165
7/14/81

T.S. (2)

DR-2830

DOE/ET/15331-T1

MASTER

TURBINE COOLING CONFIGURATION SELECTION AND DESIGN OPTIMIZATION FOR THE HIGH RELIABILITY GAS TURBINE

Final Report

By
Murdo J. Smith
Mikio Suo

~~REPRODUCED~~
Rec. - 165
Bins - 111
NTIS - 25

NOTICE
PORTIONS OF THIS REPORT ARE ILLEGIBLE
It has been reproduced from the best
available copy to permit the broadest
possible availability.

April 1981

Work Performed Under Contract No. AC05-79ET15331

United Technologies Corporation
South Windsor, Connecticut

and

United Technologies Research Center
East Hartford, Connecticut

U. S. DEPARTMENT OF ENERGY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A03
Microfiche A01

TURBINE COOLING CONFIGURATION SELECTION AND
DESIGN OPTIMIZATION FOR THE HIGH RELIABILITY GAS TURBINE

Contract No. DE-AC-05-79ET15331

Final Report, April 1981

GTR-2380

Prepared by

United Technologies Corporation
Power Systems Division
P. O. Box 109
South Windsor, CT 06074

Murdo J. Smith, Program Manager

United Technologies Research Center
East Hartford, CT 06108

Dr. Mikio Suo, Principal Investigator

Prepared for

Division of Fossil Fuel Utilization
U.S. Department of Energy
Germantown Office
Washington, DC 20545

Dr. John Fairbanks, DOE Technical Monitor

ABSTRACT

The purpose of this study was to investigate the potential of advanced turbine convectively air-cooled concepts for application to the Department of Energy/Electric Power Research Institute (EPRI) Advanced Liquid/Gas-Fueled Engine Program. Cooling of turbine airfoils is a critical technology and significant advances in cooling technology will permit higher efficiency coal-base-fuel gas turbine energy systems.

This study builds upon the results of the EPRI program (RP1319-3) that investigated a variety of cooling concept candidates for a base-load gas turbine for utility service. The candidate cooling designs relied on all convective cooling. Film cooling and related schemes introduce the risk of plugging with high ash bearing fuels.

Two new airfoil construction techniques, bonded and wafer, were the principal designs considered. In the bonded construction, two airfoil sections having intricate internal cooling configurations are bonded together to form a complete blade or vane. In the wafer construction, a larger number (50 or more) of wafers having intricate cooling flow passages are bonded together to form a complete blade or vane. Of these two construction techniques, the bonded airfoil is considered to be lower in risk and closer to production readiness. Bonded airfoils are being used in aircraft engines.

A variety of industrial materials were evaluated for the turbine airfoils. A columnar grain nickel alloy was selected on the basis of strength and corrosion resistance. Also, cost of electricity and reliability were considered in the final concept evaluation. The bonded airfoil design yielded a 3.5 percent reduction in cost-of-electricity relative to a baseline Reliable Engine design.

A significant conclusion of this study was that the bonded airfoil convectively air-cooled design offers potential for growth to turbine inlet temperatures above 2600°F with reasonable development risk.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1 INTRODUCTION	1
2 FABRICATION METHOD SELECTION	3
Review of Turbine Cooling Candidates	3
Single-Piece Cast Airfoils	3
Bonded Airfoils	4
Wafer Airfoils	6
Cooling Capability of Candidate Airfoils	7
Turbine Temperature Capability	11
Airfoil Cooling Fabrication Method Selection	15
3 AERODYNAMIC AND COOLING PERFORMANCE OPTIMIZATION	17
Design Conditions	17
Vane Design	21
Introduction	21
Description	22
Cooling Performance	24
Mechanical Capability	26
Conclusion	28
Blade Design	28
Introduction	28
Description	28
Cooling Performance	30
Mechanical Capability	32
4 MATERIALS AND FABRICATION CONSIDERATIONS	33
Airfoil Materials	33
Fabrication Process	35
5 COST-OF-ELECTRICITY AND RELIABILITY	38
6 CONCLUSIONS AND RECOMMENDATIONS	42
7 REFERENCES	44

LIST OF ILLUSTRATIONS

<u>Figure No.</u>		<u>Page</u>
2-1	Typical Single-Piece Cast Airfoils	4
2-2	Bonded Airfoil Construction	5
2-3	Wafer Airfoil Construction	6
2-4	Ideal Cooling Effectiveness for Convectively Cooled Airfoils	9
2-5	Convectively Cooled Airfoil Effectiveness (% Theoretical Limit)	9
2-6	Cooling Effectiveness of Single-Piece Cast Airfoils	10
2-7	Cooling Effectiveness of Advanced Airfoil Configurations	11
2-8	Turbine Temperature Capabilities of Candidate Vanes	13
2-9	Turbine Temperature Capabilities of Candidate Blades	14
3-1	FT50 First Stage Flowpath	18
3-2	FT50 Vane Mean Section External Contour	19
3-3	FT50 Blade Mean Section External Contour	19
3-4	FT50 Vane Mean Section Heat Transfer Coefficient Distribution	20
3-5	FT50 Blade Mean Section Heat Transfer Coefficient Distribution	20
3-6	Bonded Vane Mean Section	23
3-7	Bonded Vane Mean Section Pressure Surface Detail	23
3-8	Vane Cooling Passage Isotherms (Point A, Figure 3-6)	25
3-9	Vane Trailing Edge Isotherms (Point E, Figure 3-6)	25
3-10	Bonded Vane Surface Temperature Distribution	26
3-11	Typical Vane Cooling Passage Total Strain Suction Side (Point A, Figure 3-6)	27
3-12	Trailing Edge Total Strain (Point E, Figure 3-6)	27

LIST OF ILLUSTRATIONS
(Continued)

<u>Figure No.</u>		<u>Page</u>
3-13	Bonded Blade Mean Section	29
3-14	Bonded Blade Cooling Configuration	29
3-15	Bonded Blade Mean Section Isotherms	31
3-16	Bonded Blade Mean Section Total Strain	32
4-1	Comparison of Strength and Corrosion Durability for Industrial Engine Alloys	33
4-2	Vane and Blade Fabrication Process Block Diagram	37

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
2-1	Turbine Temperature Capability	15
3-1	Turbine Blade and Vane Aerodynamic and Thermal Design Conditions	17
5-1	Cost-of-Electricity Comparison	41

Section 1
INTRODUCTION

The Electric Power Research Institute (EPRI) contracted with United Technologies Corporation (UTC) to investigate new turbine cooling technologies with potential to provide high efficiency, reliable cooling at gas turbine combustor exit temperatures to 2300°F. In part, this program was an effort to characterize the various convective cooling schemes available for high-temperature operation. The study reported herein builds upon the EPRI work by identifying a single approach which UTC judges to be the most appropriate for future base-load utility gas turbines. The similar goals of the EPRI Reliable Engine Program and the Department of Energy (DOE) Reliable Advanced Liquid/Gas Fueled Engine program make this cooling concept equally applicable to each. The major elements of this study were to:

- o Review cooling candidates and select one concept.
- o Conduct preliminary design of the selected concept for a 100-MW output class stationary gas turbine.
- o Evaluate reliability and cost of electricity of selected design.

