current René 80 HPT blade design in the factory engine test. This was accomplished by removing one row of leading-edge cooling holes, as shown in Figure 1, and by the use of a metering plate on the bottom of the blade to control the amount of air entering the blade. Heat transfer, stress, and life analyses indicated that the bulk average temperatures of the current, CC René 80 blade and the René 150 blade would be 953 and 1005° C (1747 and 1841° F) respectively.

The René 150 blade, even though operating at a temperature 56° C (100° F) higher, had an estimated stress rupture life approximately twice that of the René 80 blade. The LCF life predictions, given in Table II, show a tenfold or greater increase in cycle life for the René 150 blade.

Table II. Calculated LCF Lives for CF6-50 (M34) HPT Blades.

Location	Temperature, ° C (° F)		Life, Hours	
	CC René 80	René 150	CC René 80	René 150
Leading Edge	1038 (1901)	1098 (2008)	4060	15,000
Trailing Edge	1064 (1948)	1092 (1997)	7520	100,000
Pressure Face	1061 (1942)	1121 (2050)	4440	100,000
Pressure Gill Hole	868 (1595)	893 (1639)	610	7,500
Suction Gill Hole	833 (1532)	881 (1617)	390	9,000
Trailing-Edge Hole	952 (1746)	957 (1755)	2810	60,000
Crossover Hole	774 (1425)	797 (1466)	370	3,500

In addition to demonstrating the increased temperature capability of René 150, the selected cooling configuration produced a reduction in the amount of cooling air required. The net cooling air reduction for the René 150 HPT blade, based on a fixed-payload CF6-50 engine, is given in Table III. At the initiation of Project 2, the M-90 René 80 HPT blade design was in use and its cooling air requirements were utilized as a baseline. During the course of the program, a new growth version of the René 80 blade was developed. It was more efficient in cooling and allowed a cooling air reduction of 0.47% W_{2C} relative to the M-90 design. The timing was such that it was possible to produce the René 150 blade casting tooling to the new M-34 design. Modification of the René 150 M-34 blade cooling configuration to produce the desired 56° C (100° F) higher operating temperature resulted in an additional cooling air reduction of 0.23% W_{2C} relative to the comparable René 80 M-34 design blade.

Table III. Cooling Air Reduction for the René 150 HPTB Blade.

Material	Blade Design	Blade Cooling Air Requirements (%W_{2C})	Δ Cooling Air (%W_{2C})
René 80	M-90	3.50	Baseline
René 80	M-34	3.03	-0.47
René 150	M-34	2.80	-0.70

The René 150 HPT blade could therefore demonstrate improvements in temperature capability, rupture life, and LCF life along with reduced cooling-air requirements and a concomitant reduction in sfc.

3.3 TOOLING DESIGN AND BLADE DRAWING RELEASE

An engineering tooling drawing for procurement of the necessary casting tooling for the blade production in Tasks IV, V, and VI was prepared. The casting tooling was obtained from Trucast Tool and Mold, Inc., Cleveland, Ohio. Preliminary casting trials were conducted utilizing this tooling, and the results indicated that a modification of the casting tooling was required in the shank area of the blade. This area, below the blade platform, required additional thickness to preclude cracking during the casting operation. This additional material would be removed by a subsequent ECM operation to produce the desired configuration.

Existing René 80 blade drawings were modified to reflect the new cooling configuration to be used for the René 150 blade. In addition, the blade finishing processes were reviewed and modified to accommodate the change from CC René 80 to DS René 150. Final engineering drawings were issued to direct the manufacture of René 150 CF6-50 HPT blades for latter portions of the project.

4.0 TASK II - PRELIMINARY RENÉ 150 SYSTEM REFINEMENT

4.1 ALLOY SCALE-UP AND EVALUATION

The objective of this subtask was to produce and qualify sufficient René 150 material to satisfy the needs of the overall project.

A specification for the procurement of René 150 bar stock was prepared and is given in Appendix B. Special Metals Division of Allegheny Ludlum, New Hartford, New York was selected as the melter for the first production-size master heat.

A 1.6 Mg (3500 lbm) heat of pure nickel was melted in a vacuum induction facility to clean the melt crucible and reduce the possibility of contaminating the René 150 heat to follow. The René 150 charge was melted and sampled. Spectrographic analysis was obtained within 30 minutes and indicated the chemistry of the heat to be within specification. However, the titanium, cobalt, and hafnium contents were near the lower limits of the specification, and additions of each of these elements were made to the heat to bring the concentrations up to the middle of the range before pouring. The heat was subsequently cast, and the remelt bar stock was conditioned to 7 cm (2-3/4 in.) diameter prior to shipping. The heat (No. 7-11158) was received at General Electric in the form of bar stock as shown in Figure 7. The net weight of the bar stock delivered was 1.387 Mg (3058 lbm).

As specified, samples were removed from the first remelt ingot, one intermediate ingot, and the last ingot for chemical analysis to determine the acceptability of the heat. The certified analyses for the material obtained from Special Metals is presented in Table IV. Comparison of these data with the specification chemistry and General Electric's analysis of a middle ingot showed the heat to be acceptable.

The heat was evaluated for castability. The test configuration, shown in Figure 8, is a hollow tube of the alloy to be tested. As the tube is directionally solidified, the tube shrinks around the alumina core, and the resultant strain (about 2%) results in grain-boundary cracking in a crack-susceptible alloy. Castability ratings for several alloys, as established by this test, range from A (no cracking) to F (gross grain-boundary cracking); the castability of the René 150 production heat is rated A, as shown in Figure 8.

Remelt Ingot 30, a middle-of-the-heat ingot, was selected for property evaluation. A 4.13 cm (1-5/8 in.) diameter bar from Ingot 30 was directionally solidified at 38 cm/hr (15 in./hr), in General Electric's Evendale DS casting facility, using parameters similar to those to be used in General Electric's Albuquerque RAM-DS facility. The bar was sectioned into longitudinal and transverse blanks that were heat treated as follows:

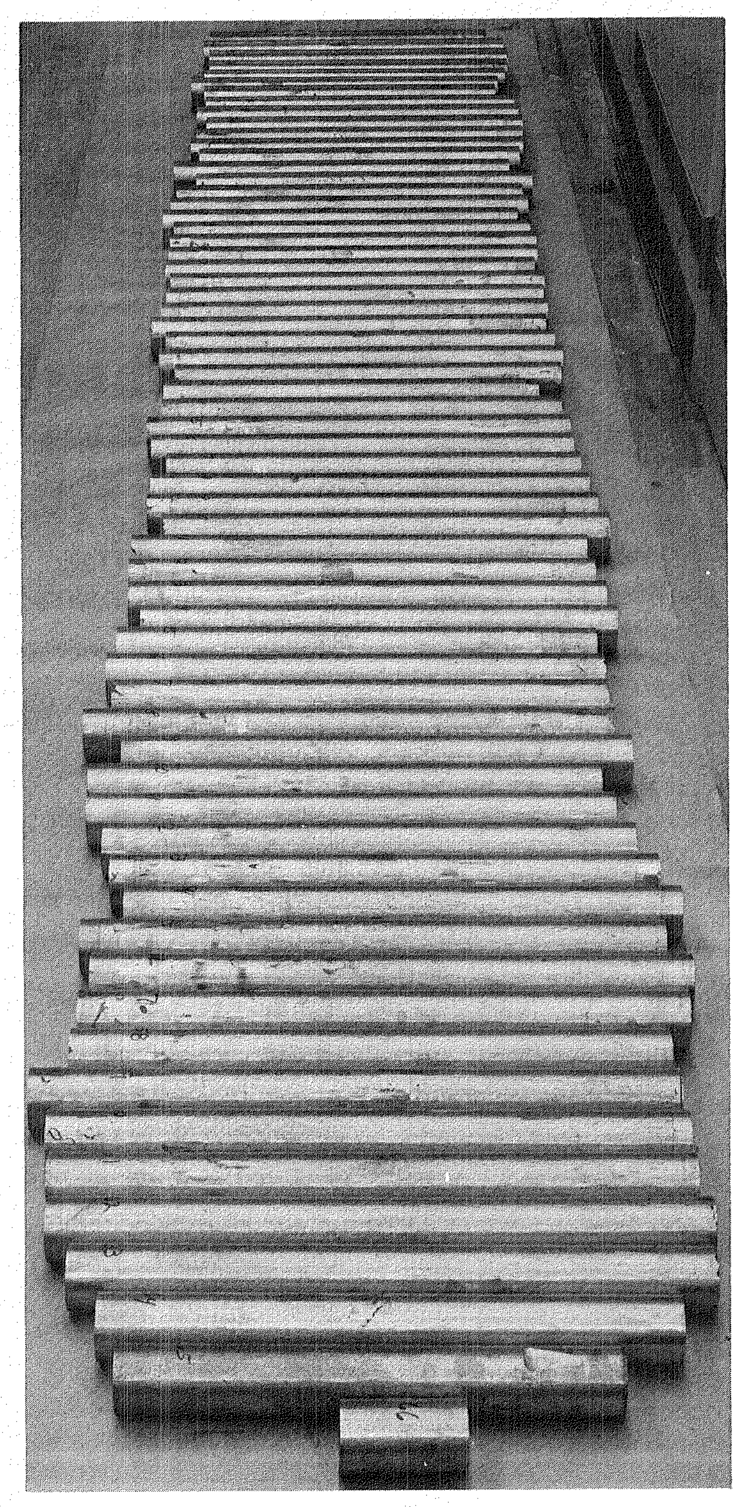
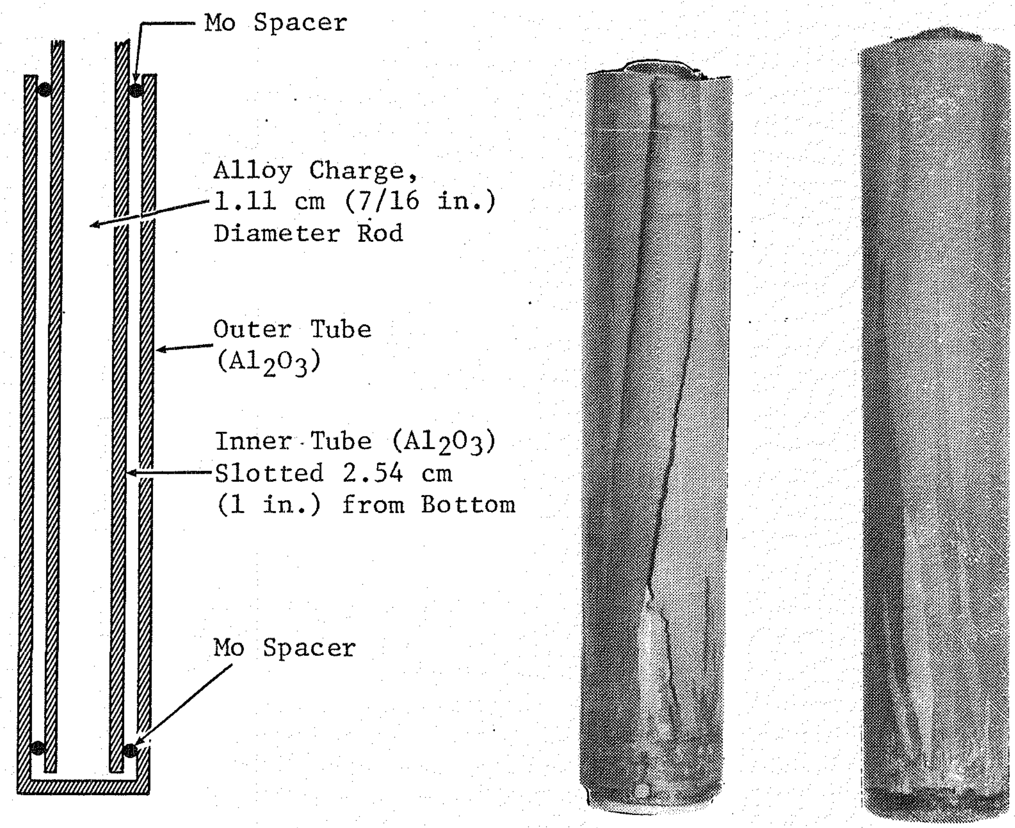


Figure 7. René 150 Remelt Ingots Cast from Heat 7-11158.

Table IV. René 150 Chemical Analysis, Weight Percent.

Elements	Specification B50TF171-1(T)	Vendor's Certified Analysis From Remelt Ingots			GE Analyses, Middle	
		First	Middle	Last	1	2
Co	11.50 - 12.50	12.0	12.0	12.0	11.96	11.92
Ta	5.75 - 6.25	5.87	5.87	5.86	5.82	5.75
Al	5.30 - 5.70	5.43	5.40	5.41	N.A.	N.A.
Cr	4.75 - 5.25	4.90	4.90	4.88	5.02	4.97
W	4.75 - 5.25	4.97	5.00	5.02	4.84	4.84
Rh	2.73 - 3.25	2.99	2.98	3.00	3.12	3.04
V	2.00 - 2.40	2.23	2.23	2.24	2.16	2.18
Hf	1.30 - 1.70	1.46	1.45	1.43	1.45	1.48
Mo	0.75 - 1.25	1.00	1.00	1.00	0.96	0.96
C	0.04 - 0.08	0.055	0.052	0.050		
B	0.01 - 0.02	0.016	0.016	0.016		
Mn	0.10 Max	<0.10	<0.10	<0.10		
Si	0.10 Max	<0.10	<0.10	<0.10		
S	0.01 Max	0.002	0.002	0.002		
P	0.01 Max	<0.01	0.01	<0.01		
Zr	-	-	-	-		
O	-	-	7 ppm	-		
N	-	-	6 ppm	-		



Test Configuration

Alloy with Poor Castability — René 150

Rating: F — A

Figure 8. René 150 Castability Test.

1205° C (2200° F), 1/2 hr, helium cool

+1080° C (1975° F), 4 hr, helium cool

+900° C (+1650° F), 16 hr, cool to room temperature (RT)

The above heat treatment is standard for René 150 and has provided a good balance of longitudinal and transverse properties. At 1205° C (2200° F) only a small amount of γ' solutioning occurs while most of it coarsens. Studies have shown that solution temperatures above 1205° C (2200° F) result in higher longitudinal strength at the expense of decreased transverse strength and ductility.

After heat treatment the specimens were machined and tested. The longitudinal specimens have a 0.4 cm (0.160 in.) diameter × 1.78 cm (0.70 in.) long gage section, and the transverse specimen gage is 0.32 cm (0.125 in.) diameter × 1.27 cm (0.5 in.) long.

The tensile and stress rupture data obtained are given in Table V. The results are also plotted on the appropriate René 150 data-base curves presented in Appendix A. Properties were as expected with the exception of the low transverse tensile ductility of one of the 980° C (1800° F) specimens. The other specimen had higher than average ductility. Such scatter in the transverse direction is not uncommon; it results from the variability in the orientation of individual grains. The stress rupture data of this heat are slightly below average properties; however, they are well within acceptable range. For most CC alloys, the -2σ limit used for heat-acceptance tests is about 60% of the average life. For Heat 7-11158 the test results indicate 75 to 80% of average life for René 150. These data confirm the acceptability of the heat for use in this program.

To provide a specimen data base for setting limits on blade component tests in Task V and for comparison with blade data, HCF tests were performed as part of this project. Eighteen 4.13 cm (1-5/8 in.) diameter bars were prepared for this evaluation. Six bars each were directionally solidified from Ingots 2, 32, and 62 in order to represent material from the first, middle, and last ingot to be cast from the heat. All the odd-number ingots from 1-63 were shipped to Albuquerque, approximately 680 kg (1,500 lbm).

Test specimens were machined from these DS bars in the desired direction and given the "standard" heat treatment prior to testing. The objective of the HCF testing was to determine the stress that would result in a minimum life of 10^7 cycles as a function of temperature, mode of excitation, and A-ratio (alternating stress/mean stress). From these data, Goodman diagrams were constructed in order to establish HCF capability in relation to turbine blade design and performance. The HCF data are given in Table VI. After the 10^7 cycle points were established at A-ratios of ∞ and 1.0, several tests were performed at an A-ratio of 0.5 in order to provide improved accuracy in the shape of the Goodman diagrams. In addition, a few tests were conducted

Table V. Stress Rupture and Tensile Properties of René 150, Heat 7-11158.

Property	Direction	Temperature, ° C	(° F)	Stress, MPa	(ksi)	Life, hr		Elongation, %	RA, %
Stress Rupture	Longitudinal	980	(1800)	259	(37.5)	68.8		27.4	38.8
	Longitudinal	980	(1800)	259	(37.5)	64.1		31.5	44.0
	Longitudinal	870	(1600)	552	(80.0)	48.8		16.7	22.5
	Longitudinal	870	(1600)	552	(80.0)	40.6		25.4	29.5
	Transverse	980	(1800)	241	(35.0)	58.3		4.0	4.7
	Transverse	980	(1800)	241	(35.0)	75.1		3.0	5.2
	Transverse	870	(1600)	448	(65.0)	54.4		-	0.8*
	Transverse	870	(1600)	448	(65.0)	157.6		-	4.7
				UTS, MPa	(ksi)	0.2% YS, MPa	(ksi)		
Tensile	Transverse	650	(1200)	980	(142.2)	792	(114.8)	10.9	19.4
	Transverse	650	(1200)	807	(117.1)	749	(108.6)	6.3	25.0
	Transverse	980	(1800)	614	(89.0)	509	(73.8)	2.3	3.2
	Transverse	980	(1800)	586	(85.0)	405	(58.8)	7.8	20.2

*Broke in Radius

Table VI. HCF Tests on René 150.

Test Temperature, °C (°F)	Specimen Direction	Mode*	A-Ratio	Maximum Stress, MPa (ksi)	Alternating Stress, MPa (ksi)	Cycles** To Failure
650 (1200)	Longitudinal	A + B	1 0	827 (120)	414 (60)	0 196 x 10^6
650 (1200)	Longitudinal	A + B	1 0	758 (110)	379 (55)	10^7 +
650 (1200)	Longitudinal	A + B	1 0	793 (115)	397 (57 5)	10^7 +
760 (1400)	Longitudinal	A + B	∞	434 (63)	434 (63)	0 614 x 10^6
760 (1400)	Longitudinal	A + B	∞	434 (63)	434 (63)	1 332 x 10^6
760 (1400)	Longitudinal	A + B	∞	400 (58)	400 (58)	10^7 +
760 (1400)	Longitudinal	A + A	0 95	827 (120)	403 (58 5)	0 391 x 10^6
760 (1400)	Longitudinal	A + A	0 95	758 (110)	370 (53 6)	0 311 x 10^6
760 (1400)	Longitudinal	A + A	0 95	689 (100)	336 (48 7)	3 767 x 10^6
760 (1400)	Longitudinal	A + A	0 95	655 (95)	319 (46 3)	6 471 x 10^6
760 (1400)	Longitudinal	A + A	∞	483 (70)	483 (70)	0 249 x 10^6
760 (1400)	Longitudinal	A + A	∞	414 (60)	414 (60)	1 224 x 10^6
760 (1400)	Transverse	A + B	∞	414 (60)	414 (60)	4 145 x 10^6
760 (1400)	Transverse	A + B	∞	379 (55)	379 (55)	8 570 x 10^6
760 (1400)	Transverse	A + A	0 95	621 (90)	302 (43 8)	0 397 x 10^6
760 (1400)	Transverse	A + A	0 95	586 (85)	285 (41 4)	7 344 x 10^6
760 (1400)	Transverse	A + A	0 95	552 (80)	268 (38 9)	10^7 +
760 (1400)	Longitudinal	A + A	∞	362 (52 5)	362 (52 5)	3 9 x 10^6
760 (1400)	Longitudinal	A + B	1 0	827 (120)	414 (60)	1 080 x 10^6
760 (1400)	Longitudinal	A + B	1 0	758 (110)	379 (55)	2 740 x 10^6
760 (1400)	Longitudinal	A + B	1 0	689 (100)	345 (50)	10^7 +
760 (1400)	Transverse	A + A	∞	345 (50)	345 (50)	0 945 x 10^6
760 (1400)	Transverse	A + A	∞	310 (45)	310 (45)	Braze Failure
760 (1400)	Longitudinal	A + A	0 5	827 (120)	276 (40)	0 537 x 10^6
760 (1400)	Longitudinal	A + A	0 5	655 (95)	219 (31 7)	10^7 +
760 (1400)	Transverse	A + B	1 0	689 (100)	345 (50)	6 2 x 10^6
760 (1400)	Transverse	A + B	1 0	655 (95)	328 (47 5)	1 783 x 10^6
760 (1400)	Transverse	A + B	1 0	621 (90)	310 (45)	10^7 +
870 (1600)	Longitudinal	A + B	1 0	689 (100)	345 (50)	10^7 +
870 (1600)	Longitudinal	A + A	∞	414 (60)	414 (60)	0 927 x 10^6
870 (1600)	Longitudinal	A + A	∞	379 (55)	379 (55)	1 241 x 10^6
870 (1600)	Longitudinal	A + A	∞	414 (50)	414 (50)	9 374 x 10^6
870 (1600)	Transverse	A + B	1 0	552 (80)	276 (40)	6 9 x 10^6
870 (1600)	Longitudinal	A + A	0 5	621 (90)	207 (30)	7 679 x 10^6
870 (1600)	Transverse	A + B	1 0	517 (75)	259 (37 5)	10^7 +
870 (1600)	Longitudinal	A + B	1 0	689 (100)	345 (50)	6 167 x 10^6
870 (1600)	Longitudinal	A + B	1 0	672 (97 5)	336 (48 7)	4 6 x 10^6
870 (1600)	Longitudinal	A + B	1 0	758 (110)	379 (55)	0 922 x 10^6
870 (1600)	Longitudinal	A + B	∞	331 (48)	331 (48)	5 760 x 10^6
870 (1600)	Longitudinal	A + B	∞	310 (45)	310 (45)	2 247 x 10^6
870 (1600)	Longitudinal	A + A	0 95	758 (110)	370 (53 6)	0 676 x 10^6
870 (1600)	Longitudinal	A + A	0 95	689 (100)	336 (48 7)	0 845 x 10^6
870 (1600)	Longitudinal	A + A	0 95	621 (90)	302 (43 8)	5 529 x 10^6
870 (1600)	Longitudinal	A + A	0 95	586 (85)	285 (41 4)	2 397 x 10^6
870 (1600)	Transverse	A + B	∞	345 (50)	345 (50)	3 652 x 10^6
870 (1600)	Transverse	A + B	∞	310 (45)	310 (45)	7 325 x 10^6
870 (1600)	Transverse	A + A	0 95	517 (75)	252 (36 5)	1 393 x 10^6
870 (1600)	Transverse	A + A	0 95	503 (73)	245 (35 5)	8 039 x 10^6
870 (1600)	Transverse	A + A	0 95	483 (70)	235 (34 1)	10^7 +
870 (1600)	Longitudinal	A + B	∞	379 (55)	379 (55)	0 401 x 10^6
980 (1800)	Transverse	A + B	∞	224 (32 5)	224 (32 5)	9 0 x 10^6
980 (1800)	Longitudinal	A + B	1 0	483 (70)	241 (35)	3 118 x 10^6
980 (1800)	Longitudinal	A + B	1 0	448 (65)	224 (32 5)	6 514 x 10^6
980 (1800)	Longitudinal	A + B	1 0	431 (62 5)	215 (31 2)	6 2 x 10^6
980 (1800)	Transverse	A + B	1 0	310 (45)	155 (22 5)	10^7 +
980 (1800)	Transverse	A + B	1 0	345 (50)	172 (25)	10^7 +
980 (1800)	Longitudinal	A + B	1 0	414 (60)	207 (30)	10^7 +
980 (1800)	Longitudinal	A + B	1 0	414 (60)	207 (30)	9 222 x 10^6
980 (1800)	Longitudinal	A + B	0 5	414 (60)	138 (20)	0 203 x 10^6
980 (1800)	Longitudinal	A + B	0 5	379 (55)	126 (18 3)	10^7 +
980 (1800)	Longitudinal	A + B	∞	345 (50)	345 (50)	3 437 x 10^6
980 (1800)	Longitudinal	A + B	∞	310 (45)	310 (45)	0 911 x 10^6
980 (1800)	Longitudinal	A + B	∞	276 (40)	276 (40)	4 608 x 10^6
980 (1800)	Longitudinal	A + B	∞	259 (37 5)	259 (37 5)	9 322 x 10^6
980 (1800)	Longitudinal	A + A	∞	345 (50)	345 (50)	2 9 x 10^6
980 (1800)	Longitudinal	A + A	∞	310 (45)	310 (45)	3 883 x 10^6
980 (1800)	Longitudinal	A + A	∞	276 (40)	276 (40)	0 657 x 10^6
980 (1800)	Longitudinal	A + A	∞	276 (40)	276 (40)	10^7 +
980 (1800)	Longitudinal	A + A	0 95	483 (70)	235 (34 1)	2 257 x 10^6
980 (1800)	Longitudinal	A + A	0 95	431 (62 5)	210 (30 4)	2 838 x 10^6
980 (1800)	Longitudinal	A + A	0 95	379 (55)	185 (26 8)	10^7 +
980 (1800)	Transverse	A + A	0 95	276 (40)	134 (19 5)	0 712 x 10^6
980 (1800)	Transverse	A + A	0 95	241 (35)	117 (17)	4 169 x 10^6
980 (1800)	Transverse	A + B	∞	276 (40)	276 (40)	0 937 x 10^6
980 (1800)	Transverse	A + A	∞	221 (32)	108 (15 6)	10^7 +

*A + A = Axial + Axial, A + B = Axial + Bending

**Note + Indicates specimen runout at indicated cycles, no failure at 650° C (1200° F) and an A-ratio of 1.0 to further characterize the fatigue behavior of René 150. The HCF data are plotted as stress versus cyclic life in Figures 9 through 13. These curves were used to establish the 10^7 cyclic fatigue life at the various test conditions. The values are shown in Table VII. The Goodman diagrams are plotted in Figures 14 through 19. For comparative purposes, previously obtained data from René 150 and CC René 80 are included on these diagrams. The following conclusions can be drawn from these data:

- At an A-ratio of ∞, in the longitudinal direction, René 150 is about equal in strength to René 80. In the transverse direction René 150 is slightly lower in strength.

- At lower A-ratios, in the longitudinal direction, René 150 is stronger than René 80. In the transverse direction, René 150 is at least equal in strength to René 80.

- Comparison with previously obtained fatigue data indicates a sensitivity of René 150 to initial DS bar size and heat treatment. The bar size and the heat treatment utilized in this study provide a structure similar to that obtained in the CF6-50 turbine blade; therefore, the data are considered to be representative of the properties in the actual blade.

Fractographic evaluation of the HCF specimens indicates that most of the failures initiated internally at microporosity sites. The remaining three specimens failed prematurely due to undetected subsurface voids. The points representing these tests are circled in Figures 9 through 17; they were not utilized in the actual curve construction in these figures.

4.2 MOLD/CORE SELECTION

The ceramic core body used in this project was selected based on fabricability and stability in contact with molten René 150 alloy. Mold material was selected to provide acceptable surface finish and adequate temperature capability for the RAM-DS process. The stability of available mold and core materials was determined by exposing samples to molten René 150, for times representative of the RAM-DS process, and subsequently examining the specimens metallographically to determine ceramic/metal reactivity.

4.2.1 Core Selection

Four ceramic core materials were evaluated in contact with molten René 150 alloy under actual DS casting conditions. These ceramic core materials were:

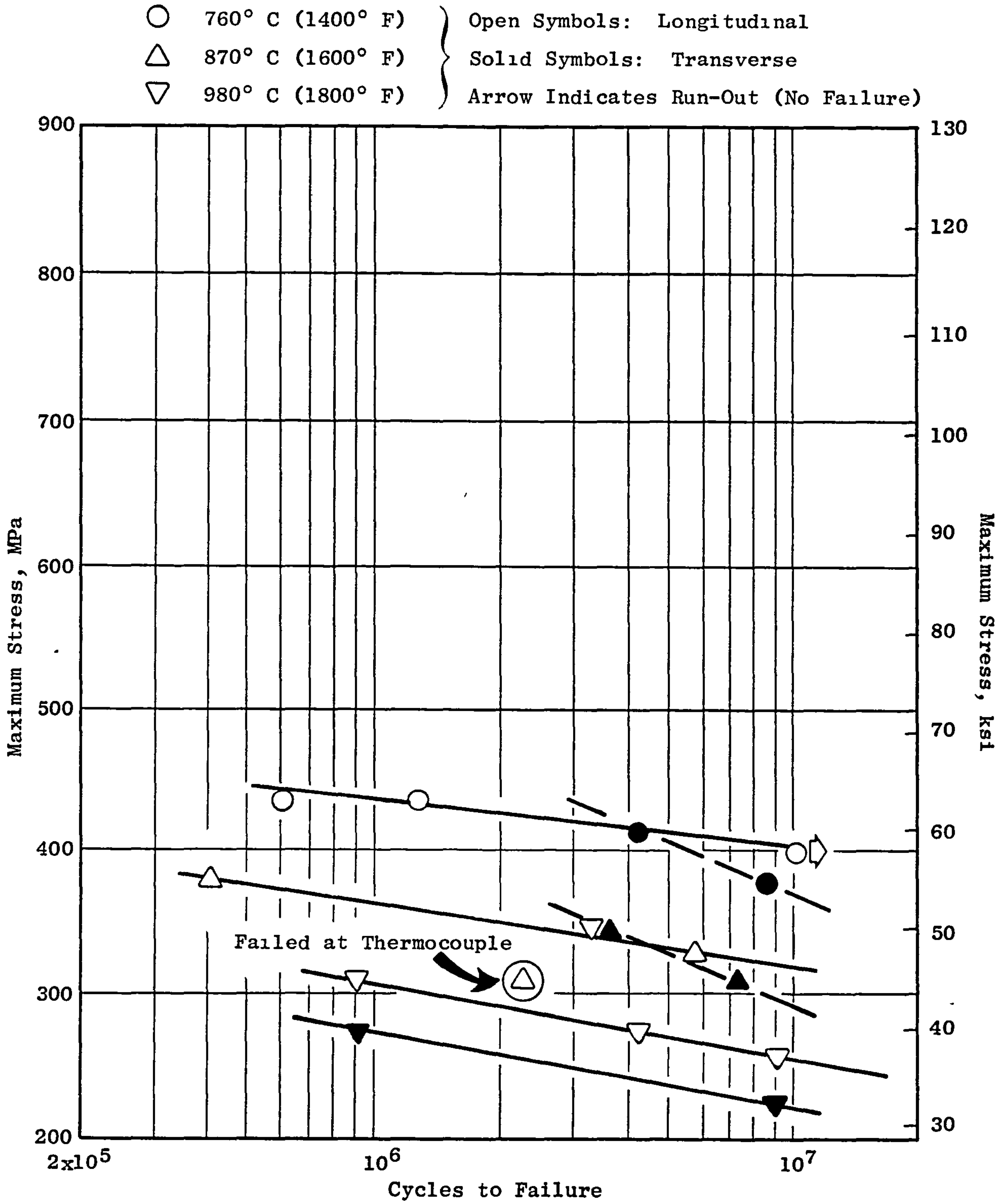


Figure 9. HCF of René 150, Axial + Bending, A = ∞.

