ERDA/NASA 0067/77/1
NASA CR-135147
PSD-R-109

THERMAL BARRIER COATING ON HIGH TEMPERATURE INDUSTRIAL GAS TURBINE ENGINES

Nils Carlson

United Technologies Corporation
Power Systems Division
South Windsor, Connecticut 06074

and

Barry L. Stoner

United Technologies Corporation
Pratt & Whitney Aircraft
East Hartford, Connecticut 06108

February 1977

Prepared for the
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Contract NAS3-20067

and the

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
Division of Conservation Research and Technology

(NASA-CR-135147) THERMAL BARRIER COATING ON HIGH TEMPERATURE INDUSTRIAL GAS TURBINE ENGINES Final Report (United Technologies Corp.) 60 p HC A04/MF A01 CSCL 10B
N77-27496
Unclas
G3/44 36692

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-135147		
4. Title and Subtitle THERMAL BARRIER COATING ON HIGH TEMPERATURE INDUSTRIAL GAS TURBINE ENGINES		5. Report Date February 1977
		6. Performing Organization Code
7. Author(s) Nils Carlson, Power Systems Division, and Barry L. Stoner, Pratt & Whitney Aircraft, both of United Technologies Corp.		8. Performing Organization Report No. PSD-R-109
		10. Work Unit No.
9. Performing Organization Name and Address United Technologies Corporation Power Systems Division South Windsor, Connecticut 06074		11. Contract or Grant No. NAS3-20067
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address Energy Research and Development Administration Division of Conservation Research and Technology Washington, D.C. 20545		14. Sponsoring Agency ~~Code~~ Report No. ERDA/NASA 0067/77/1

15. Supplementary Notes

Final report. Prepared under Interagency Agreement E(49-28)-1022. Project Manager, John S. Clark, Power Generation and Storage Division, NASA Lewis Research Center, Cleveland, Ohio 44135

16. Abstract

This study program identified significant benefits from applying thermal barrier coatings to hot section components of high temperature industrial gas turbine engines. The thermal barrier coating used in this study was a yttria stabilized zirconia material with a NiCrAlY undercoat, and the base engine used to establish improvements was the P&WA FT50A-4 industrial gas turbine engine. The design benefits of thermal barrier coatings include simplified cooling schemes and the use of conventional alloys in the engine hot section. Cooling flow reductions and improved heating rates achieved with thermal barrier coating result in improved performance.

Economic benefits include reduced power production costs and reduced fuel consumption. Over the 30,000 hour life of the thermal barrier coated parts, fuel savings equivalent to $5 million are projected and specific power (megawatts/mass of engine airflow) improvements on the order of 13% are estimated. A research and evaluation program to develop thermal barrier coating technology is recommended. The program plan culminates in an industrail gas turbine engine demonstration of the potential benefits of thermal barrier coatings.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Thermal barrier coating; Industrial gas turbine; Power cost benefits; Fuel consumption; Durability development plan; Ceramic; Electric power	Unclassified - unlimited STAR Category 44

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	55	

* For sale by the National Technical Information Service, Springfield, Virginia 22161

TABLE OF CONTENTS

LIST OF ILLUSTRATION

LIST OF ILLUSTRATIONS (Cont'd)

CONCLUSIONS AND RECOMMENDATIONS

The application of a thermal barrier coating to the hot section components of a high temperature gas turbine engine offers the potential for significant design and performance improvements with resulting economic advantages. A study was conducted to evaluate the design, performance and economic effects of applying a thermal barrier coating to the hot section components of the FT50 industrial gas turbine. This program also included the definition of a research and technology plan to achieve a commercial demonstration of an industrial gas turbine engine with thermal barrier coated hot section components.

The thermal barrier coating evaluated is composed of an yttria stabilized zirconia material bonded to the hot section component over a NiCrAlY coating. The total thickness of the coating is 0.48 micrometers (19 mils) and is applied using an arc plasma spray process. The benefits of this thermal barrier coating were studied by comparing the design requirements and economic characteristics for a high temperature industrial gas turbine, the FT50A-4, and an FT50 type engine modified to use the thermal barrier coating on its hot section components. The major design change permitted by the use of the thermal barrier coating was the substitution of simpler convective cooling schemes for the more complex film cooling schemes. The related cooling flow reductions resulted in a 4% heat rate improvement for the thermal barrier coated design relative to an uncoated design with equivalent structural life (30,000 hours). Other design advantages included the use of conventional burner materials and the potential for an improved burner exit temperature profile which results in increased turbine life. Engine performance was optimized for the thermal barrier coated design by trading firing temperature levels with coolant flow requirements necessary to achieve the 30,000 hour structural design criteria. The performance level achieved was limited by the uncooled FT50 power turbine temperature constraint imposed by the 30,000 hour structural requirement.

The performance evaluation included consideration of a simple-cycle configuration (single FT50 engine) and a combined-cycle configuration (2 FT50 engines and one two-pressure steam bottoming cycle). The heat rate improvement for both the simple-cycle and the combined-cycle configurations using thermal barrier coatings was about 4% and there was an improvement in specific power of about 13%. The combined-cycle configuration showed a slightly larger improvement in both categories. The major differences between the simple and combined-cycle configurations are apparent when considering fuel consumption. Over the 30,000 hour operating lifetime, when compared on an equal total electric energy power production basis, the fuel savings for a coated engine simple-cycle system versus an uncoated engine system approaches 196,000 barrels of oil. For the combined-cycle system, up to 410,000 barrels of oil are saved by using a coated engine combined-cycle system versus the uncoated engine combined-cycle system. These savings are significant and, when considering the residual fuel cost, amount to as much as $5 million. The maintenance and refurbishment costs associated with the thermal barrier coating are small relative to the fuel and capital costs and have essentially an insignificant effect on total power cost. Reduced electrical power production costs are estimated near 6% relative to an uncoated FT50 type engine.

A development program for thermal barrier coatings is recommended to conduct the significant research and technology activities necessary to achieve a commercial demonstration in a high temperature industrual gas turbine engine. This program is composed of four phases; Current Data Bank, Coating Technology, Design Support Technology, and Engine Programs.

The first phase, already in progress through United Technologies Corporation (UTC) research programs, is planned to draw on current UTC thermal barrier coating experience for combustors and extend this technology for turbine applications. This phase is not specifically an item to be funded under the suggested plan, but rather is an on-going UTC supported effort that will provide inputs to help guide this program in an efficient, cost effective manner. The second phase comprises the major research and technology activities of Process Technology, Durability Technology, and Erosion-Corrosion Technology. Improved thermal stress control during coating application is the main objective for the Process Technology task. Verification of increased durability for the best coating process application in a thermal fatigue environment is the main objective for the second task. A coating erosion-corrosion investigation to determine the coatings resistance or reaction to contaminated fuels with an evaluation to identify coating improvements is the primary objective for task three. The third phase is aimed at developing the design tools and measuring the coating material properties. Examples of these are development of a coating life prediction system or the measurement of thermal and mechanical property data for design use. Phase four, the final activity, is the commercial demonstration of the thermal barrier coated components in a high temperature industrial gas turbine.

1.0 INTRODUCTION

Thermal barrier coatings have been identified as having potential benefits when applied to high temperature gas turbines. The insulating effect of thermal barrier coatings as well as its potential for increased corrosion resistance can improve engine performance and increase component life. Since thermal barrier coating technology is applicable to all cooled gas turbines, NASA has initiated a limited experimental and study effort to assess the potential of the thermal barrier coating in a high temperature utility gas turbine application. This report documents a study to evaluate the benefits of thermal barrier coatings as applied to a high temperature industrial gas turbine. This study was sponsored by the Energy Research and Development Administration under Interagency Agreement No. E (49-28) - 1022.

1.1 OBJECTIVES

The objectives of this program were to evaluate the extent to which the application of thermal barrier coatings to cooled high temperature industrial gas turbine components would: (1) permit redesign to increase component life by substituting convection cooling for film cooling and by lowering metal temperatures, (2) allow trade-off of increased turbine inlet temperature and coolant requirements to optimize heat rate, and (3) reduce electrical power production costs for both simple-cycle and combined-cycle system configurations. An additional objective was the formulation of a preliminary research and technology program plan directed toward achieving a commercial engine demonstration of the benefits of thermal barrier coated cooled components.

1.2 PROGRAM

The objectives of this program were accomplished in four technical tasks, which are briefly described below.

Task I – Heat Transfer Analysis – This study was conducted to determine the coolant requirements for convectively cooled, thermal barrier coated FT50 hot section components. The thermal barrier coating assumed for this analysis was a 0.1 mm (0.004 inch) NiCrAlY bond coat and a 0.38 mm (0.015 inch) yttria-stabilized zirconia overcoat.

Task II – Performance Calculations – This portion of the study program evaluated the system trade-offs between turbine inlet temperature, coolant flow rate, metal temperature, heat rate and specific power. Calculations were made for a simple-cycle configuration and a combined-cycle, which included a steam cycle. Both "clean" light distillate and "dirty" residual fuels were considered in the performance calculations.

Task III – Impact Assessment – This task consisted of an electrical power production cost evaluation for the FT50 engine system using thermal barrier coatings. A capital cost analysis was included for simple-cycle and combined-cycle power stations. This evaluation considered estimated costs for redesign and initial coating application, and operating and maintenance costs for refurbishment of the thermal barrier coated hot section components.

Task IV – Preliminary Development Plan – Under this task, the significant research and technology activities were identified to achieve a commercial demonstration of a high temperature industrial gas turbine with thermal barrier coatings. The development plan also includes preliminary schedules for the technology advances and the component design modifications required.

1.3 FT50 ENGINE DESCRIPTION

The FT50 is a large high performance industrial gas turbine engine. It's general arrangement is a two spool gas generator configuration with a free power turbine. A cross-section of the FT50 is shown in Figure 1-1.

An 18:1 compression ratio is achieved by a 7 stage low-pressure compressor driven by a single stage low-pressure turbine, and a 10 stage high-pressure compressor driven by a single stage high-pressure turbine. The two spool design was selected to meet the compression ratio requirement with high efficiency and without the cost and mechanical complexity penalties associated with the variable geometry which would have been necessary with a single spool arrangement. The separate two stage power turbine provides the capability to have two gas turbines drive a single generator, to rematch the engine for maximum power under specific climatic conditions (this is possible since gas generator speed is not dependent on free turbine rotational speed), and to service both 60 cycle and 50 cycle markets.

The FT50 incorporates advanced cooling techniques to keep component metal temperatures low for long life while operating at high gas temperatures for high efficiency. Modular construction is featured to minimize maintenance cost and down time.

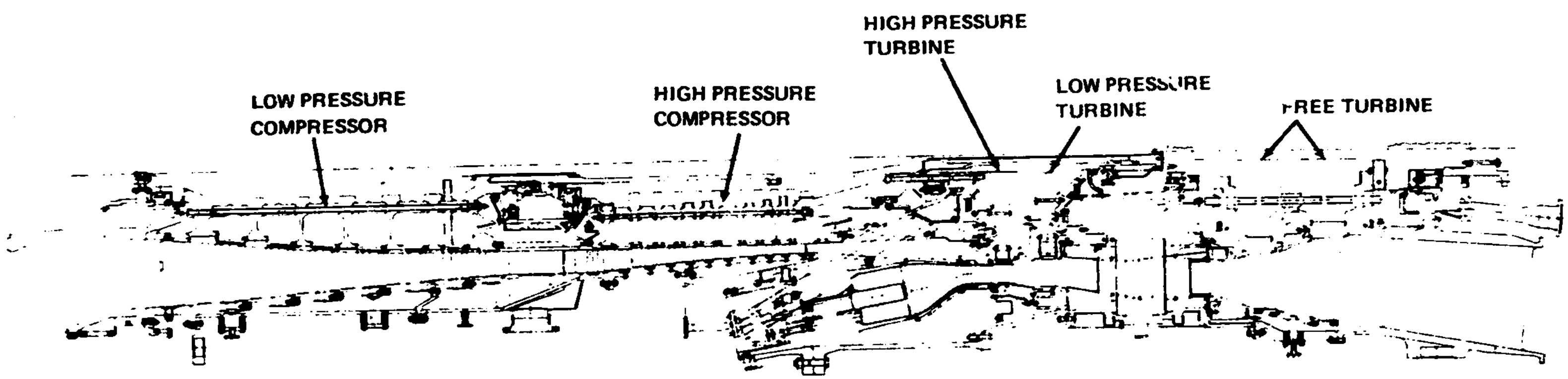


Figure 1-1 Cross-Section of the FT50 Engine

2.0 HEAT TRANSFER AND LIFE ANALYSIS

The purpose of this heat transfer and life analysis is to identify advantages and problem areas related to adding a thermal barrier coating to the hot sections of FT50A-4 gas turbine engines. The specified coating is 0.10 mm (0.004 in) NiCrAlY bond coat with a 0.38 mm (0.015 in) yttria-stabilized zirconia overcoat. The coating is applied via plasma spraying on turbine blades, vanes and platforms as well as combustion chamber and transition duct walls. One dimensional, steady state heat balances were used throughout the analysis which incorporated the coating thermal properties as identified in Appendix A. The low conductivity of the thermal barrier coating produced a high temperature difference between coating surface temperature and metal temperature. The temperature difference and, therefore, coating effectiveness was greater for areas with higher heat flux since the temperature difference is proportional to the heat flux through the coating. The high coating surface temperature reduces the heat flux substantially by reducing both the convective and radiative thermal loading.

2.1 COMBUSTOR ANALYSIS

As turbine designs using higher gas temperatures are sought, the requirements for burner combustor air and cooling air increase. This, in turn, reduces the dilution air available for tailoring the exit gas temperature profile. Without a change in geometry to reduce the surface area to be cooled (i.e., a shorter burner or change from can to annular design), material, cooling techniques and/or a thermal coating, insufficient air is available to meet the durability requirements of uprated engines.

2.1.1 Base Combustor

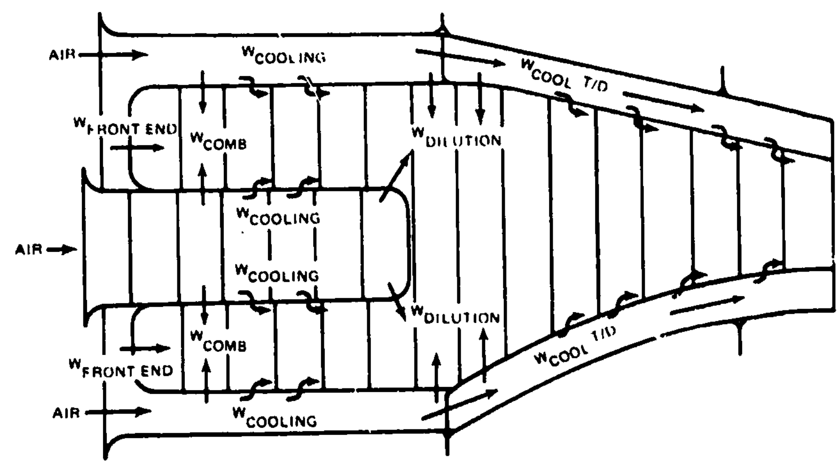
The FT50A-4 combustor design incorporates an advanced alloy that permits operation at 1144°K (1600°F) wall temperatures while meeting durability requirements of 10,000 hour creep/low cycle fatigue life with refurbishment capability to 30,000 hours. The base design includes a magnesium zirconate coating on a special combustor alloy, MERL 72, to achieve the desired wall temperature. The combustor airflow distribution is summarized below.