Advanced convective cooling with a high level of effectiveness is required for the DOE Reliable Advanced Liquid/Gas Fueled Engine (RALGFE) and the EPRI High Reliability Gas Turbine. Advanced cooling is required so that these engines can operate at high turbine inlet temperatures and thus achieve high combined-cycle efficiencies. At the same time, engine reliability and durability must be improved from current stationary gas turbines by reducing metal temperatures. Thus, substantially more difficult cooling objectives must be met. Film cooling must be avoided because of the distinct possibility that some of the wide variety of fuels used would cause plugging of film cooling holes. Thus, fuel flexibility with high reliability can be maintained only through the use of advanced convective cooling.

In the current study, the objective was to select an airfoil cooling technology and develop preliminary designs of a first stage vane and blade using the EPRI Reliable

Engine as the model. Airfoil cooling technologies are distinguished by the fabrication processes to produce the airfoil. Therefore, selecting a cooling technology connotes selection of a fabrication method. This selection was based on the work of the EPRI Advanced Turbine Cooling program (Contract RP1319-3). In addition to the preliminary design, the materials appropriate to the design and fabrication method were investigated. Then the benefits of the preliminary design were assessed by a cost of electricity analysis and a reliability analysis. Because of program rescheduling, this study was conducted somewhat in parallel with the EPRI program.

Section 2

FABRICATION METHOD SELECTION

REVIEW OF TURBINE COOLING CANDIDATES

The United Technologies Corporation (UTC) is performing the Advanced Cooling Full-Scale Demonstration Program (RP1319-3) for the Electric Power Research Institute (EPRI). Under this program, a comparative study was made of alternate turbine airfoil cooling designs. All convective air cooling designs using three different airfoil fabrication methods were compared: single-piece cast airfoils, bonded airfoils, and wafer airfoils. The candidates were compared on the basis of cooling effectiveness, development status, and manufacturing requirements.

The three types of airfoils are described below:

Single-Piece Cast Airfoils

Single-piece cast airfoils are the current state-of-the-art (Figure 2-1). The intricate internal geometrics required to achieve good cooling performance can be produced by well developed processes; a substantial vendor/manufacturer infrastructure exists to produce airfoils in quantity. The state-of-the-art design and fabrication technologies provided by the aircraft gas turbine industry are capable of providing airfoils for industrial engines substantially better than those now used in current engines. The growth potential of this class of airfoils is, however, limited. This results from the inability of the single-piece casting process to provide sufficient internal airfoil heat transfer area and to control wall thicknesses with accuracies required to permit higher temperature generation. Thus, more advanced airfoil fabrication methods are needed to achieve durable and reliable gas turbine engines capable of operating at turbine inlet temperatures of interest to this program, 2300°F and above.

(W-4802)

Figure 2-1. Typical Single-Piece Cast Airfoils

Bonded Airfoils

To permit operation at higher gas temperatures while maintaining the low metal temperatures ($\sim 1500^{\circ}\text{F}$) required for long life, the turbine airfoil must become a more effective heat exchanger. This requires that the airfoil's internal surface area must be increased and that the cooling air must vigorously "scrub" this surface area so that heat transfer coefficients are as high as possible. Because the heat fluxes through the airfoil are very large, high temperature gradients can be generated in the wall of the airfoil. To minimize this temperature drop, and the resulting thermal stresses, the wall must be as uniformly thin as possible.

These requirements for controllably thin wall, high internal surface area, intricate flow passage airfoils can be met by a fabrication process which allows the airfoil to be "opened-up" and cast in two or more pieces. The pieces are subsequently bonded together to create the completed airfoil.

In its simplest form, the bonded airfoil is provided from two halves, cast to final shape, as shown in Figure 2-2. These halves are then bonded together and finish machined (attachment and platform) to form the completed airfoil. When the airfoil is cast in individual halves, the inside airfoil surface is produced by the mold, and intricate cooling patterns can be impressed with excellent dimensional control. As can be visualized, the part is readily inspectable assuring a much easier quality assurance capability than is possible with single-piece cast airfoils. Bonded airfoil convective cooling designs are adaptable to the incorporation of internal geometries not feasible with single-piece designs. For example, inserts, additional pieces, and internal machining are all possible. For this study, a four-piece vane and two-piece blade were designed.

Bonded airfoils have been under development at United Technologies for aircraft gas turbines because of their higher performance and lower cost potential. They have been evaluated in several gas turbines engines; production manufacturing facilities have been developed; initial production runs have been set for the F-100 gas turbine engine. A more complete description of this airfoil fabrication process may be found in Reference 1.

66-8

Figure 2-2. Bonded Airfoil Construction

Wafer Airfoils

Wafer airfoils are capable of providing even more internal heat transfer surface area than bonded airfoils. Hence, they offer potential for operation at higher turbine inlet temperatures. Wafer airfoils are constructed by bonding together a stack of thin sheets ("wafers") of turbine super-alloy stock into which the desired cooling passage design has been etched. The exterior surface of the bonded stack is then machined to form the airfoil shape. Vanes are constructed with a chordwise stack of wafers; blades are constructed with a radial stack. This arrangement minimizes stresses in the bond planes. The two wafer constructions are shown in Figure 2-3. Almost any degree of cooling configuration complexity can be incorporated in the wafer construction by increasing the number of wafers and the intricacy of the cooling passages.

CHORDWISE WAFER VANE

RADIAL WAFER BLADE

Figure 2-3. Wafer Airfoil Construction

While it offers superior cooling performance, wafer airfoil technology is not as mature as the bonded airfoil. Prototype airfoils have been manufactured on an experimental shop basis for evaluation in advanced engines. Engine and cascade tests have verified the wafer's superior cooling performance. Department of Defense, Department of Energy (Reference 2) and the EPRI RP1319-3 program referred to above have provided the confirming data. Development of the wafer fabrication process for high performance aircraft engines is continuing.