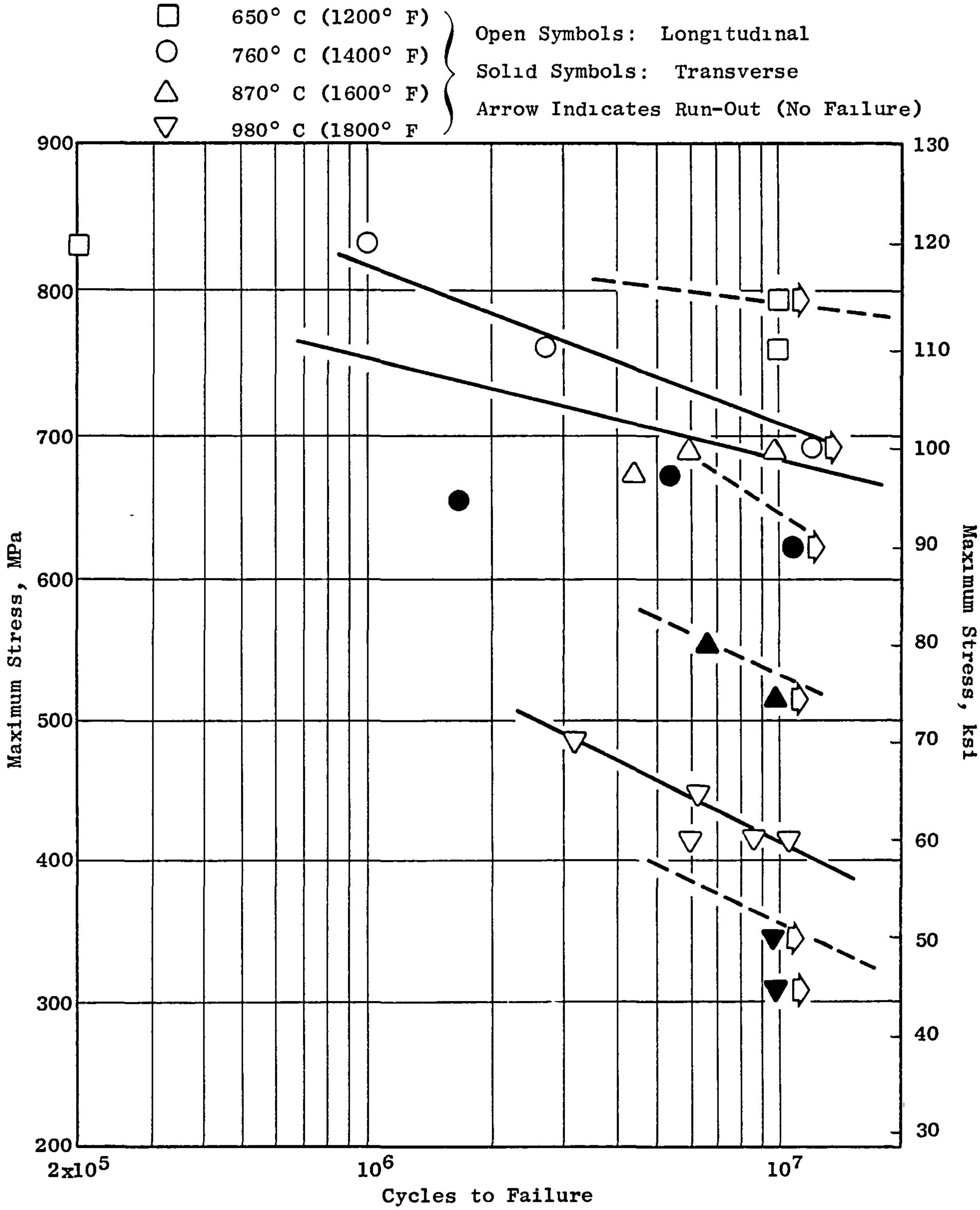


Figure 10. HCF of René 150, Axial + Bending, A = 1.0.

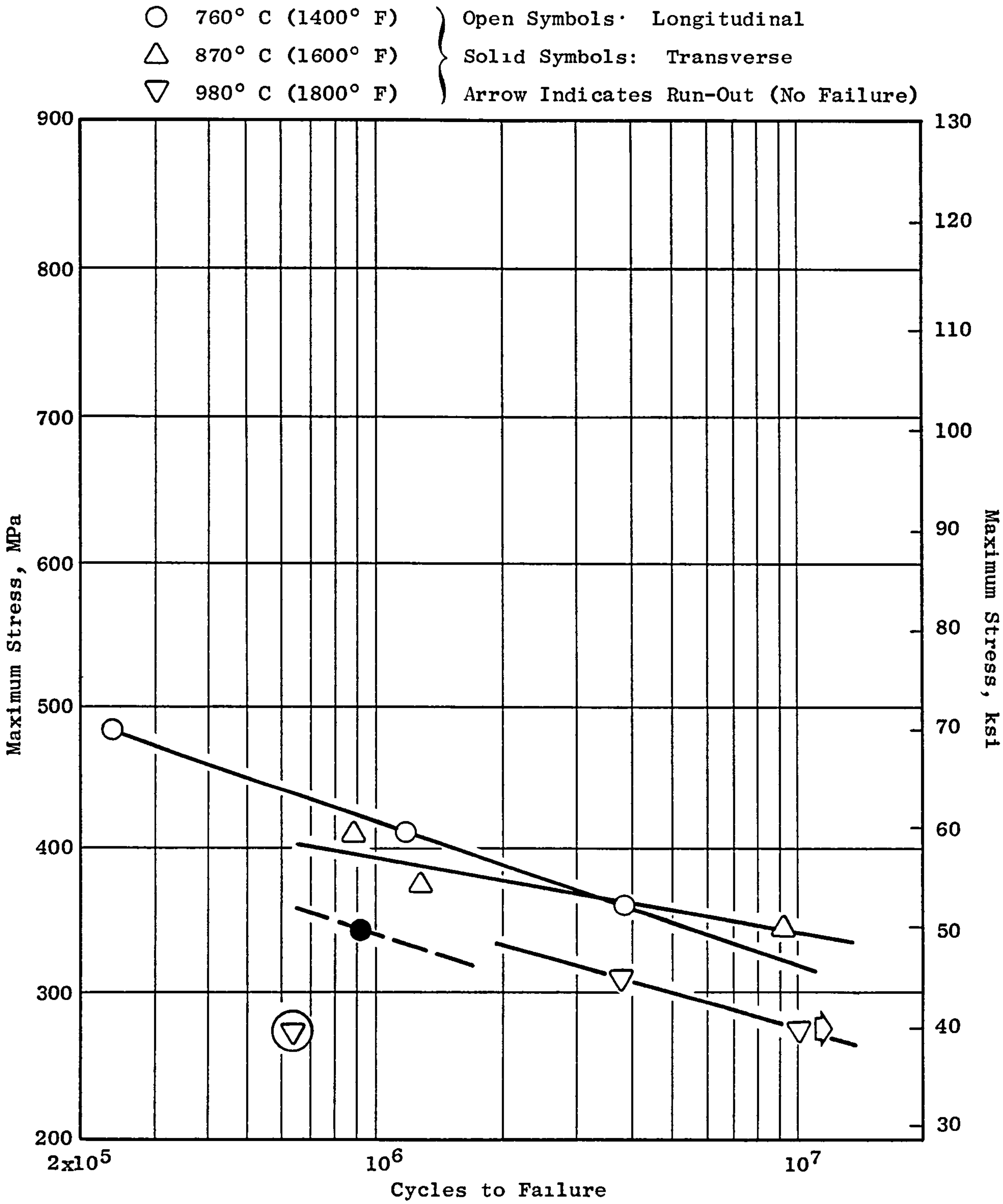


Figure 11. HCF of René 150, Axial + Axial, A = ∞.

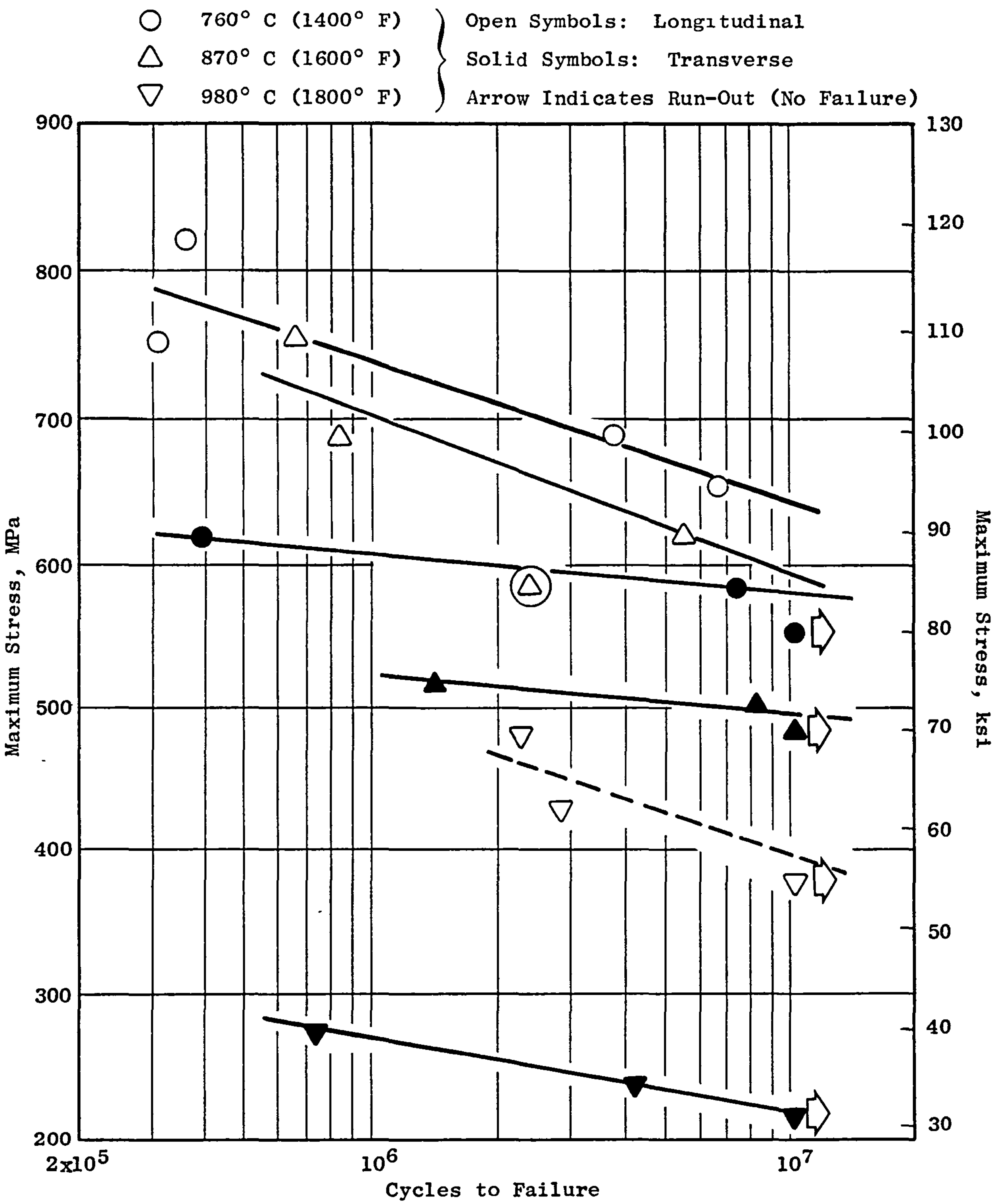


Figure 12. HCF of René 150, Axial + Axial, A = 0.95.

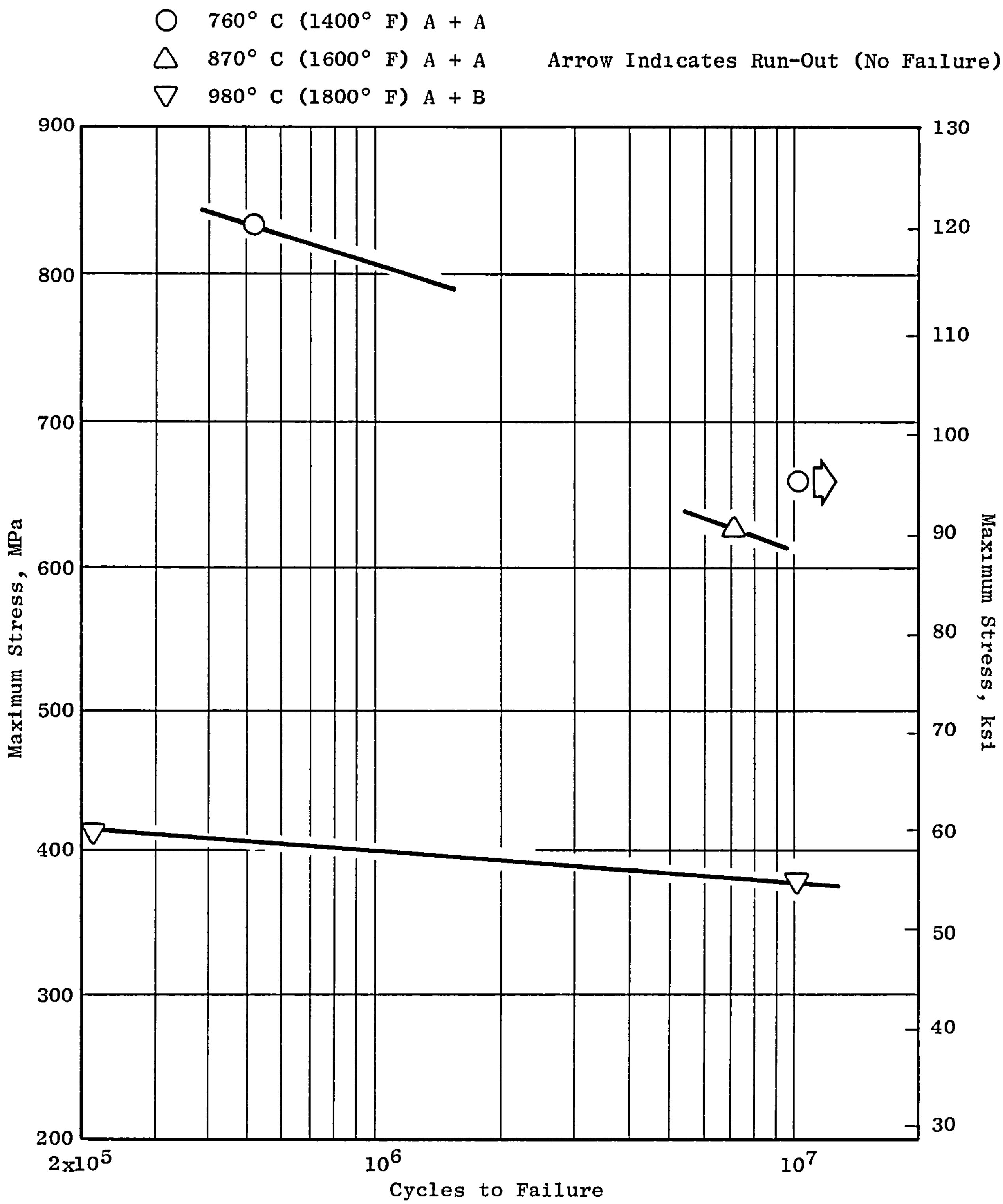


Figure 13. HCF of René 150, A = 0.5.

Table VII. Endurance Stresses for 10^7 Cycles.

Test Temperature, °C (°F)	Specimen Direction	Mode*	A-Ratio	Maximum Stress, MPa (ksi) René 150	René 80
650 (1200)	Longitudinal	A + B	1.0	793 (115)	607 (88)
760 (1400)	Longitudinal	A + B	∞	407 (59)	414 (60)
760 (1400)	Transverse	A + B	∞	372 (54)	414 (60)
760 (1400)	Longitudinal	A + B	1.0	703 (102)	648 (94)
760 (1400)	Transverse	A + B	1.0	648 (94)	648 (94)
760 (1400)	Longitudinal	A + A	∞	317 (46)	352 (51)*
760 (1400)	Longitudinal	A + A	0.5	>655 (95)	662 (96)*
760 (1400)	Longitudinal	A + A	0.95	641 (93)	572 (83)*
760 (1400)	Transverse	A + A	0.95	579 (84)	572 (83)*
870 (1600)	Longitudinal	A + B	∞	324 (47)	331 (48)
870 (1600)	Transverse	A + B	∞	290 (42)	331 (48)
870 (1600)	Longitudinal	A + B	1.0	683 (99)	496 (72)
870 (1600)	Transverse	A + B	1.0	538 (78)	496 (72)
870 (1600)	Longitudinal	A + A	∞	345 (50)	279 (40.5)*
870 (1600)	Longitudinal	A + A	0.5	600 (87)	434 (63)*
870 (1600)	Longitudinal	A + A	0.95	593 (86)	421 (61)*
870 (1600)	Transverse	A + A	0.95	496 (72)	421 (61)*
980 (1800)	Longitudinal	A + B	∞	255 (37)	234 (34)
980 (1800)	Transverse	A + B	∞	221 (32)	234 (34)
980 (1800)	Longitudinal	A + B	0.5	379 (55)	193 (28)
980 (1800)	Longitudinal	A + B	1.0	414 (60)	248 (36)
980 (1800)	Transverse	A + B	1.0	359 (52)	248 (36)
980 (1800)	Longitudinal	A + A	∞	276 (40)	193 (28)*
980 (1800)	Longitudinal	A + A	0.95	400 (58)	214 (31)*
980 (1800)	Transverse	A + A	0.95	221 (32)	214 (31)*

*Estimated values.

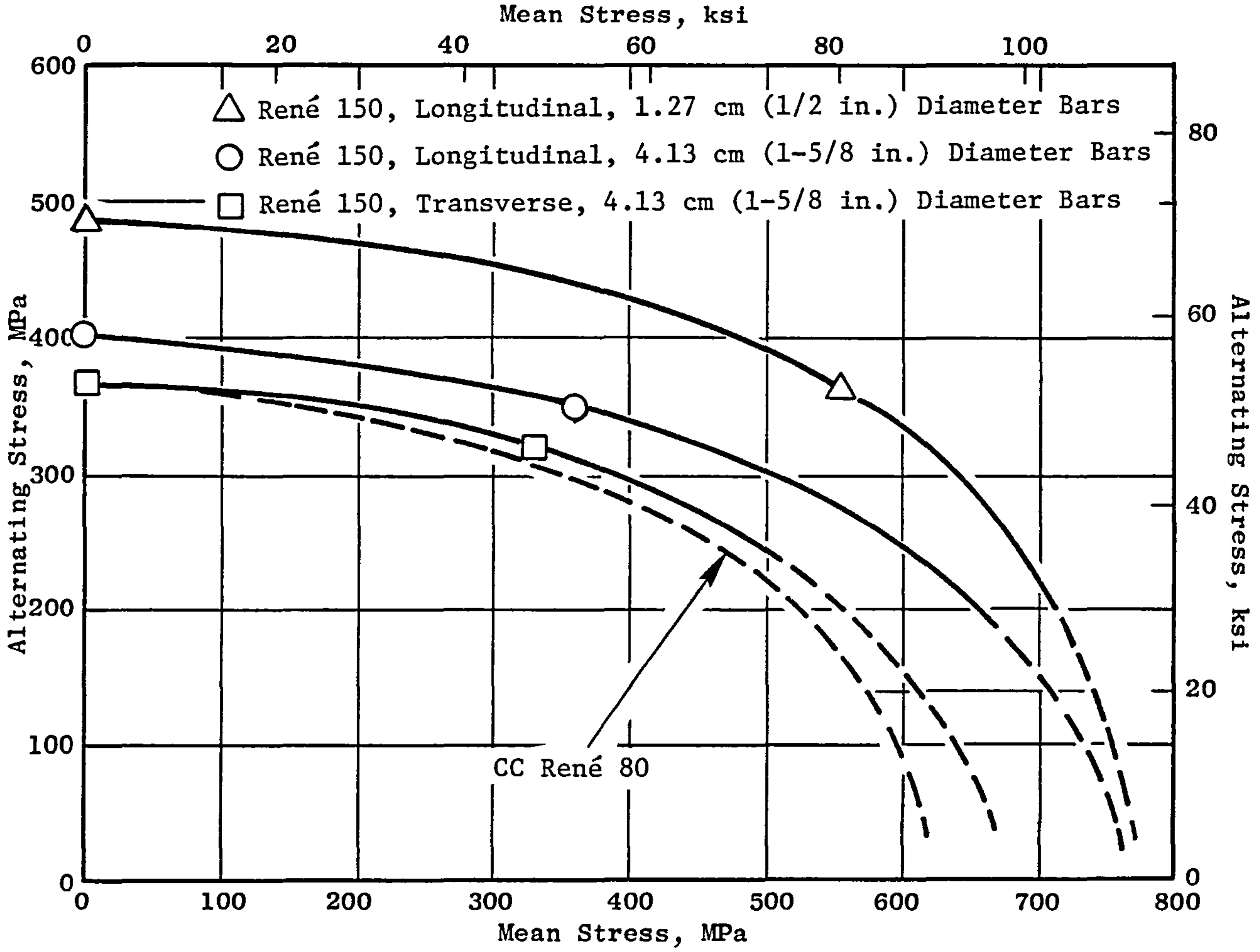


Figure 14. Goodman Diagram, 760° C (1400° F), Axial + Bending, 10^7 Cycles.

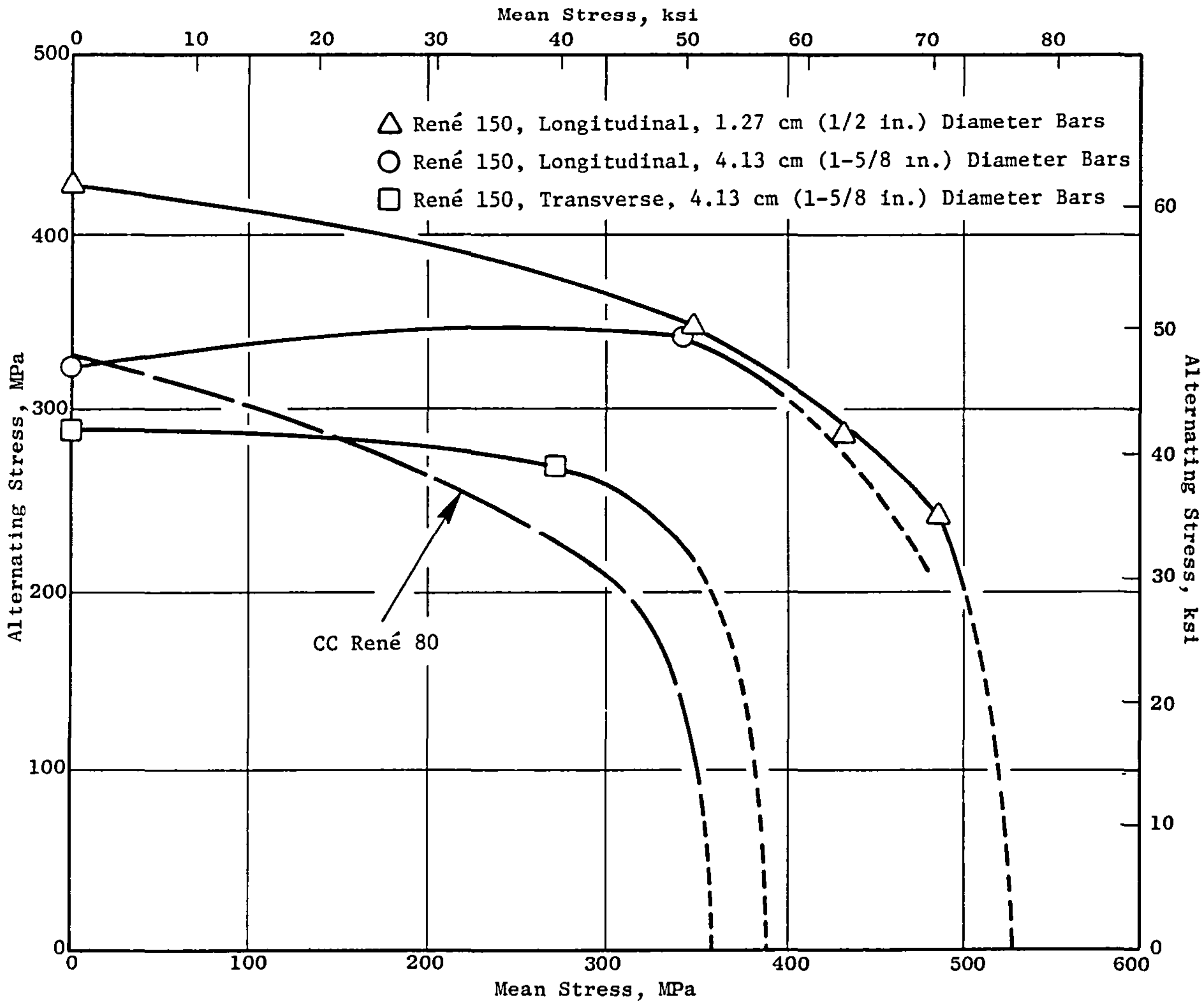


Figure 15. Goodman Diagram, 870° C (1600° F), Axial + Bending, 10^7 Cycles.

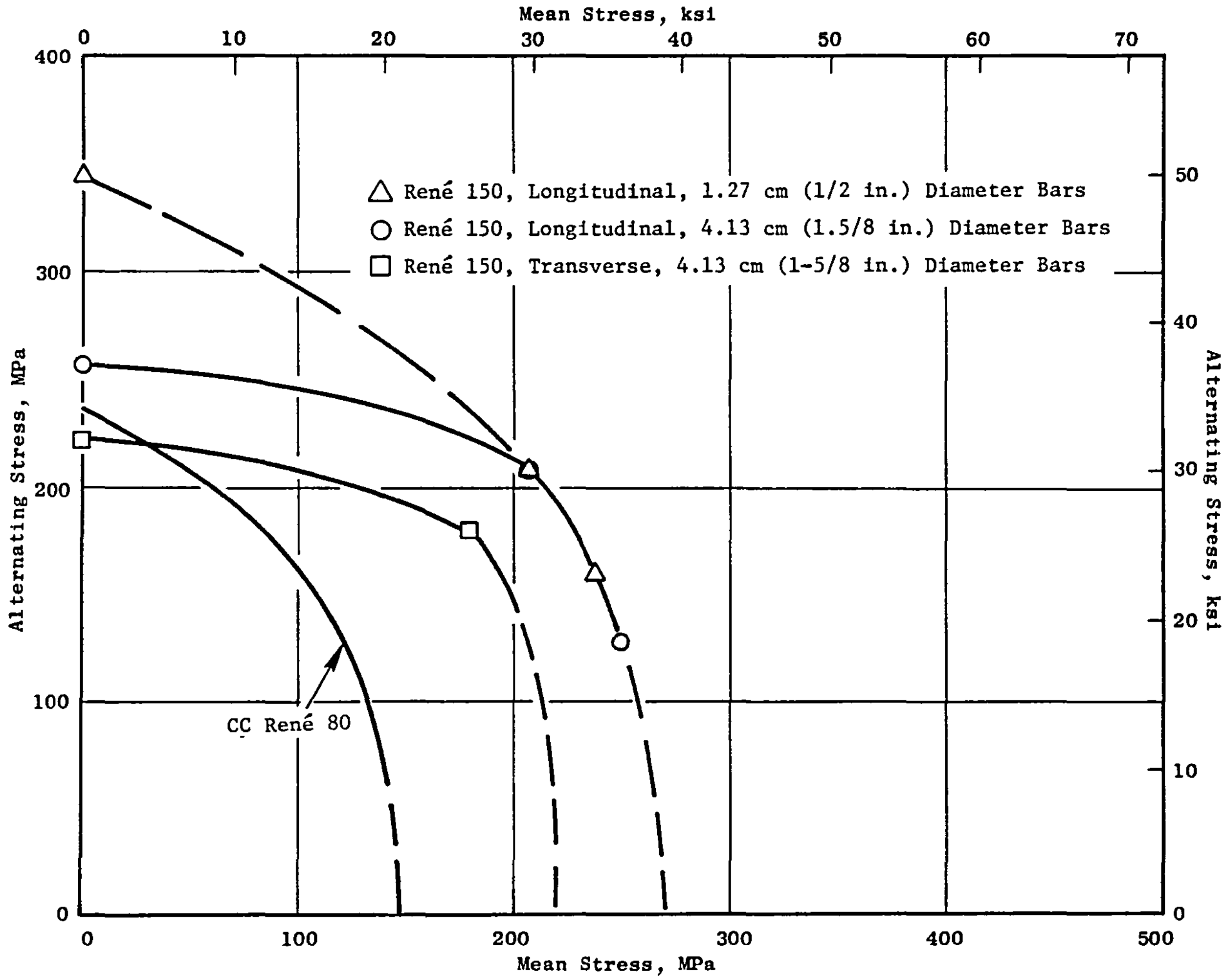


Figure 16. Goodman Diagram, 980° C (1800° F), Axial + Bending, 10^7 Cycles.

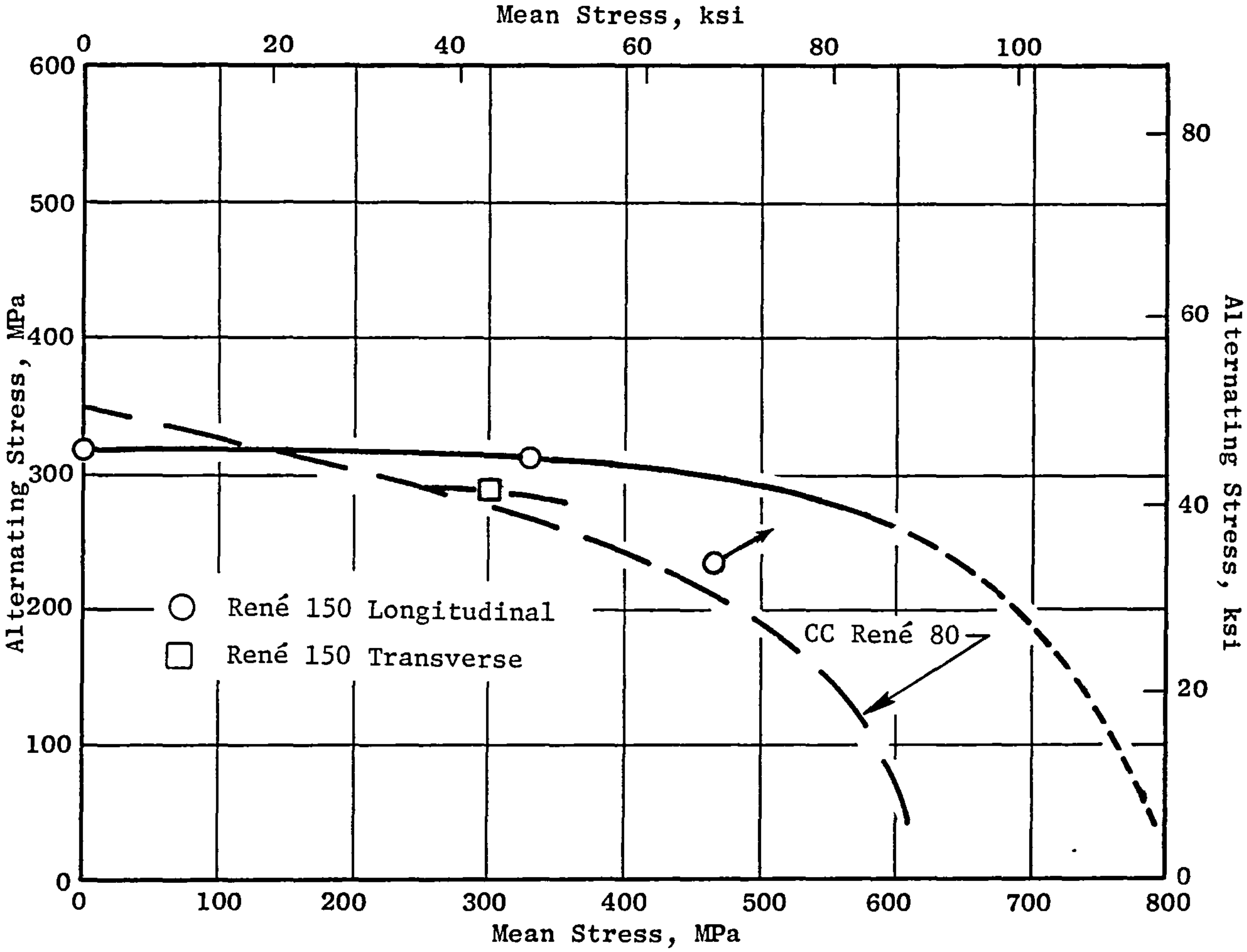


Figure 17. Goodman Diagram, 760° C (1400° F), Axial + Axial, 10^7 Cycles.