Primary combustion air	29.5%
Combustor cooling	25%
Transition duct cooling	21%
Dilution air	24.5%

In order to reduce combustor wall temperatures to 1088°K (1500°F), as requested by NASA for the purpose of this study, cooling flow requirements would increase by 5%. This air would be subtracted from the dilution air leaving only 19.5% air to tailor the radial gas temperature profile and reduce burner gas hot spots. Reducing the dilution air would increase hot spot temperature and result in higher pattern factors and lower turbine durability. Pattern factor is calculated using the following equation:

$$PF = \frac{T_{HOT\ SPOT} - T_5}{T_5 - T_4}$$

The transition duct design does not have magnesium zirconate coating since the louver cooling is sufficient to achieve acceptable wall temperatures although cooling air requirements are high. The louver cooling works by laying a thin film of cool air parallel to the liner surface, see Figure 2-1. Air is introduced in a series of small holes on a raised step (knuckle). There are minimum hole size requirements to facilitate fabrication and prevent plugging, and maximum hole spacing limitations to insure that the coolant enters the combustor as a continuous film, and not descrete jets. Since the hole sizing and spacing provides the minimum possible cooling level, there is no reason to add coating.



FT50 BURNER/TRANSITION

T_{METAL} AT A4 CONDITIONS 1144°K (1600°F)

$W_{FRONT\ END}$ 17.5% WA_B

W_{COMB} 12% WA_B

$W_{COOLING}$ 25% WA_B

$W_{DILUTION}$ 24.5% WA_B

$W_{COOL\ T/D}$ 21% WA_B

NOTE W_{AB} BURNER AIRFLOW

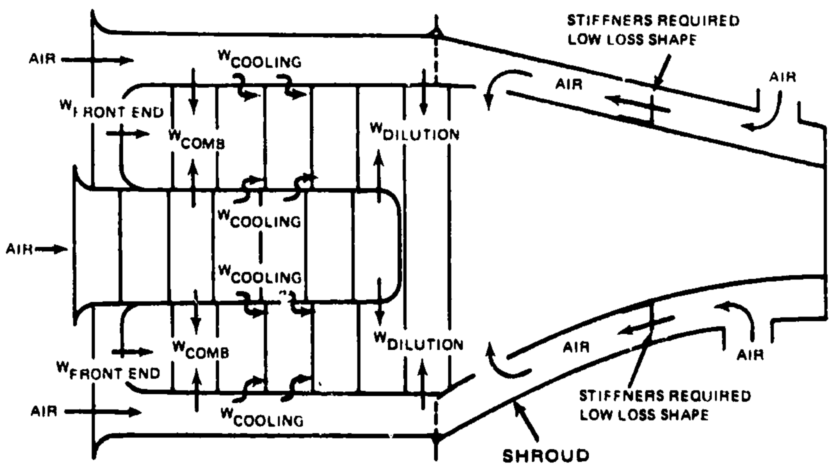
Figure 2-1 Base Engine Design

2.1.2 Thermal Barrier Coated Combustor

As an alternative design, this study evaluated the use of a yttria stabilized zirconia coating on conventional Hastelloy X material for both the burner surfaces and the transition duct to meet the durability requirements. The design criteria is the same as the base design, 10,000 hours creep/low cycle fatigue interaction life with the capability for refurbishment to extend component life to 30,000 hours. The thermal calculations were performed using standard P&WA design programs with appropriate boundary conditions.

Although information Referenced in Appendix A indicates that low radiative emissivity for yttria stabilized zirconia could be expected, experience with other thermal barrier coatings has shown that dirt, oxidation, and erosion increase the emissivity levels after a relatively short operating time. The emissivity level used for this study, based on engine operating experience, was 0.8. If initial emissivity levels of 0.3 to 0.4 could be achieved on a sustained basis, the coating could further reduce the radiative component of wall heat flux.

The use of the thermal barrier coating on the combustor and transition duct was found to allow elimination of film cooling in the transition duct. By increasing the transition duct shroud velocity significantly, convective cooling was determined to be sufficient to cool the transition duct but not the main combustor. The required cooling is much greater in areas of maximum flame temperatures. Therefore, film cooling was selected for the main burner and convective cooling for the transition duct. The convective design (Figure 2-2), with the bulk of the transition duct coolant counter-flowing in the annular passage around the transition duct, permits a second use of the coolant for dilution. The additional dilution air available for the thermal barrier coated design could be used to tailor the gas temperature profile and reduce the burner pattern factor. The large increase in available dilution air should allow a significant reduction in pattern factor; however, this cannot be analytically quantified and a testing program is needed to verify the improvement. The benefits for improved gas temperature control are realized in the turbine, especially in the first vane where reduced coolant requirements are possible with profile tailoring. This benefit will be discussed further in Section 2.2.1.



THERMAL BARRIER COATED CONFIGURATION (A4 CONDITION)
PLUS CONVECTIVELY COOLED TRANSITION DUCT

A)	B)
T_{METAL} 1144°K (1600°F)	T_{METAL} 1088°K (1500°F)
$W_{FRONT\ END}$ = 17.5% WA_B	$W_{FRONT\ END}$ = 17.5% WA_B
W_{COMB} = 12% WA_B	W_{COMB} = 12% WA_B
$W_{COOLING}$ = 25% WA_B	$W_{COOLING}$ = 30% WA_B
$W_{DILUTION}$ = 45.5% WA_B	$W_{DILUTION}$ = 40.5% WA_B
$W_{COOL\ T/D}$ = 0	$W_{COOL\ T/D}$ = 0

Figure 2-2 Thermal Barrier Coated Design

As shown in Figure 2-2, the combustor wall cooling is the same as the base FT50 A-4 design for 1144°K (1600°F) metal temperature. If film cooling is increased from 25% to 30% of burner air flow, combustor metal temperature can be reduced to 1088°K (1500°F). The dilution air flow ($W_{Dilution}$) available for either wall temperature case, with the convectively cooled transition duct, is greater than the base FT50A-4 dilution flow. Therefore, the thermal barrier coated design can be cooled to 1088°K (1500°F) and still have a more than adequate supply of dilution air for tailoring the gas temperature profile entering the turbine.

One question to be answered is whether the required convective heat transfer coefficients for convective cooling can be achieved with a realistic geometry and the available pressure drop. Figure 2-3 shows the required transition duct shroud heat transfer coefficients, at FT50A-4 conditions, to produce a given wall temperature in the transition duct, with and without coating. The uncoated case is beyond reach. For the coated case, the effect of wall emissivity is seen to be small because at the relatively low gas temperatures of the transition duct, convection is the primary heat load component.

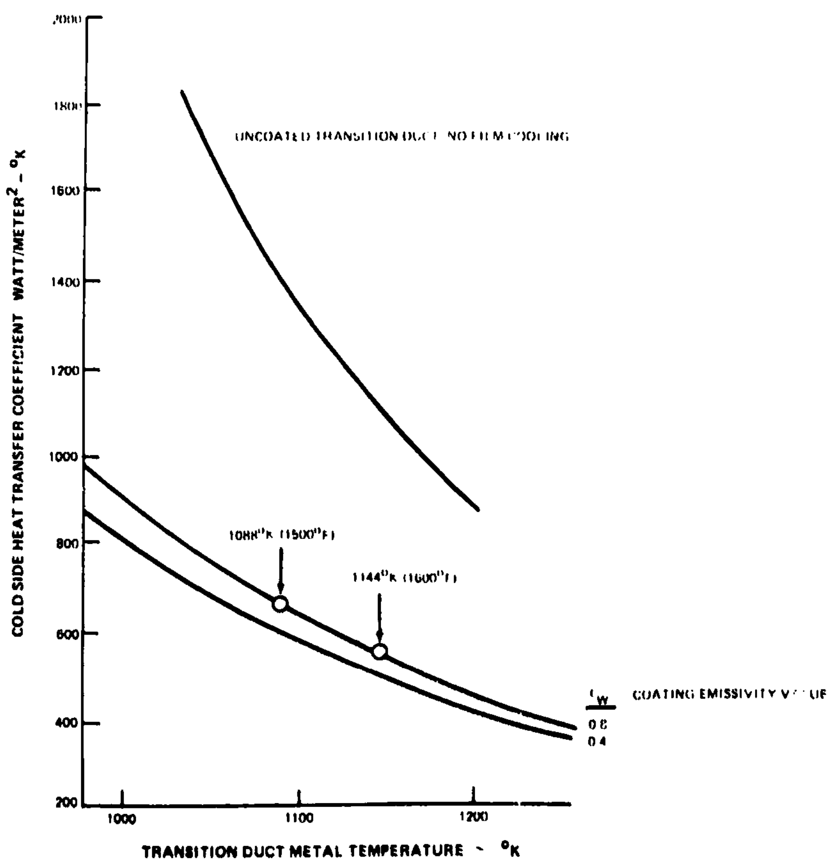


Figure 2-3 Heat Transfer Coefficient Requirements for Transition Duct

The maximum heat transfer coefficient required is approximately 1000 watt/m^2 - °K (5674 Btu/ft^2 hr - °F). This level can be achieved with a 1.5 cm (0.6 in) high annular passage around the transition duct for the available pressure drop.

Therefore, a thermal barrier coated combustor/transition duct design will allow reduced wall temperatures and increased dilution air flow compared to the base FT50A-4 design. The increased dilution flow represents the capability to improve the base pattern factor and to tailor the turbine entry gas profile to maximize turbine durability for a given turbine inlet temperature.

2.2 TURBINE ANALYSIS

The turbine blade and vane cooling schemes were designed incorporating the insulative properties of the thermal barrier coating. Cooling scheme simplifications were made, where possible, to design convective cooling configurations in place of film cooling configurations to eliminate the need for drilling coolant holes. The components evaluated were the first-stage turbine vane and platforms, the first-stage blade, and the second-stage vane and blade. An example of a first-stage vane configuration with leading edge film cooling, also described as showerhead cooling, is shown in Figure 2-4. Showerhead cooling consists of an array of leading edge cooling holes which face the on-coming flow and provide protection to the structure by the coolant film that is ejected. Eliminating showerhead cooling holes and designing cooling schemes with simple convective cooling configurations combined with thermal barrier coatings results in simpler design, and eliminates the concern over showerhead hole plugging.

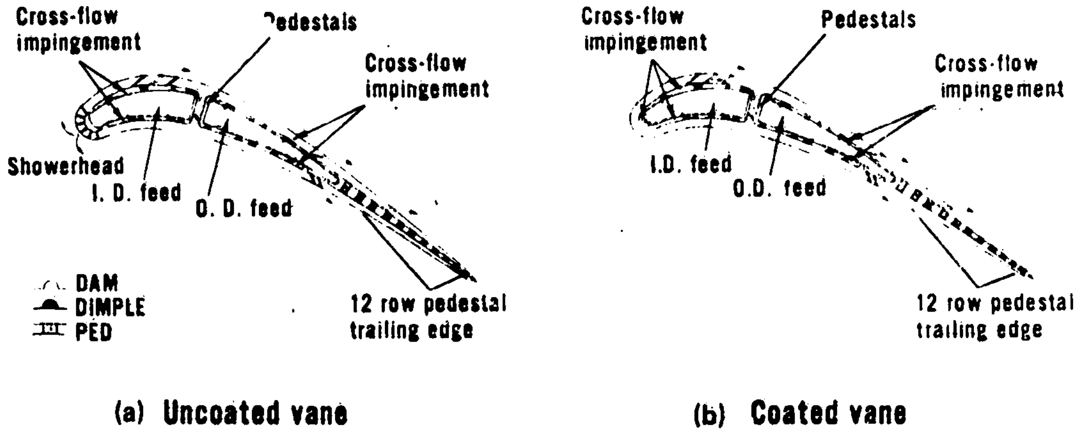


Figure 2-4 FT50 First Stage Turbine Vane

The base FT50A-4 gas generator turbine was designed without a thermal barrier coating and was limited at 1144°K (1600°F) maximum metal temperatures to avoid severe corrosion penalties. With the redesign of the turbine to incorporate the thermal barrier coating, the corrosion life was assumed to be removed because the coating was assumed to have unlimited corrosion resistance. The design criteria for the thermal barrier coated turbine was a 1%-creep life of 30,000 hours.

2.2.1 First Vane Analysis With Thermal Barrier Coating

Figure 2-4a shows the base FT50A-4 first vane cooling configuration. The leading edge has a showerhead cooling scheme and the pressure and suction walls are cooled with a combination of film cooling and internal cross flow impingement. The trailing edge is film cooled and has internal pedestals. The cooling flow rates are given in Table 2-I.

TABLE 2-I.

FIRST VANE COOLING FLOWS
FT50A-4 Conditions – Rotor Inlet Temperature = 1455°K (2160°F)

Uncoated FT50A-4 Vane	Thermal Barrier Coated Vane	
T_{metal} = 1144°K (1600°F)	T_{metal} = 1088°K (1500°F)	T_{metal} = 1144°K (1600°F)
$W_{Airfoil}$ = 8.0% WA_E	$W_{Airfoil}$ = 3.9% WA_E	$W_{Airfoil}$ = 3.0% WA_E
$W_{Platform}$ = 3.36% WA_E	$W_{Platform}$ = 2.85% WA_E	$W_{Platform}$ = 2.5% WA_E
W_{Total} = 11.36% WA_E	W_{Total} = 6.75% WA_E	W_{Total} = 5.5% WA_E

Figure 2-4b shows the thermal barrier coated version of the first vane with the leading edge showerhead cooling holes deleted. In order to cool this leading edge area, an array of impingement holes has been incorporated in the front insert tube. The impingement jets give internal heat transfer coefficients high enough to cool the coated leading edge area. Due to high heat fluxes along the vane suction side, film cooling plus internal impingement is still needed to maintain acceptable wall temperatures, although less cooling flow is necessary for the thermal barrier coated design (see Table 2-I). The external pressure side heat transfer coefficients are much lower than the suction side so that no film cooling is needed on the front portion of the vane. Toward the aft end of the pressure side of the airfoil, the external heat transfer coefficient increases until film cooling is needed to maintain acceptable wall temperatures in the trailing edge region. The pedestal cooled trailing edge region has coolant flow rates similar to the base FT50A-4 values at that location. The thermal barrier coated airfoil cooling is greatly reduced from base FT50A-4 levels as presented in Table 2-I. Vane platform cooling is accomplished with multipass impingement cooling plus film cooling for both the base FT50A-4 and the thermal barrier coated configuration. The platforms will be coated so that reduced platform film cooling will be possible for the coated configuration and the internal multipass impingement scheme will be the same as the base FT50A-4 configuration. The reduction in platform cooling air is also given in Table 2-I for the thermal barrier coated configuration.