COOLING CAPABILITY OF CANDIDATE AIRFOILS

The term "airfoil cooling effectiveness," (ϕ) is used to quantify the cooling performance of turbine airfoils. It is the ratio of the temperature differential between the hot gas and the airfoils' metal to the differential between the hot gas and the incoming cooling air temperatures.

$$\phi = \frac{T_{\text{GAS}} - T_{\text{METAL MAX}}}{T_{\text{GAS}} - T_{\text{COOLANT}}}$$

Thus, effectiveness is essentially a measure of the heat transfer performance of an airfoil, being a percentage that the gas-to-metal ΔT is of the total ΔT available for cooling. For example, if an airfoil had a maximum (hot spot) temperature of 1500°F when exposed to a 2500°F gas stream using cooling air supplied at 500°F, it would have an effectiveness of 0.5. (This is a very high value, as will be shown shortly, and represents an airfoil with a higher level of cooling technology than is available today.) Gas turbine temperature parameters are quite sensitive to effectiveness. If the example airfoil above had an effectiveness of 0.4, the gas temperature (and hence the engines' output and efficiency) would have to be decreased substantially i.e., $T_{\text{GAS}} = 2167^\circ\text{F}$.

To help assess the relative heat transfer performance of the three candidate cooling technologies, a theoretical effectiveness was defined. The convective cooling theoretical limit is based on the fact that all of the heat passing through the airfoil wall must be removed by raising the coolant temperature. The absolute

level of the theoretical cooling effectiveness curve is not general because it depends upon external film coefficients and specific geometric factors, but the level changes only slightly for relatively large film/geometric changes. The assumptions made to generate the theoretical limit include:

- 1) A uniform surface metal temperature.
- 2) A given airfoil external geometry (FT50*) and heat transfer coefficient distribution.
- 3) Cooling air is heated up to the surface metal temperature.
- 4) No temperature drop across the airfoil wall.

Mathematically integrating the heat input and cooling air required for the FT50 first stage vane and blade geometries resulted in the theoretical cooling effectiveness values shown in Figure 2-4. This curve illustrates the influence that the flow rate of cooling air through the airfoil has on effectiveness. As mentioned above, an airfoil is a heat exchanger, hence its performance is improved as coolant flow is increased. But as the curve shows, the rate of improvement decreases rapidly as flow continues to increase. As is seen, large differences in geometry and flow conditions between the blade and vane produced only a small difference in effectiveness limits. The higher vane values are used in subsequent figures.

Actual airfoils will have lower effectiveness levels than this theoretical because of the finite temperature drop through the airfoil wall, the non-uniformity of the surface temperatures and because the cooling air never reaches the surface metal temperature. To help compare the cooling performance of single-piece, wafer, and bonded airfoil constructions, lines of 80, 60, and 40 percent of theoretical cooling limit curves have been added and are shown in Figure 2-5 along with effectiveness characteristics of airfoils used in current gas turbine engines.

*The FT50 is a United Technologies 100-MW class industrial gas turbine.

Figure 2-4. Ideal Cooling Effectiveness for Convectively Cooled Airfoils

Figure 2-5. Convectively Cooled Airfoil Effectiveness (% Theoretical Limit)

It is seen that airfoils used in current engines have relatively poor cooling performance. This is a result of the obsolescent status of most current industrial engines. Their designs were laid down 10-to-15 or more years ago; turbine inlet temperatures were low (1700-1800°F) and hence high levels of cooling performance were not required. Also, airfoil fabrication capabilities were limited to relatively simple internal cooling geometries. Future industrial engines require airfoils with cooling effectiveness levels substantially higher. To achieve a turbine inlet temperature of 2300°F, for example, the first stage turbine vane needs to achieve an effectiveness of approximately 0.5 or 60 to 80 percent of theoretical vs. the 40-50 percent that today's airfoils display.

The cooling effectiveness of the three candidate airfoils are shown in the next two figures. First, Figure 2-6 compares the cooling performance of single-piece cast airfoils. The current engine blades and vanes reach effectiveness levels of 40-50% of theoretical; the present state-of-the-art of single-piece cast airfoils, however, is such that 60% of the maximum theoretical effectiveness level is achievable.

Figure 2-6. Cooling Effectiveness of Single-Piece Cast Airfoils

Figure 2-7 shows the improvements over state-of-the-art single-piece cast airfoils which the bonded and wafer airfoils can provide. The wafer airfoils provide the greater benefits, showing potential for achieving 80% of theoretical. The bonded airfoil construction is seen to have a cooling performance potential approaching the wafer, or levels that are 70-75% of theoretical.

Figure 2-7. Cooling Effectiveness of Advanced Airfoil Configurations

TURBINE TEMPERATURE CAPABILITY

To evaluate the impact that turbine airfoil cooling performance has on gas turbine engine capabilities, the effectiveness parameter must be translated into turbine temperatures. The relationship between turbine inlet temperature (defined here as the combustor exit temperature) and turbine cooling flow required can be calculated from the cooling effectiveness when the airfoil metal temperature, combustor pattern factor, compressor discharge temperature, and cooling air temperature are specified. By further specifying a maximum practical limit of cooling airflow, the maximum turbine inlet temperature capability for each airfoil candidate can be determined.

In the computations to determine the maximum turbine temperature capability, the following conditions were assumed:

$$\begin{array}{ll} T_{\text{metal hot spot}} = 1450^{\circ}\text{F} & T_{\text{compressor exit}} = 700^{\circ}\text{F} \\ \text{Combustor pattern factor} = 0.2 & T_{\text{cooling air}} = 400^{\circ}\text{F} \end{array}$$

These conditions are consistent with the goals of the High Reliability Gas Turbine program and would result in a long life, durable baseload gas turbine. By varying cooling effectiveness at different cooling technology levels (% of theoretical effectiveness), it is possible to parametrically construct the potential temperature capabilities of gas turbines incorporating various cooling technologies. It should be stressed that turbine airfoil cooling calculations must simultaneously address a large set of complex heat transfer problems and mechanical constraints. The effectiveness values obtained in this study result from simplified, single-point preliminary design of each airfoil. Exact definition of effectiveness vs. cooling flow and the resulting turbine temperature capability would require substantially more work. However, the accuracy of the work done to date is sufficient to rank the candidates and to indicate their relative potential.

The relationship between cooling flow and maximum combustor exit temperatures for vanes and blades are presented in Figures 2-8 and 2-9. It can be seen that increasing the cooling flow results in higher permissible turbine temperatures, but that maximum limits are set by practical cooling flow considerations. For the vanes, geometric and performance factors limit the maximum flow to about 5 to 6 percent. For the blades, the limits are lower, normally in the 3 to 4 percent range because of additional constraints imposed by centrifugal forces. For a given percentage of theoretical effectiveness applied to both vanes and blades, the maximum allowable combustor exit temperature is set by the practical vane cooling flow limits.