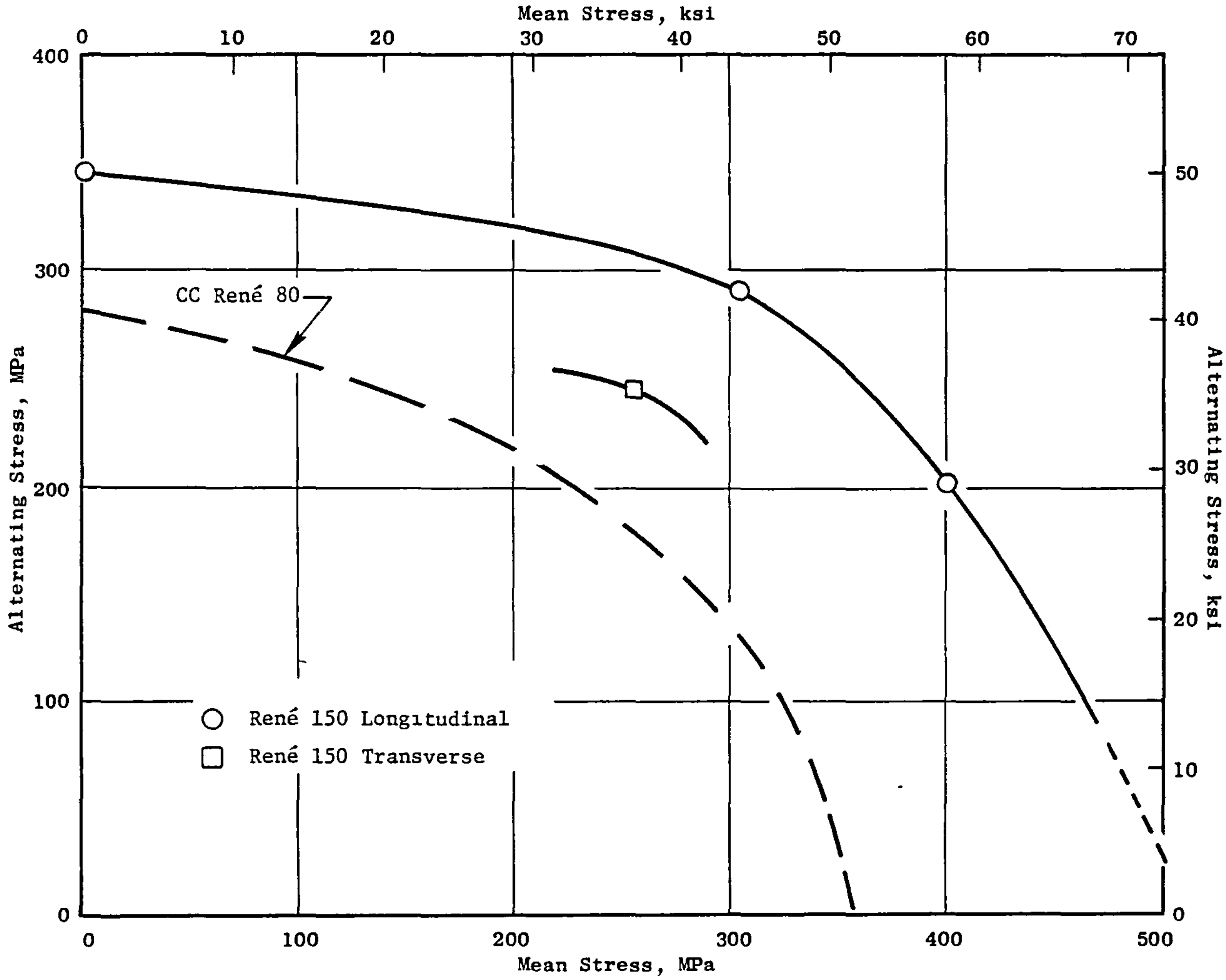


Figure 18. Goodman Diagram, 870° C (1600° F), Axial + Axial, 10^7 Cycles.

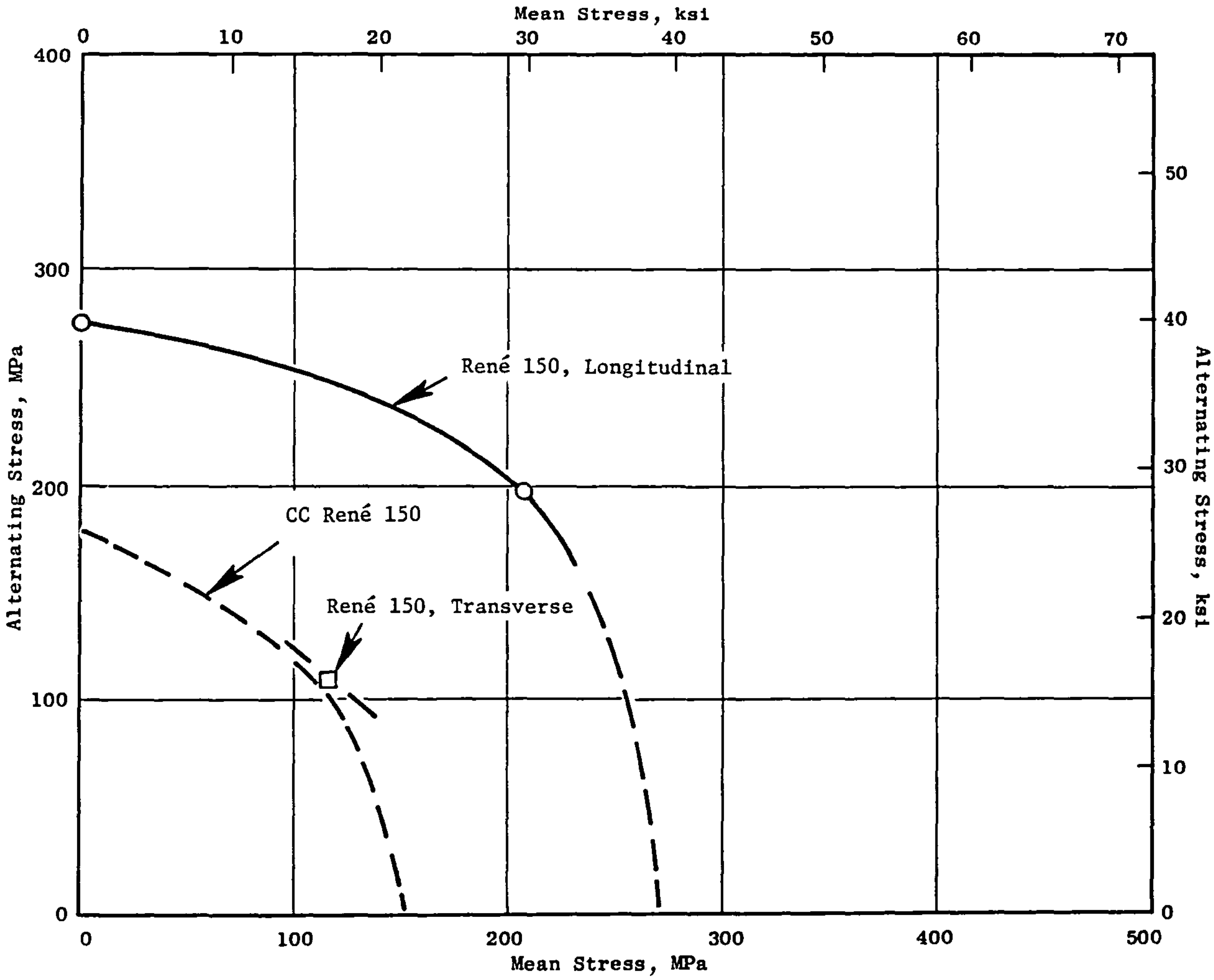


Figure 19. Goodman Diagram, 980° C (1800° F), Axial + Axial, 10^7 Cycles.

SR-605	}	Sherwood Refractories Division
SR-731		
DS-1	}	Misco Ceramic Products Division
DS-4		

Two core configurations were considered: the older M90 configuration and the newly introduced M34 configuration; these designs represent the blades to be used in Tasks IV, V, and VI.

Nine CF6-50 castings were made using various cores in an alumina face-coat, mullite-shell mold. Only the SR-731 core material demonstrated adequate mechanical strength at the selected casting temperature. Lack of core strength results in movement of the core (sag) and poor wall-thickness control in the castings. This can be seen in Figure 20; photomicrographs are presented of airfoil cross sections showing the walls of castings made with DS-1 core as compared to SR-731 cored castings. Reaction between the various core materials and René 150 was very slight and acceptable.

A typical metal/core interface is shown in Figure 21. Metal penetration was irregular and occurred to a depth of only about 5.1 μm (0.0002 in.). Generally a thin oxide layer was present at the interface. As can be seen in the figure, no alloy depletion was evident; the microstructure of the alloy was uniform up to the metal/core interface. Based on this evaluation, SR-731 was selected as the core-body material for this program.

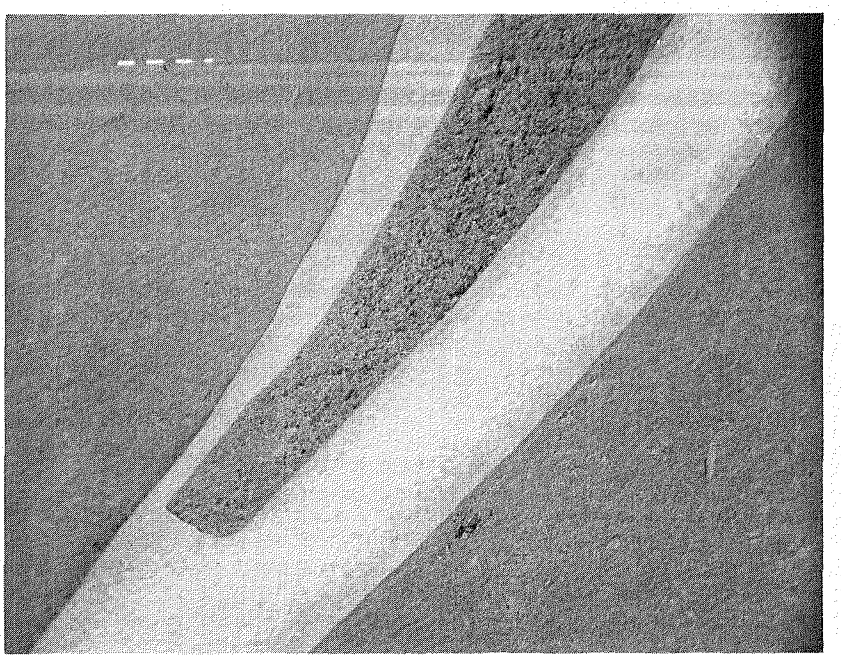
4.2.2 Mold Selection

Four different mold/face-coat combinations also were examined:

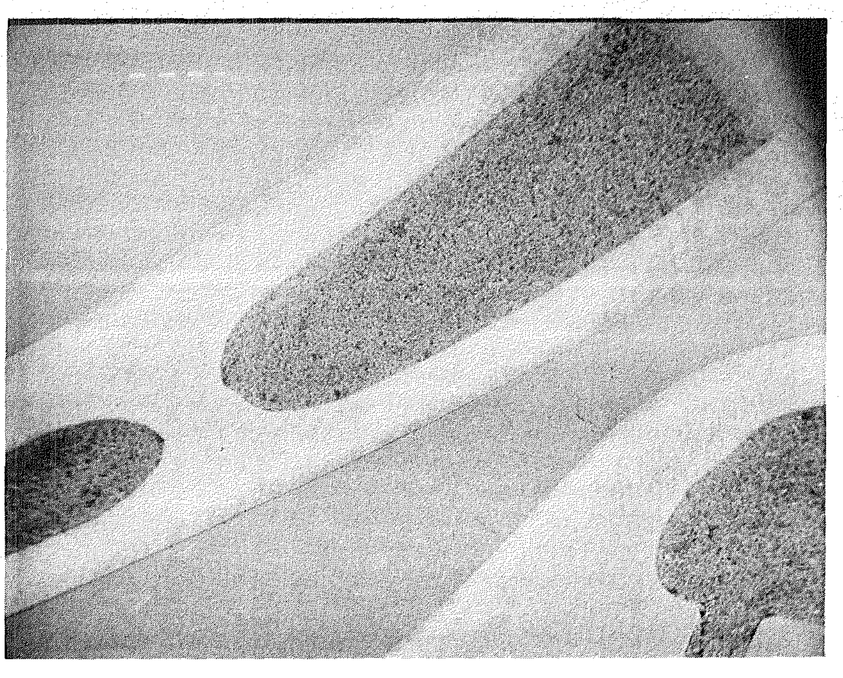
- Mullite Stucco/Alumina Face Coat
- Mullite Stucco/Zircon Face Coat
- Mullite Stucco/Silica Face Coat
- Alumina Stucco/Alumina Face Coat

Eleven CF6-50 castings were made using the M34 core configuration and SR-731 core material. External visual examination of the completed castings indicated the unacceptability of the silica face-coat system and the all-alumina shell/face coat system. The silica face coat sagged at the casting temperature with resulting deleterious effects on the casting surface. During insertion into the hot furnace, the all-alumina shell split as a result of the inherently poor thermal-shock resistance of alumina.

Castings from both the zircon and the alumina face-coated, mullite-stuccoed molds appeared to have excellent surface quality. Metallographic specimens representing each of the mold/core combinations were examined for possible reaction between the René 150 alloy and the ceramics.

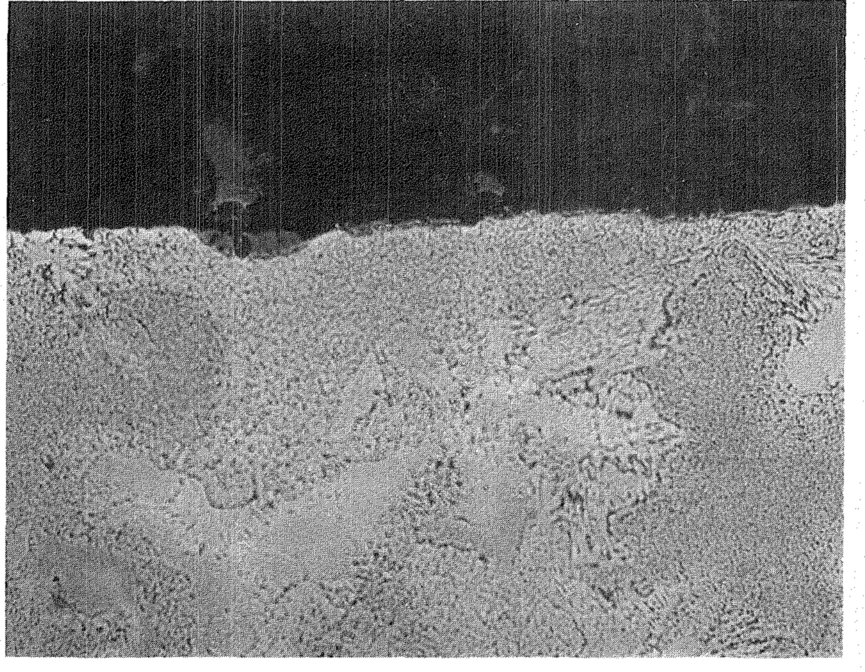


DS-1 (Poor Wall Thickness Control) 1587.5 μm



SR-731 (Acceptable Wall Thickness Control) 1587.5 μm

Figure 20. Airfoil Cross Sections of Internal Wall Thickness Control with Two Core-Material Candidates.



No. 8-1684 , Etched

50.8 µm

Figure 21. Metal/Core Interface in CF6-50 Turbine Blade, René 150 Alloy, SR-731 Core.

All of the mold materials evaluated produced a relatively smooth casting surface and little or no reaction with the René 150 alloy. From a metal/mold reaction standpoint, all of the combinations of shell and face-coat materials would be acceptable.

Based on these results, and predominantly for mechanical strength consideration, the SR-731 core material and the zircon and alumina face-coated, mullite-stuccoed molds were selected for further evaluation. It appears that René 150 is chemically compatible with a wide range of mold and core materials.

4.3 PRELIMINARY CASTING TRIALS

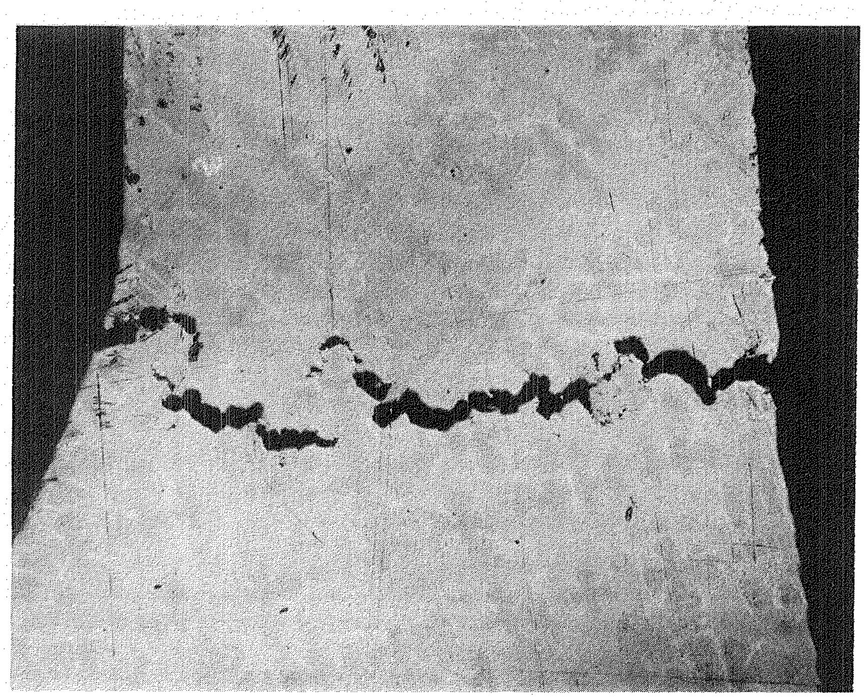
Casting process refinement studies were conducted using the SR-731 core material and the alumina face-coated, mullite-stuccoed mold system. Preliminary process parameters were sufficiently defined to produce acceptable René 150 castings using the older CF6-50 M90 design tooling. This tooling was originally designed for conventional casting and was modified for directional solidification.

The first molds were cast using the new wax die and preliminary process parameters that produced acceptable castings with the older tooling. This wax die was machined so as to produce blade castings to final dimension in the shank area. Thirty-two René 150 CF6-50 M34 blades were cast. All blades showed various degrees of cracking in the shank area (visually apparent after macroetching). Modifications to the temperature and time process variables in the RAM-DS facility did not eliminate the cracking.

As a further check, an additional nine CF6-50 M34 blades were cast using the most castable alloy investigated to date for the RAM-DS process. All nine blades showed cracking similar to that of the René 150 blades. Four GE23 blades were also cast using the same René 150 heat to check castability. No cracking was observed using similar evaluation procedures.

Thus the primary cause of cracking probably was mold constraint of the metal in the shank area of the blade during cooling. The extensive deformation associated with the grain-boundary cracks, shown in Figure 22, supported this hypothesis. A tooling or mold modification was deemed necessary.

Two approaches were selected for further evaluation in an attempt to eliminate cracking. The first involved a ceramic mold modification; a nylon pad was encapsulated in the mold and then vaporized during subsequent mold-firing operations. The resulting mold contained an internal void area in the shank region. It was anticipated that this would alter the shell strength and/or heat-transfer characteristics and thereby reduce the tendency for cracking. This approach would allow the blade casting to be produced in the net-shape configuration.



No. 8-1680, Etched

508 μm

Figure 22. Cross Section Showing Extensive Deformation and Grain-Boundary Cracking of the Shank Area in CF6-50 René 150 Blade Casting.

Twenty-one molds of this configuration were cast. The results of these trials were encouraging; less than 20% of the blades exhibited cracking at fluorescent-penetrant inspection (FPI). An additional 30 blades were cast to confirm these results and to qualify this modification. The results were disappointing; more than 75% of the castings exhibited visual cracks. It was evident that a substantial amount of process development would be required to establish this as a viable casting process.

The second approach involved modifying the blade wax die in such a way that the resulting metal thickness in the shank region could be increased. It was anticipated that increasing the load-bearing capacity in this region would reduce or eliminate the tendency for cracking. Wax die inserts were produced that would allow the blade wax patterns to be produced in the following configurations:

1. A net-shape airfoil and shank.

2. A net-shape airfoil with 0.81 mm (0.032 in.) thick pads in the pocket area on both sides of the shank.

3. A net-shape airfoil with 3.18 mm (0.125 in.) thick pads in the pocket area of both sides of the shank.

The location of the pads mentioned above is shown in Figure 23. Trial blades in each of these configurations were cast. In order to accommodate the increased mold cross section caused by the addition of either the 0.81 mm (0.032 in.) pad or the 3.18 mm (0.125 in.) pad, the cross sections of the moving chill, stationary chill, and radiation baffle were increased. The height of the furnace was increased 1.27 cm (1/2 in.) as a result of the additional charge required in the melt cup to fill the increased volume of these blade configurations.

The results of the casting trials revealed that the blades with the 0.81 mm (0.032 in.) pads still contained some shank cracks, but those with the 2.18 mm (0.125 in.) pads exhibited no shank cracking. Twenty-seven additional blade castings were produced with 3.18 mm (0.125 in.) pads on both sides of the shank in order to qualify this approach. The first seven castings were made using variable furnace parameters in order to establish the process for this configuration. The last 20 castings were made using a fixed set of casting parameters based on the results from the initial seven castings. None of these 20 castings exhibited shank cracking at FPI.

Based on these results this approach was selected for use on the remainder of the castings to be produced in this program, and a preliminary casting-process specification was prepared.

The additional material in the blade shank region was removed by an ECM operation at Lehr Precision Tools, Inc., Cincinnati, Ohio, during subsequent blade-finishing operations in order to restore the blade to the desired configuration.

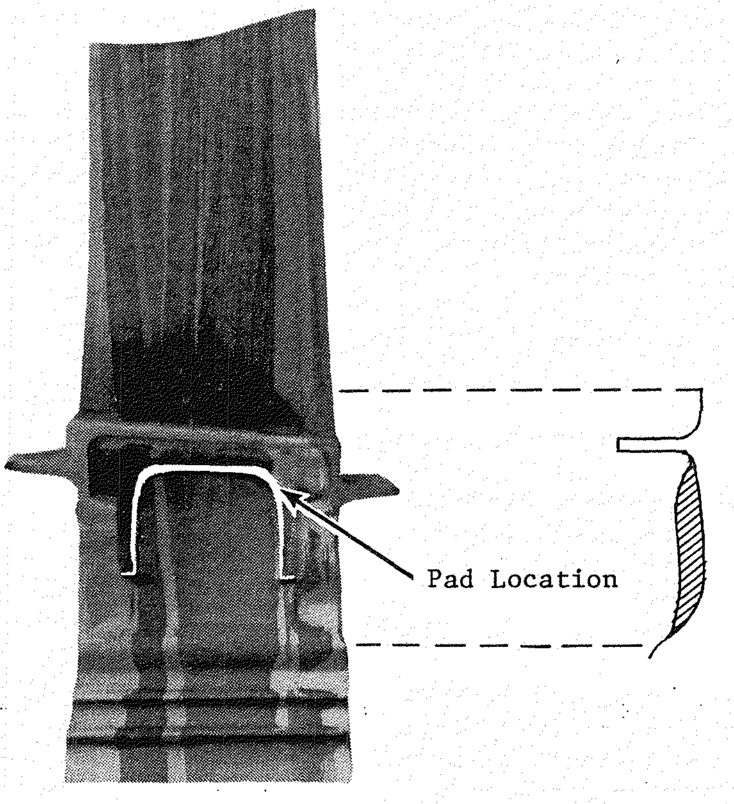


Figure 23. Pad Location to Prevent Shank Cracking.

5.0 TASK III - COATING ADAPTATION AND EVALUATION

The electroplate aluminide (EA) NiCrAlHf coating process was selected for use in externally coating the René 150 CF6-50 blades in this project.

For operation in a CF6-50 engine, a list of minimum requirements for coated René 150 was established and is summarized in Table VIII. Candidate EA NiCrALHf coatings were evaluated against several of these critical coating requirements including:

- Thickness
- 1150° C (2100° F) Oxidation
- 925° C (1700° F) Corrosion
- DBTT (Ductile/Brittle Transition Temperature)
- 980° C (1800° F) Stress Rupture
- Strip and Recoat Behavior

From candidate coatings, one was selected as best meeting the coating criteria. The selected coating contained three successive electroplated layers of chromium and nickel, followed by a single pack-cementation process adding hafnium and aluminum to the coating. The selected EA NiCrAlHf coating microstructure is shown in Figure 24 and consists of a graded composition of Ni, Cr, Al, and Hf. The initial screening tests permitted the selection of this desired EA NiCrAlHf coating.

5.1 COATING ADAPTATION

Six separate activities were conducted to adapt the selected EA NiCrAlHf coating to the René 150 CF6-50 HPT blade. These were:

- Design and Fabrication of Multiblade Plating Mixture
- Design and Fabrication of Multiblade Pack-Cementation Box
- Evaluation of Internally Aluminided René 150 Blades
- EA NiCrAlHf Coating of René 150 Blades
- Development of Strip and Recoat Capabilities
- Evaluation of Airflow on Coated Blades

Table VIII. Criteria for EA NiCrAlHf Coating of CF6-50 Stage 1 Turbine Blades.

In addition to meeting specification requirements, the EA coating shall meet the following release criteria before engine testing:

1. External thickness: 63.5 to 114.3 μm (2.5 to 4.5 mil).
2. Internal thickness (at crossover holes): $\leq$ 6.35 mm (0.25 mil).
3. LCF test specimens with aluminide plus Hf coating, simulating the internal blade coating, must not show more than a 30% reduction in fatigue strength at 760° C (1400° F) compared to uncoated René 150 data.
4. No internal coating cracks when examined metallographically at 500X after hot component-fatigue tests when tip deflection is at the level for CF6-50 blades.
5. External-coating corrosion resistance: Penetration of coating must not occur in a Mach 0.05 500-hour oxidation test at 1095° C (2000° F), and cycled six times per hour.
6. External-coating corrosion resistance: Penetration of coating must not occur in a 250-hour corrosion test at 930° C (1700° F), 5 ppm salt, and one cycle per hour.
7. Pass CF6-50 airflow requirements.
8. LCF and sustained peak-loading cyclic fatigue (SPLCF) tests at 985° C (1800° F) and HCF tests at 760 and 870° C (1400 and 1600° F) must be capable of meeting René 80 capabilities after coating (EA).
9. SETS thermal fatigue typical test on trailing-edge section to show onset of cracking in not less than 1000 cycles from 1055 to 315° C (1950 to 600° F).
10. DBTT must be below that of Codep on René 80.
11. Stress rupture testing of EA coated specimens must be capable of meeting minimum uncoated René 150 data at 980° C (1800° F).
12. These criteria are inadequate for more extensive use of the coating beyond the engine testing planned for MATE 2. Additional criteria would have to be met for the next step in engine testing.

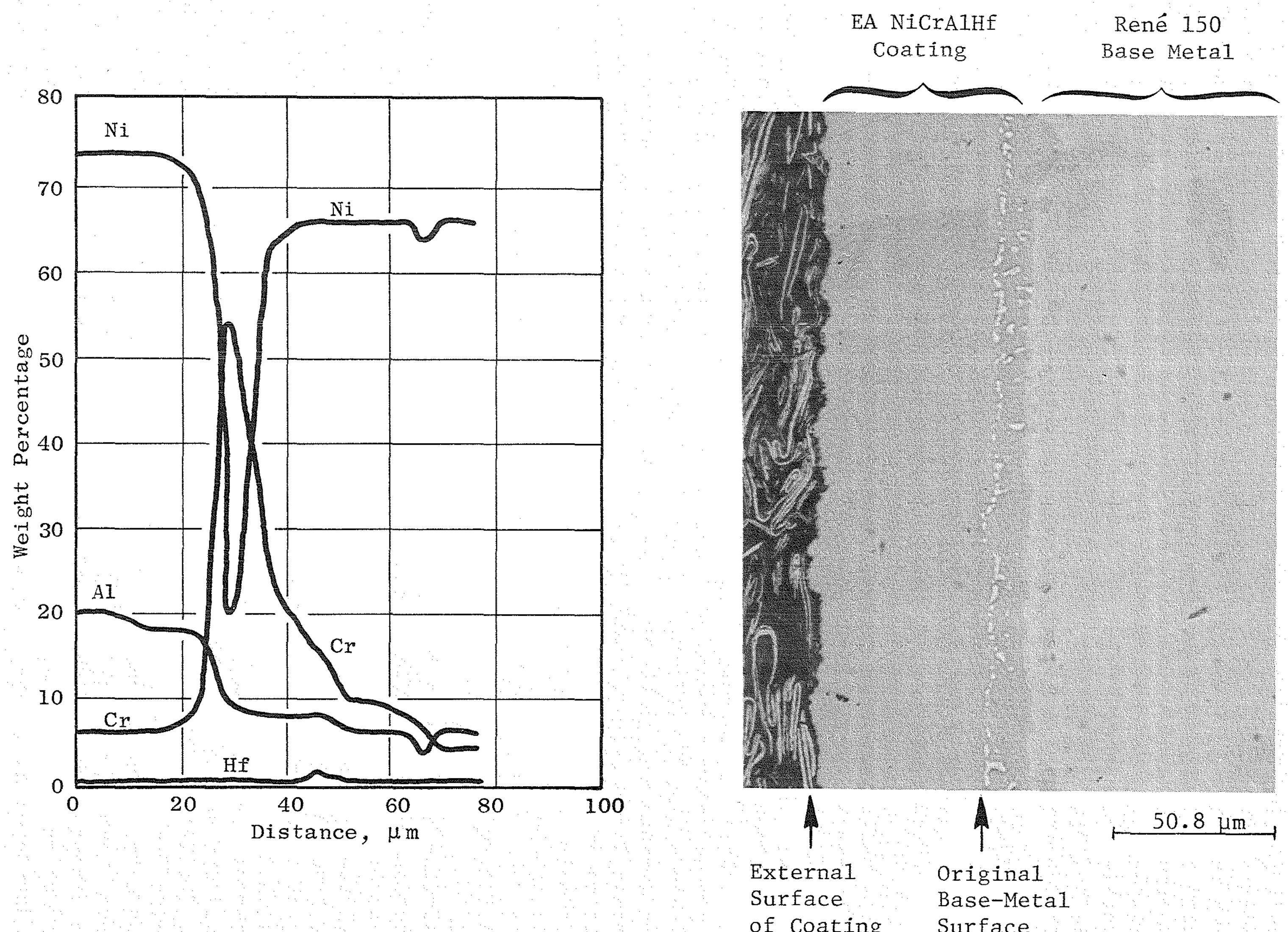


Figure 24. Microprobe Trace and Typical Microstructure of an EA NiCrAlHf Coated René 150 Specimen Selected for CF6-50 Blade.

5.1.1 Multiblade Plating Fixture

Initially two single-blade plating fixtures, shown in Figure 25, were constructed to provide uniform plated-layer thicknesses on the blades. Empirical modification of these fixtures allowed for demonstration of the capability to maintain the plated-layer thicknesses within the ±20% acceptance range as shown in Figures 26 and 27. However, since more than 200 blades were to be coated as part of this project, it was necessary to electroplate several blades simultaneously to complete the work economically. Previous work with the EA process on other airfoil alloys and configurations demonstrated that it is possible to concurrently electroplate several airfoils. Using this background, and considering the size of the CF6-50 blade, a four-blade plating fixture was designed and constructed; it consisted of three parts:

1. Base plate (Figure 28)

2. Polyester resin fixturing blocks for securing the turbine blades (Figure 29)

3. Manipulation of titanium screening (fixture anodes) surrounding the airfoil.

Two qualification plating trials were made using this fixture and evaluated metallographically for plating uniformity and acceptability. Plated-layer thickness measurements, shown in Table IX, indicate that all four positions produce plated layers at least as uniform as those produced by the single-blade plating fixture. These thicknesses were considered acceptable, and the fixture was qualified. The plated-layer thickness data was used to compute Ni/Cr ratios, shown in Table X, which aid in the identification of variations in the composition of the coating. A second fixture was available for assembly had the need arisen.