In order to achieve a 1088°K (1500°F) first vane maximum metal temperature without the thermal barrier coating, total cooling air must be increased approximately 20-40% over the vane cooling level at 1144°K (1600°F). The cooling level is a function of both rotor inlet temperature and pattern factor as shown in Figure 2-5. The metal temperatures indicated are the maximum metal temperature at the hot spot location and include effects of engine deterioration, trim and pattern factor for the nominal coating thickness. Note that an increase of about 67°K (120°F) in high pressure turbine rotor inlet temperature ($T_{t5.1}$) can be tolerated with no change in cooling or metal temperature if pattern factor can be reduced (hot spot temperature reduced) to a value of 0.3 from the base value of 0.4. The lower burner transition duct cooling levels obtained with the thermal barrier coating make such a reduction in pattern factor a strong possibility.

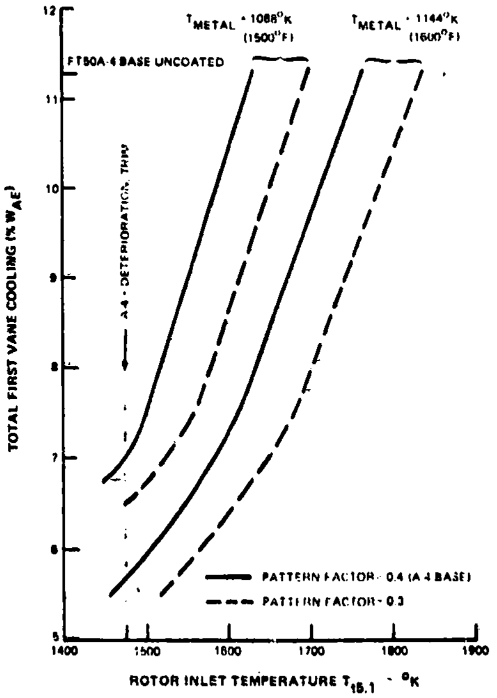


Figure 2-5 Coated Vane Cooling Level with Rotor Inlet Temperature

A slight increase in performance can be gained by reducing vane cooling due to a reduction in the pressure losses associated with injecting a low velocity cooling film into a high velocity gas stream. The pressure loss estimate was based on pressure loss increasing 0.1% for every 1% cooling change in the high velocity regions of the airfoil where the velocity difference between cooling film and mainstream is the greatest. The impact on overall performance is small but not insignificant since this effect will tend to counteract the effect of increased airfoil drag due to thermal barrier coating roughness.

The final result of the first vane analysis showed that the 1088°K (1500°F) metal temperature, which is desirable from a durability viewpoint, can be obtained with the thermal barrier coated design at rotor inlet temperatures substantially greater than the FT50A-4 design conditions.

2.2.2 First-Stage Blade and Second-Stage Airfoil Analysis

The requirements for film cooling were eliminated in the first-stage blade and the second-stage vane with the addition of the thermal barrier coating. Coolant flow reductions as high as 58% are realized with the thermal barrier coated designs. Figures 2-6 thru 2-8 show the uncoated FT50A-4 design and the redesigned thermal barrier coated designs at two metal temperatures, 1088°K (1500°F) and 1144°K (1600°F), with their required cooling flows.

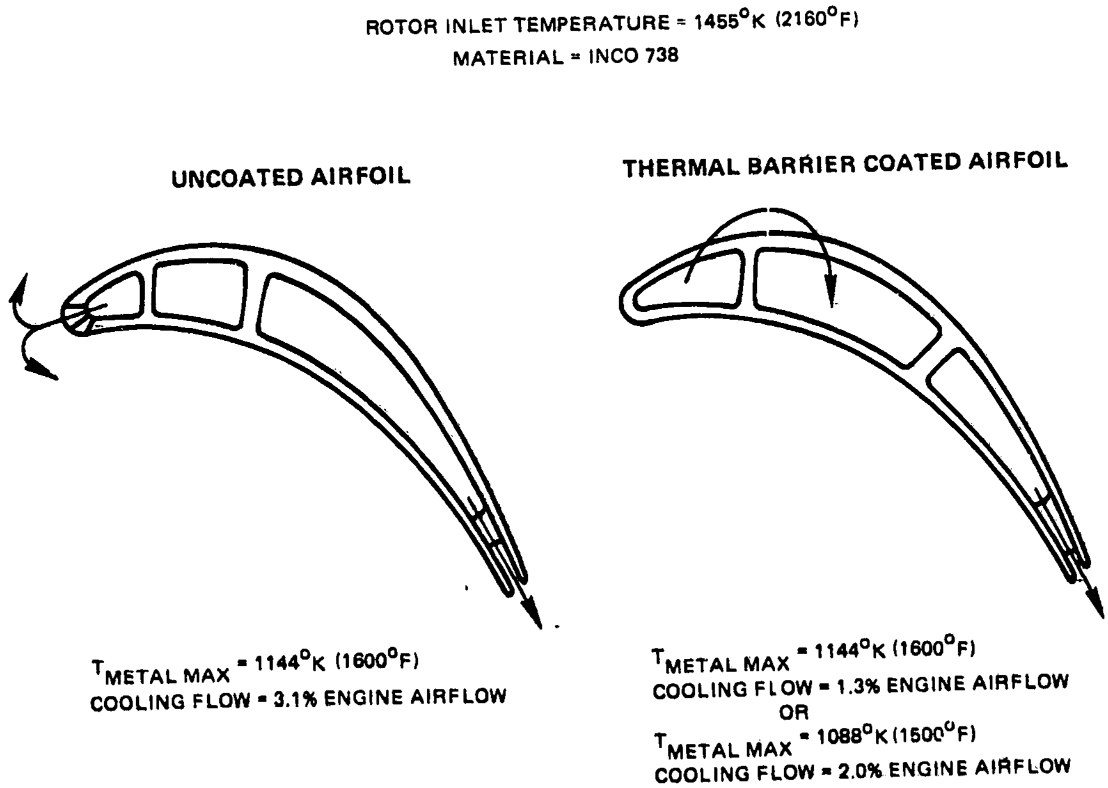
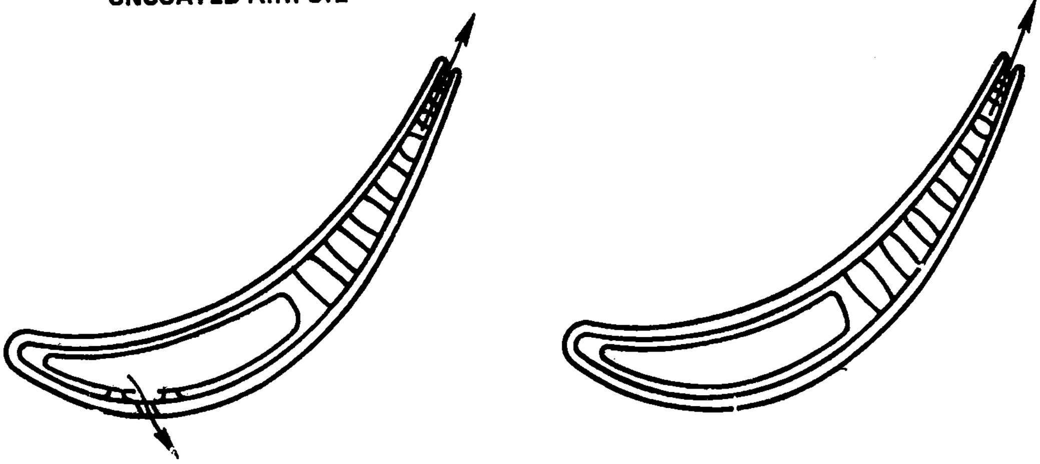


Figure 2-6 First Stage Turbine Blade

ROTOR INLET TEMPERATURE = 1455°K (2160°F)

MATERIAL = AMS 5382

UNCOATED AIRFOIL | **THERMAL BARRIER COATED AIRFOIL**



$T_{METAL\ MAX}$ = 1144°K (1600°F)
COOLING FLOW = 1.6% ENGINE AIRFLOW

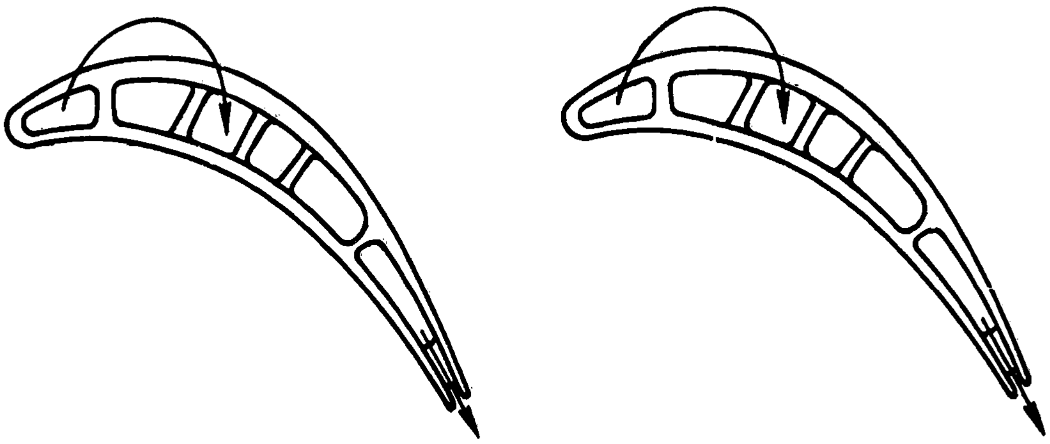
$T_{METAL\ MAX}$ = 1144°K (1600°F)
COOLING FLOW = 0.9% ENGINE AIRFLOW
OR
$T_{METAL\ MAX}$ = 1088°K (1500°F)
COOLING FLOW = 1.4% ENGINE AIRFLOW

Figure 2-7 Second Stage Turbine Vane

ROTOR INLET TEMPERATURE = 1455°K

MATERIAL = INCO 738

UNCOATED AIRFOIL | **THERMAL BARRIER COATED AIRFOIL**



$T_{METAL\ MAX}$ = 1144°K (1600°F)
COOLING FLOW = 0.5% ENGINE AIRFLOW

$T_{METAL\ MAX}$ = 1144°K (1600°F)
COOLING FLOW = 0.35% ENGINE AIRFLOW
OR
$T_{METAL\ MAX}$ = 1088°K (1500°F)
COOLING FLOW = 0.8% ENGINE AIRFLOW

Figure 2-8 Second Stage Turbine Blade

The FT50A-4 gas generator turbine has two essential design life criteria: (1) Maximum metal temperature equal to or below 1144°K (1600°F) to minimize hot corrosion, and (2) a 1% creep life of 30,000 hours at Peak Power, 313°K (104°F) day. Two options are possible to take advantage of the coating's insulative qualities while still adhering to these design criteria. These are reduced coolant usage or increased cycle temperature. First blade cooling flow rates as a function of rotor inlet temperature were calculated for constant maximum metal temperature (Figure 2-9) and for constant life (Figure 2-10) in order to evaluate engine performance benefits. (Similar calculations were conducted for the second vane and second blade.) Table 2-II summarizes the cooling flow requirements of the coated and uncoated FT50A-4 airfoils for the maximum metal temperature design criteria and Table 2-III summarizes the cooling flow requirements for the coated airfoils satisfying the 30,000 hour creep life design criteria. As can be seen from the two tables, thermal barrier coated airfoils require more cooling flow at the FT50A-4 design rotor inlet ($T_{5.1}$ = 1455°K (2160°F)) to satisfy the 30,000 hour creep life criteria than they do to satisfy the 1144°K (1600°F) maximum metal temperature design criteria. Thus the creep life design criteria is limiting for the thermal barrier coated FT50A-4 airfoils. The actual maximum metal temperature of a thermal barrier coated FT50A-4 airfoil satisfying the creep life design criteria becomes a function of rotor inlet temperature as is shown in Figure 2-11 for the first blade.

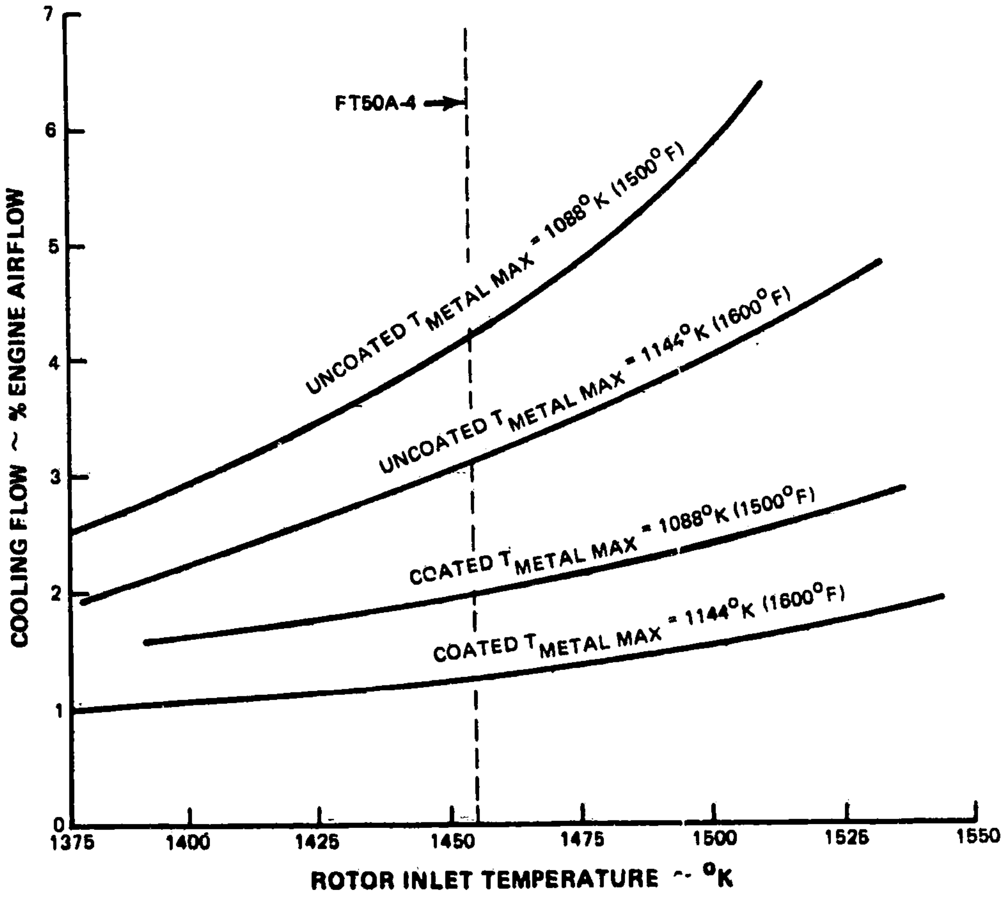


Figure 2-9 First Stage Turbine Blade Cooling Flow Rate for Maximum Metal Temperature