Figure 2-8 is the more important of the two curves. The cooling capabilities of the first stage vanes dominate in setting limits on maximum gas temperatures at which the gas turbine can operate. This figure shows that airfoils of the type currently used in industrial engines ("current single-piece cast") would limit an engine to operating at combustor exit temperatures below about 1800°F, and, as

noted above, this is with cooling air at 400°F, having been cooled from the 600-700°F levels at which it exits the compressor. But, many engines operate at temperatures greater than this; why? They do, because their airfoils run at metal temperatures much hotter than the 1450°F hot spot temperatures selected for this program, and they sacrifice a substantial amount of useful service life in doing so.

Using conventional modern airfoils ("state-of-art single-piece cast") would allow this example engine to operate at temperatures up to about 2100°F. These 60% of theoretical vanes thus provide a very large, 300°F, increase in engine capability with equal durability.

Figure 2-8 indicates that the bonded technology airfoils would allow operation up to about 2400°F. This is an increment of 600°F above the capabilities of airfoils used in industrial engines now on the market. And again, the durability benefits of a 1450°F maximum airfoil temperature are retained. Finally, the high degree of internal heat transfer area fineness which the wafer construction provides results in engine temperature potential up to about 2700°F.

Figure 2-8. Turbine Temperature Capabilities of Candidate Vanes

Figure 2-9 displays similar information for the first stage blades. The reduced temperatures to which the blades are exposed compared to the vanes results in their being able to operate at high engine temperature conditions. Both the bonded and wafer blades could maintain the 1450°F airfoil temperatures when running with combustors exit temperatures above 2600°F.

Figure 2-9. Turbine Temperature Capabilities of Candidate Blades

The maximum temperature capability of the various cooling schemes is summarized in Table 2.1. It can be seen from this analysis, that both bonded and wafer airfoils emerge as qualified to meet the needs of the Department of Energy (DOE) and the Electric Power Research Institute's (EPRI) Reliable Advanced Liquid/Gaseous Fueled Engine Programs. In addition, they both have potential to participate in the more challenging arena of DOE's High Temperature Turbine Technology (HTTT) Program. Small changes in metal temperature, cooling air supply temperature, coolant flow rate or airfoil design details would allow the bonded and wafer airfoils to operate in the 2600°F to 3000°F turbine inlet temperature range associated with the HTTT Program.

TABLE 2-1. TURBINE TEMPERATURE CAPABILITY

Cooling Configuration	Maximum Combustor Exit Temperature 5% Cooling Flow Limit °F
Advanced Single-Piece Cast	2070
Bonded	2400
Wafer	2700

AIRFOIL COOLING FABRICATION METHOD SELECTION

The previous discussion was based on data generated in the EPRI RP1319-3 program, this study, and the DOE EY-76-C-05-5035 program for the bonded airfoil and the wafer airfoil fabrication methods. UTC data were used for the airfoils made by the single-piece casting method. The referenced EPRI study indicated that the design features leading to high cooling effectiveness for wafer construction could be applied to bonded construction; however, specific designs were needed for verification.

This study explored specific designs assuming bonded vane and blade construction at a combustor exit temperature of 2150°F. At this temperature, current and advanced single-piece cast construction cannot meet the stringent design requirements, as both the bonded and wafer constructions can. At the required conditions, the bonded vane would use 3.4 percent cooling flow and the wafer would use 1.9 percent. Similarly for the blade, both bonded and wafer constructions are adequate with 1.08 percent and 0.84 percent cooling flows required respectively.

Since both the bonded and wafer design can meet the desired metal temperature at the assumed conditions, they were then compared on the basis of growth potential, development risks, manufacturing capability, and cost of electricity. The results were as follows.

1. Both the bonded and wafer constructions have exceptional growth characteristics using all convective air-cooled designs. Extrapolating the effectiveness values for the specific designs studied to higher cooling flows would permit the bonded design to operate at a combustor exit temperature of approximately 2400°F while the wafer design could operate up to above 2700°F.

With additional study of designs intended to operate at these growth temperatures and with small adjustments in the requirements, it was concluded that both bonded and wafer constructions would offer growth into the 2600 to 3000°F combustor exit temperature range.

2. Development cost and risk at this time are much higher for the wafer construction than for the bonded. Bonded airfoils have already had significant process development, engine test experience, and production facility development. Wafer airfoils have been experimentally made, but production methods for their manufacture have not been developed.
3. Manufacturing facilities are available for bonded airfoils because of the aircraft engine commitment to the process. An additional investment is required for increasing the capacity of the facilities to produce large industrial engine-sized airfoils, but the cost of this increased capacity would be substantially less than for a new facility to produce wafer airfoils.
4. The cost-of-electricity difference between the bonded airfoils and wafer airfoils was found to be small. The airfoil cost differential is a small percentage of the gas turbine capital cost, and the lower cooling flow for the wafers gives only a slightly improved efficiency.

Based on these considerations, the bonded airfoil fabrication method was selected for further analysis in this study. The sections that follow discuss the specific bonded airfoil design completed under this study including aerodynamics, cooling configuration, materials, cost and reliability.

Section 3

AERODYNAMIC AND COOLING PERFORMANCE OPTIMIZATION

DESIGN CONDITIONS

The overall design conditions used in this study are those corresponding to the Electric Power Research Institute (EPRI) 100-MW Reliable Engine and are given in Table 3-1. A turbine inlet temperature of 2150°F has been used because it reflected the then Reliable Engine requirement. The concern expressed by the potential utility users is that satisfactory reliability cannot be maintained at higher turbine inlet temperatures. While 2150°F has been used as the primary design temperature, the impact of operation at 2300°F and higher has been addressed in growth potential discussions. The concern of the utilities has been satisfied by keeping the metal temperature at 1450°F for the higher temperatures. These conditions are for a single-shaft engine with an overall pressure ratio of 14 to 1 and a three-stage turbine. They also correspond to an engine with a 0.2 combustor pattern factor and cooling air which is pre-cooled to 400°F.