5.1.2 Multiblade Pack-Cementation Box

Similar to the need for a multiblade plating fixture, a multiblade pack-cementation box was needed to coat the blades in reasonable time and cost. Three boxes were constructed, and each had a capacity of 20 blades. These boxes, retorts, and pilot production-size furnaces have characteristic heating rates, temperature distributions, etc. which are critical parameters in producing coatings by pack cementation. Because the René 150 blades would be coated in these pilot production-size facilities, all test specimens (oxidation and corrosion pins, bars for HCF, LCF, etc.) were coated in these facilities to avoid any subtle differences in coatings that could result from using different facilities. To qualify these multiblade retorts and the pilot production-size furnaces, four practice runs were made on blades, and the coating was evaluated. The scanning electron micrograph and corresponding microprobe scan are shown in Figure 30 and represent an acceptable coating. Key features of the acceptability of this coating are: chromium and hafnium distribution throughout the coating, aluminum penetration beyond the chromium layer, and a small degree of substrate voiding. The X-ray oscilliograms shown in Figure 31

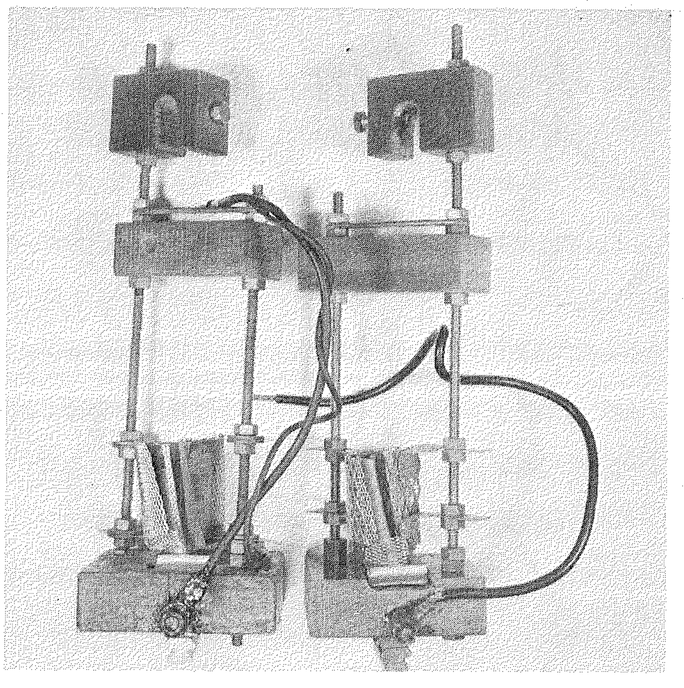


Figure 25. Fixtures for Applying Controlled Layer Thicknesses of Nickel and Chromium in the EA NiCrAlHf Process for HPT Blades.

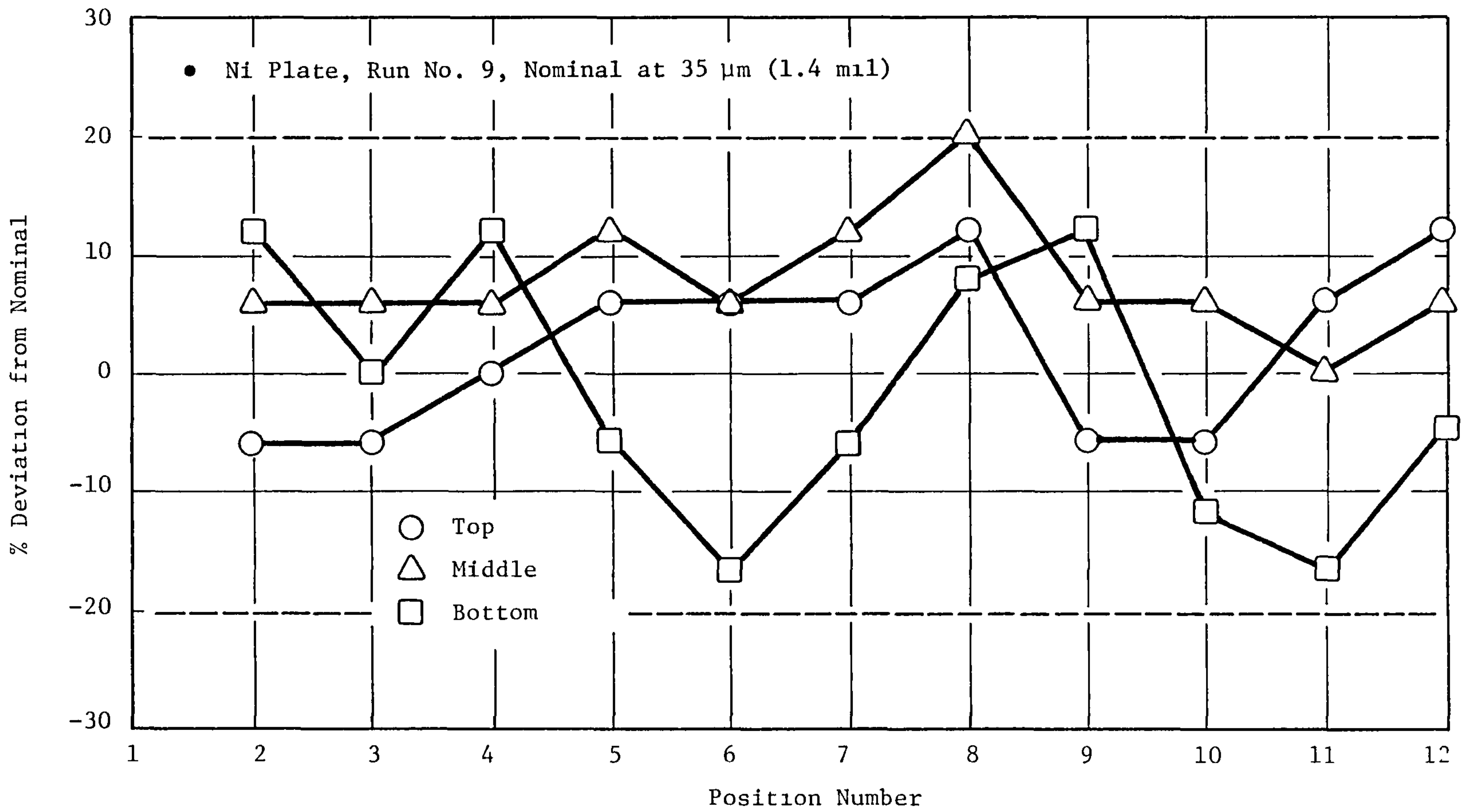


Figure 26. Deviation from Nominal Thickness Versus Position Number for Ni Plate.

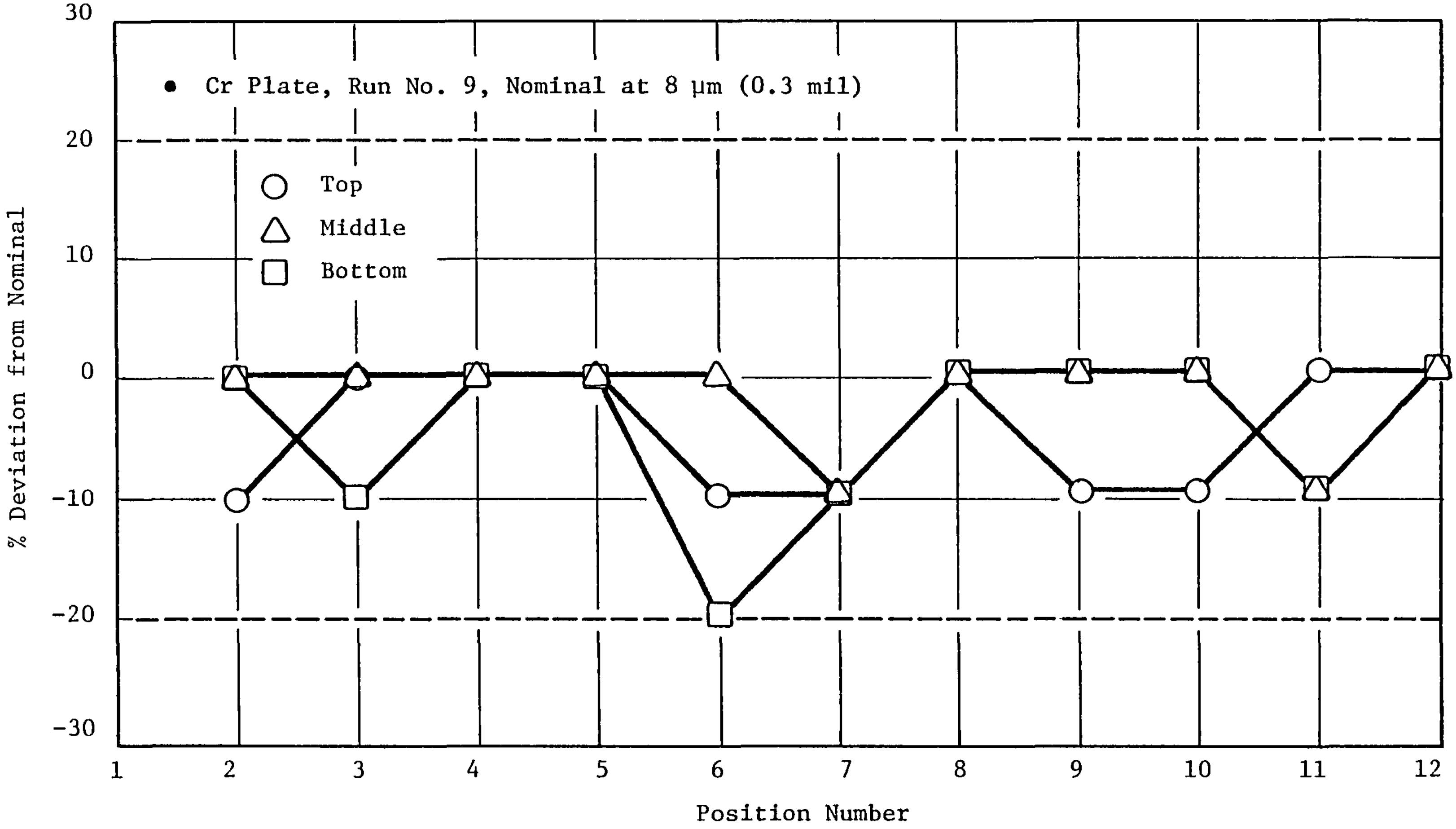


Figure 27. Deviation from Nominal Thickness Versus Position Number for Cr Plate.

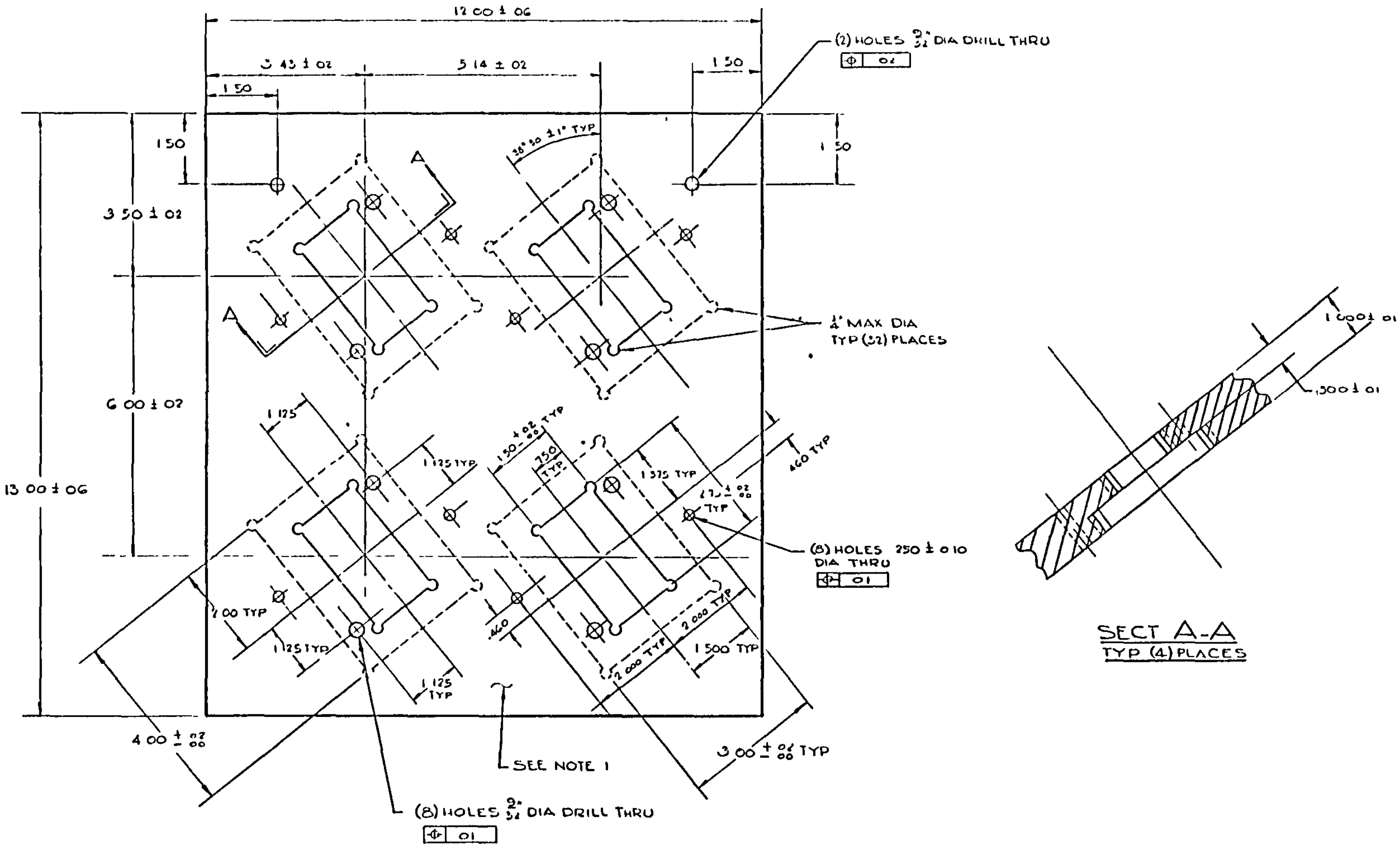


Figure 28. Multiblade Plating Fixture Base Plate Drawing.

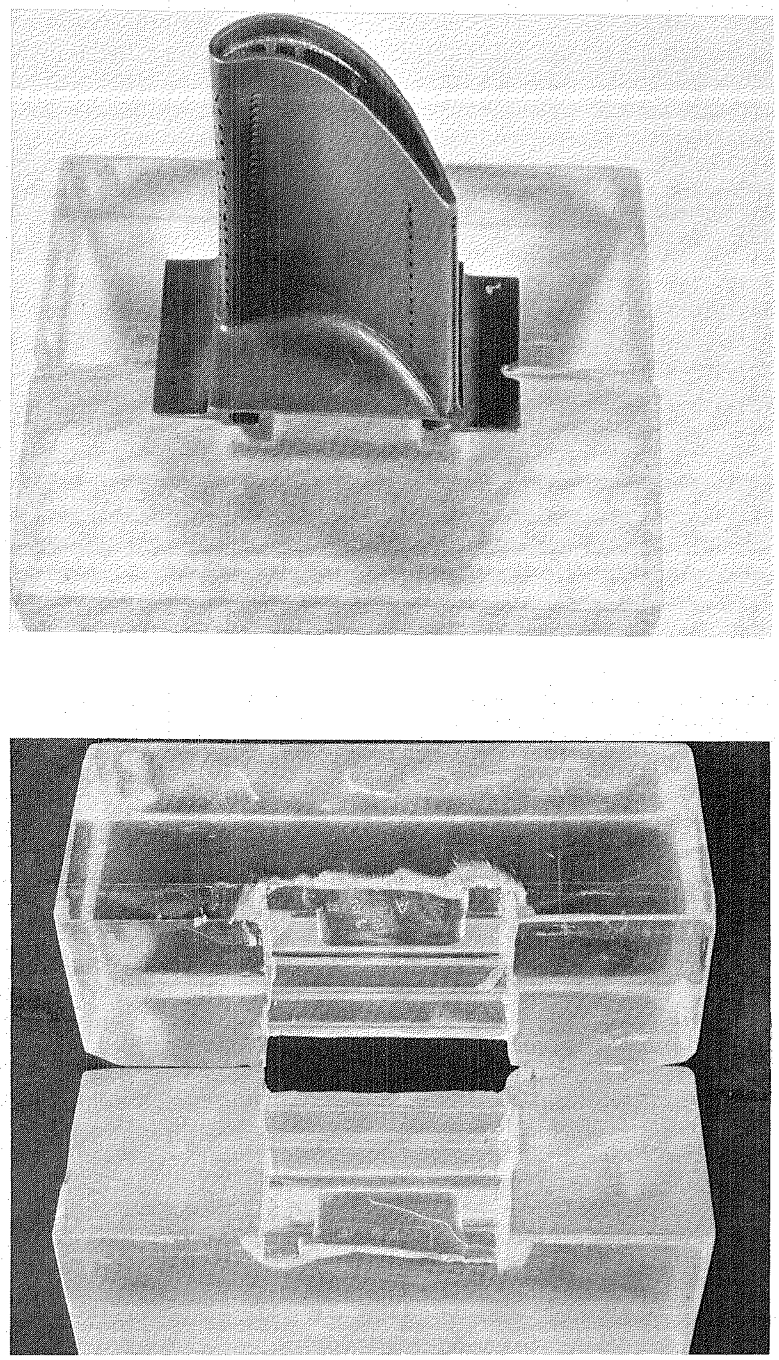


Figure 29. Upper: Polyester Resin Fixturing Block for Securing the Turbine Blades in the Base Plate;
Lower: Block Split to Release Blade.

Table IX. Plating Thickness Measurements.

Rack Position No	Airfoil No and Location	Electroplated Layer Thickness, μm (mil)		
		Cr (Inner)	Ni	Cr (Outer)
1	S/N 2525, Top	0-4 6 (0-0 18)	28-48 (1 1-1 9)	0 5-8 9 (0 02-0 35)
1	S/N 2525, Middle	1 5-4 6 (0 06-0 18)	25-56 (1 0-2 2)	2 8-8 6 (0 11-0 34)
1	S/N 2525, Bottom	2 0-5 1 (0 08-0 20)	25-46 (1 0-1 8)	4 1-8 1 (0 16-0 32)
2	S/N 8532, Top	0-6 1 (0-0 24)	28-46 (1 1-1 8)	2 0-10 2 (0 08-0 40)
2	S/N 8532, Middle	1 0-5 1 (0 04-0 20)	36-56 (1 4-2 2)	4 1-10 2 (0 16-0 40)
2	S/N 8532, Bottom	1 5-4 1 (0 06-0 16)	28-46 (1 1-1 8)	4 1-8 1 (0 16-0 32)
3	S/N 2433, Top	0-6 1 (0-0 24)	25-64 (1 0-2 5)	3 0-11 2 (0.12-0 44)
3	S/N 2433, Middle	0-6 1 (0-0 24)	25-71 (1 0-2.8)	1 5-12 2 (0 06-0 48)
3	S/N 2433, Bottom	0-4 8 (0-0 19)	25-61 (1 0-2 4)	2 5-11 2 (0 10-0 44)
4	S/N 8901, Top	0-6 1 (0-0 24)	25-48 (1 0-1 9)	1 0-8 1 (0 04-0 32)
4	S/N 8901, Middle	0-7 1 (0-0 28)	28-64 (1 1-2 5)	1 5-10 2 (0 06-0 40)
4	S/N 8901, Bottom	0 5-5 6 (0 02-0 22)	25-46 (1 0-1 8)	3 0-8 1 (0 12-0 32)
Single-	René 150 EA-2, Top	0 8-4 6 (0 03-0 18)	28-48 (1 1-1 9)	3 3-11 2 (0 13-0.44)
Blade	René 150 EA-2, Middle	1 0-4 1 (0 04-0 16)	30-46 (1 2-1 8)	3 3-9.1 (0 13-0 36)
Rack	René 150 EA-2, Bottom	0 3-2 5 (0 01-0 10)	25-36 (1 0-1 4)	2.0-8 1 (0 08-0 32)
Plating Thickness Goal	--- ---	0-2 5 (0-0 1)	33-53 (1 3-2.1)	5 6-8 6 (0 22-0 34)

Plating thickness ranges were based on microscopic measurements at 15 locations around the periphery of the airfoil

Table X. Ni/Cr Ratios for Multiblade Plating Fixture.

Rack Position No.	Airfoil No and Location	Trailing Edge (Position No's 1, 2, 14, 15)	Airfoil Sides and Leading Edge (Position No's 3-13)
1	S/N 2525, Top	4 4-35	3 3-4.0
1	S/N 2525, Middle	3 8-5 9	3.3-4.2
1	S/N 2525, Bottom	3 4-4 8	3.3-4 7
2	S/N 8532, Top	3 7-14	2 8-4 0
2	S/N 8532, Middle	3 7-7 2	3 2-4.2
2	S/N 8532, Bottom	3 3-5 0	3 2-5 0
3	S/N 2433, Top	3 6-9 2	3 0-5.0
3	S/N 2433, Middle	3 3-22	3 3-5.0
3	S/N 2433, Bottom	2 8-10	3 3-6 4
4	S/N 8901, Top	5 6-25	2 2-5.9
4	S/N 8901, Middle	4 0-17	3 3-5 0
4	S/N 8901, Bottom	2 7-8 6	3 0-6.9
Single-	René 150 EA-2, Top	3 7-7 0	3.1-4.6
Blade	René 150 EA-2, Middle	3 7-7 1	3 2-4 0
Rack	René 150 EA-2, Bottom	3 4-11.8	3 3-4 7

For multiblade plating fixture No 1, plating Run 2 electroplated thickness (as-plated condition) ratios were based on microscopic measurement at 15 locations around the airfoil periphery

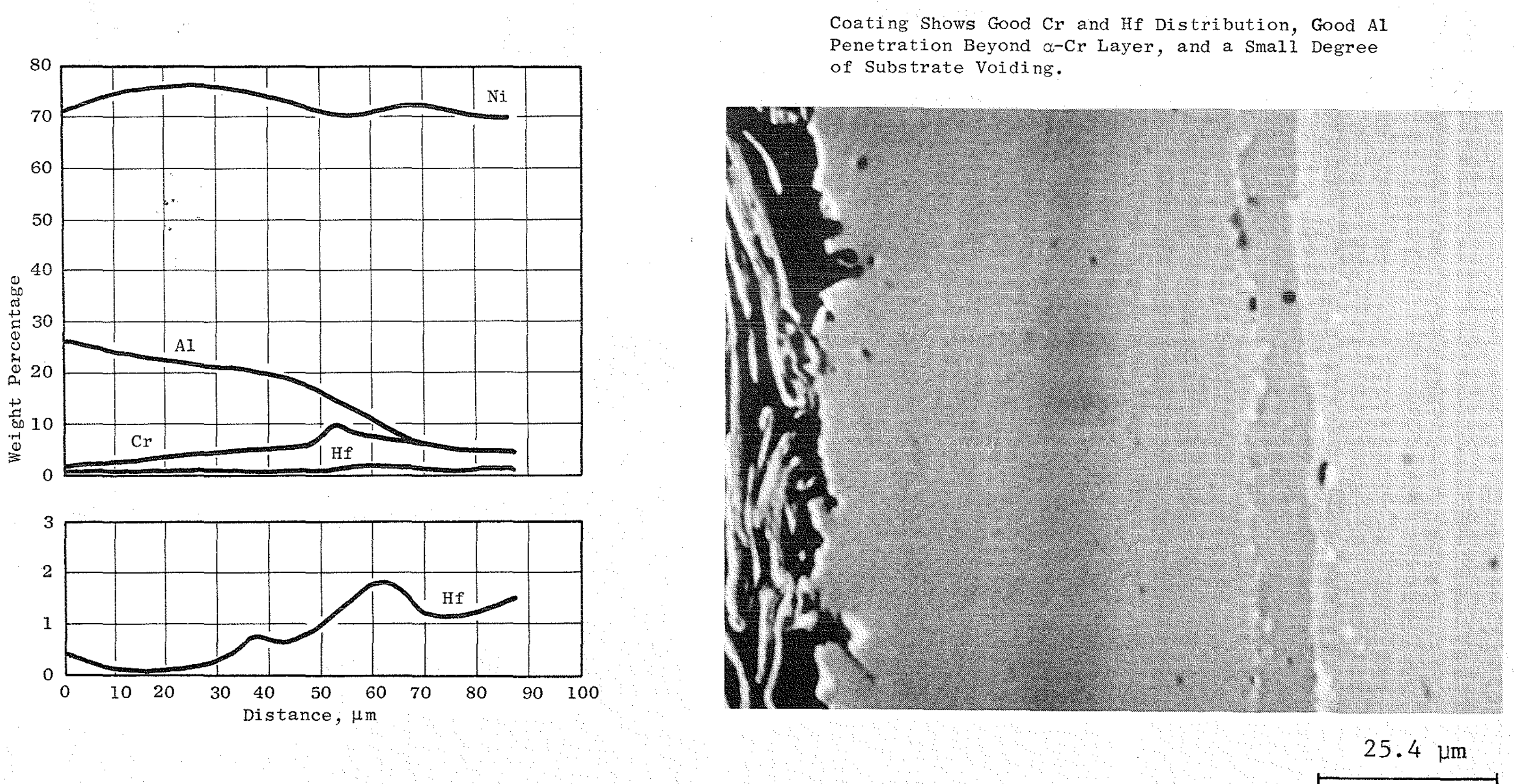


Figure 30. Scanning Electron Micrograph and Related Microprobe Scan of an EA NiCrAlHf Coating on a René 150 Turbine Blade Leading Edge.

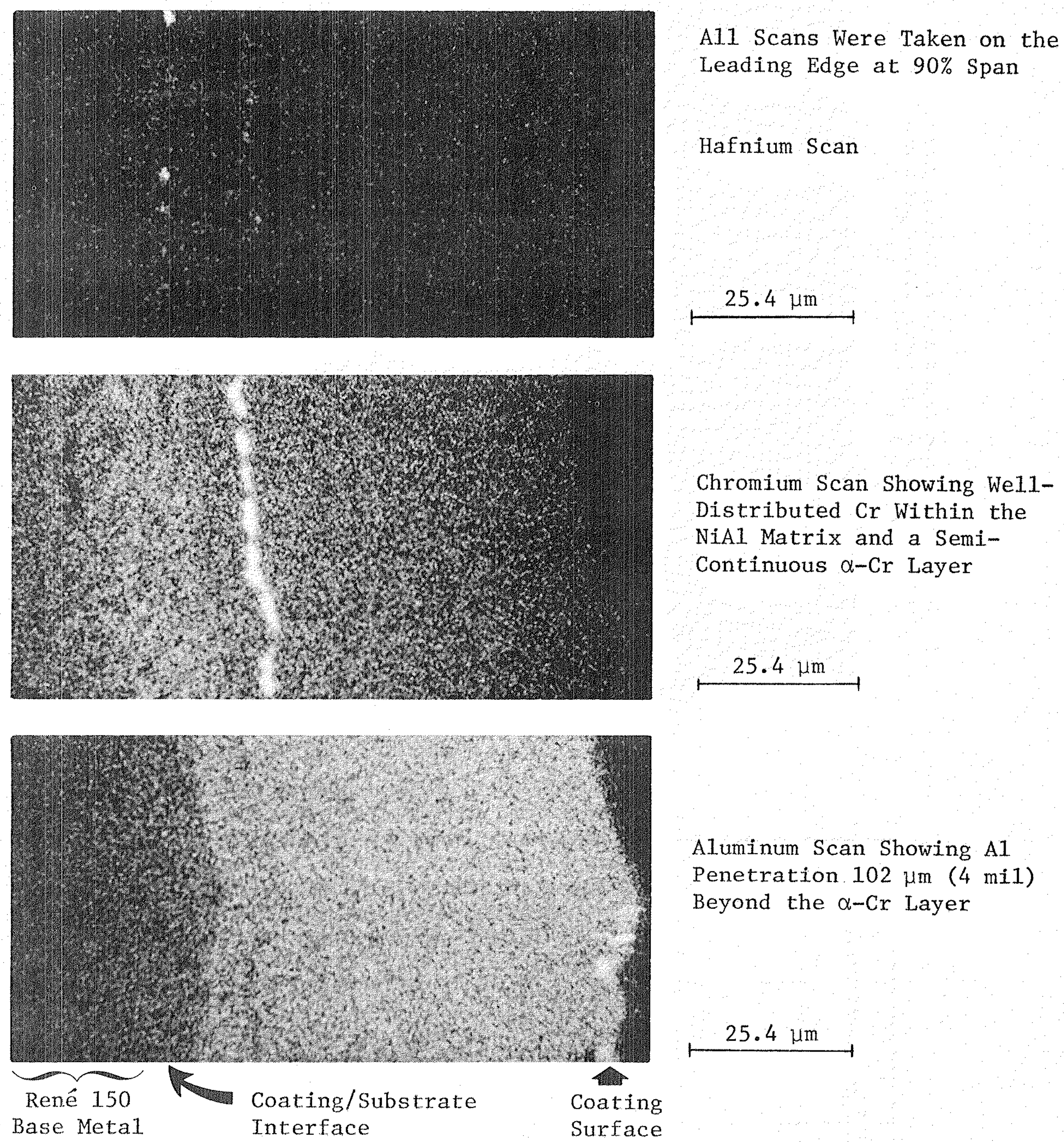


Figure 31. Qualitative X-Ray Oscillograms of an EA NiCrAlHf Coated and Fully Heat Treated René 150 Turbine Blade.

demonstrate these desirable coating features in a specimen removed from the leading edge of an EA NiCrAlHf coated and heat treated René 150 turbine blade. Hardness readings, shown in Figure 32, indicate such a coating has a γ nickel layer below the α chromium layer; this is more ductile than a $\gamma + \gamma'$ outer layer and substrate.

The final coating trial was made on four René 150 blades and showed good coating reproducibility. The coating had a morphology and thickness similar to those previously achieved on other blades and specimens.

5.1.3 Properties of Internally Aluminided René 150

Originally it was planned to modify the pack-cementation procedure to prevent the internal aluminiding of the turbine blades. By flowing hydrogen into the internal blade passages it is possible to prevent the aluminum vapors from entering through the cooling holes.

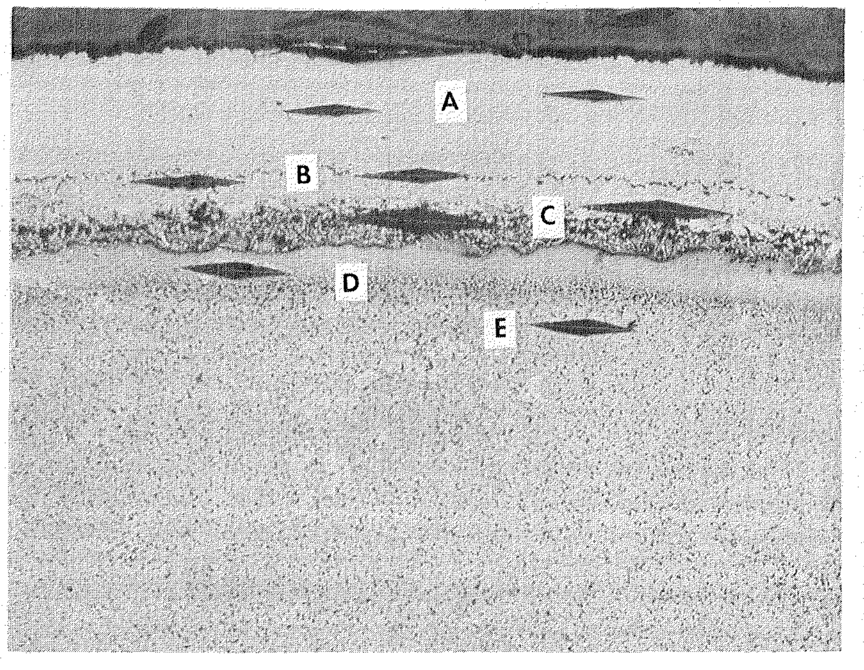
A modified coating box was constructed and tested, but results indicated that hydrogen flow rates through the individual cooling cavities had to be regulated. Even though flow-rate control was possible, such a "plumbing" system was considered impractical for an 80-blade coating run with multiblade coating boxes. The alternative was to permit internal aluminiding to occur as with conventional, air-cooled blades. As indicated in Table VIII, the LCF requirement of the blade interior is conservatively estimated at 30% less than the LCF strength of René 150 at 760° C (1400° F). This requirement was estimated using the calculated stress distribution of the blade interior. Based on the thickness of aluminide that results in conventional coating, it was expected that the coated René 150 will exceed the LCF requirement at 760° C (1400° F). To determine the precise amount of internal aluminiding which would occur, a CF6-50 blade was produced with the cooling-hole configuration planned for the program.