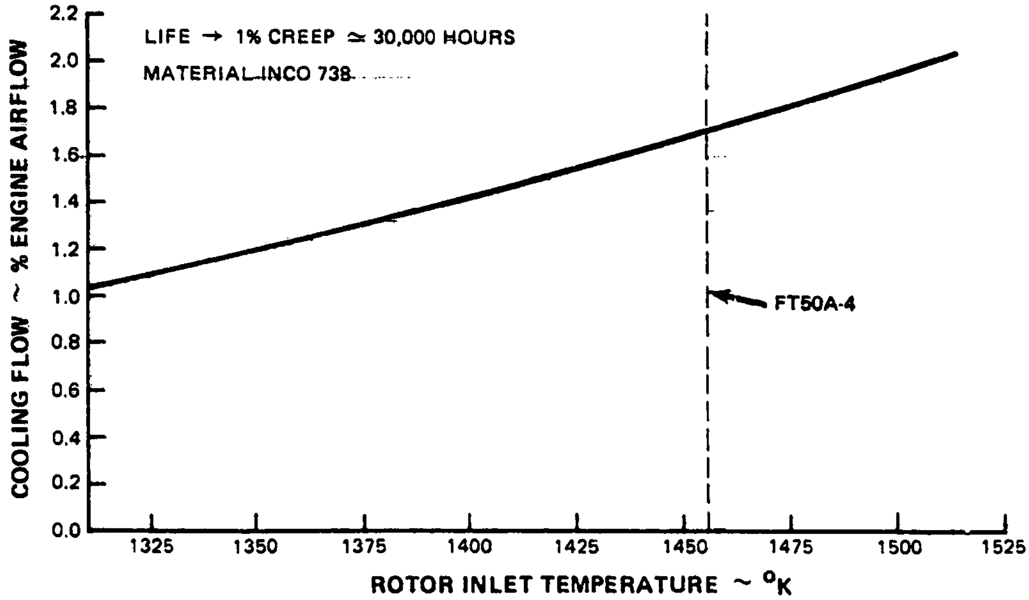


Figure 2-10 First Stage Turbine Blade Cooling Flow Rate for Constant Life

TABLE 2-II

TURBINE COOLING FLOW REQUIREMENTS USING MAXIMUM METAL TEMPERATURE AS DESIGN CRITERIA

Airfoil	Uncoated T_{max} = 1144°K (1600°F)	Coated T_{max} = 1144°K (1600°F)	Coated T_{max} = 1088°K (1500°F)
1st Blade	3.1% WAE*	1.3% WAE	2.0% WAE
2nd Vane	1.6% WAE	0.90% WAE	1.4% WAE
2nd Blade	0.5% WAE	0.35% WAE	0.8% WAE
Total Cooling	5.2% WAE	2.55% WAE	4.2% WAE

*WAE = Engine Airflow

TABLE 2-III

COOLING FLOW REQUIREMENTS FOR THERMAL BARRIER COATED AIRFOILS
USING THE 30,000 HOURS CREEP LIFE DESIGN CRITERIA
Airfoil Material = INCO 738 (Blades), AMS 5382 (Second Vanes)

Airfoil	Cooling Flow	Maximum Metal Temperature
1st Blade	1.7% WAE*	1114°K (1545°F)
2nd Vane	0.9% WAE	1144°K (1600°F)
2nd Blade	0.55% WAE	1114°K (1645°F)
Total Cooling	3.15% WAE	

*WAE = Engine Airflow

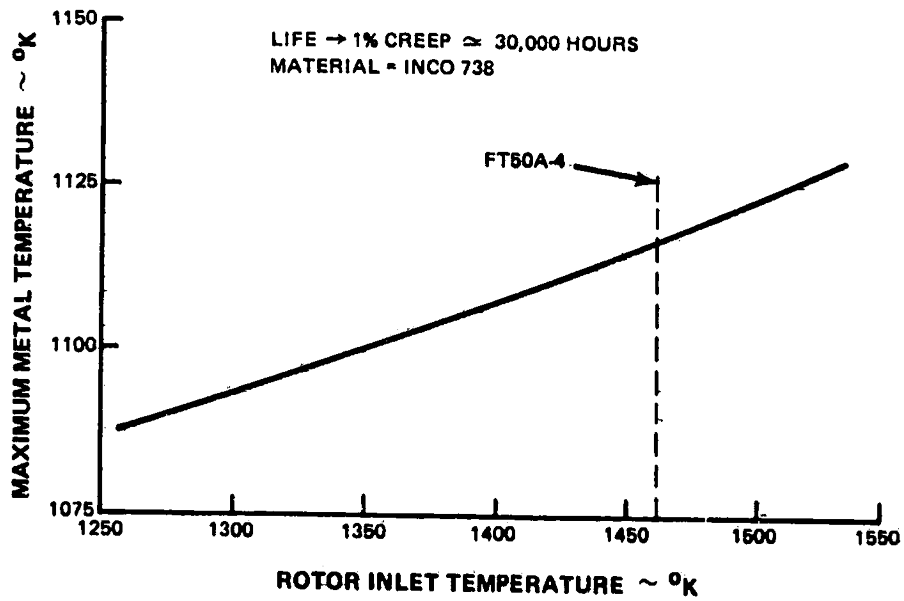


Figure 2-11 First Stage Blade Maximum Metal Temperature for Design Creep Life

The increase of the firing temperature with thermal barrier coated components was limited by the uncooled FT50A-4 power turbine blades which are made of Udimet 700. The high pressure turbine rotor inlet temperature, $T_{t5.1}$, was limited to 1477°K (2200°F) because the power turbine inlet temperature was constrained by the 30,000 hours creep criteria to 1088°K (1500°F). The use of an increased strength material for the power turbine blades or the use of a cooled power turbine would allow firing temperatures above 1477°K (2200°F).

Thermal barrier coatings in the "as sprayed" state have surface roughness levels measured between 6.35 to 8.89 X 10^{-6}m (250 to 350 micro inches). Conventional metallic coatings have "as deposited" surface roughness levels measured near 1.78 X 10^{-6}m (70 micro inches). However, experience has demonstrated that after relatively short run periods, the metallic coating surfaces increase in roughness level due to dirt, oxidation, erosion, and corrosion. Limited experience with thermal barrier coatings after short run periods has not indicated increased roughness levels.

Assuming that initial metallic coating and thermal barrier coating surface roughness levels remain unchanged during operation, a performance comparison can be calculated to reflect the aerodynamic effects and the heat transfer effects d e to the roughness difference. The uncooled turbine component efficiency penalty calculated due to the increased surface roughness of the thermal barrier is 0.5%.

In addition, the higher thermal barrier coated roughness increases the turbulent external heat transfer coefficient which results in a 10% increase in coolant requirement. However, the use of the thermal barrier coating decreases the heat flux into the airfoil which reduces the requirement for coolant relative to the coolant required for an airfoil without a thermal barrier coated by 50% so that there is still a substantial reduction in net heat load. Also the lower net coolant requirement reduces the aerodynamic mixing loss from injecting the coolant into the main gas stream, for example, trailing edge discharge mixing losses.

The aerodynamic loss differences in the turbine nearly cancel the penalty due to the surface condition. The net effect of reduced heat flux and resulting thermal cycle benefits, due to the reduced coolant requirement, remains significant. Additional performance benefits are possible if smoothing of the coating surface can be accomplished through coating processing techniques. These additional benefits are discussed in NASA TM-X3191.

All of these aerodynamic and thermodynamic effects have been incorporated in the performance results presented in Section 3.0.

3.0 PERFORMANCE ANALYSIS

An analysis to define the effects of thermal barrier coated hot section components on performance was made using a sophisticated powerplant performance analysis program called "State-of-the-Art Performance Program" (SOAPP). The program is based on a modularized representation of the system components, permitting virtually complete freedom in defining the power system configuration. The program is capable of analyzing the steam bottoming cycle as well as the gas turbine cycle and will calculate performance for variations in turbine rotor inlet temperature, cooling airflow, cooling air distribution, component characteristics, boiler pressure, and steam flow rate, all of which were used in this study. The FT50A-4 simulation, with and without an appropriate steam bottoming cycle, was used as the base from which the thermal barrier coatings were calculated.

3.1 PERFORMANCE SUMMARY

The FT50A-4 compressor operating point was held constant throughout the study of the various coated and uncoated turbine configurations. The base engine was the FT50A-4 uncoated design operating at a high pressure turbine rotor inlet temperature of 1455°K (2160°F) and with turbine cooling flow set to maintain turbine metal temperatures at a maximum of 1144°K (1600°F). The base engine turbine airfoil life at the 1144°K (1600°F) maximum metal temperature was 10,000 hours. An increased life uncoated design, also operating at a rotor inlet temperature of 1455°K (2160°F), was requested for comparison by NASA which had coolant flow required to maintain turbine airfoil maximum temperatures at 1088°K (1500°F). This uncoated design had 30,000 hours creep life. Both the base engine and the increased life designs are corrosion limited.

An optimization study was conducted to determine the best engine performance with a thermal barrier coated hot section achieving the 30,000 hour life to 1% creep as a structural criteria. The thermal barrier coating was assumed to have a corrosion life greater than 30,000 hours.

Improved performance was attained with increased turbine rotor inlet temperature; however, the level was limited by the power turbine materials. At power turbine inlet temperatures greater than 1088°K (1500°F), the power turbine life does not meet the 30,000 hour criteria. The optimized thermal barrier coated engine performance resulted in a heat rate improvement of 3.8% over the uncoated engine designed at a 1088°K (1500°F) metal temperature. Both the thermal barrier coated engine and the 1088°K (1500°F) metal temperature uncoated engine meet the 30,000 hour life criteria. The optimized thermal barrier coated engine had a 1.5% heat rate improvement over the uncoated turbine 1144°F (1600°F) metal temperature base engine as well as increased turbine life (10,000 hours to 30,000 hours). The thermal barrier coatings resulted in similar improvements in the combined cycle configuration.

Higher levels of engine performance would be possible if the power turbine constraint could be relaxed through use of advanced materials or a cooled airfoil design. This example is typical of the limitations incurred from applying new technology features into an established engine design. The optimum benefits for a new technology feature can only be realized when considered in the design philosophy during preliminary design phases.

Table 3-I summarizes the improvements resulting from the thermal barrier coatings comparing to the base uncoated engine and the increased life uncoated engine.

TABLE 3-I

ESTIMATED PERFORMANCE IMPROVEMENTS WITH THERMAL BARRIER COATINGS ON BURNER AND TURBINE

ISO Conditions

288°K (59°F) Ambient

Sea Level

	HEAT RATE		SPECIFIC POWER	
	SIMPLE CYCLE	COMBINED CYCLE	SIMPLE CYCLE	COMBINED CYCLE
Base Engine Comparison*	-1.5%	2.1%	+7.1%	+7.8%
Increased Life Engine Comparison**	-3.8	-4.1%	+12.8%	+13.4%

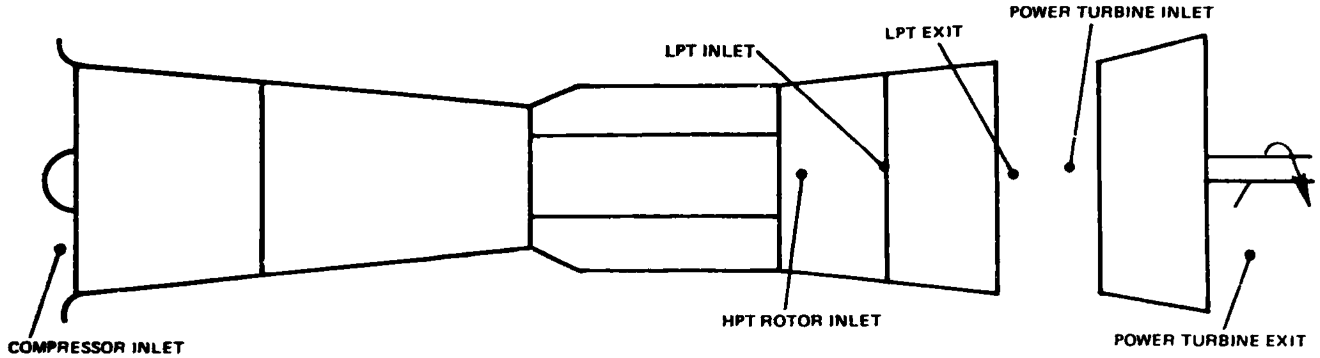
*Coated engine (30 k hr life) relative to uncoated base engine (FT50A-4, $T_{max\ metal}$ = 1144°K (1600°F))
**Coated increased life engine (30 k hr life) relative to uncoated increased life engine ($T_{max\ metal}$ = 1088°K (1500°F))

Note: Rotor inlet temperature for the coated engine = 1480°K (2204°F), for the uncoated base engine and uncoated increased life engine = 1455°K (2160°F).

3.2 UNCOATED PERFORMANCE

3.2.1 Base Engine Simple Cycle

The FT50A-4 was chosen as the base from which the thermal barrier coating performance effects would be calculated. The cycle characteristics of this reference engine with 1144K (1600°F) turbine airfoil maximum metal temperature are illustrated in Figure 3-1. However, since the turbine life of the base engine is limited by hot corrosion to 10000 hours, an increased life uncoated engine was defined to operate at 1088 K (1500°F) turbine airfoil maximum metal temperatures and its cycle characteristics are also presented in Figure 3-1. This second uncoated design has at least 30,000 hours life. The turbine airfoil cooling flows for each of these engines are shown on Table 3-II.



	FT50A-4 BASE 1144°K (1600°F) $T_{MAX\ METAL}$	FT50A-4 WITH INCREASED LIFE 1088°K (1500°F) $T_{MAX\ METAL}$
OPR	17.85	17.84
TT5.1 ~ °K (°F)	1454 (2157°F)	1454 (2157°F)
TCA - TOTAL (% WAE)	21.82	27.09
η_{GEN}	0.987	0.987
MW	110.11	104.54
WF ~ kg/HR (lbm/HR)	27109 (60,000)	26374 (58000)
HR ~ kJ/kW-HR (BTU/kW-HR)	10594 (10051)	10855 (10299)
THERMAL EFF.	0.3398	0.3317
DESIGN LIFE ~ HR	1000C	30000

STATION	W	T	P	W	T	P
COMPRESSOR INLET	368.5 (167)	288 (58)	0.101	368.5 (169)	288 (58)	0.101
HPT ROTOR INLET	331.6 (150)	1454 (2157)	1.681	321.6 (146)	1454 (2157)	1.678
LPT INLET	350.6 (159)	1202 (1704)	0.729	344.4 (156)	1188 (1678)	0.703
LPT EXIT	365.0 (166)	1047 (1425)	0.410	364.8 (165)	1027 (1389)	0.390
POWER TURBINE INLET	365.0 (166)	1047 (1425)	0.407	364.8 (165)	1027 (1389)	0.387
POWER TURBINE EXIT	370.1 (168)	777 (939)	0.108	370.3 (168)	770 (926)	0.108

	PR	η	PR	η
HPT	2.308	0.878	2.388	0.878
LPT	1.777	0.886	1.803	0.886
POWER TURBINE	3.765	0.900	3.581	0.900

W = AIRFLOW RATE kg/SEC (lb/SEC)
T = TEMPERATURE °K (°F)
P = PRESSURE MPa
PR = PRESSURE RATIO
η = EFFICIENCY
OPR = OPERATING PRESSURE RATIO
TCA = TURBINE COOLING AIR
η_{GEN} = GENERATOR EFFICIENCY
WF = FUEL FLOW RATE
HR = HEAT RATE

Figure 3-1 Simple Cycle Configuration Uncoated Base Engine

TABLE 3 II

TURBINE AIRFOIL COOLING FLOWS

Source	Description	FT50A-4 $T_{max\ metal}$ = 1088°K (1500°F) T_{rotor} = 1455°K (2160°F) (% W_{AE})	FT50A-4 $T_{max\ metal}$ = 1144°K (1600°F) T_{rotor} = 1455°K (2160°F) (% W_{AE})	Thermal Barrier Coated T_{rotor} = 1480°K (2204°F) (% W_{AE})
Station 4.0	1st Vane	10.5	8.0	4.36
Station 4.0	1st Blade	4.13	3.10	1.82
1	2nd Vane	2.70	1.57	1.10
13th Stage	2nd Blade	1.11	.50	.865
	Total Turbine Cooling Air	27.09	21.82	16.01

1 Station 4.0 source for the FT50A-4/1088°K (1500°F) $T_{max\ metal}$, 13th stage source for all other cases.

3.2.2 Base Engine Combined Cycle

The steam bottoming cycle for the base engine and the increased life uncoated engine were defined using the following groundrules:

1. Steam turbine exit quality was held at 0.9 to provide maximum power output with acceptable steam turbine life.

2. Pinch points for the superheater, high pressure boiler, low pressure boiler, and deaerator were held at 283 K (50° F) to provide practically sized heat exchangers.