TURBINE BLADE AND VANE

TABLE 3-1. AERODYNAMIC AND THERMAL DESIGN CONDITIONS

TEMPERATURES

Turbine Inlet Temperature	2150°F
Hot-Spot Vane Gas Temperature	2463°F
Maximum Blade Relative Temperature	1881°F
Coolant Temperature	400°F
Maximum Metal Temperature	1450°F

PRESSURES

Turbine Inlet Pressure	191 psia
Vane Exit Static Pressure	119 psia
Blade Exit Static Pressure	73 psia
Vane Coolant Supply Pressure	181 psia
Blade Coolant Supply Pressure	120 psia

The detailed design relied heavily upon closely related designs from UTC's FT50 gas turbine engine because the Reliable Engine had not been sufficiently specified for detailed heat transfer calculations. The FT50 turbine flow path, airfoil contours, airfoil count, and airfoil external heat transfer coefficients were utilized as the basis for the heat transfer design. The detailed geometric and heat transfer coefficient conditions used are shown in Figures 3-1 through 3-5, together with the overall design conditions of Table 3-1. These allowed preliminary design of cooling configurations for the first stage vane and blade, including an estimate of the required cooling airflow. The cooling configurations and the cooling flows were assumed to be exemplary of the cooling configurations which would be designed for the Reliable Engine.

Figure 3-1. FT50 First Stage Flowpath

Figure 3-2.
FT50 Vane Mean Section External Contour

Figure 3-3.
FT50 Blade Mean Section
External Contour

66-16

Figure 3-4. FT50 Vane Mean Section Heat Transfer Coefficient Distribution

66-17

Figure 3-5. FT50 Blade Mean Section Heat Transfer Coefficient Distribution

The design criteria for the preliminary design were:

1. Only convective cooling was to be used to eliminate any question of plugging of film cooling holes,
2. The maximum metal temperature was to be kept below 1450°F to maximize hot corrosion life, and
3. Thermal stresses were to be considered to assure that the steady state thermal strains would be within the bounds of acceptable past experience.

VANE DESIGN

Introduction

The vane design goal was to meet the high level of turbine cooling effectiveness of 0.49 with a minimum quantity of cooling air using only convective cooling. Film cooling was ruled out to avoid the risk of hole plugging from dirty fuels. The supply pressure to the cooling air was assumed to be a level readily available in the Reliable Engine without an auxiliary pump. This pressure plus trailing edge discharge provided the driving potential for convective cooling.

The design goal was met through the utilization of several design concepts. The first was to obtain a large quantity of internal cooling surface area augmentation through the use of many parallel channels. These channels achieved a large surface area enhancement with minimal pressure drop penalties. The second was to minimize the use of internal heat transfer coefficient augmentation such as provided by impingement and trip strips. The large pressure drop normally associated with these devices was thus minimized. The third was to maintain as isothermal a surface as possible. This was to minimize the heat transfer to the airfoil and thus to minimize the heat transferred to the coolant. The temperature rise of the coolant was thus reduced, and this in turn allowed a smaller quantity of cooling air to cool the trailing edge. The fourth was to use a thin outer wall on the airfoil.

This reduced the temperature drop through the outer wall and increased cooling effectiveness. The implementation of these concepts resulted in an airfoil which met the design goals.

Description

Cross-sectional views of the first stage vane are shown in Figures 3-6 and 3-7. The vane is cooled with channels in the chordwise direction. These channels are shown in detail in View A-A in Figure 3-6. Air flows radially outward in the center cavity and enters the surface cooling channels a short distance from the leading edge on the suction side. Part of the air flows forward to the leading edge and then back to the trailing edge on the pressure side. The rest of the air flows to the rear in the suction surface passages to the trailing edge. Both streams of air combine near the trailing edge and discharge through the trailing edge. The primary mode of heat transfer augmentation in this scheme is surface area augmentation. In addition, there is some heat transfer coefficient augmentation on the suction side and at the trailing edge with trip strips. The cooling channel width is 0.090-inches over most of its length, with the exception of a short region from (B) to (C) on Figure 3-6. In that region the channel width and height are increased to reduce velocity and heat transfer area and thus minimize overcooling of that portion of the pressure surface. This serves to reduce the heat pickup by the coolant so that the air has a greater ability to cool when it reaches the trailing edge.

A significant feature of this design is that it has a relatively thin (0.040-in.) outer wall. This thin outer wall allows a higher effectiveness for a given level of coolant flow by reducing the conduction path length. In order to utilize an airfoil with such a thin outer wall, it is necessary to also have an inner wall bonded to the outer wall to give structural rigidity to the airfoil. This structural feature of a thin outer wall supported by an inner wall takes great advantage of the split airfoil fabrication process. It would not be possible to make such an airfoil using standard one-piece casting techniques.

Figure 3-6. Bonded Vane Mean Section

Figure 3-7.

Bonded Vane Mean Section
Pressure Surface Detail

Cooling Performance

From the maximum gas temperature, coolant temperature, and maximum metal temperatures of Table 3-1, the effectiveness requirement of the vane is calculated to be 0.49. This is a high level of effectiveness for a convectively cooled vane.

The coolant flow required to achieve 0.49 effectiveness in the bonded configuration is 3.40 percent of engine airflow. This is very low for an airfoil with an effectiveness of 0.49. Thus, the design not only represents a high level of effectiveness for convective cooling, but also represents a low level of cooling flow for the level of cooling effectiveness. This low flow is possible because of the thin skin and the area augmentation produced by the channels. Such a low cooling flow could not have been achieved with thicker walls and the more standard heat transfer coefficient augmentation obtained with impingement or trip strips alone.

The temperature distribution in the vane was calculated using two dimensional analyses at several chordwise locations. The results of a typical analysis are shown in Figure 3-8, which shows isotherms calculated at the chordwise location (A) on Figure 3-6. Trailing edge isotherms are shown in Figure 3-9. The external heat transfer coefficients used for each calculation were taken from Figure 3-4. The internal heat transfer coefficients were for fully developed channel flow. In places where trip strips were located, these coefficients were increased to account for the increased turbulence. The coolant temperature at each chordwise location was calculated by considering the heat load from all upstream locations. The temperature distribution calculations resulted in a chordwise surface temperature map, which is shown in Figure 3-10. As can be seen, the surface temperature is very uniform. This is the purpose for dividing the flow on the suction surface. The coolant which cools the region between 0 and 2 inches on the suction surface is at a relatively low velocity as it goes forward to cool the leading edge region and the pressure side. Thus, the metal in that region is not as overcooled as it would have been had it been cooled with higher velocity air required to cool the aft regions of the suction surface.

Figure 3-8.

Vane Cooling Passage Isotherms
(Point A, Figure 3-6)

Figure 3-9.

Vane Trailing Edge Isotherms
(Point E, Figure 3-6)

66-21

Figure 3-10. Bonded Vane Surface Temperature Distribution

Achieving an isothermal airfoil surface is important because it optimizes the heat load to the coolant. In a design which is only convectively cooled, the heat pickup of the coolant is a critical feature of the design. If, for example, the surface was locally overcooled, the corresponding heat flux to the airfoils would be greater and the coolant air temperature rise would be greater. This higher temperature coolant would cause the trailing edge to overheat.