The middle row of leading-edge, film-cooling holes of a René 80 CF6-50 HPT blade was brazed shut. This blade was electroplated, hafnide/aluminided, and sectioned along the full length of the row of crossover holes. Figures 33 and 34 show that the aluminide thicknesses were relatively uniform throughout the first cooling cavity and crossover holes. Thicknesses were higher than expected at 22.9 μm (0.9 mil) for an outer aluminide layer and 15.2 μm (0.6 mil) for the inner diffusion (base metal and aluminide) layer. No hafnium was seen in the internal coating, as is shown by the X-ray oscillograms in Figure 35.

On these blades, the outer aluminide layer was 20.3 μm (0.8 mil) thick, and the inner diffusion layer was 12.7 μm (0.5 mil) thick at a similar location. No hafnium was observed in the internal coating. Several trials utilizing René 125 LCF specimens to define the aluminiding coating parameters proved unsuccessful due to excessive diffusion. In order to establish these parameters, a trial run was made using previously tested, bare René 150, LCF specimens. Metallographic examination of these specimens revealed an outer aluminide layer thickness of 25.4 μm (1.0 mil) and an inner diffusion layer

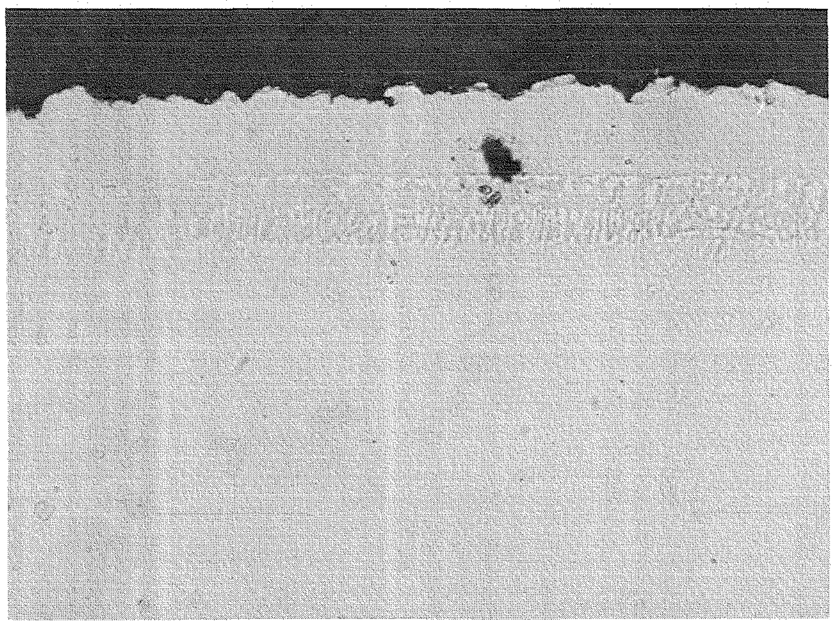
Area	Knoop Hardness	Equivalent Hardness (Rc)
A	480	46
B	440	44
C	329	30
D	448	44
E	502	48

Lightly Etched/Phosphoric



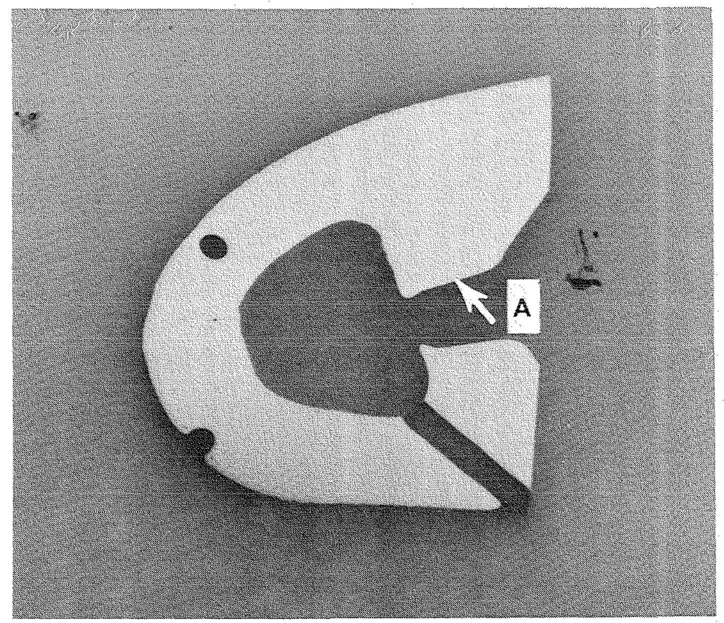
101.6 μm

Figure 32. Photomicrograph of Knoop Hardness Indentations Across EA NiCrAlHf Coated René 150 Showing Ductile Inner Nickel Layer (Point C).



50.8 μm

Photomicrograph of Area "A" Showing Depth of Internal Aluminiding with a 0.23 μm (0.9 mil) Outer Layer and a 0.15 μm (0.6 mil) Inner Layer



2540 μm

Mounted Surface of a René 80 Leading Edge; Arrow Points Out Crossover Hole (Area A) Where Thermal Stresses are LCF Limiting

Figure 33. Internal Aluminiding on a René 80 Fully Machined Turbine Blade with Cooling-Hole Configuration Simulating the René 150 Design.

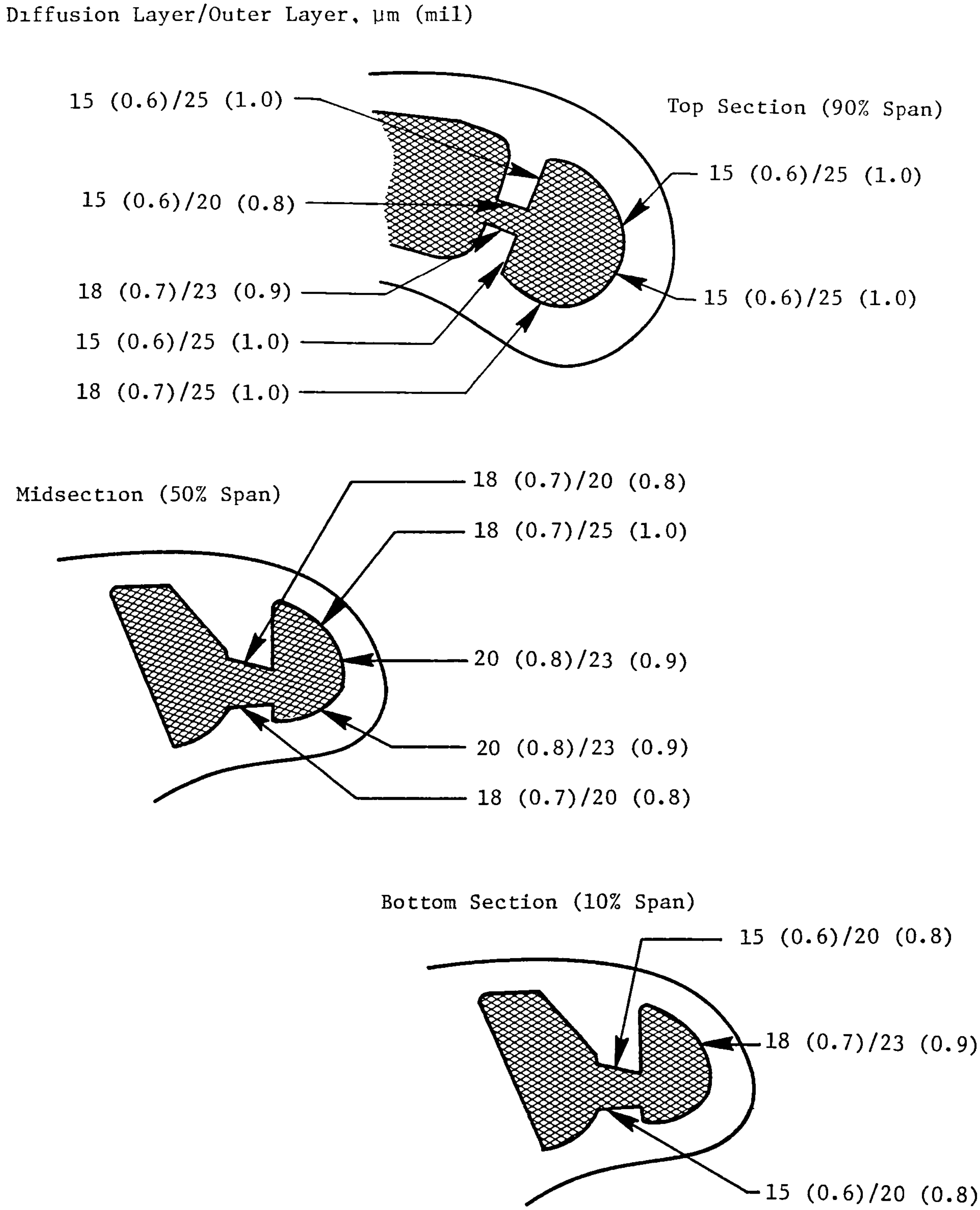


Figure 34. Internal Aluminiding Depths as Seen on a René 80 Fully Machined Turbine Blade with Cooling-Hole Configuration Simulating the René 150 Design.

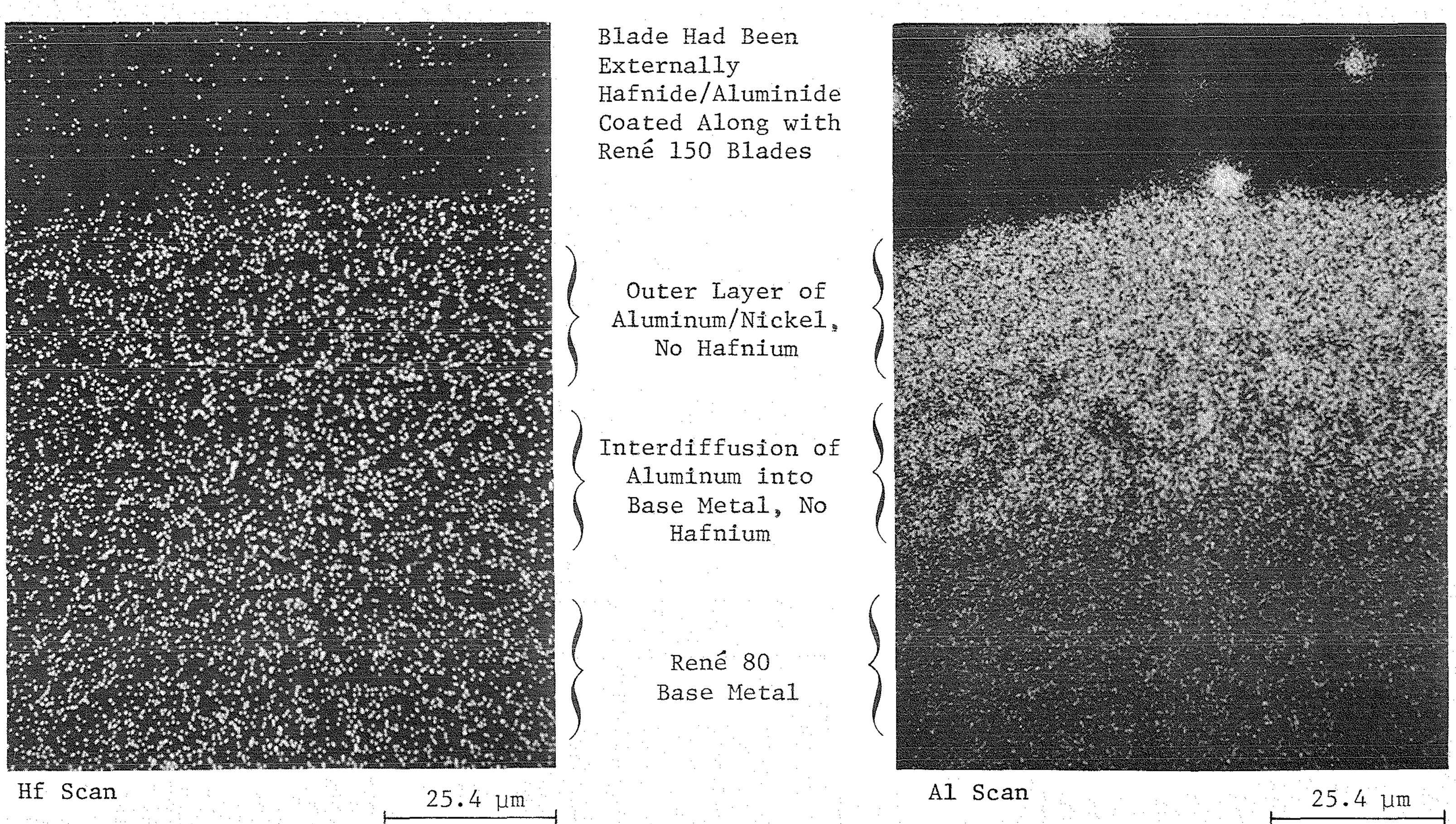


Figure 35. Qualitative X-Ray Oscillograms of an Internal Coating on a Finish-Machined René 80 Turbine Blade.

thickness of 22.9 μm (0.9 mil). The remaining René 150 LCF specimens were coated using similar parameters. Based on micrometer measurements, the aluminiding was similar to that observed on the blades. A summary of the internal aluminiding simulation study is given in Table XI.

Table XI. Internal Aluminiding Simulation Summary.

Specimen/Blade Description	Run No.	Substrate Material	Inner Cylinder Pack Composition	Coating Thickness, μm (mil)	
				Outer (Additive) Layer	Inner (Diffusion) Layer
3 Corrosion Pins	A-1	René 80	98% Al_2O_3 2% FeO_2	22 9 (0 9)	15.2 (0 6)
		René 80	95% Al_2O_3 5% FeO_2	20.3 (0.8)	15.2 (0.6)
		René 80	90% Al_2O_3 10% FeO_2	17.8 (0.7)	15.2 (0.6)
2 LCF Specimens	1	René 125	75% Al_2O_3 25% FeO_2	0	0
		René 125	85% Al_2O_3 15% FeO_2	0	1.27 (0 05)
2 LCF Specimens	2	René 125	95% Al_2O_3 5% FeO_2	0	48.8 (1.92)
		René 125	100% Al_2O_3	20.3 (0.8)	156.5 (6.16)
2 LCF Specimens	3	René 150	100% Al_2O_3	25.4 (1 0)*	22.9 (0.9)*
3 LCF Specimens	4	René 150	100% Al_2O_3	20.3 (0.8)*	17.8 (0 7)*
René 80 Blade (Simulating René 150 Blade Cooling-Hole Pattern)	---	René 80	---	22.9 (0 9)	15.2 (0.6)
GE23	---	René 150	---	20.3 (0.8)	12.7 (0.5)

*Estimated Values of Coating Thickness

Strain-controlled LCF testing at 760° C (1400° F) was performed on these coated specimens. The LCF results are given in Table XII and compared with bare René 150 in Figure 36. The LCF strength loss due to aluminiding was less than expected; it ranged from approximately 20% at higher stress levels to 0% at lower stress levels. Design analysis of these data indicated that this property level was acceptable for operation in the planned CF6-50 factory engine test.

Table XII. Low Cycle Fatigue Tests on Aluminided René 150.

- Longitudinal Specimens, 760° C (1400° F)
- A Ratio = 0.95, K_t = 1.0, 20 cpm

Alternating Pseudostress, MPa (ksi)	Cycles to Crack Initiation (Ni)	Cycles to Failure (Nf)
627 (91.0	3,100	3,800
542 (78.6)	5,000	5,300
487 (70.7)	Not Detectable	132,400*
461 (66.9)	15,000	15,400
*Specimen Runout at Indicated Cycles, No Failure		

5.1.4 EA NiCrAlHf Coat René 150 Blades

The purpose of this subtask was to demonstrate that the desired EA NiCrAlHf coating can be applied to the CF6-50 blade configuration with a quality level equivalent to that observed on test specimens. The only René 150 blades available during this time period were castings without cooling holes. To obtain a preliminary evaluation, one of the single-blade plating fixtures was modified to accept the oversized dovetails of the blade castings. This involved machining of the base plate and requalification of the newly positioned anode fixture. Metallographic evaluation of the blades plated in this modified fixture demonstrated the capability of meeting the ±20% plating thickness acceptance range.

During the course of this study a process improvement was evaluated which improved the overall EA coating process. The process involved elimination of the nickel-strike procedure which produced a 1 μm (0.04 mil) nickel layer on the surface of the blade. Its inclusion had been an attempt to provide a better surface for the subsequent chrome plating. Metallographic examination of René 150 blades coated without the nickel strike revealed that fewer blisters and a cleaner substrate/plating interface were produced than on blades coated with the nickel strike. There were no apparent differences in the coating itself. The nickel-strike procedure was deleted from future plating operations.

The final coating trial was made on four René 150 blades and showed good coating reproducibility with morphology and thickness similar to those obtained on other blades and specimens.

5.1.5 Strip and Recoat

Stripping procedures for the EA coating, at any of the three steps in the coating process, were developed and successfully tested on specimens. The

Test Temperature: 760° C (1400° F)

Test Conditions: A = 0.95, K_t = 1.0, Frequency = 20 cpm

Test Specimen: Longitudinal Orientation

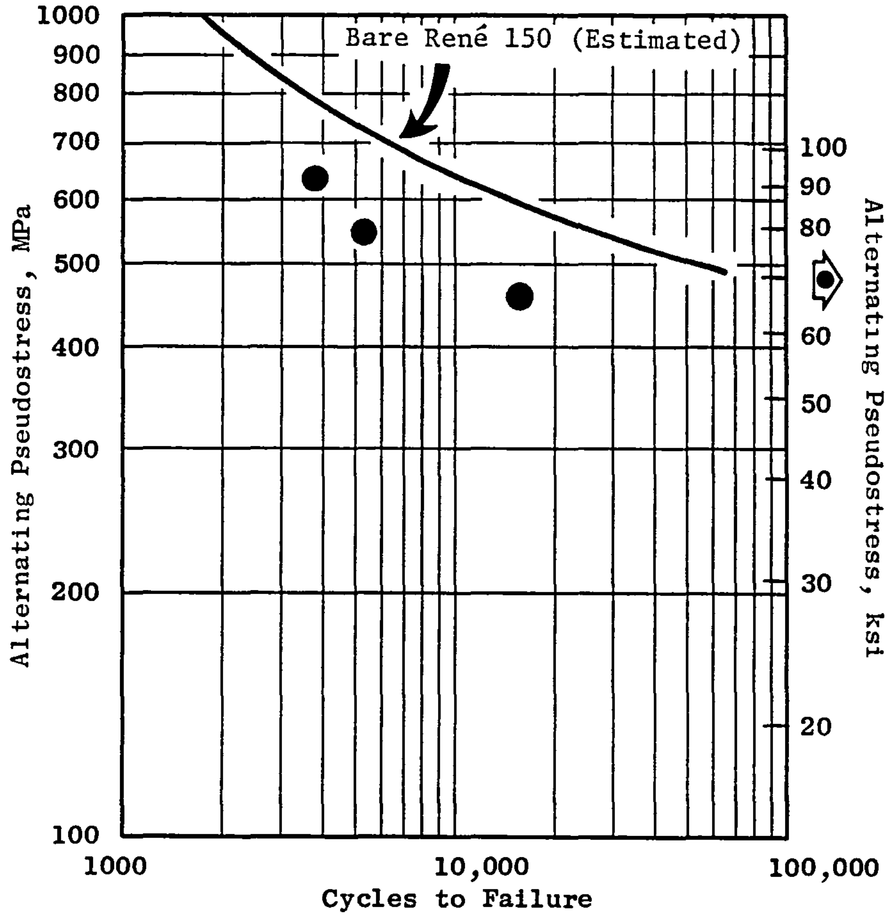


Figure 36. Strain Control LCF Aluminided René 150.

procedures are presented in Table XIII. The as-plated Ni/Cr layers can be easily stripped with no deleterious effects on the base metal. In the heat-treated condition, the coating can be removed with the exception of the diffusion zone. Two steps are required to remove the fully processed coating. A portion of the diffusion zone remains, but there are no detrimental effects on the base metal. Recoating following these stripping procedures was successfully accomplished.

These procedures were also tested specifically on René 150 blades to ensure that there were no problems peculiar to this blade configuration which would adversely effect them.

Coated René 150 blades were satisfactorily stripped using the established procedure when the plated-layer thicknesses were within the acceptability limits. This capability was confirmed on René 80 blades plated in the multi-blade fixture. Metallographic examination of the blades showed complete removal of the coating with no evidence of base-metal attack.

5.1.6 Airflow on Coated Blades

A finish-machined René 80 CF6-50 blade was EA NiCrAlHf coated and airflow tested. This test showed that the blade-cooling airflow was slightly below the process limit requirements. Metallographic examination revealed that the aluminide layer in the film-cooling holes had reduced the hole diameter by approximately 76 μm (3 mil) this is a greater reduction than anticipated. Therefore, the drilled film-cooling hole size for the René 150 blade was increased to offset this effect and ensure that adequate cooling airflow was provided to the blade.

5.2 COATING EVALUATION

Four separate activities were conducted in the evaluation of the EA NiCrAlHf coating. These were cyclic oxidation, cyclic corrosion, erosion specimens, and mechanical properties of EA-coated René 150.

5.2.1 Cyclic Oxidation

Initial screening indicated that the EA coating would provide base-metal protection for 500 hours at 1095° C (2000° F). To reconfirm this protective capability, five coated specimens underwent a 500-hour, thermal-cyclic oxidation test. Heating was provided by combustion of natural gas at Mach 0.05, and the temperature was cycled six times per hour from 370 to 1095° C (700 to 2000° F). One specimen was removed every 100 hours for evaluation. Weight change data are given in Table XIV and Figure 37. Metallographic examination of the 500-hour specimen revealed a localized coating failure, a 254 μm (10 mil) pit. This localized type of attack has not been observed previously on this coating/base-metal system.

Table XIII. Coating Stripping Procedures.

As-Plated Stripping Procedures

- Cr Plate

  -- Immerse 50 v/o 22° Bé HCl
  -- Room Temperature to 38° C (100° F)
  -- Immerse Until Cessation of Reaction
  -- Rinse in Deionized H_2O

- Ni Plate

  -- Immerse in Enthone L-90 As-Recieved
  -- Room Temperature to 38° C (100° F)
  -- Rinse in Deionized H_2O

Diffused Nichrome Stripping Procedures

- Aqueous Solution : $FeCl_3$ - 200 g/liter
  $CuSO_4$ - 150 g/liter
  Acetic Acid - 75 moles/liter

- Heat Solution to 54° C (130° F)

- Immerse Part for 15-20 Minutes

- Water Rinse

Stripping Procedures (Two Steps) for Full-Processed EA NiCrAlHf

Step 1: β-NiAl Additive Layer Strip

- Aqueous Solution of: 25% HNO_3
  75% H_3PO_4
- Heat Solution to 75° C (170° F)
- Immerse Part 15-20 Minutes
- Water Rinse

Step 2: Al Rich, γ-NiCr Additive Layer and Diffusion Zone

- Aqueous Solution of: 200 g/liter $FeCl_3$
  100 moles/liter
- Heat Solution to 54° C (130° F)
- Immmerse Part 55 Minutes
- Water Rinse
- Grit Blast

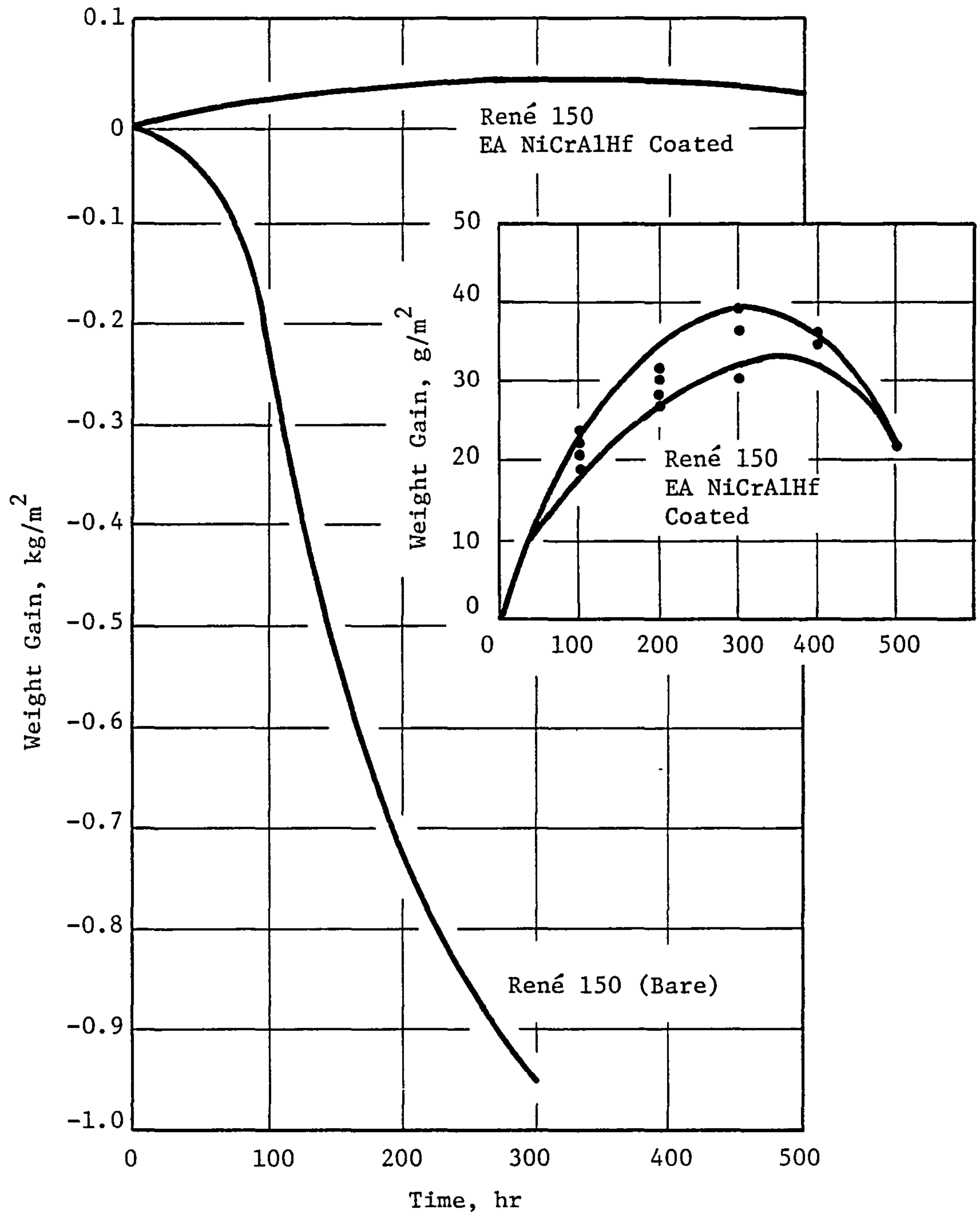


Figure 37. 1093° C (2000° F) Dynamic Oxidation Test on Pins - Mach 0.05, 6 Cycles per Hour.

A possible cause of the localized coating failure was surface contamination of the specimen. An energy-dispersive analysis of X-rays (EDAX) analysis of the pit region was performed in an attempt to verify this, but the results were inconclusive. In general, the remainder of the coating on the 500-hour specimen looked very good with approximately two-thirds of the original coating remaining. This coating is acceptable from an oxidation standpoint.

Table XIV. Dynamic Oxidation Results.

• 1095° C (2000° F)

Specimen Number	Weight Change, g/m²				
	Interruption Time, hr				
	100	200	300	400	500
3	20.6	28.5	30.2	---	---
4	23.8	---	---	---	---
5	22.2	27.0	---	---	---
6	19.0	30.2	39.7	34.9	22.2
7	22.2	31.7	36.5	36.5	---

5.2.2 Cyclic Corrosion

Initial screening demonstrated that the coating would protect the René 150 base metal to 250 hours in corrosion rig testing at 925° C (1700° F). To confirm this protective capability, coated specimens were subjected to a 500-hour thermal-cyclic corrosion test with 5 ppm sea salt injection. The temperature was cycled once per hour from 925 to 270° C (1700 to 500° F). It was originally planned to test five specimens and remove one specimen for evaluation every 100 hours; however, only four rig-test sites were available in the time frame planned. In the interest of expediency, it was decided to proceed with the test and schedule specimen removal at 150, 250, 350, and 500-hour test intervals. The specimens were actually removed for evaluation at the following times: 160, 252, 318, and 490 hours. The 318-hour specimen was planned for 350 hours but was removed prematurely due to visual evidence of possible coating distress. Metallographic examination revealed coating failure at 252 hours with approximately 51 μm (2 mil) of base-metal attack. The 318-hours specimen showed 508 μm (20 mil) of base-metal attack. It is estimated that the actual coating failure occurred shortly before 250 hours.

This coating is judged to possess acceptable corrosion resistance for operation in the planned CF6-50 factory engine test.

5.2.3 Erosion Specimens

Metallographic examination of a plated dummy erosion specimen revealed that the plated-layer thicknesses were not within the desired limits but were judged acceptable for testing. The total plated-layer thicknesses and Ni/Cr ratios at various locations on the erosion specimen are shown in Table XV. All of the specimens were photographed to document the initial conditions. The five bare and five EA NiCrAlHf coated René 150 erosion specimens were delivered to NASA for testing in accordance with contractual requirements.

5.2.4 Mechanical Properties of EA Coated René 150

To verify that EA coated René 150 met the minimum criteria (Table VIII), selected mechanical-property testing was performed. These tests were 980° C (1800° F) stress rupture and 760 and 980° C (1400° F and 1800° F) high cycle fatigue.

5.2.4.1 Stress Rupture

The results of the 980° C (1800° F) stress rupture testing are given in Table XVI and compared graphically with bare René 150 and René 80 in Figure 38. EA coated René 150 was equivalent to bare René 150 and was therefore acceptable from a stress rupture standpoint.

5.2.4.2 High Cycle Fatigue

The results of the 760 and 980° C (1400 and 1800° F) HCF testing are given in Table XVII and compared with HCF results on bare René 150 in Figures 39 and 40. From these data, the following observations were made.

- At 750° C (1400° F), for the conditions tested, EA-coated René 150 showed approximately 25% reduction in HCF resistance from bare René 150 in the longitudinal direction. Tests in the transverse direction showed only a slight (<5%) reduction.
- At 980° C (1800° F), for the conditions tested, EA-coated René 150 showed only a slight HCF resistance reduction (<5%) from bare René 150 in the longitudinal direction. Tests in the transverse direction showed that coated René 150 was slightly better than bare René 150.

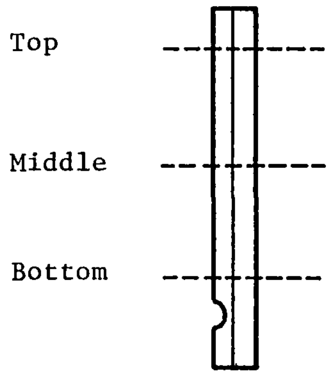
Design analysis of these data showed that EA-coated René 150 possessed acceptable mechanical properties.