3. Gas Turbine exhaust stack temperature was held at 422 K (300° F) to prevent condensation of sulfuric acid in the stack.

To satisfy these groundrules, a two pressure steam bottoming cycle was selected. The steam flow and boiler pressures were optimized to provide the lowest heat rate. Figures 3-2 and 3-3 show schematics of the steam systems including pressures, temperatures, and steam flows for the base engine and the increased life uncoated engine configurations, respectively.

COMBINED CYCLE

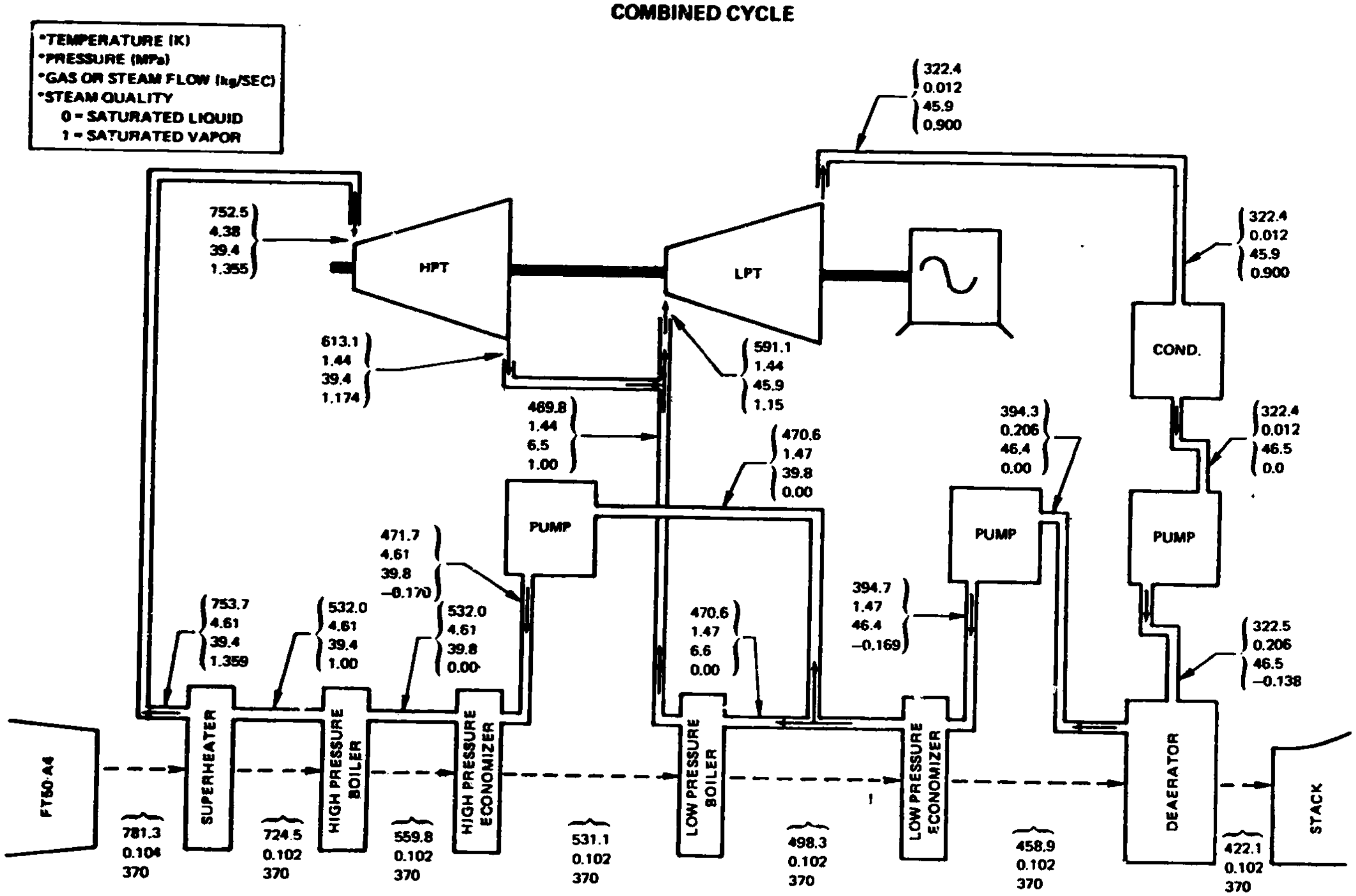


Figure 3-2 Steam System for Base Engine Configuration (Uncoated), 1144°K (1600°F) T_{max}

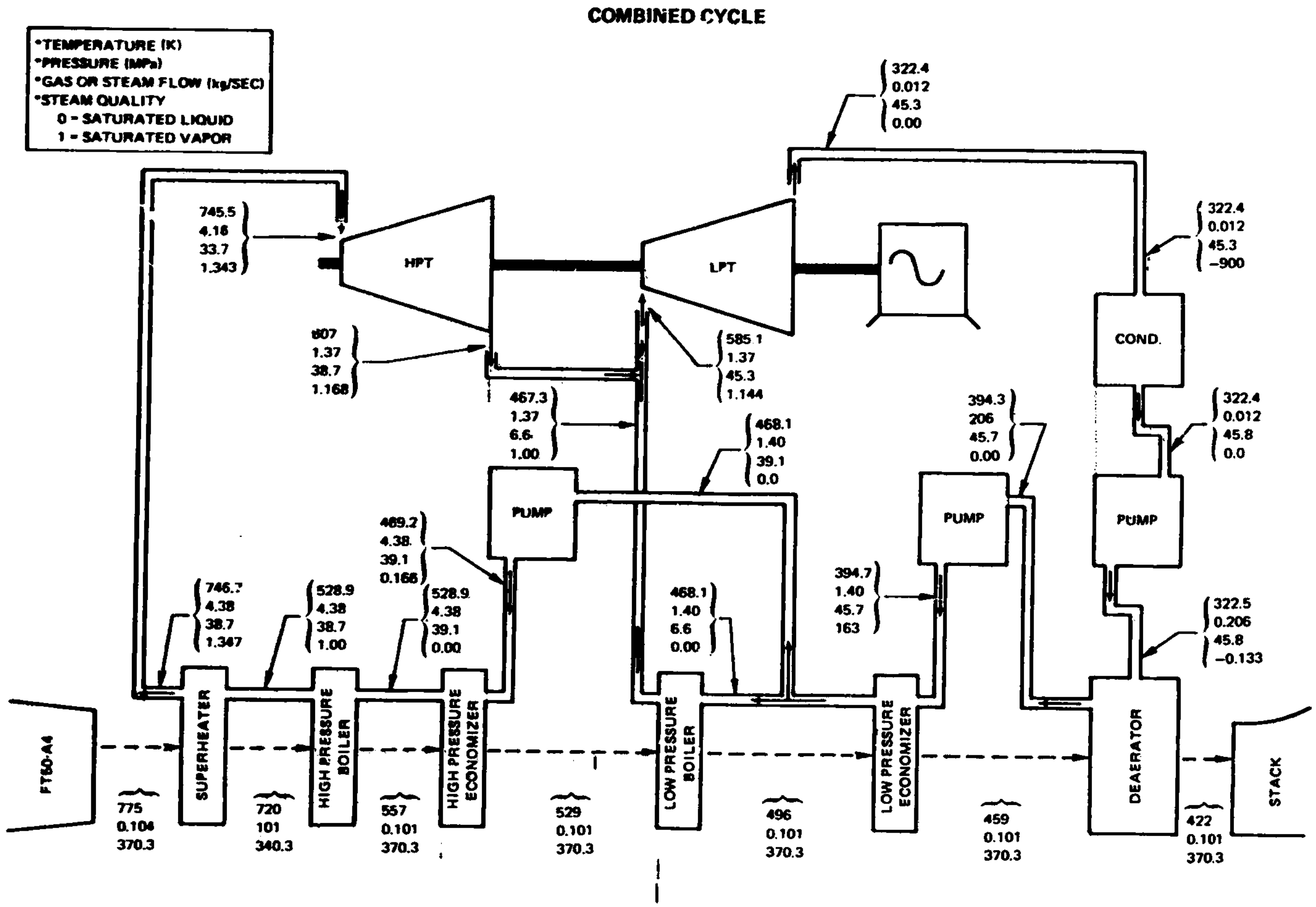


Figure 3-3 Steam System for Increased Life Engine Configuration (Uncoated), 1088°K (1500°F) T_{max}

3.3 THERMAL BARRIER COATED PERFORMANCE

3.3.1 Thermal Barrier Coating Simple Cycle

Application of the thermal barrier coating to the turbine airfoils could result in (1) reductions in cooling flow required to maintain a given metal temperature, (2) increased turbine gas temperatures at a given cooling flow rate and turbine metal temperature, or (3) a combination of decreased cooling flow and increased gas temperature to provide the lowest heat rate. Figure 3-4 illustrates the performance effects of a variation in cooling flows and turbine gas temperature to maintain 1088 K (1500°F) and 1144 K (1600°F) maximum metal temperatures and to maintain a constant 30,000 hour turbine life. The figure indicates that increased gas temperature and increased metal temperature reduce the heat rate until reaching the power turbine constraint. The uncooled power turbine does not benefit from the use of thermal barrier coatings and is therefore limited to a 1088°K inlet temperature to meet the 30,000 hour life criteria.

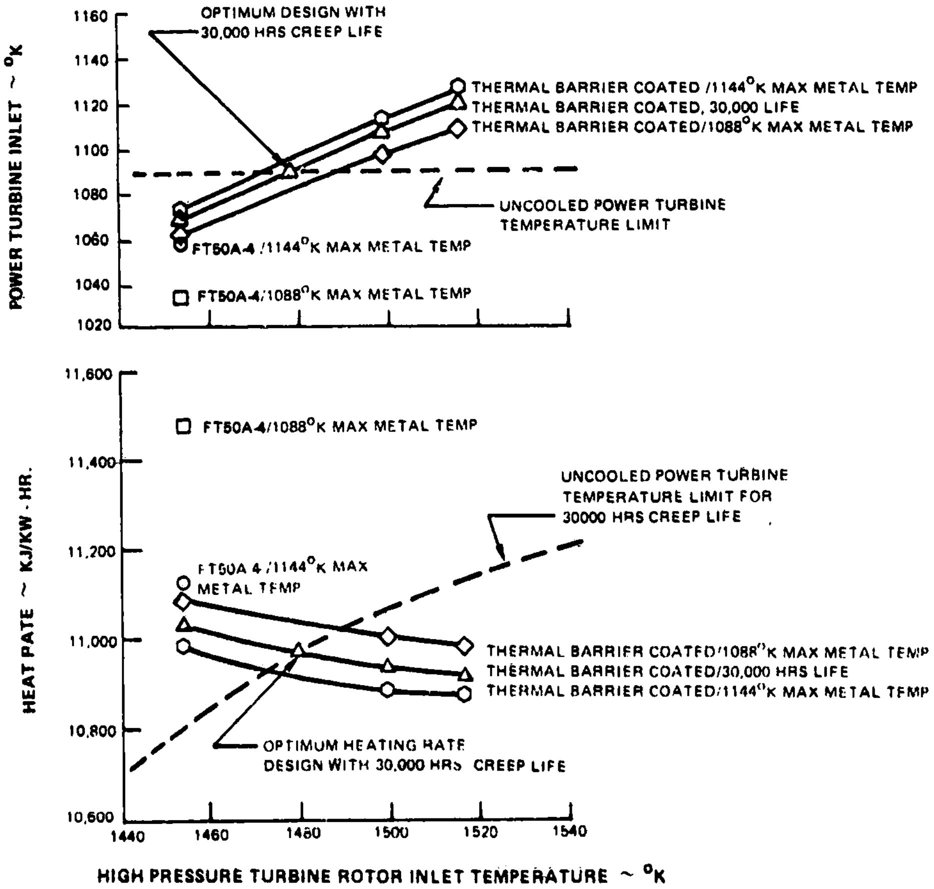
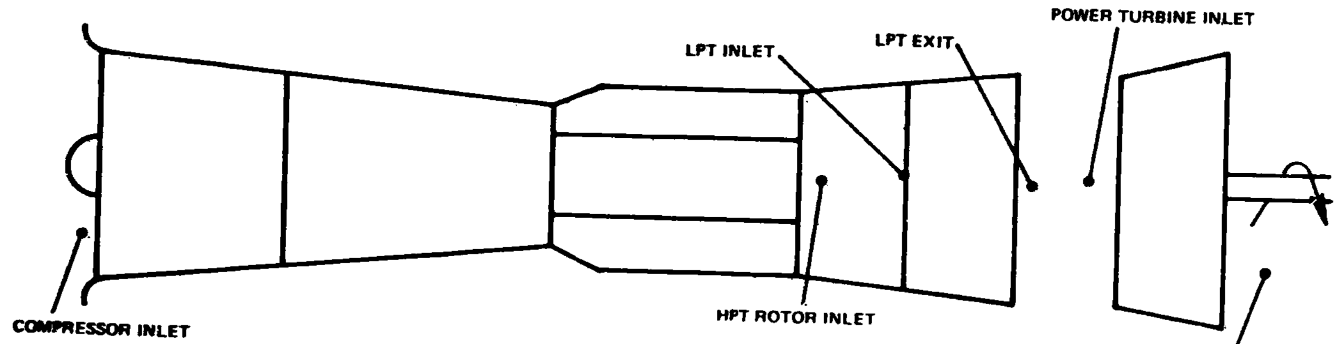


Figure 3-4 Performance Optimization

Of the three thermal barrier coated turbines, the 30,000 hour turbine was chosen over the 1144°K (1600°F) maximum metal temperature turbine because it met the turbine life criteria, and the 1088°K (1500°F) maximum temperature turbine because of a better heat rate. The gas turbine pressures, temperatures and airflows for the selected thermal barrier coated engine are illustrated on Figure 3-5.