Mechanical Capability

The temperature distributions of Figures 3-8 and 3-9 were also used to calculate thermal strain. The thermal strain maps derived from Figures 3-8 and 3-9 are shown on Figures 3-11 and 3-12. These strains were calculated using a beam-type analysis for strains out of the plane of the figure and represent a preliminary design estimate of the level of the thermal strain problem. The thermal strains are well within the bounds of UTC's experience. Thus, the designs appear sound from the thermal strain point of view and warrant further detailed design and subsequently a full three-dimensional stress analysis.

Figure 3-11.

Typical Vane Cooling Passage
Total Strain Suction Side
(Point A, Figure 3-6)

Figure 3-12.

Trailing Edge Total Strain
(Point E, Figure 3-6)

Conclusion

The bonded airfoil vane has several important design features. It achieves a cooling effectiveness of 0.49 with a low cooling flow of 3.40 percent engine air-flow. This design approaches 80 percent of the theoretical convective cooling limit. It does this with the use of internal area enhancement and a thin skin made possible in the bonded design. The temperatures and strain distribution are consistent with reliable operation.

BLADE DESIGN

Introduction

The bonded blade has a lower required effectiveness (0.29) than the vane because of a lower relative gas temperature. The structural design of the blade is, however, more difficult than that of the vane because of high centrifugal stresses. To emphasize reliability it was decided to use the minimum structural departure from a conventional one-piece airfoil that was adequate from a heat transfer viewpoint. Heat transfer coefficient augmentation with thick-walled airfoils and other conventional design features resulted in an efficiently cooled airfoil. The resulting design was mechanically simpler and could be fabricated from two pieces as opposed to four pieces required for the vane.

It is important to note that higher effectiveness levels required by higher turbine inlet temperatures could be met in the blades by utilizing the vane cooling concepts discussed above. This degree of design complexity requires further design studies to meet specific design objectives.

Description

Cross-sectional and cutaway views of the blade are shown in Figures 3-13 and 3-14. The cutaway view of Figure 3-14 is taken along the bonding surface shown on Figure 3-13.

Figure 3-13. Bonded Blade Mean Section

Figure 3-14.
Bonded Blade Cooling Configuration

Cooling air flows into the blade through the root and makes three radial passes before ejecting through the blade trailing edge. Some air also ejects through the blade tip after one pass. This is done to overcome a common problem in blades, trailing edge tip overheating. The cooling passages in this case utilize trip strips and pedestals to augment heat transfer coefficients. The trip strips in the leading edge and the pedestals in the trailing edge will require optimization in final design. The trip strips are expected to be smaller in size relative to the size of the airfoil than in standard one-piece casting practice. Smaller size trip strips are more efficient in cooling. Similarly, the pedestals are expected to be smaller in diameter relative to their height than in standard one-piece casting practice.

Cooling Performance

For the 2150°F turbine inlet temperature design point, the blade design does not limit the turbine inlet temperature. A one-piece conventionally cast airfoil could achieve the effectiveness level required of the blade (0.29) with a higher cooling flow. The bonded airfoil design has an advantage because the small trip strips and pedestals are only made practical by the two-piece design. Bonded airfoil design also has the advantage of carefully controlled wall thickness allowing thinner more aerodynamically efficient trailing edges.

The cooling flow to the blade is very low at 1.08 percent of engine air flow due to the low cooling effectiveness requirement. An airfoil made from one-piece conventional castings for an effectiveness of 0.29 was estimated to require 1.4 percent cooling flow, a 30 percent increase. While this difference is not critical at 2150°F, it would be so at higher turbine temperatures.

A two-dimensional isotherm map of the blade is shown on Figure 3-15. The difficulties encountered in designing an airfoil of this type are exemplified by these isotherms. The leading edge is the hottest spot on the airfoil; the trailing edge is the coldest. This indicates that the airfoil is more limited by the heat transfer coefficients at the leading edge than by the cooling air heat rise. Further

optimization could be made on this airfoil to make the temperature profile more uniform and to bring the leading edge metal temperature within the design intent. However, this was not done in the belief that the design shown is sufficiently close to the goal to assure that the configuration is essentially correct.

Figure 3-15. Bonded Blade Mean Section Isotherms

Mechanical Capability

The thermal strain distribution which occurs with the temperature distribution of Figure 3-15 is shown in Figure 3-16. As would be expected from the temperature distribution, the maximum compressive strain occurs at the leading edge. The strain level there, 0.173 percent, is well within the UTC design criteria. The maximum tensile strain, 0.457 percent, occurs in the cold rib near the leading edge. This level of tensile strain in a cold rib is also satisfactory.

Figure 3-16. Bonded Blade Mean Section Total Strain

Section 4
MATERIALS AND FABRICATION CONSIDERATIONS

AIRFOIL MATERIALS

The alloy selection primarily took into consideration corrosion resistance, creep thermal fatigue resistance, and state of development of the alloy.

Corrosion resistance and creep thermal fatigue resistance are inversely related to each other, as shown in Figure 4-1. In this figure, the relative creep thermal fatigue life is plotted against the relative corrosion life for a number of cast industrial turbine alloys. The cast alloys shown are grouped into three bands by type:

1. Conventional casting,
2. Columnar grain, and
3. Single crystal.

66-24

Figure 4-1. Comparison of Strength and Corrosion Durability for Industrial Engine Alloys

Each of these bands trade creep thermal fatigue life against corrosion life. This is most readily seen in the conventional casting band where the greatest amount of experience exists. The positions of Rene 80, IN792, IN738, MM509, and IN939 show that materials with decreasing creep thermal fatigue life have increasing corrosion life. If these alloys are cast in columnar grain form, as indicated by CG IN792 and CG IN738, the alloys increase in creep thermal fatigue life while maintaining their corrosion life. Alloys which are cast as single crystals can have even better properties. Alloys which are cast as single crystals can have even better properties. Alloys 300SC and 400SC are single crystal alloys which are being developed to have high strength and good corrosion life. This development is being carried out at Pratt & Whitney Aircraft, Commercial Products Division, under Contract N00C24-78C-5346, "Single Crystal Superalloy Turbine Airfoils for Marine Gas Turbine Engines," for the Navy Sea Systems Command.

Of the alloys considered, Rene 80, IN738, IN792, and MM509 are well-developed alloys. IN939 is a relatively new alloy that has not yet been extensively utilized. There is limited experience with CG IN792 and even less with CG IN738. However, because they are based on the well-known conventional alloys IN792 and IN738, these columnar-grained alloys are considered to be small extensions of the state-of-the-art. In contrast, alloys 300 SC and 400 SC are new alloys which are just beginning to undergo development. Their chemistry is not yet completely established, but several compositions have been identified which will meet the goals shown on Figure 4-1. They can be defined roughly as nickel-based alloys with a high chromium content. They do not contain molybdenum, vanadium, or high levels of tungsten, which would promote hot corrosion attack.