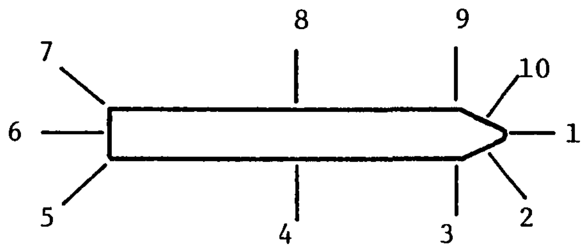
5.3 FINAL COATING SELECTION

Although the EA NiCrAlHf coating met all of the minimum requirements for use on the René 150 blade in the planned factory fan engine test, an alternate coating, developed by General Electric subsequent to the initial EA coating

Table XV. Electroplating Thickness Measurements.

- René 150 Erosion Bars





Specimen Location		1	2	3	4	5	6	7	8	9	10
Top	Total Plate Thickness, µm	34.4	59.9	39.6	44.7	36.1	23.9	38.6	41.7	32.8	53.8
	Total Plate Thickness, mil	3.68	2.36	1.56	1.76	1.42	0.94	1.52	1.64	1.29	2.12
	Ni/Cr Ratio	4.7	4.4	6.8	4.5	5.4	13.7	5.3	4.9	6.7	3.1
Middle	Total Plate Thickness, µm	69.6	50.6	36.1	52.8	45.2	23.9	38.6	51.8	49.3	57.9
	Total Plate Thickness, mil	2.74	2.00	1.42	2.08	1.78	0.94	1.52	2.04	1.94	2.28
	Ni/Cr Ratio	4.5	4.0	5.4	3.3	4.3	13.7	5.3	3.6	4.8	4.2
Bottom	Total Plate Thickness, µm	46.7	44.7	36.3	51.8	42.4	20.8	41.4	49.3	30.7	37.1
	Total Plate Thickness, mil	1.84	1.76	1.43	2.04	1.67	0.82	1.63	1.94	1.21	1.46
	Ni/Cr Ratio	6.7	6.3	8.4	3.2	6.2	33.3	7.5	4.8	12.7	7.0

Aim (Total Plate Thickness Range): 38.6 - 64.5 µm (1.52 - 2.54 mil)

Table XVI. Stress Rupture Tests on EA NiCrAlHf Coated René 150.

- Longitudinal Direction, 980° C (1800° F)

Stress, MPa (ksi)	Life, hr
345 (50)	13.0
276 (40)	42.7
241 (35)	91.0
207 (30)	227.5

Table XVII. HCF Tests on EA NiCrAlHf Coated René 150.

- Axial + Axial, A Ratio = 0.95

Temperature, ° C (° F)	Specimen Direction	Maximum Stress, MPa (ksi)	Cycles to Failure
760 (1400)	Longitudinal	758 (110)	6,500
760 (1400)	Longitudinal	655 (95)	21,600
760 (1400)	Longitudinal	483 (70)	2,560,000
760 (1400)	Longitudinal	483 (70)	14,575,000
760 (1400)	Transverse	586 (85)	400,000*
760 (1400)	Transverse	552 (80)	153,000*
760 (1400)	Transverse	552 (80)	2,069,000
760 (1400)	Transverse	517 (75)	3,154,000*
980 (1800)	Longitudinal	483 (70)	69,200
980 (1800)	Longitudinal	448 (65)	974,000
980 (1800)	Longitudinal	414 (60)	1,922,000
980 (1800)	'Longitudinal	379 (55)	5,985,000
980 (1800)	Transverse	414 (60)	60,500
980 (1800)	Transverse	379 (55)	2,200*
980 (1800)	Transverse	379 (55)	4,300*
980 (1800)	Transverse	345 (50)	10,000,000+
980 (1800)	Transverse	310 (45)	1,393,000

*Specimen thread failure

+Indicates specimen runout at indicated cycles, no failure

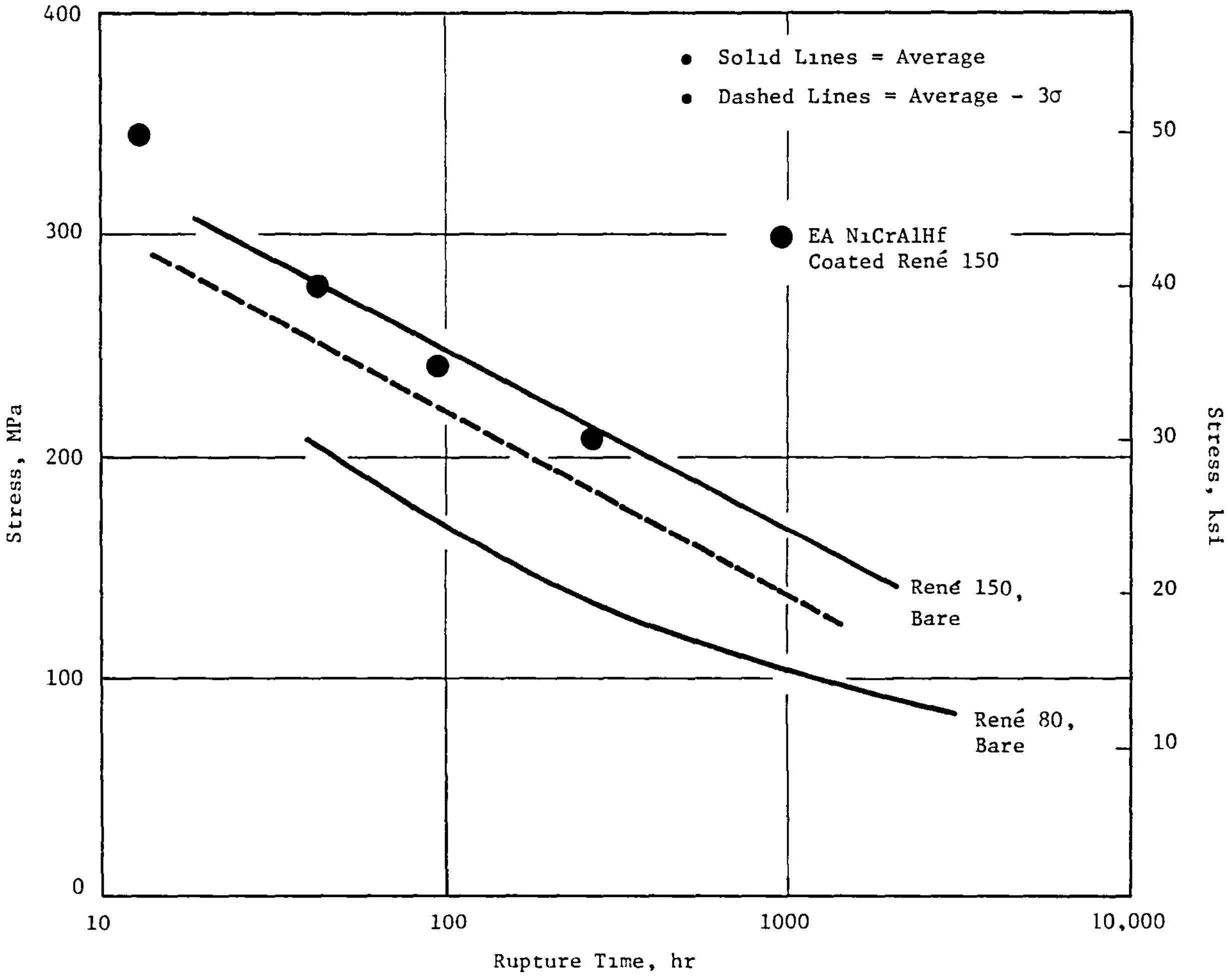


Figure 38. René 150 and René 80 Stress Rupture - 980° C (1800° F).

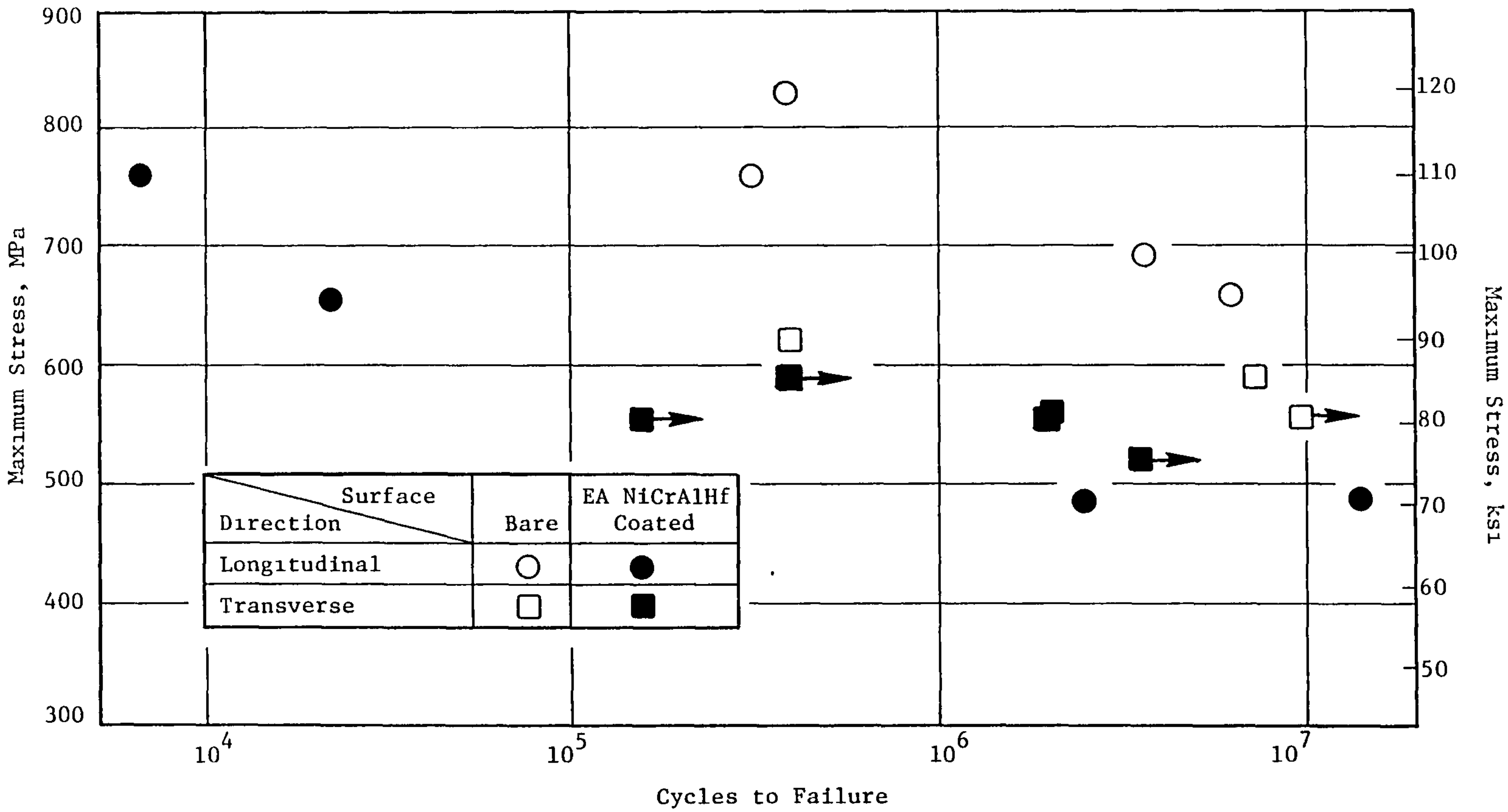


Figure 39. HCF of Coated René 150 at 760° C (1400° F) - Axial + Axial, A = 0.95.

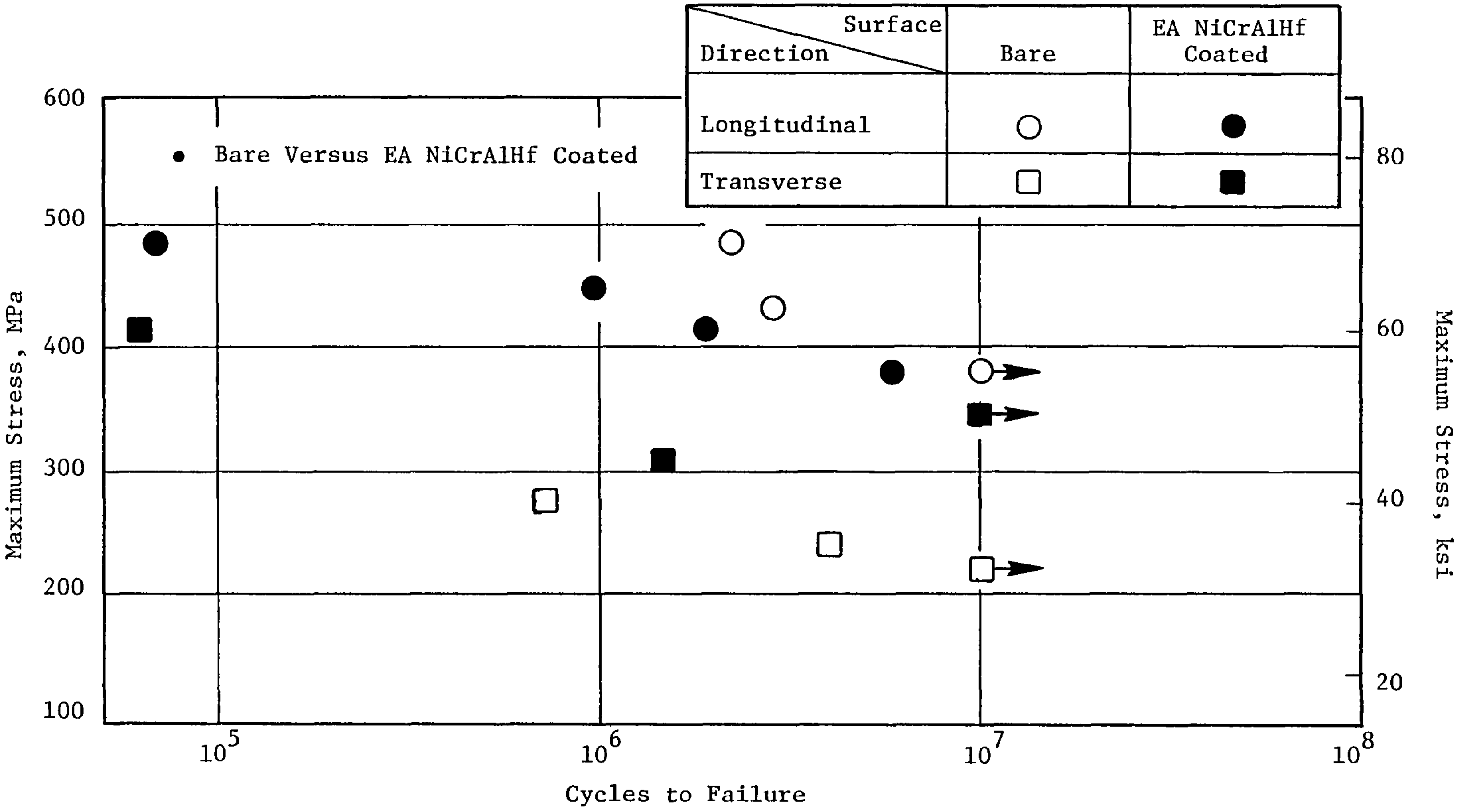


Figure 40. HCF of Coated René 150 at 980° C (1800° F) - Axial + Axial, A = 0.95.

selection, was selected for evaluation in the subsequent tasks of this project. This alternate coating, designated AC 402, demonstrated significant improvements in all areas of coating performance, as shown in Table XVIII.

Table XVIII. Coating Property Comparison, EA NiCrAlHf Versus AC 402.

Property	EA NiCrAlHf	AC 402
Environmental Resistance		
Cyclic Oxidation Life, hr	500	1850
Cyclic Oxidation Life, hr	250	4200
Mechanical Properties Compared to Bare René 150		
980° C (1800° F) Stress Rupture	Equivalent	Equivalent
760° C (1400° F) HCF		
Longitudinal	25% Reduction	16% Reduction
Transverse	<5% Reduction	Not Tested
980° C (1800° F)		
Longitudinal	<5% Reduction	<5% Reduction
Transverse	Slightly Better	Not Tested

6.0 TASK IV - FINAL RENÉ 150 SYSTEM REFINEMENT

6.1 TOOLING PROCUREMENT

The casting tooling was obtained from Trucast Tool and Mold, Inc., Cleveland, Ohio. The total blade wax die layout was conducted by Monarch Tool Co., Cleveland, Ohio. The minor amount of rework necessary to bring the tooling into compliance with engineering drawing requirements was completed satisfactorily. No changes were needed in the tooling for the blade airfoil, the core, or the core placement within the blade.

6.2 FINAL-DESIGN CASTING TRIALS

The 20 blades cast in Task II, with the shank material addition to improve blade castability, were fully evaluated in terms of grain structure, FPI, visual inspection, and X-ray inspection. No major problems were encountered, and no modifications to the preliminary casting process specification were required.

6.3 PREPRODUCTION RUN

A preproduction run of 61 castings was made to qualify the final casting process specification. An overall yield of 80% was obtained through core removal, visual, grain, X-ray, and preliminary FPI inspections. Based on this excellent yield, the casting process specification and acceptance criteria, shown in Appendix C, were approved by the NASA Project Manager and used for the production of the component and engine test blades.

6.4 COST ANALYSIS AND PROJECTIONS

An analysis of the estimated manufacturing cost for a production-size lot of finished René 150 HPT blades, produced to the final-process specification and acceptance criteria, was performed. The results are given in Table XIX.

Costs are shown as a percentage of the total cost for a CC René 80 CF6-50 part of the same configuration, and they are strongly influenced by yield. At 80% yield, as an example, it can be seen that the René 150 finished blade is only 142% of the CC René 80 blade. This cost ratio, approximately 1.4, met the target goal, namely: to refine a blade-casting process which would allow the production of René 150 blades at a cost of 1.5 times that of CC René 180 turbine blades.

Finished-part yields of 80% are unreasonably high; however, the analysis shown in Table XIX considered René 150 raw material at the present Project 2 program cost compared to René 80 at production cost. Raw material is a significant driver of the total cost. As can be seen in Figure 41, for René 150 material cost represents 2/3 of the total casting cost. Use of revert in production quantities reduces this cost considerably.

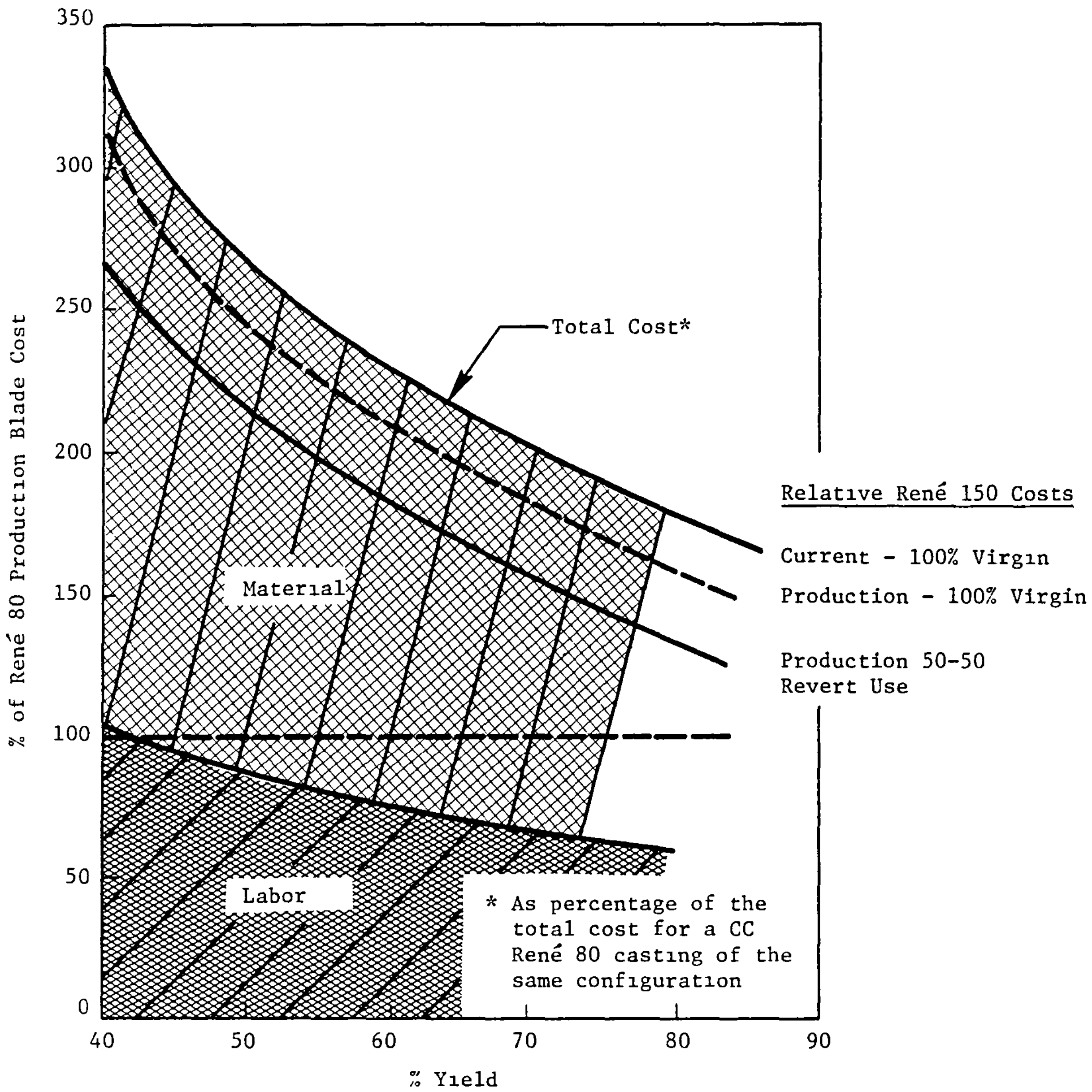


Figure 41. RAM-DS René 150 CF6-50 Turbine Blade Casting Cost.

Table XIX. René 150 CF6-50 Turbine Blade Costs.*

Costs	Yields**		
	40%	60%	80%
Casting Cost	173.57	118.29	90.66
Finishing Cost	51.54	51.54	51.54
Total Cost	225.11	169.83	142.20
Cost Ratio, DS René 150/CC René 80	2.2	1.7	1.4

*As a percentage of the total cost for a CC René 80 CF6-50 blade of the same configuration.

**Finished Part Yields

The analysis presented in Figure 42 considers finished turbine blade costs (not including coating). At a finished-part yield of 57.5%, the cost of a René 150 turbine blade is 1.5 times that of a René 80 turbine blade; this is the target goal of this project. A 57.5% yield can be reasonably attained for such hardware in production.

The inclusion of coating costs in the analysis indicated that a yield of 62% would be required to offset the cost differential between the EA NiCrAlHf or AC 402 coating and the Codep coating presently used on CC René 80. This yield was considered reasonable for production hardware.

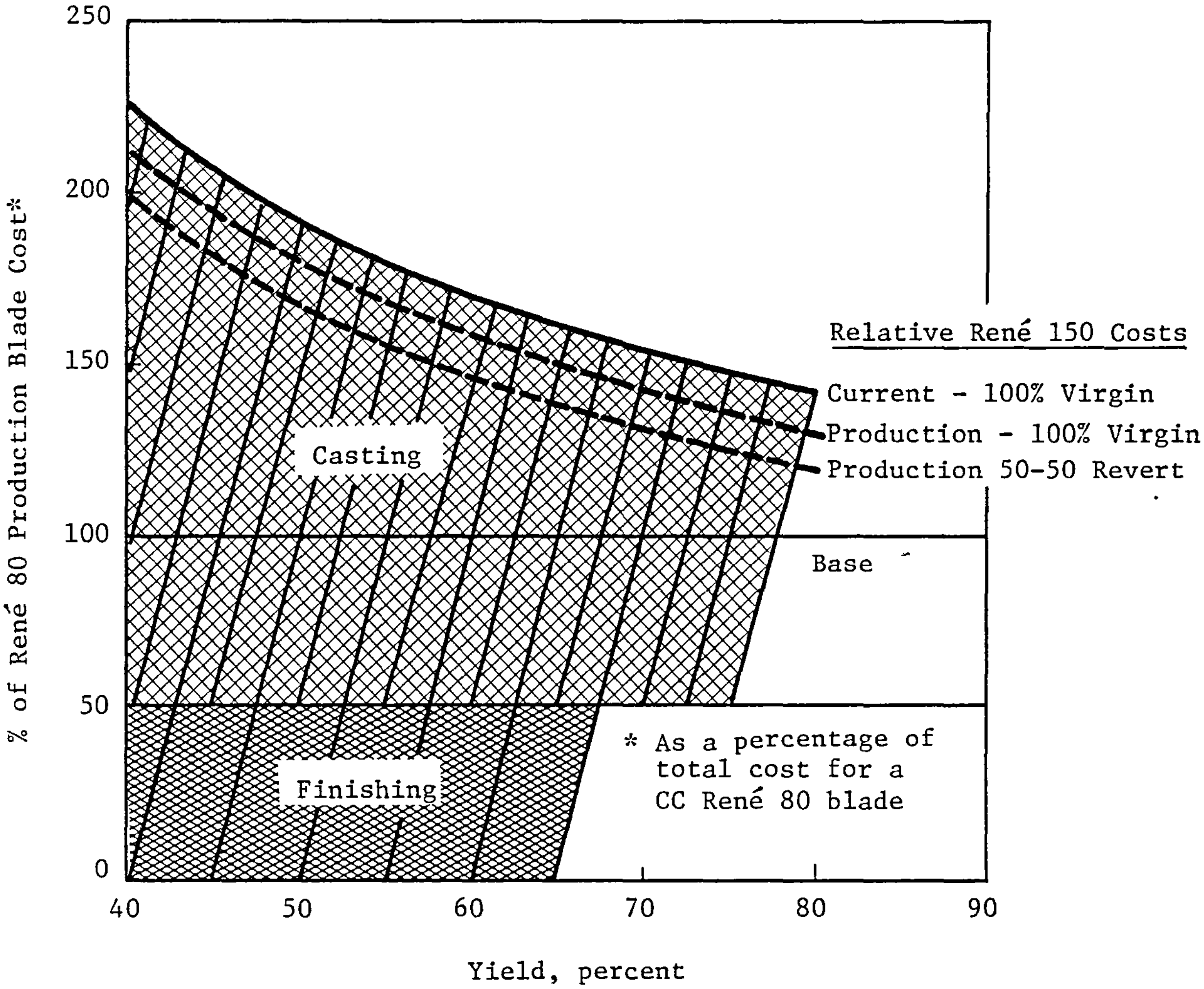


Figure 42. RAM-DS René 150 CF6-50 Finished Turbine Blade Costs.

7.0 TASK V - COMPONENT-TEST BLADE PRODUCTION AND EVALUATION

7.1 COMPONENT-TEST BLADE PRODUCTION

The René 150 CF6-50 HPT blades for this task were cast to the process specification developed in Task IV - Final René 150 System Refinement. The castings were serialized and processed through selected casting-facility operations. No grit blasting or other operations which would cold-work the blade surface were allowed because subsequent heat treatment would have resulted in recrystallization. The castings were then solution heat treated, and the majority of the blade cooling holes were drilled using standard laser, EDM, and Electro-Stream drilling methods. Even though these techniques had been used previously to drill René 150, each method was evaluated on the actual CF6-50 HPT blade configuration prior to the drilling of the project hardware. Appropriately selected scrap blades were drilled and examined visually and metallographically to determine the quality of the hole produced and to ensure that the fixturing used to hold the blade during drilling did not produce subsequent recrystallization. In every instance the hole quality was within normally acceptable limits, and no recrystallization was produced. The next step in the blade processing was tip-cap brazing. Here again the CF6-50 HPT blade configuration was evaluated visually and metallographically in order to confirm the adequacy of the brazing procedures. The braze joints examined were totally acceptable, and the project hardware was brazed. The remainder of the standard casting-facility operations (including airfoil polishing, FPI, and gauging) were then performed on the castings in accordance with engineering drawing requirements. The additional material in the shank region of the blade, as discussed previously, was removed by an ECM operation at Lehr Precision Tool, Inc., Blue Ash, Ohio. The final machining of the blade dovetail was then performed using standard techniques which had been evaluated and proven to be acceptable for René 150. The remaining hole-drilling operations were then successfully completed. Where required for component test, the finished turbine blades were coated using the coating system selected in Task III - Coating Adaptation and Evaluation. Fifty-six René 150 CF6-50 Stage 1 HPT blades were then delivered for component testing.

7.2 COMPONENT-TEST BLADE EVALUATION

The purpose of this subtask was to provide maximum assurance that a safe and successful fan engine test could be run incorporating the René 150 HPT blades. The component-oriented tests, in addition to the more basic material evaluations, formed the basis for life and reliability predictions for the engine test.

7.2.1 Blade Strain Distribution, Frequency, and Nodal Patterns

The test blades were mounted in a dovetail-slot holding fixture and excited by acoustical energy produced by a siren. The spectrum from 0 to 30,000 cps was scanned.

7.2.1.1 Blade Strain Distribution

At each resonant frequency the relative strain distributions were determined by strain gages covering the entire blade. The location of the maximum vibratory stress point was established for each mode of excitation. These data were used in conjunction with component HCF data, instrumented core engine data, and steady-state stresses determined by analysis to establish the permissible vibratory-stress limits.

7.2.1.2 Blade Frequency

The resonant-frequency data for the various excitation modes is given in Table XX. The interference or Campbell diagram, Figure 43, shows the blade natural frequencies as a function of temperature and engine speed. These calculated curves reflect the changes in natural frequency that are produced by variations in the modulus of elasticity with temperature, centrifugal stiffening with engine speed, and damper loading with engine speed. The per/rev lines indicate the number of aerodynamic excitations for each revolution. Engine operation at conditions representative of the intersection of the blade natural frequency and aerodynamic excitation lines could produce HCF-related problems. The instrumented core engine test provided information on the relative strengths of each mode encountered during actual engine operation and determined which operating conditions should be most strenuously avoided.

Table XX. Blade Natural Frequencies for Various Excitation Modes at Room Temperature.

Mode of Excitation	Blade Natural Frequency, Hz	
	No Damper Load	Full Damper Loads*
First Flexural	1,568	1,808
First Axial	2,832	3,064
First Torsional	5,350	5,752
Second Flexural	6,058	6,826
Second Torsional	8,124	9,302
Third Flexural	10,664	N.A.
First Complex	12,638	12,850
Two Stripe	15,292	15,476

*This Value is Used in Calculations for the Interference Diagram.