	30,000 HRS. TURBINE LIFE
OPR	17.83
TT5.1 ~ °K (°F)	1480 (2204)
TCA - TOTAL (% WAE)	16.01
η_{GEN}	0.987
MW	117.91
WF ~ kg/SEC (lbm/SEC)	28606 (63000)
HR ~ kJ/kW-HR (BTU/kW-HR)	10440 (9905)
THERMAL EFF.	0.3448

STATION	W	T	P
COMPRESSOR INLET	368.4 (167)	288 (58)	0.101
HPT ROTOR INLET	337.5 (153)	1480 (2204)	1.684
LPT INLET	351.8 (160)	1238 (1768)	0.753
LPT EXIT	365.0 (166)	1084 (1491)	0.481
POWER TURBINE INLET	365.0 (166)	1084 (1491)	0.428
POWER TURBINE EXIT	370.4 (168)	798 (976)	0.108

	PR	η
HPT	2.238	0.878
LPT	1.745	0.886
POWER TURBINE	3.958	0.900

W = AIR FLOW RATE kg/SEC (lbm/SEC)
T = TEMPERATURE °K (°F)
P = PRESSURE MPa
PR = PRESSURE RATIO
η = EFFICIENCY
OPR = OPERATING PRESSURE RATIO
TCA = TURBINE COOLING AIR
η_{GEN} = GENERATOR EFFICIENCY
WF = FUEL FLOW RATE
HR = HEAT RATE

Figure 3-5 Optimized Simple Cycle Configuration for Thermal Barrier Coated FT50

The turbine cooling flows used to calculate the optimized thermal barrier coated engine performance are shown on Table 2-II in the turbine analysis section (Section 2.0). The reduced flow requirements were calculated for Inco 738 blade material and AMS 5382 vane material which are the same materials used in the base engine. Although further reduced cooling flow requirements are possible with an increased strength material, a perforamnce analysis was not made because the performance benefit of the thermal barrier coating was sought without other benefits that could be incorporated in an uncoated engine.

Table 3-III shows the power (MW), fuel flow (WF), heat rate (HR) and thermal efficiency (η TH) of the thermal barrier coated turbine with residual ("dirty") and distillate ("clean") fuels for the 1088°K (1500°F) and 1144°K (1600°F) metal temperature turbines as well as the 30,000 hour turbine. All engines are shown in both the simple cycle and combined cycle configurations. The performance difference between residual (42990 kJ/kg (18500 Btu/lbm) HHV) and distillate (44960 kJ/kg (19350 Btu/lbm)HHV) fuel was very small and resulted from the difference in mass flow required to provide the same heat. No derating of turbine inlet temperature was assumed when using the residual fuel. The performance improvement for the thermal barrier coated turbine and burner were the result of decreased cooling flow and vane pressure loss, and increased turbine rotor inlet temperature.

3.3.2 Thermal Barrier Coated Combined Cycle

The steam bottoming cycle for the optimized thermal barrier coated engine was designed to satisfy the same groundrules as the base engines steam cycles. Because of the increased power turbine discharge temperature of the thermal barrier coated engine, the steam cycle operated at higher temperatures and pressures increasing the steam cycle power output and efficiency. Figure 3-6 illustrates the pressures, temperature and steam flows of the steam bottoming cycle used with the thermal barrier coated engine.

TABLE 3-III

PERFORMANCE SUMMARY

	SIMPLE CYCLE					COMBINED CYCLE*			
	UNCOATED			COATED		UNCOATED		COATED	
Life Criterion/Max. Metal Temp. or Creep Limit	1088°K (1500°F) RESID.	1144°K (1600°F) RESID.	1144°K (1600°F) DISTIL.	30K HRS RESID.	30K HRS DISTIL.	1088°K (1500°F) RESID.	1144°K (1600°F) RESID.	30K HRS RESID.	30K HRS DISTIL.
Rotor Inlet Temp ~ °K (°F)	1454 (2157)	1454 (2157)	1454 (2157)	1480 (2204)	1480 (2204)	1454 (2157)	1454 (2157)	1480 (2204)	1480 (2204)
Cooling Air (% WAE)	27.90	21.82	21.82	16.01	16.01	27.09	21.82	16.01	16.01
**									
GAS TURBINE									
Power Output ~ MW	104.54	110.11	110.11	117.91	117.92	205.94	217.90	233.48	232.74
Fuel Flow ~ kg/Hr (lbm/Hr)	26374 (58000)	27109 (60000)	26105 (57500)	28606 (63000)	27546 (61000)	52750 (116000)	54423 (120000)	57444 (126500)	55148 (121500)
Heat Rate ~ kJ/kW·Hr (Btu/kW·Hr)	10855 (10300)	10594 (10050)	10671 (10124)	10440 (9905)	10515 (9976)	11022 (10457)	10748 (10197)	10587 (10045)	10665 (10119)
Thermal Eff	.3317	.3398	.3374	.3448	.3424	.3266	.3350	.3460	.3376
Specific Power ~ kW-Sec/kg (kW-Sec/lbm)	283.69 (128.68)	298.81 (135.54)	298.81 (135.54)	319.97 (145.14)	319.97 (145.14)	279.43 (126.75)	295.66 (134.11)	316.80 (143.70)	315.79 (143.24)
STEAM SYSTEM									
Power Output ~ MW						83.108	86.164	94.392	93.914
PLANT									
Power Output ~ MW						289.05	304.06	327.87	326.65
Heat Rate ~ kJ/kW·Hr (Btu/kW·Hr)						7853 (7451)	7702 (7307)	7539 (7153)	7599 (7210)
Thermal Eff						.4584	.4674	.4775	.4738
Specific Power ~ kW-Sec/kg (kW-Sec/lbm)						392.20 (177.90)	412.56 (187.14)	444.87 (201.79)	443.22 (201.04)

*Two Gas Turbines, One Steam Turbine
**High heat value (HHV) for residual fuel is 42990 kJ/kg (18500 Btu/lbm), and for distillate fuel is 44960 kJ/kg (19350 Btu/lbm). Low heat value (LHV) for residual fuel is 40780 kJ/kg (17550 Btu/lbm), and for distillate fuel is 42360 kJ/kg (18230 Btu/lbm)

ORIGINAL PAGE IS OF POOR QUALITY

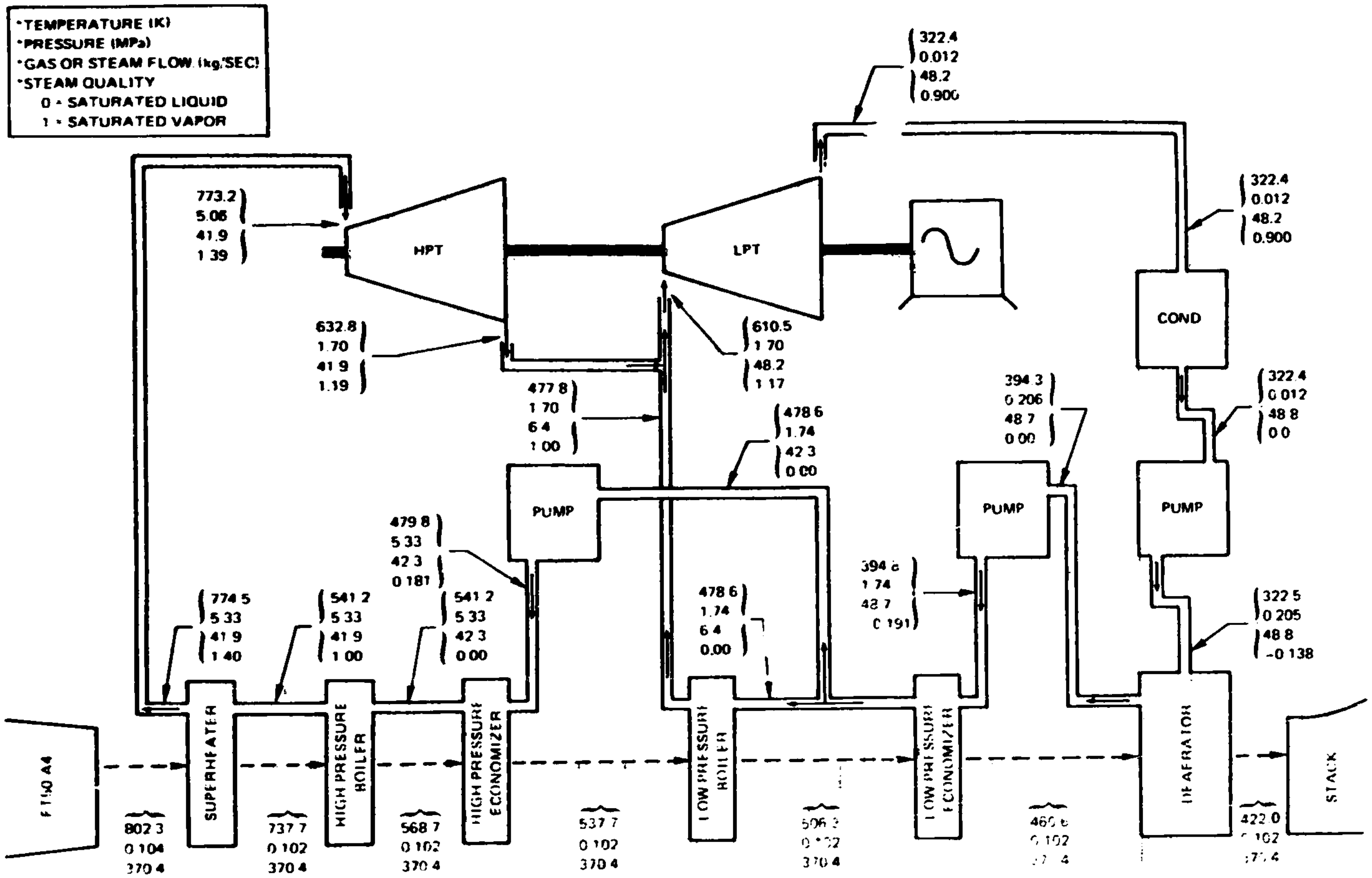


Figure 3-6 *Optimized Combined Cycle Configuration for Two Thermal Barrier Coated FT50 Engines With 30K Hrs. Life*

4.0 COST IMPACT ASSESSMENT

This section contains the assumptions used in the cost analyses and the results of the cost impact assessment. Both capital and operating costs are expressed in mid-1976 dollars. No escalation or interest has been included because both depend on start date and construction period; however, cost estimates are presented in sufficient detail to allow one familiar with power plant economics to readily adjust the values to any future period. The capital cost values presented are budgetary-type estimates and are not an offer on the part of United Technologies Corporation to commit to a firm contract for equipment.

4.1 CAPITAL COST ASSUMPTIONS

4.1.1 Simple-Cycle System

The simple-cycle station consists of a single FT50-type engine, all associated equipment needed to generate power, transformer equipment for 230 kV, 60-cycle output power, one fuel storage tank, a fuel containment dike, land and all necessary site equipment, including the peripheral fencing. The power generation site is assumed to be located near an East Coast commercial/industrial area where the land, estimated at $100,000 per acre, is adjacent to a rail siding. The entire unit is self-contained except for remote computer controls and monitoring equipment which permit unattended operation. The site area contains the gas turbine-generator building (approximately 0.6 acres), a square dike (capable of containing a spill of the entire fuel tank at a depth not to exceed three feet), a pump house and switchyard. The average simple-cycle site size is five acres.

The basic gas turbines with their associated equipment, as noted in Table 4-I, include foundations and, in the case of the residual-fueled units, a fuel treatment system. Whereas a complete breakdown of individual equipment capital costs was developed, only the composite value is presented in order to protect the proprietary nature of the individual components, and particularly that of the gas turbine. Two fuels, a clean distillate (141,800 Btu/gallon) and a residual-type (150,000 Btu/gallon) were considered, and then were used along with the performance estimates to size the tank farm. The tank capacity was based on a 30-day storage capacity at a load factor of 0.45.

The additional equipment capitalized during construction was estimated at three percent of the construction cost (material, equipment and installation labor), and the system was assumed to be designed and constructed by a typical A&E (Architectural and Engineering) firm who would add to the total direct construction cost a 10% allowance for contingency and 15% allowance for engineering services and construction supervision. All profit allowances are included in the estimates of the individual line items. The bottom line (specific capital cost) is the sum of all category entries divided by the net plant output.

TABLE 4-I

CAPITAL COSTS (IN DOLLARS) – SIMPLE-CYCLE SYSTEMS

	Case				
	1088°K (1500°F) T_{metal}	1144°K (1600°F) T_{metal}	1144°K (1600°F) T_{metal}	30,000 Hr. Thermal Barrier Coated	30,000 Hr. Thermal Barrier Coated
Fuel Type	Residual	Distillate	Residual	Distillate	Residual
Output Power – MW	104.54	110.11	110.11	117.91	117.91
FPC Accounts 341, 343, 344 and 345 – Gas Turbine And Associated Equipment (Note 1)	11,067,[illegible]	10,868,500	11,077,700	10,918,500	11,142,500
FPC Accounts 341, 345, and 346 (Items Not Included Above)					
Land and Site Preparation	497,000	518,500	508,100	571,200	519,600
Oil Pump House and Spare Equip. Bldg.	95,000	91,000	95,000	91,000	95,000
Tank Farm	272,400	285,600	277,100	298,100	286,600
Miscellaneous Power Plant Equipt.	166,200	170,400	170,400	176,000	176,000
Total Items Not Included Above (FPC Accounts 341, 345, 346)	1,030,600	1,065,500	1,050,600	1,136,300	1,077,200
FPC Account 353 – Station Equipment Power Transformer and Assoc. Equip.	692,200	705,300	705,300	723,100	723,100
Other Capitalized Expenses (3% of above)	383,700	379,200	385,020	383,400	388,300
Direct Construction Costs	13,173,600	13,018,500	13,218,600	13,161,300	13,331,100
Contingency (10%)	1,317,400	1,301,960	1,301,900	1,316,200	1,331,100
Engineering and Construction Supervision (15%)	1,976,000	1,952,800	1,952,800	1,974,200	1,999,700
Total Station Cost	16,476,000	16,273,200	16,523,300	16,451,700	16,663,800
Specific Cost ($ per kW)	157.5	147.8	150.1	139.5	141.3

Note 1 The following equipment is included in these accounts.

Turbine engine and generator	Fuel oil heater and pumps
Turbine enclosure, foundation andair cooler	Fuel piping and thermal insulation
Air start system and bearing motor	Miscellaneous pump and tanks
Flexible coupling	Computer and control panels (on and off-site)
Lube oil purification and fire protection	Breeching
Inlet air filters	Accessory Electrical Equipment
Emergency cooling system	Foundation
Expansion joints	

4.1.2 Combined-Cycle System

The combined-cycle system consists of two FT50-type gas turbine engines, a single two-pressure steam turbine, and associated electrical and mechanical equipment. The system output is nominally 300 MW depending upon the operating conditions, as noted in the performance section of this report. This station is assumed to be located at the typical Middletown, USA location where land is valued at $1000 per acre. The combined-cycle system is to be self-contained, including the administration building, repair and storage facilities, a rail siding, and the fuel storage tank farm. Each of the basic turbines in the combined-cycle system, incorporates the same set of equipment at essentially the same cost as that noted for the simple-cycle system.