The alloy selected for this application was CG IN738 for both the vane and the blade. Initial considerations indicated that conventionally cast IN738 would be appropriate for this application. It has good corrosion life and adequate strength for the first stage of the Reliable Engine and is a well-developed alloy with known properties. However, one other parameter of importance became apparent during the configuration preliminary design process: the airfoils would have relatively thin walls even in a large size. The thin walls potentially could cause porosity problems in the castings. Experience has shown that columnar grained alloys have

reduced porosity because of the controlled solidification process which is utilized. Therefore, a columnar grained form of IN738 designated CG IN738 was selected. It has the disadvantage of being not as well characterized as IN738, but this disadvantage was judged to be of less importance than the advantage of reduced porosity.

FABRICATION PROCESS

The bonded vane and blade fabrication process has been under development for several years at United Technologies (UTC) for aircraft engine use. The airfoil is cast in two or more pieces and subsequently the pieces are bonded in a special process to make one monolithic airfoil with 100 percent of the strength of the base material. The coolant passages which would be formed by a ceramic core in a single-piece conventional casting are formed on the outer surfaces of each of the separate pieces of the airfoil. Using this process, more complex cooling passages can be fabricated than with an internal ceramic core. The bonded airfoil process has been developed to take advantage of the properties of both columnar-grained and single-crystal cast alloys. This is important in applications where high strength and corrosion resistance are required. Airfoils made using the process have accumulated many hours of engine experience, and a facility to manufacture bonded airfoils in quantity has been established.

Fabrication of the airfoils designed in this program for industrial engines by the bonded process is a straightforward extension of the aircraft engine state of the art. The primary difference in these airfoils is that they are several times larger than aircraft engine airfoils. It is judged that the larger size should pose no significant new problems. However, experience has shown that each new airfoil requires a certain amount of manufacturing development. Therefore, it is expected that the significant change in size will require some fabrication development effort. Another difference is that the vane must be fabricated from more than two pieces, which is the current state of the art. Two-piece bonded airfoils are adequate in most aircraft applications where film cooling may be used. In the current design where the airfoil is entirely convectively cooled, more complex configurations with additional pieces were required. This will also take some

manufacturing development. The alloy, CG IN738, which would be primarily used in these airfoils, requires some development, as stated above, and its castability in the bonded airfoil process must also be demonstrated. At this point, it appears that a reasonable extension of the state of the art in each of these areas will allow the vanes and blades configured here to be fabricated by the bonded airfoil process.

The vane airfoils, as shown in Figure 3-6, would be fabricated from four pieces. The two pieces which make up the airfoil pressure and suction surface outer walls would be cast simultaneously in one mold. The mold would have the suction surface and the pressure surface located as in the final airfoil except they would be displaced slightly by a ceramic piece, known as a strongback, spanning the center of the mold cavity. Mirror images of the desired cooling channels molded on the ceramic strongback would form the cooling passages. These airfoil outer wall pieces would be cast columnar grained CG IN738. The two pieces which form the cooling passage pressure surface and suction surface inner walls would be formed from a sheet alloy, as sheet alloy is preferred where the inner wall geometry is very simple.

The platforms for the root and tip of the vane airfoil would be cast separately in a conventional casting process using IN738 alloy. The potential problem of porosity which led to the selection of CG IN738 in the airfoil would not be a problem in the platforms, therefore IN738 would be adequate.

A fabrication process block diagram for the complete vane fabrication is shown in Figure 4-2. In the airfoil outer wall casting step, the two outer walls would be cast in one mold as discussed above. The columnar grain is achieved by a controlled solidification process. In a separate step, the two inner wall pieces would be formed. Subsequently, in the airfoil outer to inner wall bonding step, each outer wall would be bonded to its corresponding inner wall. In the suction-to-pressure surface bonding step, the suction and pressure surface subassemblies would be bonded together to make the complete airfoil. In the platform-brazing step, the platforms that had been cast in the platform casting step would be brazed to the

airfoil. At this point, the airfoil would be similar to an airfoil which had been cast in one piece. Subsequent operations such as machining and coating would be as for a conventional airfoil.

The blades would be fabricated in a similar manner as the vanes but would be simpler, as shown in Figure 3-17. The complete process is described in Reference 1, and will be briefly described here. The desired airfoil shape, platforms, and root attachments would be made from wax and used to make a casting mold. The two separate blade pieces would be cast in this single mold with a ceramic strongback separating the pieces. The coolant passages would be formed by the ceramic strongback and the airfoil surface by the opposite side. The columnar-grained CG IN738 would solidify by controlling the rate of cooling. Subsequent to casting, the two halves of the blade would be bonded together. The blades would then be finish machined, and a corrosion resistant coating would be applied.

Figure 4-2. Vane and Blade Fabrication Process Block Diagram

Section 5

COST-OF-ELECTRICITY AND RELIABILITY

The cost of electricity for a gas turbine combined cycle power plant with these airfoil cooling configurations has been calculated using the same methodology utilized in the Reliable Engine program. The equation used to calculate the levelized cost of electricity is:

$$\text{COE} = \frac{(\text{LFC} + \text{LFOM}) 1000 \text{ mills}/\$}{\text{CR} \times \text{CF} \times 8760 \text{ hrs/yr}} + \text{LVOM} + \text{LFU}$$

where:

- COE = cost-of-electricity
- LFC = levelized fixed charges (capital)
- LFOM = levelized fixed operation and maintenance cost
- CR = capacity ratio
- CF = capacity factor
- LVOM = levelized variable operation and maintenance cost
- LFU = levelized fuel cost
- CR = $C_{\text{eff}}/C_{\text{NP}}$
- C_{NP} = name plate capacity (NEMA)
- C_{eff} = $C_{\text{NP}} - m \ln(1 - r + re^{C_{\text{NP}}/m})$
- m = utility characteristic (m = 1000 used here)
- r = equivalent unscheduled outage rate.

This equation is sensitive to airfoil costs in the LFC term, to reliability and power output in the CR term, and to engine efficiency in the LFU term. The equation was used to obtain a change in cost-of-electricity relative to the base case which was the Phase I Reliable Engine configuration reported in Reference 2.

Airfoil costs were calculated in terms of a cost factor. The Phase I Reliable Engine turbines used a cost of airfoils appropriate to one-piece conventionally cast airfoils. The split-cast airfoil costs were estimated as a factor on these conventional airfoil costs.