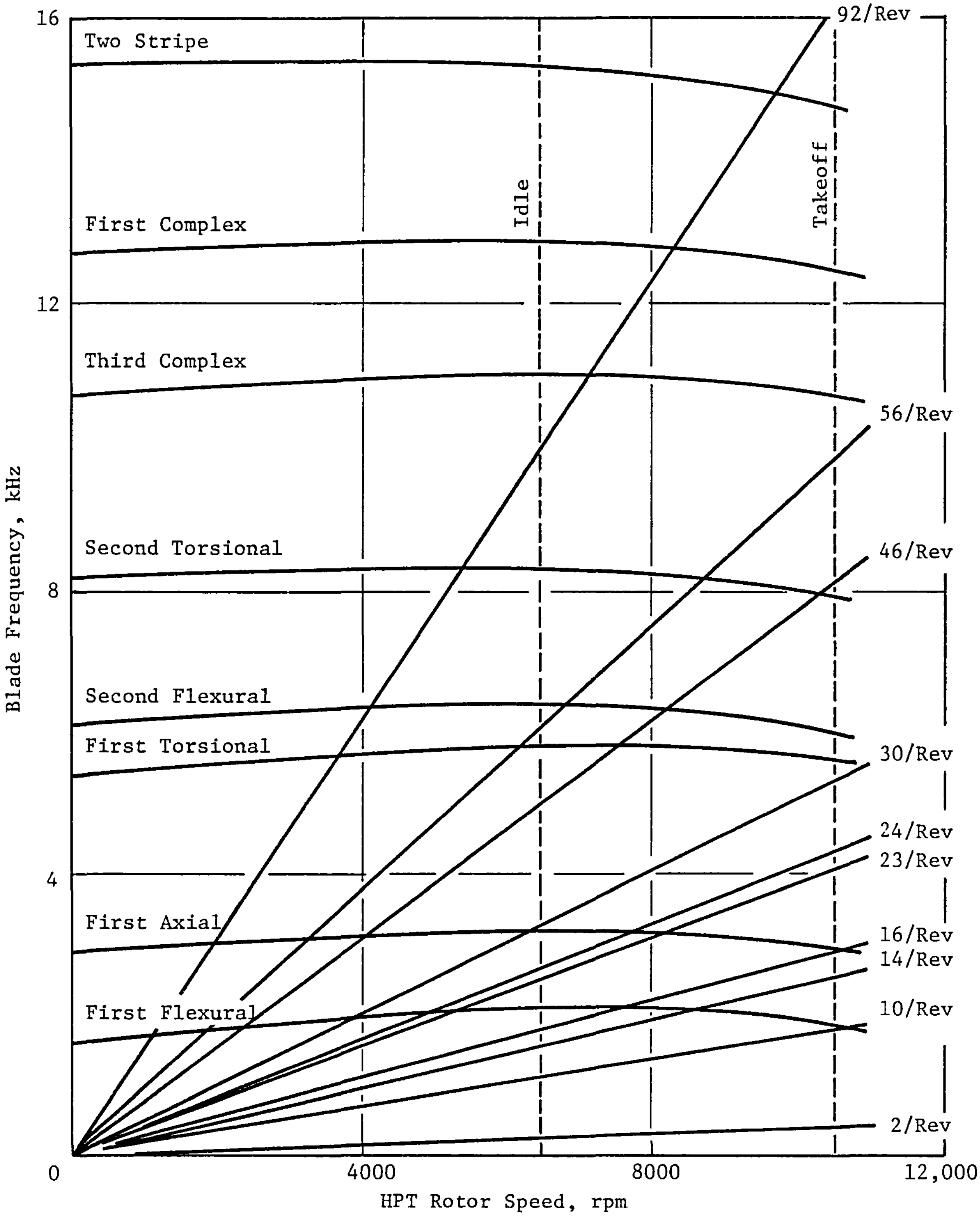


Figure 43. Blade Frequency Versus HPT Rotor Speed.

7.2.1.3 Blade Nodal Patterns

The blade nodal patterns for the various excitation modes were determined and are shown in Figures 44 through 46. These nodes, or points of zero deflection, provided information about how the blade moved in response to the various types of stimuli and were used in the understanding of the actual vibratory behavior of the blade. The effect of damper loading, which varies with engine speed, on the location of the nodes is also illustrated.

7.2.2 High Cycle Fatigue

The elevated-temperature, HCF component testing was performed at 930° C (1700° F). One purpose of this test was to establish the blade fatigue strength relative to test-bar data. The other purpose was to determine the stress/strain capability of René 150 in the CF6-50 blade configuration. A blade was initially instrumented with an array of thermocouples in order to establish a specific temperature profile. After the desired temperature profile was obtained, a test blade was substituted with only one reference thermocouple in order to minimize any effect due to the thermocouples. Then a shake table was used to drive the blade to failure in the first-flexural mode using a calibrated tip deflection. Blade failure in this test was indicated by a marked drop in blade frequency. The failures occurred in the expected locations for both the coated René 150 and René 80 blades. In addition to the thermocouple, strain gages were placed at selected locations on the blade in order to provide stress versus tip-deflection information.

Both the EA NiCrAlHf coated and the AC 402 coated René 150 blades were tested. The calibrated tip-displacement data are given in Table XXI. In general, these results indicate that the coated René 150 blades were basically similar in response to the current bill-of-material (BOM) coated René 80 blades which were tested at the same time. Design analysis of the data showed that the René 150 blade fatigue strength was within the acceptable range relative to test-bar data, thereby verifying the integrity of the blade design. In addition, the René 150 blades demonstrated improved stress/strain capability, relative to the René 80 blades, based on the strain gage results obtained during the test. The results of this test were used to provide revised Goodman diagrams for design requirements and to refine the engine stress limits established by the blade strain-distribution test.

7.2.3 Impact Tests

7.2.3.1 Ballistic-Impact Test

A ballistic-impact test was performed on three coated René 150 blades and one coated René 80 blade. The test involved heating the blades to 870° C (1600° F) in air and then impacting them with a 4.445 mm (0.175 in.) diameter steel ball at a velocity of 366 m/sec (1200 ft/sec); this produced an impact energy of approximately 27 J (20 ft-lbf). Each blade was impacted on the convex side between the gill and leading-edge holes. This is the region in which FOD is normally observed during actual engine operation. The René 80 blade

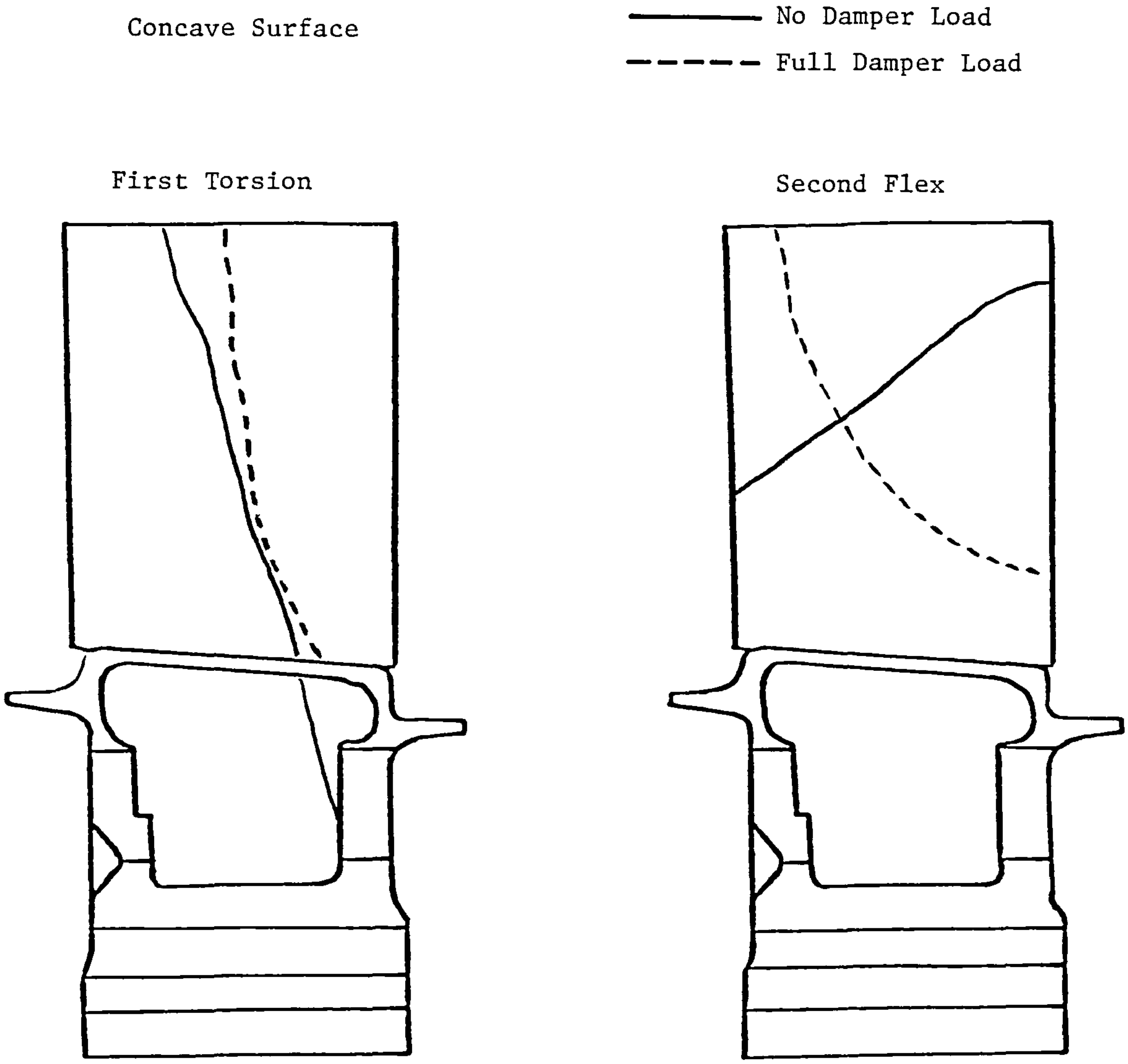


Figure 44. René 150 CF6-50 Stage 1 HPT Blade First-Torsion and Second-Flex Nodal Patterns.

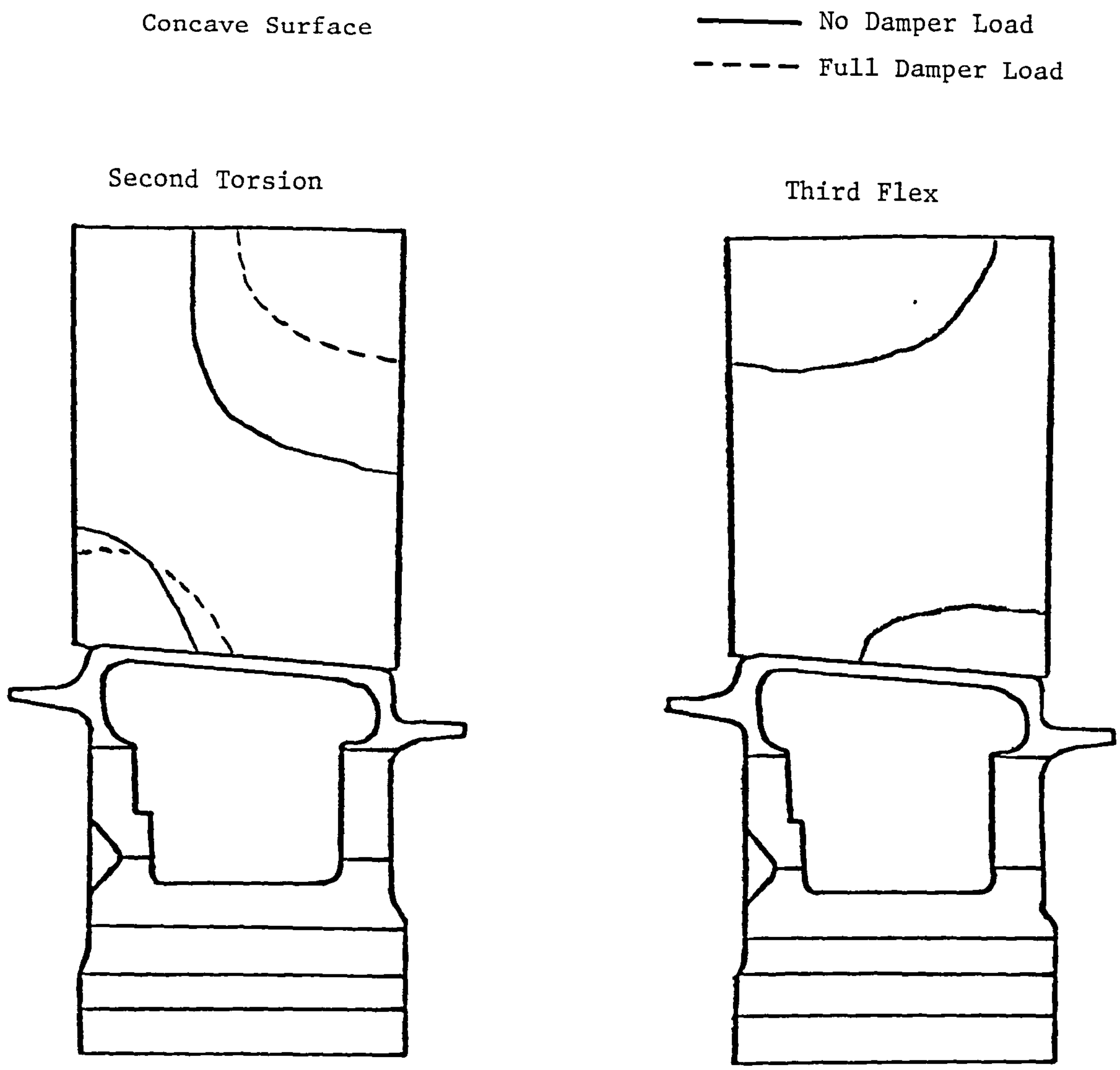


Figure 45. René 150 CF6-50 Stage 1 HPT Blade Second-Torsion and Third-Flex Nodal Patterns.

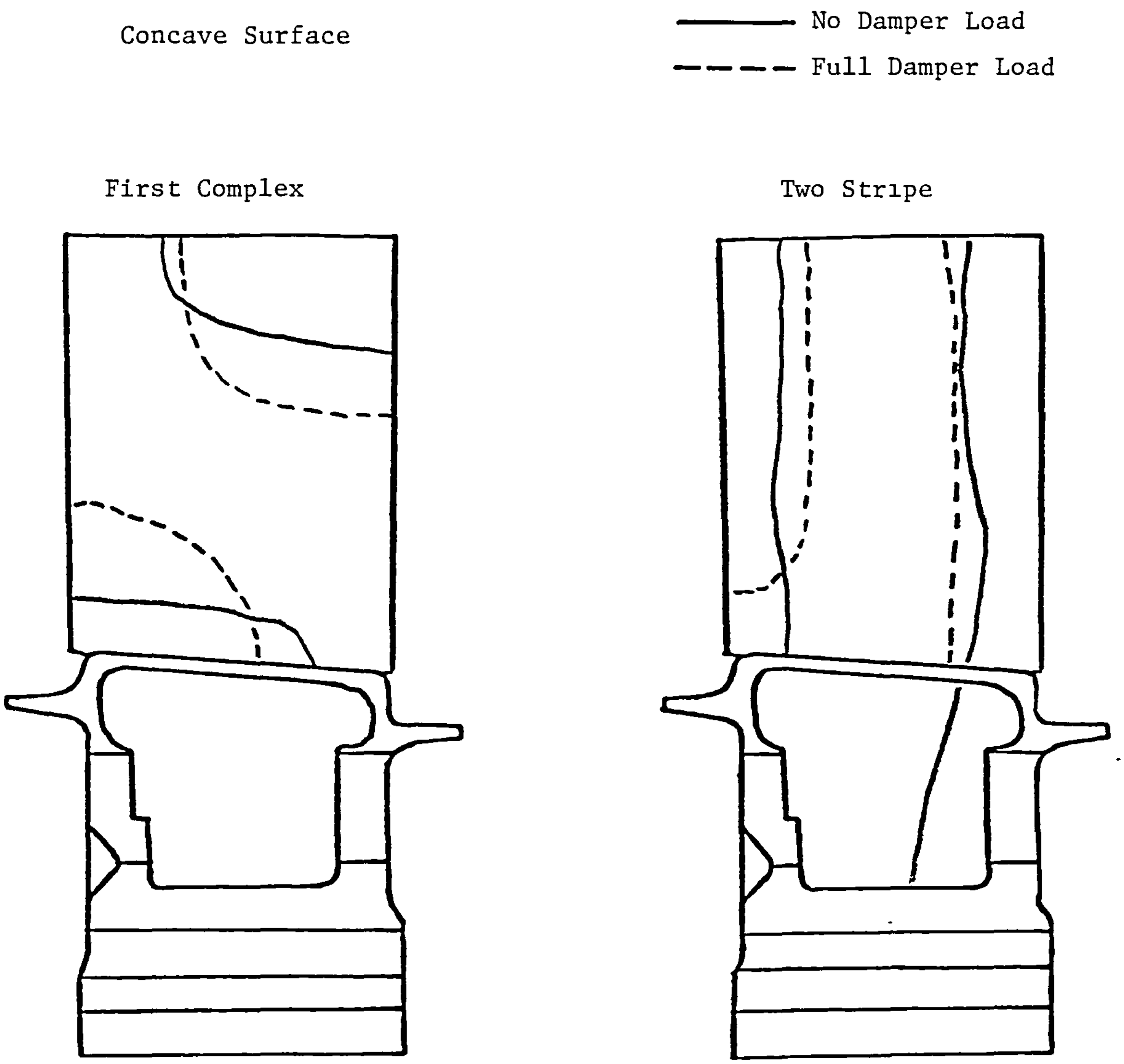


Figure 46. René 150 CF6-50 Stage 1 HPT Blade First-Complex and Two-Stripe Nodal Patterns.

Table XXI. CF6-50 Stage 1 HPT Blade, HCF Test, First-Flexural Mode of Vibration.

• 930° C (1700° F)

Type of Blades	Tip Displacement at Failure, μm (mil)	Number of Blades
EA NiCrAlHf Coated René 150	533 (21)	1
	610 (24)	2
	686 (27)	9
	762 (30)	2
AC 402 Coated René 150	610 (24)	1
	686 (27)	5
BOM Coated René 80	559 (22)	0
	635 (25)	3
	711 (28)	9
	787 (31)	1

exhibited catastrophic damage; a complete section of the leading edge was detached. The René 150 blades showed penetration of the convex blade wall and slight bulging of the concave blade wall, but the blades were still intact. Based on these tests, the René 150 CF6-50 HPT blade has improved FOD resistance compared to the standard René 80 blade.

7.2.3.2 Modified Charpy Impact Test

In this method the coated blades were clamped in the dovetail and impacted across the airfoil with a modified Charpy impact tester in order to determine gross impact-resistance capability. The René 150 HPT blade exhibited more than a 2X improvement in average impact resistance over the comparable-design René 80 standard blade. The test results are given in Table XXII.

7.2.4 Simulated Engine Thermal Shock

The purpose of the SETS test on blades was to confirm the improved thermal-fatigue resistance of René 150 that had been demonstrated previously on test bars. In this test the coated airfoil sections of three René 80 and five René 150 CF6-50 Stage 1 HPT blades were alternately heated to approximately 1093° C (2000° F) in a gas flame and then cooled to approximately 370° C (700° F) by a blast of ambient air. The total time for each of these cycles was 65 seconds. The test results are given in Table XXIII and

Table XXII. CF6-50 Stage 1 HPT Blade, Modified Charpy Impact Test at Room Temperature.

Material	Blade No.	Impact Resistance, J (ft-lbf)
René 150	125	270 (199)
	332	258 (190)
	474	175 (129)
	Average	235 (173)
René 80	1	103 (76)
	2	104 (77)
	3	77 (57)
	Average	95 (70)

Table XXIII. SETS Test, Crack Length Versus Number of Cycles, René 80 and René 150 CF6-50 Stage 1 HPT Blades.

Blade Number	Alloy	Crack Length, cm (in.) SETS Cycles				
		500	1000	2000	3000	4000
1	René 150	---	---	---	---	---
2	René 150	---	---	---	---	---
3	René 150	---	---	---	---	---
4	René 150	---	---	---	---	---
5	René 150	---	---	---	---	---
6	René 80	---	---	---	0.320 (0.126)	0.635 (0.250)
7	René 80	---	---	---	0.396 (0.156)	0.965 (0.380)
8	René 80	---	---	0.013 (0.005)	0.396 (0.156)	1.524 (0.600)

shown in Figure 47. The René 150 blades were markedly superior in that they exhibited no cracking while the René 80 blades contained substantial cracking. These results confirm the improved thermal-fatigue resistance of René 150.

7.2.5 Core Engine Test

Twenty René 150 CF6-50 Stage 1 HPT blades were installed and tested in a land-based CF6-50 core engine. The details of this test are classified as Category 2 FEDD data and will be reported in Volume II of this contract report.

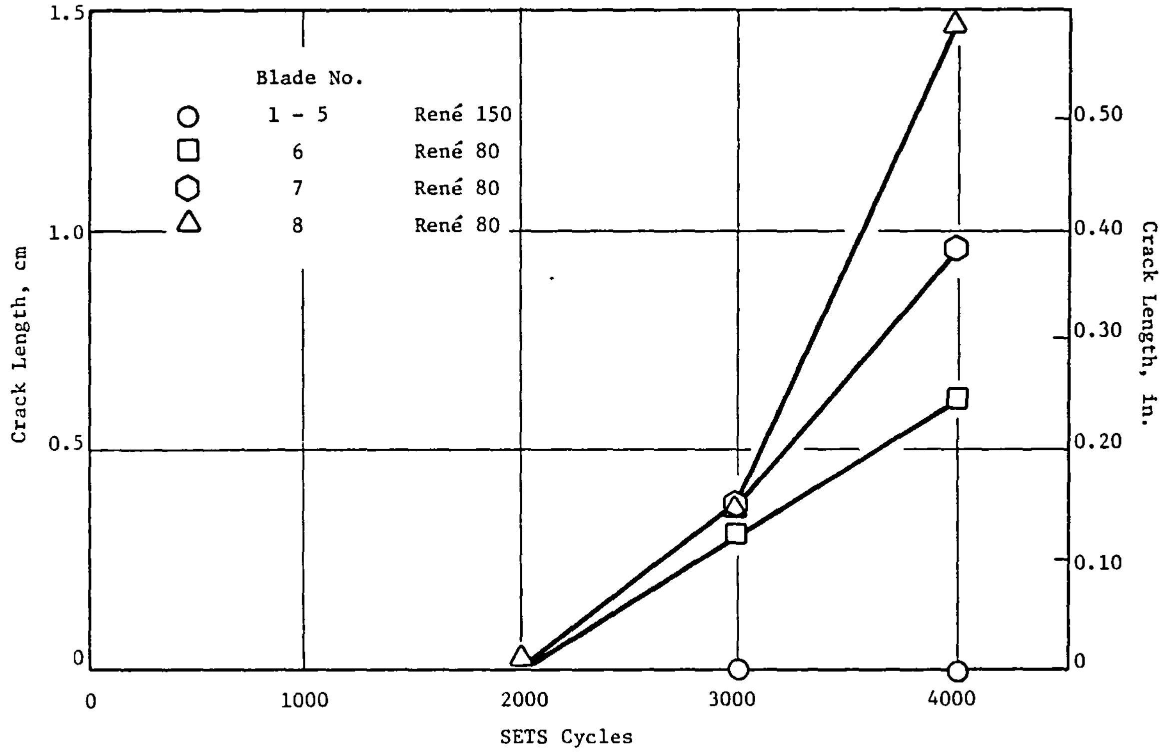


Figure 47. Crack Length Versus Number of SETS Cycles, René 80 and René 150 CF6 Stage 1 HPT Blades.

8.0 TASK VI - ENGINE-TEST BLADE PRODUCTION

The René 150 CF6-50 HPT blades for this task were cast to the process specification developed in Task IV - Final René 150 System Refinement. In accordance with processes evaluated in Section 7.1, the castings were serialized and processed through the casting facility, had the cooling-hole pattern drilled, were tip-cap brazed, and were finish machined and inspected in accordance with the engineering drawing requirements. The casting yield of 62% on the René 150 blades was fairly high. Some significant losses were experienced in the blade-manufacturing operations, but these were caused by the soft tooling that was utilized. These losses would not be expected in full production. The additional material in the shank region of the blade, discussed previously, was removed by an ECM operation at Lehr Precision Tool, Inc., Blue Ash, Ohio.

The finished turbine blades were coated using the coating system selected in Task III - Coating Adaptation and Evaluation. The blades were then delivered for fan engine testing.

9.0 TASK VII - ENGINE TEST

The coated René 150 CF6-50 Stage 1 HPT blades were installed and tested in a land-based CF6-50 fan engine. The details of this test are classified as Category 2 FEDD data and will be reported in Volume II of this Project report.

10.0 ANALYSIS OF RESULTS

This program demonstrated the capability of achieving manufacturing production status of René 150 as an air-cooled HPT blade alloy as evidenced by:

1. The procurement and use of a production-size heat of material.

2. Evolution of a DS casting process including mold and core materials, withdrawal rates, and casting geometry definition (to control casting cracking) to achieve a satisfactory casting yield of 62%.

3. Definition and utilization of a blade manufacturing process that employed state-of-the-art machining, cleaning, and hole-drilling methodology plus brazing and heat-treatment sequencing to avoid the surface recrystallization associated with the thermal exposure of cold-worked material.

4. Manufacture of engine-quality turbine blades to prescribed standards was achieved for engine testing as measured by dimensional, visual, and nondestructive inspection requirements.

This program further demonstrated the capability of achieving suitable operational performance through:

1. Evaluation and scale-up of an overlay environmental-protection coating to satisfy the engine-evaluation phase of the project.

2. Fulfillment of the design criteria of physical and mechanical properties as measured by component and test-bar data to satisfy the operation of the René 150 HPT blades at a bulk operating temperature 56° C (100° F) higher than companion CC René 80 blades.

11.0 CONCLUSIONS

1. The project was completed with favorable results in all phases; the way was cleared to proceed with accelerated endurance engine testing of project hardware.

2. Based upon procurement of a large, production-size heat that met property and cleanliness requirements, producibility of satisfactory René 150 casting stock was established.

3. Castability of René 150 into complex, large, air-cooled turbine blades with a directionally solidified structure was successfully demonstrated by:

   - Relative insenitivity to mold and core material.
   - Satisfactory casting yields as measured by grain, visual, and fluorescent-penetrant inspections.

4. Manufacturing to a cost of 1.5 times that of conventionally cast René 80 blades could be achieved as indicated by:

   - Application of state-of-the-art shop processes requiring only modest modifications (including hole drilling, cleaning, brazing, machining, etc.)
   - Avoidance of surface recrystallization by control of shop sequencing of heat treating and braze operations
   - Maintaining a reasonable Manufacturing scrap rate.
   - Production 50/50 revert use.

5. DS René 150 achieved expected mechanical and physical property capabilities in both bare and coated test bars and blades.

APPENDIX A

RENÉ 150 PROPERTY DATA BASE

René 150 composition is tabulated below. Figures 48 through 53 present the tensile properties; Figure 54 illustrates rupture strength. Figures 55 and 56 show resistance to oxidation and hot corrosion, respectively. Figure 57 describes the thermal expansion properties, and Figures 58, 59, and 60 show the effects of low cycle fatigue. Thermal conductivity is displayed in Figure 61. Figures 48 through 61 provide the nominal curves for the properties involved.

Composition, Weight Percent

	Nominal	Heat 7-11158
Chromium	5	4.9
Cobalt	12	12.0
Aluminum	5.5	5.40
Tantalum	6	5.87
Vanadium	2.2	2.23
Rhenium	3	2.98
Tungsten	5	5.00
Molybdenum	1	1.00
Hafnium	1.5	1.45
Carbon	0.06	0.052
Boron	0.015	0.016
Zirconium	0.03	0.01
Nickel	Balance	

Density: 8.72 Mg/m^3 (0.315 lbm/in^3)

Standard Heat Treatment: 1205° C (2200° F)/1/2 hr + 1080° C (1975° F)/ 4 hr + 900° C (1650° F)/16 hr

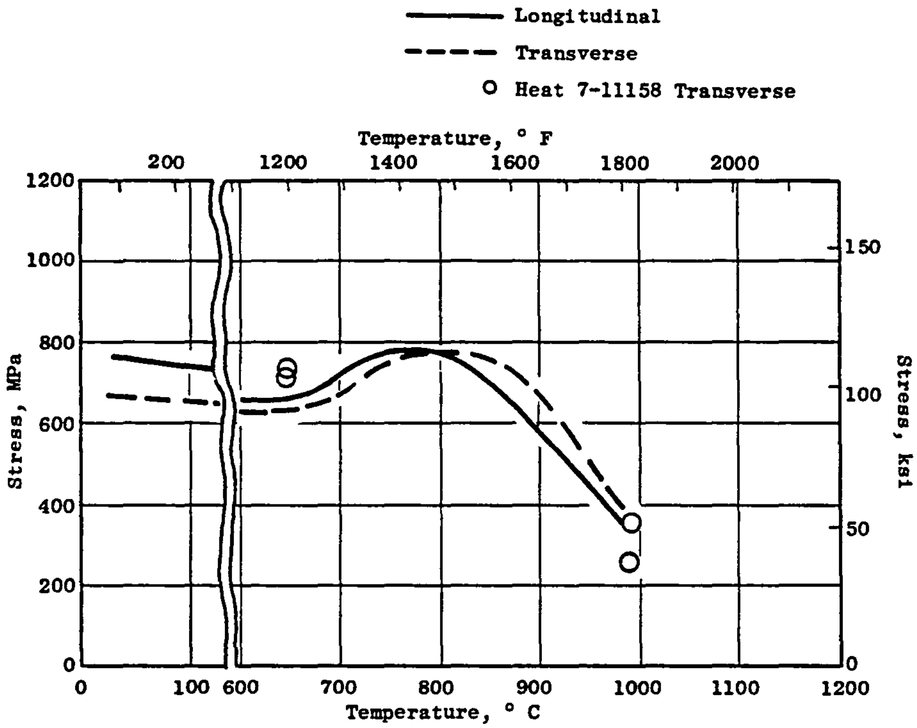


Figure 48. René 150 0.02% Yield Strength.

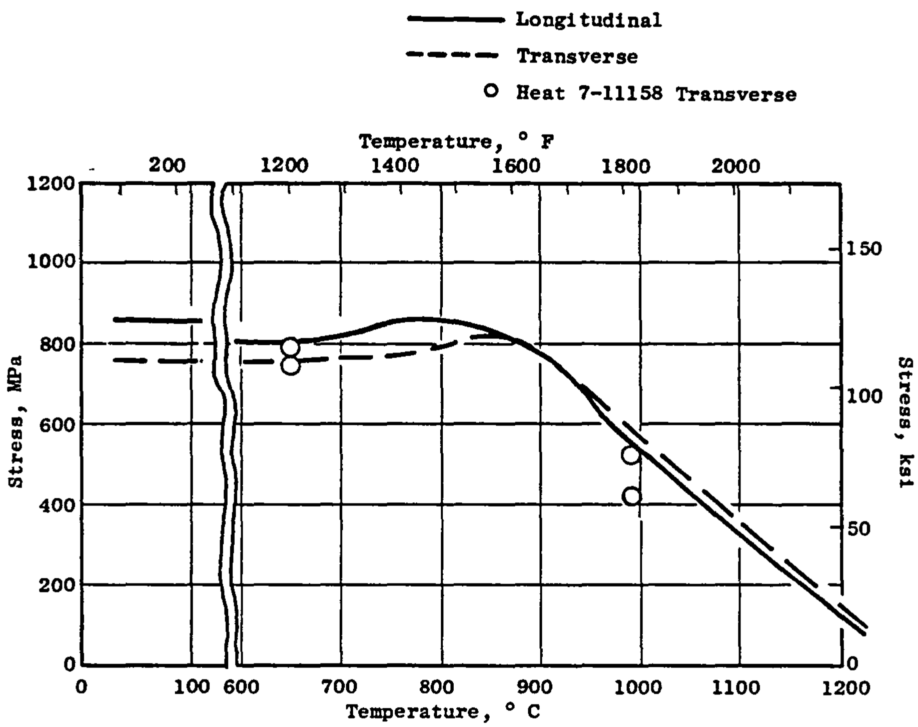


Figure 49. René 150 0.2% Yield Strength.