The heat energy in the gas turbine exhausts is transferred to the steam system in a single unfired, dual-flow, waste-heat boiler divided by means of a baffle down its centerline. In this manner, no intermixing of engine exhaust gases in this boiler are allowed, thereby alleviating backflow problems when only one gas turbine is operating. The single, two-pressure steam turbine is connected to its own generator, the power from which, as well as that from the gas-turbine-driven generators, is transformed to a line voltage of 500 kV at 60 cycles. Steam turbine waste heat is rejected through a wet, mechanical draft cooling tower, whereas the combined exhaust flow of the gas turbines is directed up a single, 45.7m (150 ft) stack after exiting the waste heat boiler.

Only residual fuel with a heating value of 150,000 Btu per gallon was considered for the combined-cycle stations. Fuel storage on-site was considered adequate for a 60-day period at a load factor of 0.65 (enough for approximately 936 hours of operation). Two cylindrical fuel storage tanks with conical roofs were assumed, and the surrounding rectangular dike area was sized to contain the simultaneous spill of both tanks to a height not exceeding three feet. Including the tank farm, 50 acres were allowed for each combined-cycle site.

The additional equipment capitalized during construction was estimated at three percent of the sum of all equipment, materials and construction labor. This system was also assumed to be designed and constructed by a typical A&E firm who would add to the total direct construction cost an additional 15% allowance for contingency and 20% for engineering and construction supervision services. All profit allowances have been included in the individual line items. It should be noted that the basic cost correlations, for which both the simple-cycle and combined-cycle economic estimates have been made, refer to an East-Coast site. Consequently, it was necessary to make an adjustment to the combined-cycle system estimates to reflect Middletown, USA construction costs. This was accomplished by utilizing a procedure from an unpublished EPA report. This procedure makes adjustments primarily on the basis of different labor rates, since materials and equipment do not vary with site location. As a result, the estimates for the Middletown, USA site are not presented on a line-item basis, but rather only on a total construction cost basis, excluding escalation and interest. Because of the detail used in developing the basic East Coast estimates, it is believed these Middletown, USA site estimates have a high degree of reliability.

4.2 OPERATING COST ASSUMPTIONS

This section contains the assumptions associated with developing the power station production cost analysis for both the uncoated and the thermal barrier coated FT50 machines operating in the simple-cycle and combined-cycle modes. For both types of systems, a capital recovery factor of 0.18 was used which incorporates not only utility profit, but also depreciation insurance, taxes, and all other fixed station cost charges. The load factors considered for the simple-cycle system are 12 percent and 45 percent (1050 hours and 3940 hours, respectively); whereas, the load factors for the combined-cycle system are 45 percent and 65 percent (3940 hours and 5700 hours, respectively).

The fuel charges are directly proportional to the heat rates of the respective systems as noted in the section presenting system performance. The residual fuel was assumed to cost $2.15 per million Btu's, and, the distillate fuel, when available, was assumed to cost $2.60 per million Btu's. The following assumptions were made with respect to operating and maintenance charges. For all systems, the basic operating and maintenance charge of 2.0 mils per kW-hr was assumed to cover all (steam and gas turbine) system costs except those for the hot parts in the gas turbine; these latter parts were considered separately. In addition, a charge of 30.0 mils/million Btu's was added for fuel additives in residual fuels. In the systems containing the gas turbines limited to a maximum metal temperature of 1088°K (1500°F), all hot parts (burner, transition duct, blades and vanes in high and low turbines) were assumed to have a 30,000 hour life. However, refurbishment of these parts was necessary after 10000 and 20000 hours of operation. United Technologies Corporation refurbishment costs were used while tear-down and rebuild labor was based on United Technologies Corporation time estimates and a total utility burdened man-hour rate of $20 per hour. For the 1144°K (1600°F) maximum allowable metal temperature gas turbine cases; it is necessary to replace the turbine parts after 10,000 and 20,000 hours of operation although the burner and transition duct still have a 30,000 hour life. In addition, the blades and vanes must be refurbished at 3300 hour intervals, while the burner parts must be refurbished at 5000 hour intervals. Refurbishment charges and replacement part costs are based on United Technologies Corporation rates while tear-down and rebuild charges were assumed at utility rates, as above. For the thermal barrier coated cases, all parts are assumed to last 30,000 hours although recoatings were considered parametrically for intervals of 5000 hours, 10,000 hours, and 15,000 hours. Recoating costs and labor charges are based on UTC rates as in the previous cases. The respective engine coating/refurbishment charges were added to the base 2.0 mils per kW/hr estimates and the fuel additive charge (when necessary) to determine total operating and maintenance charges. These were then added to the respective capital and fuel charges to determine the overall power production cost expressed in mils per kW/hr.

Although these power production charges are presented in terms of mid-1976 dollar values, sufficient detail is presented to allow the reader to make other adjustments based on different assumptions. Whereas the absolute level of these charges may vary, depending on time of construction, site selection, and economic conditions, it is believed that the relative charges, and in particular the incremental changes due to thermal barrier coatings, should not change. It is these incremental values which are of particular interest in determining the overall benefits to be derived from adapting such technical innovation.

4.3 DISCUSSION OF RESULTS

A breakdown of the capital charges for the five simple-cycle systems is presented in Table 4-I. Shown in this table is a list of the component equipment which is included in these remote-controlled, single gas-turbine-engine stations. Cost allowances are also made for the land, associated buildings, transformer, site preparation, miscellaneous equipment, contingency, and engineering and supervision. The A&E contractor profit, installation labor, and insurance during construction are included in the respective line items to protect the propriety of these data since they relate to an actual UTC product. The advantage in increasing the allowable metal temperature and the use of thermal barrier coating can be shown by comparing the 1144°K (1600°F) metal temperature case ($150 per kW) and thermal barrier coated case ($141 per kW ($139 per kW with distillate fuel)) with the 1088°K (1500°F) metal temperature base FT50 system ($157.5 per kW). These estimates also indicate that the difference in capital cost between a system using a distillate fuel and one using a residual-type fuel is small, the primary difference being due to the tank farm requirements and its associated dike area for the distillate fuel case and the fuel treatment system for the residual fuel case.

The breakdown of station equipment costs, land cost, contingency charge, and engineering and supervision allowances for East coast combined-cycle systems is presented in Table 4-II. As noted previously, the UTC cost correlations relate to costs at this location so they were presented in detail. However, corrections to the Middletown, USA site for these systems are presented at the bottom of the table. The differences which are specifically related to the labor, fringe and supervision charges during construction only differ in these areas by five percent. The materials, equipment and engineering charges are assumed not to vary between the two locations, although contingency and profit entries are reduced for the Middletown site because of the lower overall construction cost estimate. Overall,the difference between the East coast location and Middletown site amounts to approximately 1.3 percent, so for all practical purposes the East-coast-related combined -cycle estimates provide a reasonable amount of system cost breakdown detail. As mentioned, because of uncertainty in construction start dates, cost escalation rates and utility interest charges, all values are presented in terms of mid-1976 dollars excluding interest and escalation. For those who desire, these estimates can be adjusted to future start up dates by assuming construction periods of two years for the simple-cycle system and four years for the combined-cycle system.

The total power production cost estimates are presented in Tables 4-III and 4-IV for the simple-cycle and the combined-cycle systems, respectively. Each table contains a breakdown of capital, fuel, and operating and maintenance charges. The two load factors for the simple-cycle system are representative of peak-load and intermediate-load operation; those for the combined-cycle system correspond to intermediate-load and base-load operation. In each table, attention is directed to the results for the parametric variation of overhaul periods with the TBC systems. As noted, there is an essentially insignificant effect on total power cost caused by this parametric refurbishing time variation for both the simple-cycle and combined-cycle systems. This occurs because these costs, which are estimated to be as high as $1.1 million for the TBC case with 5000-hour overhaul rates, are small relative to those for fuel and capital. For purposes of defining results, only a single operating and maintenance charge (equal to the highest value in a given category of coated case) need be

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 4-II

CAPITAL COSTS (IN DOLLARS) COMBINED-CYCLE SYSTEMS

	Case		
	1088°K (1500°F) T_{metal}	1144°K (1600°F) T_{metal}	30,000 Hr. Thermal Barrier Coated
FPC Account No. 341 Structures and Improvements			
Land and Site Preparation	504,100	520,500	546,000
Buildings: Administration, Steam Turbogenerator, Spare Equip.	2,097,600	2,108,500	2,125,500
Circulating Water System (including piping)	443,600	454,900	484,900
Tank Farm and Oil Pump House	1,135,600	1,156,500	1,193,300
Stack	397,900	399,500	399,500
Total Account No. 341	4,578,800	4,639,900	4,749,200
FPC Account No. 313 Boiler Plant Equipment			
Waste Water Filter	12,348,600	12,597,400	13,179,800
Boiler Feed Pumps and Motors	27,800	29,900	36,300
Boiler Feed Tank Deaerator and Condensate Tank	29,600	30,400	32,500
Demineralizer	232,700	236,200	247,900
Piping and Thermal Insulation	2,468,400	2,559,100	2,803,500
Miscellaneous Pumps	266,200	272,300	288,800
Total Account No. 512	15,379,100	15,731,600	16,596,500
FCP Account No. 314 Steam Turbogenerator			
Steam Turbine, Generator and Pedistal	5,753,400	5,799,000	6,118,900
Condenser, Tubes and Ejector	407,200	413,300	433,900
Condenser Pump, Vacuum Pump and Motors	76,700	77,800	81,800
Cooling Tower (Wet, Mechanical-Draft Type)	968,500	982,900	1,031,700
Circulating Water Valves, Pumps and Expansion Joints			
Make-up Structure and Screene	545,300	551,000	570,000
Chlorination Equipment			
Total Account No. 314	7,751,100	7,824,000	8,236,300
FPC Accounts 341 (Cont), 343, 344, and 345			
Gas Turbine and Associated Equip (Note 1)	22,128,200	22,151,000	22,280,600
FPC Account 346 Miscellaneous Power Plant Equipment	270,000	276,600	286,700
FPC Account 353 Station Equipment			
Power Transformer and Assoc. Equipt.	1,001,200	1,019,800	1,044,300
Other Capitalized Expenses (3%)	1,533,300	1,549,300	1,595,800
Direct Construction Costs	52,641,700	53,192,200	54,789,400
Contingency (15%)	7,896,300	7,978,800	8,128,400
Engineering and Construction Supervision (20%)	10,528,300	10,638,400	10,957,900
Total Station Cost, Installed on East Coast	71,066,300	71,809,400	73,965,700
Specific Cost, per kW	245.9	236.2	225.6
Total Station Cost, Installed at Middletown USA Site	70,337,700	70,857,100	73,036,500
Specific Cost, per kW	242.8	233.2	222.8

Note 1 The following equipment is included in these accounts.

- Turbine engine and generator
- Turbine enclosure, foundation and air cooler
- Air start system and bearing motor
- Flexible coupling
- Lube oil purification and fire protection
- Inlet air filters
- Emergency cooling system
- Expansion joints
- Fuel treatment system
- Fuel oil heater and pumps
- Fuel piping and thermal insulation
- Miscellaneous pump and tanks
- Computer and control panels (on and off-site)
- Breeching
- Accessory electrical equipment
- Foundation

TABLE 4-III

TOTAL POWER PRODUCTION COST
Mills per Kw-Hr
SIMPLE – CYCLE CASES
EAST COAST SITE

Case	Fuel Type	Overhaul Period	Capital	Fuel	O&M	Total
		Load Factor: 0.12				
1088°K (1500°F) T_{metal}	Resid.	Base*	26.55	22.12	2.06	50.43
1144°K (1600°F) T_{metal}	Resid.	Base*	25.26	21.59	2.54	49.39
1144°K (1600°F) T_{metal}	Distil.	Base*	25.31	26.30	2.54	54.15
30,000 Hr. Thermal Barrier Coated	Resid.	5,000 Hr.	23.78	21.27	2.31	47.36
		10,000 Hr.	23.78	21.27	2.12	47.17
		15,000 Hr.	23.78	21.27	2.06	47.11
		30,000 Hr.	23.78	21.27	2.00	47.05
30,000 Hr. Thermal Barrier Coated	Distil.	5,000 Hr.	23.89	25.91	2.31	52.11
		10,000 Hr.	23.89	25.91	2.12	51.92
		15,000 Hr.	23.89	25.91	2.06	51.86
		30,000 Hr.	23.89	25.91	2.00	51.80
		Load Factor: 0.45				
1088°K (1500°F) T_{metal}	Resid.	Base*	7.08	22.12	2.06	31.26
1144°K (1600°F) T_{metal}	Resid.	Base*	6.74	21.59	2.54	30.86
1144°K (1600°F) T_{metal}	Distil.	Base*	6.75	26.30	2.54	35.88
30,000 Hr. Thermal Barrier Coated	Resid.	5,000 Hr.	6.34	21.27	2.31	29.92
		10,000 Hr.	6.34	21.27	2.12	29.73
		15,000 Hr.	6.34	21.27	2.06	29.67
		30,000 Hr.	6.34	21.27	2.00	29.61
30,000 Hr. Thermal Barrier Coated	Distil.	5,000 Hr.	6.37	25.91	2.31	34.59
		10,000 Hr.	6.37	25.91	2.12	34.40
		15,000 Hr.	6.37	25.91	2.06	34.34
		30,000 Hr.	6.37	25.91	2.00	34.28

*For details of Base Hot-Part overhaul, see text

TABLE 4-IV

TOTAL POWER PRODUCTION COST

Mills per Kw-Hr

COMBINED – CYCLE CASES
MIDDLETOWN, USA SITE

Case	Fuel Type	Overhaul Period	Capital	Fuel	O&M	Total
		Load Factor: 0.45				
1088°K (1500°F) T_{metal}	Resid.	Base*	11.00	16.00	2.04	29.04
1144°K (1600°F) T_{metal}	Resid.	Base*	10.56	15.70	2.42	28.68
30,000 Hr. Thermal Barrier Coated	Resid.	5000 Hr.	10.09	15.36	2.22	27.67
		10,000 Hr.	10.09	15.36	2.09	27.54
		15,000 Hr.	10.09	15.36	2.04	27.49
		30,000 Hr.	10.09	15.36	2.00	27.45
		Load Factor: 0.65				
1088°K (1500°F) T_{metal}	Resid.	Base*	7.62	16.00	2.04	25.66
1144°K (1600°F) T_{metal}	Resid.	Base*	7.31	15.70	2.41	25.42
30,000 Hr. Thermal Barrier Coated	Resid.	5,000 Hr.	6.99	15.36	2.22	24.57
		10,000 Hr.	6.99	15.36	2.09	24.44
		15,000 Hr.	6.99	15.36	2.04	24.39
		30,000 Hr.	6.99	15.36	2.00	24.35

*See Text for Details on Hot-Part Overhaul considered. Although the operating and maintenance charge on the steam portion of the combined-cycle systems likely will be less than that for the gas turbine portion of these systems, the conservative estimate of 2.0 mill per kW-hr has an insignificant effect on the overall power costs.