The reliability of the airfoils in terms of the equivalent unscheduled outage rate was assumed to be the same as the reliability of the Phase I Reliable Engine airfoils. The effect of variations in reliability is discussed further below.

The power output and the heat rate were calculated for a combined cycle power plant. These parameters depend strongly on the level of turbine cooling flow and its effect on aerodynamic and cycle performance. In these calculations all cooling and leakage flows except the airfoil cooling flow to the first vane and blade were held constant. This was to assure that only the effects directly attributable to the new first stage airfoil cooling would influence the results.

Table 5-1 shows the cost of electricity for three possible turbine configurations. The Phase I Reliable Engine configuration is the base case from which changes in the cost of electricity were calculated. The second turbine configuration is the base case turbine with the first vane and blade replaced by the bonded airfoils. The third turbine configuration is the base case turbine with the first vane and blade replaced by wafer airfoils taken from the "Advanced Full Scale Engine Demonstration" program, Electric Power Research Institute Contract RP 1319-3.

Going from the base case to bonded airfoils, the cost of electricity is reduced 3.5 percent, a significant improvement. However, of greater interest is a comparison with the turbine configuration utilizing wafer airfoils. The change in cost of electricity for wafer vanes and blades is reduced 4.4 percent. Thus, the results show that the bonded airfoil design achieves 80 percent of the potential reduction in cost of electricity calculated for the wafer design. Differences in cost of electricity of this magnitude are more likely due to the fineness of the design and analysis than the design concepts themselves. Therefore, other factors such as development risk, the status of manufacturing technology, and the existence of production facilities should be considered in selecting the configuration to be used. The production-ready status of the bonded design and the existence of a production facility only requiring modification to account for larger airfoil sizes verifies the desirability of the initial selection of the bonded airfoil approach.

It can be seen from Table 5-1 that engine efficiency (through the term LFU in the Cost of Electricity equation) is the predominant factor determining cost of electricity. The cost of electricity is affected by the parameters of airfoil cost and reliability, but not strongly so. As an example, the effect of increasing the airfoil costs by a factor of two from the base case was determined to change the cost of electricity by only 0.05 mills per kilowatt hour. Reliability was examined in a similar manner. The effect of doubling and halving the failure rates of the turbine airfoils was found to change the cost of electricity by only 0.02 mills per kilowatt hour. Thus, the changes in cost of electricity calculated here can be seen to be almost entirely from the effects that reduced cooling air flow has on engine efficiency.

The airfoil cost factors were estimated from consideration of the manufacturing processes previously described. This analysis showed that bonded vane costs would be 1.4 times the cost of a one-piece cast design. The bonded blade cost was estimated to be the same as the one-piece design.

An extensive reliability analysis was unnecessary because of its minimal impact on the cost of electricity. The reliability of airfoils using a new fabrication technique could be evaluated using analyses which have been developed for aircraft engine airfoils and have been applied to the Reliable Engine. However, the reliability sensitivity studies discussed above indicate that efforts to apply this analysis to the current problem would have little effect. The baseline Reliable Engine turbine reliability has been maintained in the current bonded design by continuing use of all-convective cooling and avoiding cooling holes prone to external plugging. The bonded airfoils incorporate generously sized internal cooling passages to eliminate internal plugging. Although the bonded interface represents an area of additional risk, the more uniform airfoil surface temperature and the more gradual strain development obtained with the bonded design represents risk-reducing factors relative to the single-piece cast airfoils of the reliable engine.

TABLE 5-1. COST OF ELECTRICITY COMPARISON

Parameter	A	B	C
	Phase I Reliable Engine	Bonded Airfoils	Wafer Airfoils
Vane Cooling - %	6.76	3.4	2.25
Blade Cooling - %	2.10	1.08	0.85
Vane Cost Factor	1.0	1.4	1.5
Blade Cost Factor	1.0	1.0	1.25
Heat Rate - Btu/kWhr	7848	7603	7543
Power - MW	288	313	320
LFC	71.537	68.55	67.70
LFOM	18.037	16.612	16.123
r	0.0485	0.0485	0.0485
CR	0.945	0.944	0.944
CF	0.7	0.7	0.7
LVOM	1.178	1.086	1.054
LFU	77.32	74.91	74.31
COE	93.95	90.70	89.85
Δ COE - %	BASE	-3.5	-4.4

Section 6

CONCLUSIONS AND RECOMMENDATIONS

The bonded airfoils studied under this program are prime candidates for development for industrial/utility gas turbines. The specific bonded airfoils studied in this program required only 2/3 the cooling flow of modern, state-of-the-art single-piece cast airfoils when operating at a combustor exit temperature of 2150°F. More significantly, the bonded airfoil concept is projected to be capable of operating at a turbine inlet temperature of 2400°F. Changes in design and operating parameters could make temperatures in the range of 2600°F or higher achievable with all convectively air-cooled bonded airfoils.

Bonded airfoils are under continued development for aircraft gas turbine purposes. Extension of the process from the two-piece construction now used in aircraft designs to four-piece construction introduces some risk. Such development risk is small compared to the major risk associated with other cooling methods being investigated for high temperature service - water cooling and transpiration cooling. Bonded construction offers a unique ability to fully inspect the internal and external surfaces after casting and before bonding, improving quality control. The amount of cooling air used, even at the growth temperatures, is similar to current levels, and cooling of the cooling air presents no unique problems. The bonded airfoil construction has been chosen over the wafer construction method for immediate development because of the more advanced state of the bonded process.

The current application of the bonded airfoil construction technique to aircraft engines ensures a continuation of the traditional role where industrial turbines capitalize on advanced development efforts in the military/commercial aircraft engine field. There are, however, additional efforts needed for industrial engine applications directed towards utilizing new industrial alloys, and toward making parts larger in size. Also, efforts must be made to extend the process to more complex casting configurations. Fabrication facilities which exist for aircraft engine airfoil production need to be modified to accommodate the larger size and the lower production quantities of industrial engine airfoils.

Development should proceed on the bonded airfoil construction. The improved cooling effectiveness obtainable with the bonded construction will enable higher turbine inlet temperatures to be obtained while maintaining airfoil metal temperatures low. This will allow the long, reliable life-times required for baseline electric power generation gas turbines to be achieved.

Section 7

REFERENCES

1. Mayfield, J., "Computer Controlled Production Gains," Aviation Week and Space Technology, December 3, 1979.
2. "High Reliability Gas Turbine Combined Cycle Development," Phase I Final Report, United Technologies Corporation, Power Systems Division, prepared for Electric Power Research Institute, Research Project 1187-1.