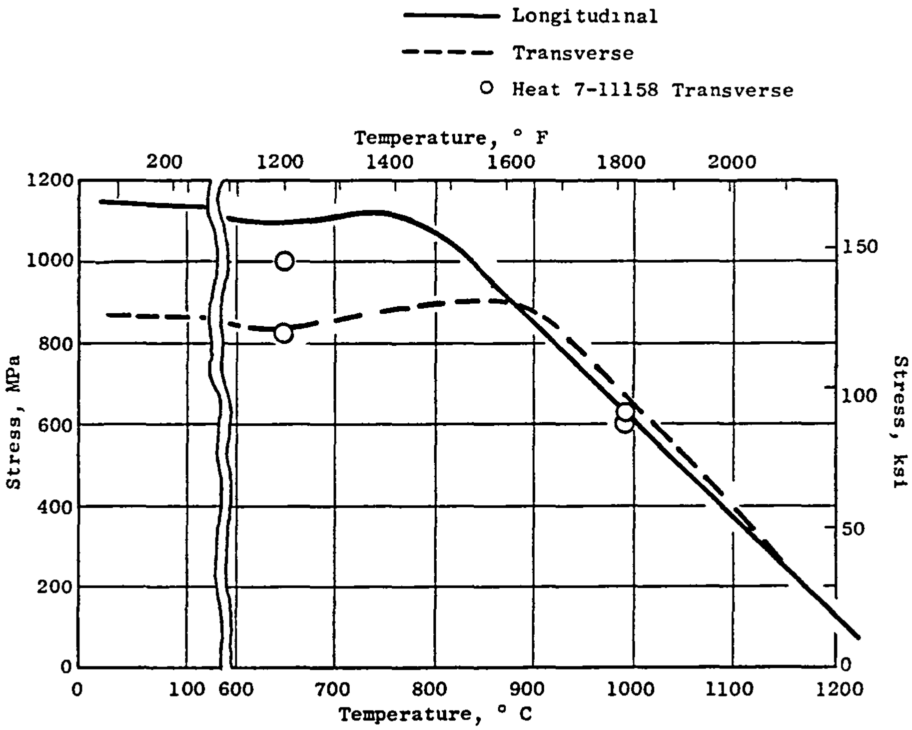


Figure 50. René 150 Ultimate Tensile Strength.

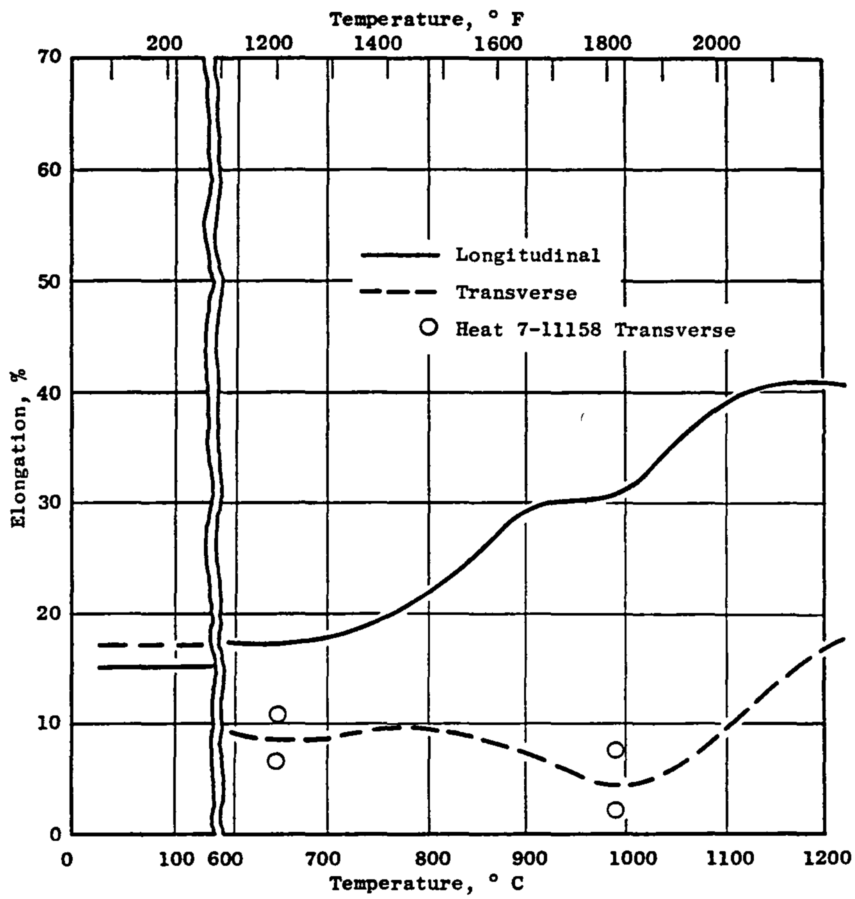


Figure 51. René 150 Tensile Elongation.

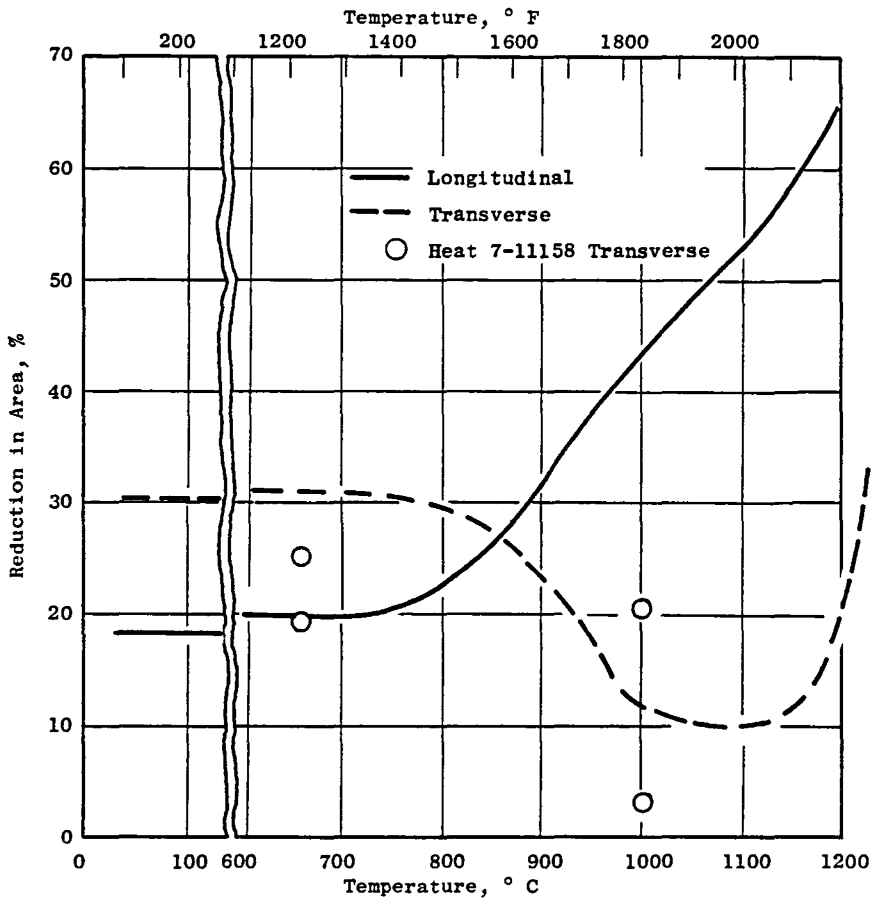


Figure 52. René 150 Tensile Reduction in Area.

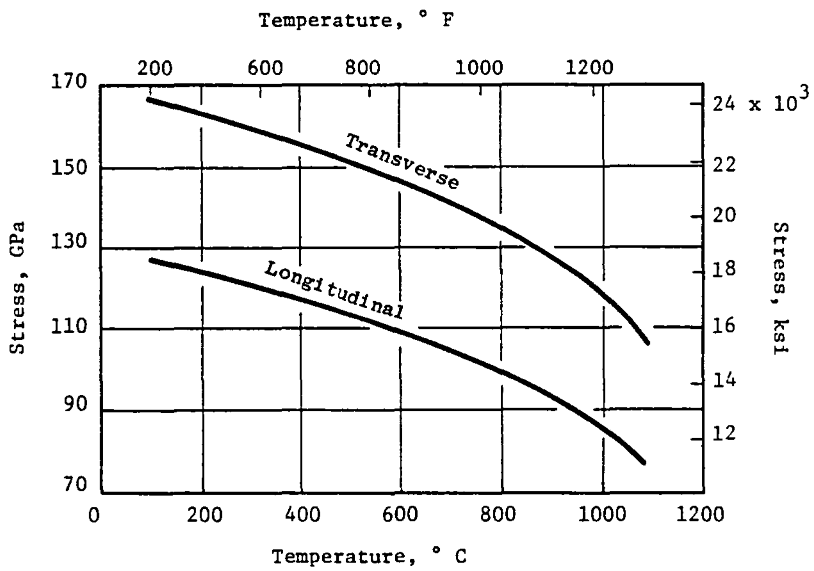


Figure 53. René 150 Tensile Modulus of Elasticity.

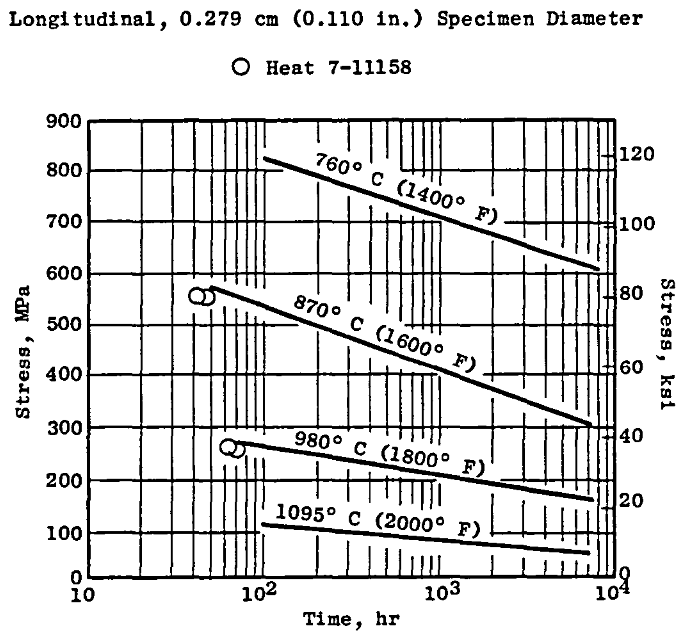


Figure 54. René 150 Isothermal Rupture Strength.

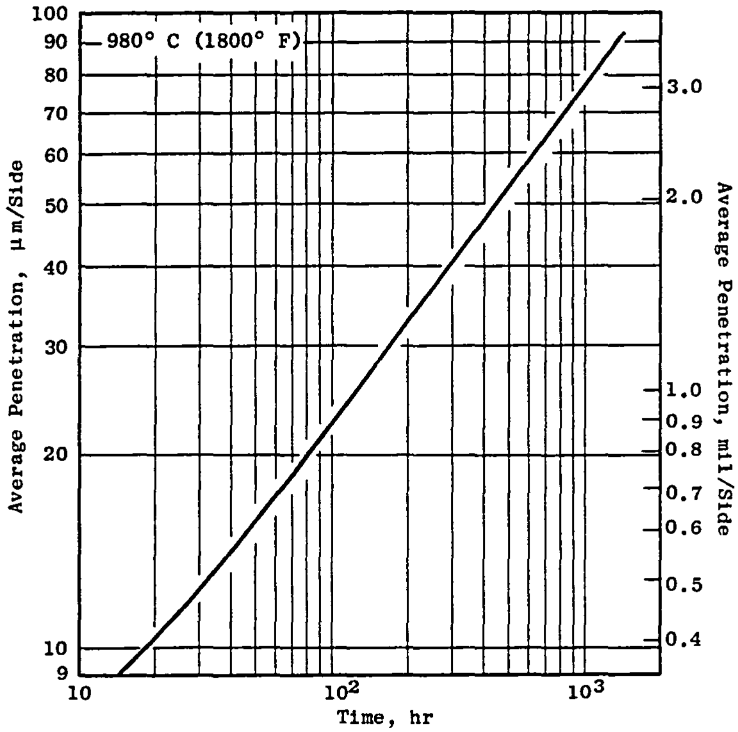


Figure 55. René 150 Dynamic Oxidation.

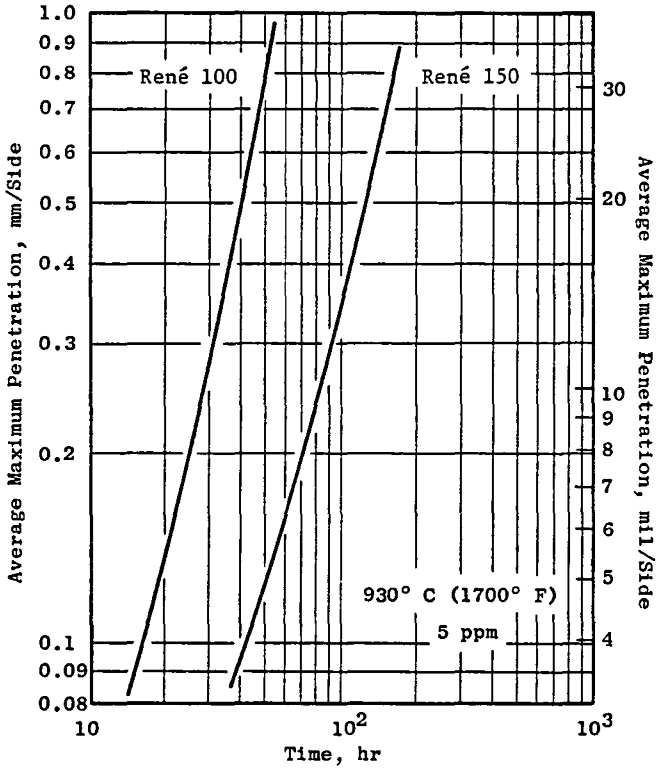


Figure 56. René 150 Hot Corrosion.

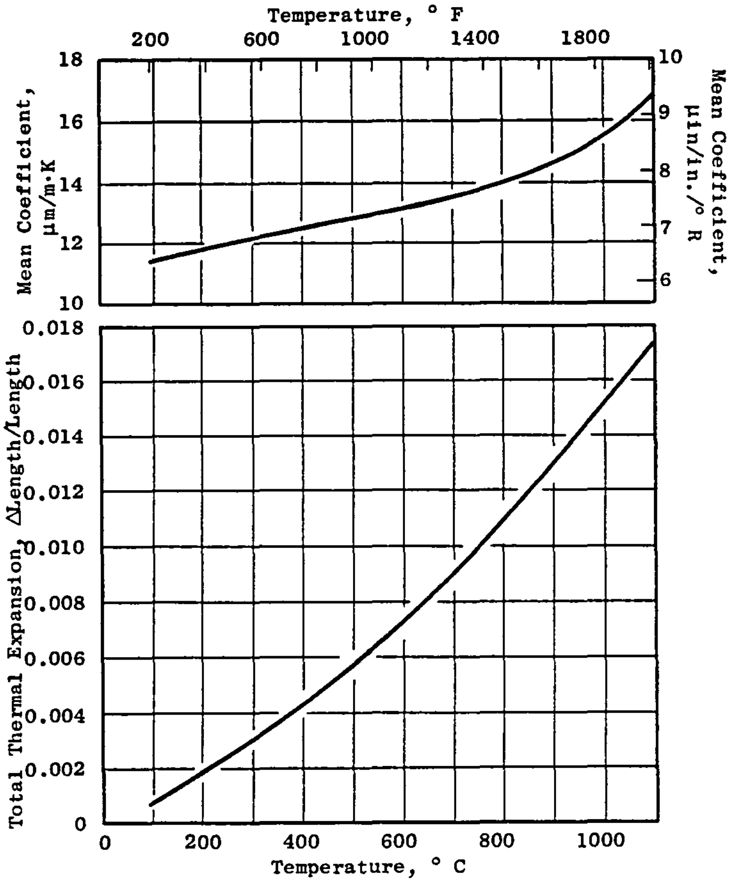


Figure 57. René 150 Thermal Expansion.

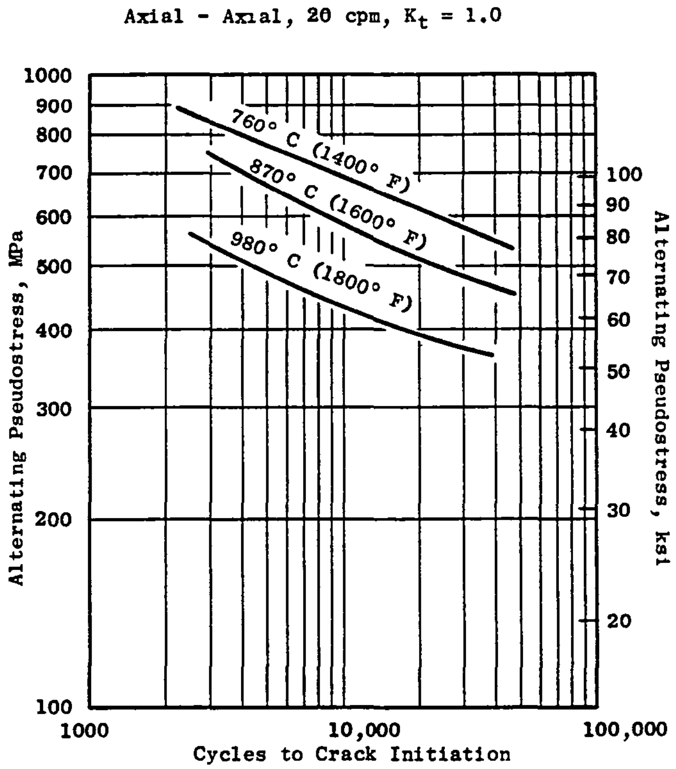


Figure 58. René 150 LCF, A = ∞, Cycles to Crack Initiation.

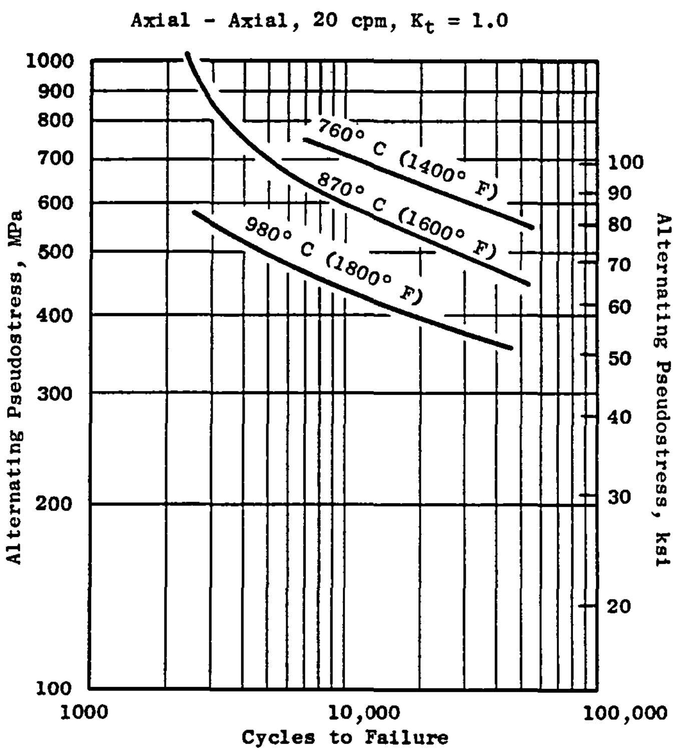


Figure 59. René 150 LCF, A = ∞, Cycles to Failure.

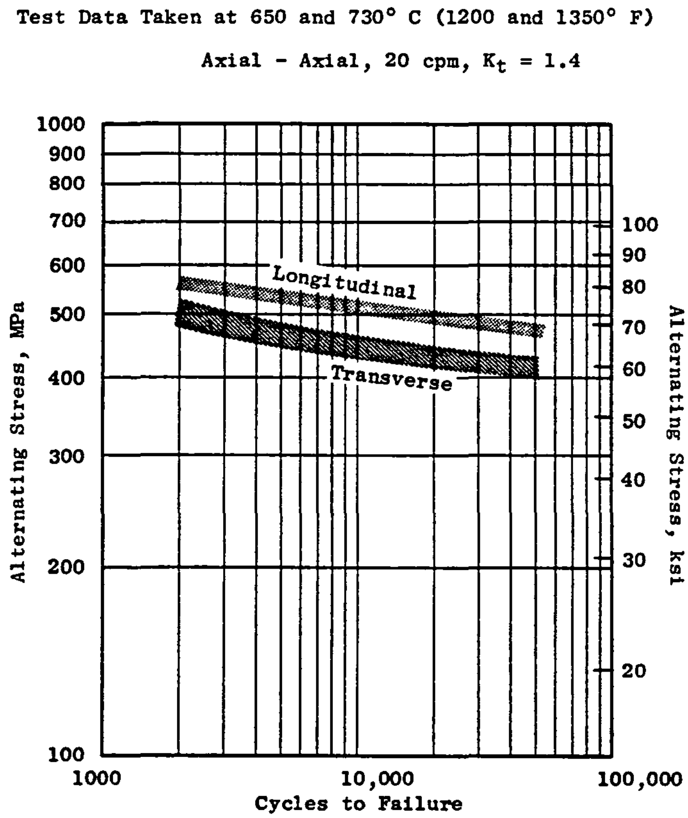


Figure 60. René 150 LCF, A = 1.

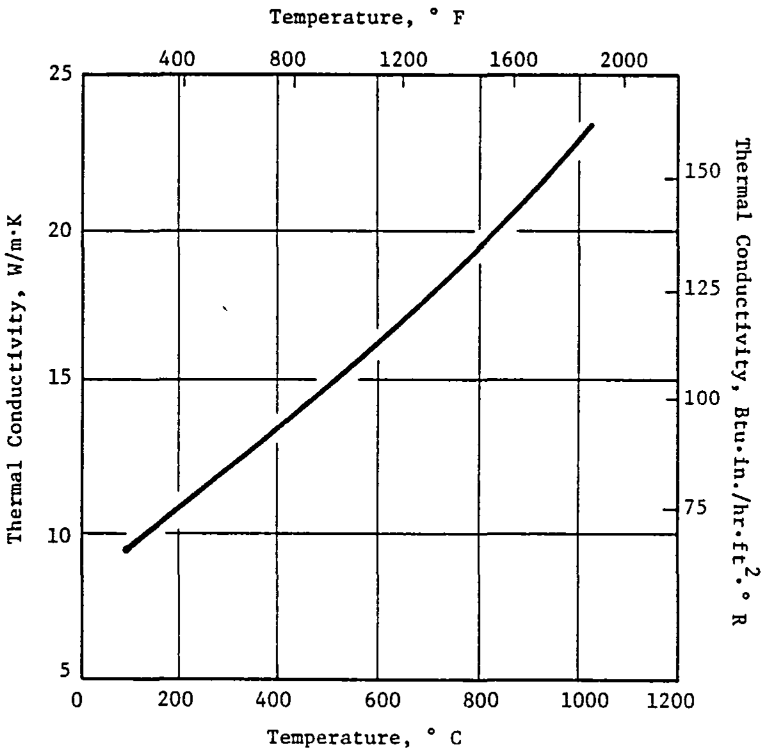


Figure 61. René 150 Thermal Conductivity.

APPENDIX B

RENÉ 150 ALLOY BAR STOCK SPECIFICATION

The purpose of this Temporary Specification is to establish a GE designation for the material or process specified herein and to provide a procurement document for AEBG usage. This Temporary Specification shall remain in effect only until Specification B50TF171-S1 is issued.

1. SCOPE

1.1 Scope. This specification presents requirements for vacuum-cast, nickel-base-alloy bar stock for remelting as precision-investment, vacuum-melted, cast parts.

1.1.1 Classification. This specification contains the following class: CLASS A: As-Cast

1.2 Definitions. For purposes of this specification, the following definitions shall apply:

Purchaser - The procuring activity of the Aircraft Engine Business Group (AEBG) of the General Electric Company that issued the procurement document invoking this specification.

Heat - The induction-vacuum-melted, as-cast bars produced from alloy melted in a single furnace charge.

1.3 Condition. Unless otherwise specified on the purchase order, bar shall be as-cast and descaled.

2. APPLICABLE DOCUMENTS

2.1 The following documents shall form a part of this specification to the extent specified herein. Unless a specific issue is specified, the latest revision shall apply.

GENERAL ELECTRIC SPECIFICATIONS

P29TF19	Acceptability Limits for Trace Elements in Nickel- and Cobalt-Base Superalloys

3. REQUIREMENTS

3.1 Raw Material

3.1.1 Master heat metal is identified as a nickel-base alloy known as René 150.

3.1.2 Chemical Composition, Percent (Master and Remelt Heat)

Carbon	0.04-0.08	Chromium	4.75-5.25
Manganese	0.10 Max.	Tungsten	4.75-5.25
Silicon	0.10 Max.	Rhenium	2.75-3.25
Sulfur	0.01 Max.	Vanadium	2.00-2.40
Phosphorous	0.01 Max.	Hafnium	1.30-1.70
Cobalt	11.50-12.50	Molybdenum	0.75-1.25
Tantalum	5.57-6.25	Boron	0.01-0.02
Aluminum	5.30-5.70	Nickel	Remainder

3.1.2.1 Trace-element content shall be determined and measured per P29TF19, CLASS A.

3.1.3 The analysis made by the manufacturer to determine the percentages of elements required by this specification shall conform to the requirements of 3.1.2 and shall be reported in the certificate of test herein specified.

3.2 Manufacturer

3.2.1 Material shall be produced by vacuum-induction melting.

3.3 Certificate of Test

3.3.1 The vendor shall furnish, with each shipment, three copies of a certificate of test showing the numerical results of tests for chemical composition from each location in each heat in the shipment. The certificate shall show that the results are in accordance with the requirements of this specification and shall be mailed by the manufacturer to the Purchaser with or preceding the shipment of the material. The certificate of test shall also contain the following information:

(a) Purchase order number
(b) Master heat numbers
(c) Sizes and quantities
(d) Specification number, CLASS, and revision number

3.4 Marking

3.4.1 Each cast bar shall be stamped with this specification number, CLASS, revision number, and master heat number. All cast-bar bundles or boxes shall have the identifying purchase order number, master heat number, and this specification number, CLASS, and revision number clearly marked on the outside with a suitable tag.

4. QUALITY ASSURANCE PROVISIONS

4.1 Material shall be uniform in quality and condition, clean, sound, and free from foreign materials and internal and external imperfections.

4.2 Chemical Analysis

4.2.1 Chemical analyses shall be conducted on each heat in accordance with standard ASTM methods or by methods agreed upon by the purchaser and vendor.

4.2.2 A separate chemical analysis shall be performed on material taken from the first, last, and middle cast bars poured from each master heat. The results of chemical analysis from each location shall be reported in the certificate of test.

4.2.2.1 Specimens for trace-element analysis shall be taken from the middle cast bar or as agreed upon between purchaser and vendor.

5. PREPARATION FOR DELIVERY

5.1 Packing and Marking

5.1.1 All material shall be suitably packed to prevent damage or loss in shipment. Each shipment shall be legibly marked with the purchase order number, manufacturer's name, sizes, heat numbers, and this GE specification number, CLASS, and revision number.

APPENDIX C

FINAL CASTING PROCESS SPECIFICATION AND ACCEPTANCE CRITERIA

RAM-DS Equipment Operational Procedures

Operation Number	Operation Description
1.	Close Isolation Valve
2.	Switch Operation Mode to Manual
3.	Vent Load Chamber to Atmosphere
4.	Open Load Chamber Door
5.	Shut Load Chamber Vent Valve
6.	Clean Chill Platform
7.	Place Mold on Chill Platform
8.	Align Mold Foot with Chill Platform Edges
9.	Attach Mold Foot to Chill Platform
10.	Place Insulation Around Chill Platform Support
11.	Place Insulation Strip Across Mold Foot Attachment Wire
12.	Close Load Chamber Door
13.	Switch Operation Mode to Automatic
14.	Switch Isolation Valve to Open
15.	Push Start Button
16.	Set Down Speed Control Pot to 12 in./hr
17.	Mark Furnace Number, Run Number, and Date on Strip Chart Recorder
18.	Allow Time for Automatic Casting and Withdrawal Cycle Completion
19.	Turn Speed-Control Pot to Maximum
20.	Allow Blade Mold to Withdraw Completely Through Isolation Valve Closure
21.	Switch Isolation Valve to Close
22.	Switch Operation Mode to Manual
23.	Vent Load Chamber to Atmosphere
24.	Open Load Chamber Door
25.	Shut Load Chamber Vent Valve
26.	Clip Mold Attachment Wires
27.	Remove Mold from Chill and Place in Knockout Area
28.	Mark Casting ID on Base of Casting Starter
29.	Remove Insulation from Chill Platform Support
30.	Remove Used Attachment Wire from Chill Platform
31.	Repeat Cycle Starting with Operation 6

Operation Number	Operation Description
010	Cast per ACD MATE Process Parameters
020	Remove Shell
030	Identify with Serial Number
040	Macroetch Per P4TF2 CL-C
045	Grain Inspection and Preliminary Visual Inspection
050	Remove Gating from Casting
065	Preliminary Fluorescent Pentrant Inspection
075	Preliminary X-Ray Inspection
085	Alloy Verification
090	Core Removal
100	Flow Check
105	In-Process Fluorescent Penetrant Inspection
110	Grind Blade Tip and Shank to +1.0 to 1.5 mm (+0.040 to 0.060 in.) Over Finish Dimensions
120	Net Vapor Degrease
125	In-Process Fluorescent Penetrant Inspection
130	Rhodine Leach Per Operation Sheet No. 6050-0
140	Internal Fluorescent Penetrant Inspection
150	Drill Cooling Holes
160	Tip Cap Braze Per P10F1 using B50TF90 CL-A Filler Metal
170	Inspect Tip Cap Braze
180	Clean Using Vibratory Tumbler - Sweco
190	Hot-Vapor Degrease
195	In-Process Fluorescent Penetrant Inspection
200	Polish Airfoil to Required Surface Finish
210	Hot-Vapor Degrease
220	Alkaline Clean
230	Macroetch Per P4TF2 CL-D
235	In-Process Fluorescent Penetrant Inspection - Acceptable Blades to Operation 260
240	Remove Defects from Blades by Polishing
250	Repeat Operations 230 and 235
260	Hot-Vapor Degrease
270	Vapor Blast - 1200 Grit Alumina
275	Ultrasonic Wall-Thickness Measurement and Gauging
280	ECM Excess Stock from Blade Shank Area
285	Final Fluorescent Penetrant Inspection per P3TF2 CL-H

Operation Number	Operation Description
290	Final X-Ray Inspection
300	Final Machining
310	Fluorescent Penetrant Inspection of Machined Areas
320	Coat Blade Airfoils
330	Final Cooling-Hole Flow Check
340	Deliver Finished Blades for Testing

The acceptance limits for the visual, grain, fluorescent penetrant, wall thickness, and X-ray inspections are given on the MATE 2 René 150 Stage 1 high pressure turbine blade casting drawings.

RAM-DS Casting Parameters

Alloy:	Premium René 150 per B50TF171-2(T)
Charge Weight:	600 - 700 grams
Hold Time:	24 min.
Withdrawal Speed:	12 in./hr.
Chill Location:	5/16 in. Above Top of Radiation Baffle
Fuse Plug:	1/2-in. Configuration
Filters:	4 Ceramic 1/2-in. Diameter Balls
Shell:	Alumina Face Coat with Mullite Stucco, Zircon, Slurry Back-Up
Shell Configuration:	CF6-50, 9186M34 Configuration with DS Starter and Melt Cup Inserts. 0.125 in. Thick Pad Insert on Shank Pocket Area Below Platform.

Temperature Set Points

Top	1491 ± 11° C (2715 ± 20° F)
Bottom	1466 ± 11° C (2670 ± 20° F)

Voltage Limit

Top	140 Volt Max.
Bottom	140 Volt Max.

Special Equipment Specification

Winding Design

Top Zone	2-3/4 in. Long, 18 Turns/in. + 3-1/4 in. long, 8 Turns/in.
Bottom Zone	4-3/4 in. Long, 18 Turns/in.
Furnace ID	3-3/8 in.

Thermocouple Location/Type

Type - Pt-Pt/13% Rh

Location:	Top Zone	1/2 in. from Bottom of Zone
	Bottom Zone	1 in. from Bottom of Zone
	Monitor	Between Top and Bottom Zones

Chill Dimension

Stationary Chill Opening	3 in. x 2-1/8 in.
Moving Chill Dimension	2-3/4 in. x 1-7/8 in.
Radiation Baffle Opening	2-3/4 in. x 1-7/8 in.

End of Document