It is noted that because of the lower assumed cost of residual fuel relative to that assumed for the distillate fuel, and the fact that the heat rates of the engines with these respective fuels differ only slightly, the residual fueled systems are estimated to produce the lowest cost power.

Upon examining the differences in fuel savings attributable to the use of thermal barrier coatings in the gas turbine, the following important observations can be made. The savings in fuel between that of the simple-cycle engine with a maximum metal temperature of 1088°K (1500F) and that of the thermal barrier coated engine amounts to nearly $3.5 million, from a savings of nearly 200,000 barrels of oil when compared on an equal total electric energy production basis. (The total electric energy produced with the 1088°K (1500°F) maximum metal temperature simple-cycle engine over its 30,000 hour life can be produced with the thermal barrier coated engine in 26,600 hours, with both engines using residual fuel.) Between the simple-cycle engine designed for a maximum metal temperature of 1144°K (1600°F) and the thermal barrier coated engine, the benefit is less, but is still respectable, amounting to over $1.3 million from a savings of 77,000 barrels of oil on an equal total energy production basis. For the combined-cycle systems, larger savings per two-engine installation are predicted. On the same basis as above, a comparison between the base engine operation at 1088°K (1500F) maximum metal temperature and the thermal barrier coated engine conditions reveals that the combined-cycle system would be expected to provide a cost savings of over $5 million, the equivalent of 409,000 barrels of oil. Between the maximum metal temperature of 1144°K (1600F) condition and the coated case, the expected savings over the engine life would be approximately $3 million, or the equivalent of 229,000 barrels of oil per two-engine unit, again compared on a total energy basis. These forecast savings show that improved performance with thermal barrier coating more than makes up for any incremental costs of increased operating and maintenance charges due to the coatings. Furthermore the savings from only a few engines should more than pay for any costs associated with the coating development program.

4.4 CONCLUSIONS OF ECONOMIC STUDY

From an economic standpoint, the use of thermal barrier coatings in an advanced FT50-type engine is predicted to result in a power reduction cost of 3-6% for the simple-cycle and 3-5% for the combined cycle relative to an uncoated engine design. In addition, an incentive to use this concept is provided by the fact that over the engine operating life, a considerable amount of oil can be conserved while still meeting a given level of consumer power demand. The results are presented in terms of mid-1976 dollar values. An increase in system cost (due to escalation and the need to charge for interest during construction) as well as any increase in fuel charge would serve to improve attractiveness of the system. Whereas the operating cost estimates of these systems are based on the best possible equipment cost correlations, no allowance has been made for on site power consumption. Relative to the cost of the total cost of energy, however these costs would likely comprise less than 2% of the total power production cost and, therefore, would not have a significant effect on the results presented herein.

5.0 DEVELOPMENT PLAN FOR THERMAL BARRIER COATINGS

5.1 PROGRAM OVERVIEW

A development program has been devised for thermal barrier coatings aimed at conducting the significant research and technology activities necessary to achieve a commercial demonstration in a high temperature industrial gas turbine engine. The plan shown in Figure 5-1 has four phases. These are Current Data Bank, Coating Technology Development, Design Support Technology, and Engine Demonstration Programs. The first phase, described as the Current Data Bank, involves taking advantage of in-house experimental and production engine combustor coating development activities and experience. The current thermal barrier coated combustor components now in production and accumulating field experience are listed in Figure 5-2. Also included in the Current Data Bank is United Technologies Corporation (UTC) internal research and development work to apply thermal barrier coatings to turbine components. These activities, which are UTC funded, provide a substantial technical base on which significant additional research and technology activities directed toward achieving a commercial engine demonstration of thermal barrier coatings can be developed.

The major research and technology activities are described in the second phase titled Coating Technology Development. Three technology areas are identified; these are Process Technology, Durability Technology, and Erosion-Corrosion Technology. The objectives for the Process Technology Plan, shown in Figure 5-3, are to develop a temperature controlled arc plasma spray process to increase coating life by reducing coating residual thermal stress levels, and to develop coating application techniques for cooled turbine components. The Durability Technology Plan, shown in Figure 5-4, is aimed at testing the best coating process on turbine and combustor components in a thermal mechanical fatigue environment. The purpose of the Erosion-Corrosion Technology Plan is to evaluate and develop the coatings resistance levels to an erosive-corrosive environment. The Erosion-Corrosion Technology Plan is shown in Figure 5-5.

The third phase, described as New Design Support Technology, involves thermal barrier coating material design properties and design tools development. Material properties for design use are categorized as thermal or mechanical properties and detailed in Figure 5-6. Design tools development includes computer program modifications and the development of a coating life prediction system. The computer program modifications are planned as part of P&WA internal research and development activities not to be charged to contract.

The fourth phase, Engine Programs, is the final phase of activity to demonstrate the use of thermal barrier coatings on hot section components in a high temperature gas turbine engine.

The following sections provide supporting information for the technical programs of Phases II and III, and a general discussion of Phase IV. Phase I is not specifically an item to be funded under this plan but rather is an on-going UTC supported effort that will provide inputs to help guide this development in an efficient, cost effective manner.

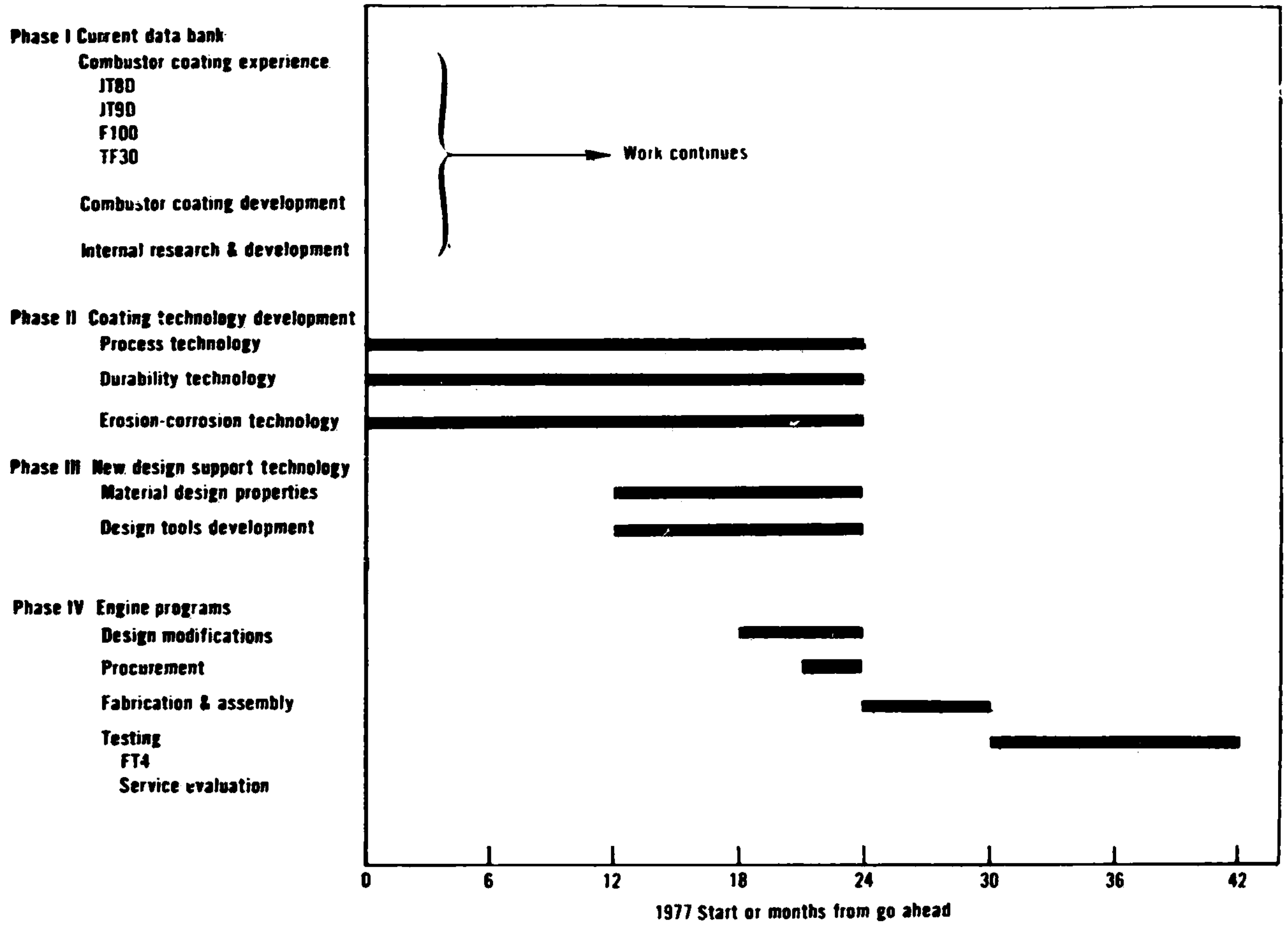


Figure 5-1 Thermal Barrier Coating Development Plan Schedule

ENGINE	PART	B/M COATING	UNDERLAYER	MIDLAYER	OUTLAYER
F100	Combustor	PWA 53-33	Ni-20Al	None	ZrO_2-MgO
	Augmentor liner	PWA 53-33	Ni-20Al	None	ZrO_2-MgO
	Convergent flat liner	PWA 53-33	Ni-20Al	None	ZrO_2-MgO
	Divergent flap seal	PWA 53-33	Ni-20Al	None	ZrO_2-MgO
	Divergent flap	PWA 53-33	Ni-20Al	None	ZrO_2-MgO
J58	Transition duct	PWA 53-33	Ni-20Al	None	ZrO_2-MgO
	Flame holder	PWA 53-33	Ni-20Al	None	ZrO_2-MgO
	Nozzle flaps and seals	PWA 53-33	Ni-20Al	None	ZrO_2-MgO
	Afterburner liner	PWA 53-33	Ni-20Al	None	ZrO_2-MgO
	2nd vane retaining ring	PWA 53-33	Ni-20Al	None	ZrO_2-MgO
TF-30P100	Burner cans	PWA 253-1	Ni-20Cr	35 (Ni-20Cr)+ 65 (ZrO_2-MgO)	ZrO_2-MgO
	Transition duct	PWA 253-1	Ni-20Cr	35 (Ni-20Cr) + 65 (ZrO_2-MgO)	ZrO_2-MgO
	Afterburner duct liner	PWA 253-3	Ni-5Al	35 (Ni-5Al)+ 65 (ZrO_2-MgO)	ZrO_2-MgO
TF-30P412	Burner Cans	PWA 253-1	Ni-20Cr	35 (Ni-20Cr)+ 65 (ZrO_2-MgO)	ZrO_2-MgO
	Afterburner duct liner	PWA 253-3	Ni-5A	35 (Ni-5Al)+ 65 (ZrO_2+ MgO)	ZrO_2-MgO
JT8D-17	Burner cans	PWA 253-1	Ni-20Cr	35 (Ni-20Cr) + 65 (ZrO_2-MgO)	ZrO_2-MgO
JT9D-3,7	Combustor	PWA 253-3	Ni-5Al	35 (Ni-5Al) + 65 (ZrO_2-MgO)	ZrO_2-MgO
JT9D 70	Combustor	PWA 254	CoCrAlY	Graded CoCrAlY + ZrO_2-MgO	ZrO_2-MgO

Figure 5-2 *Bill-of-Material Applications of Thermal Barrier Coatings*

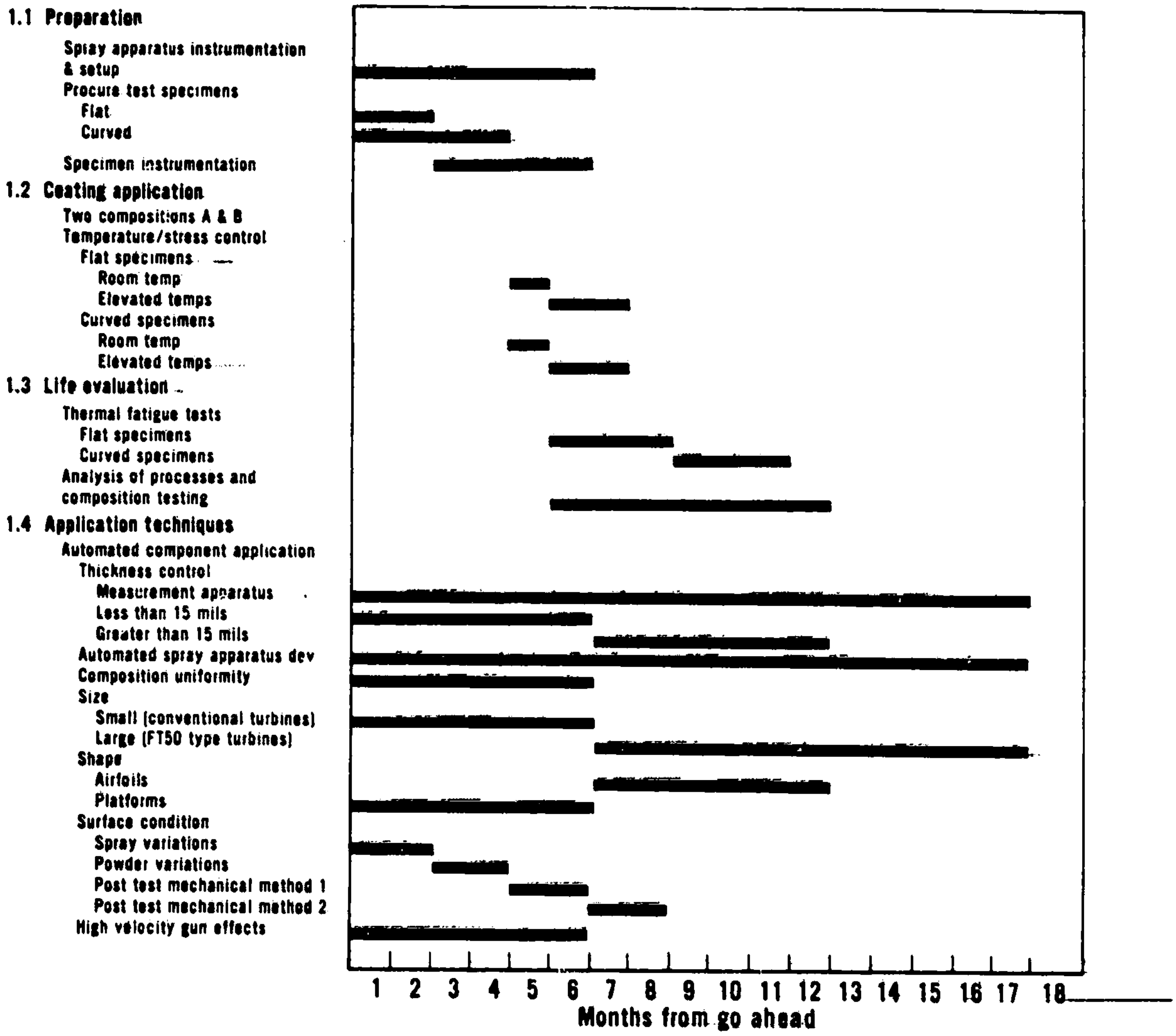


Figure 5-3 Phase II Coating Technology Development, Task 1 Process Technology

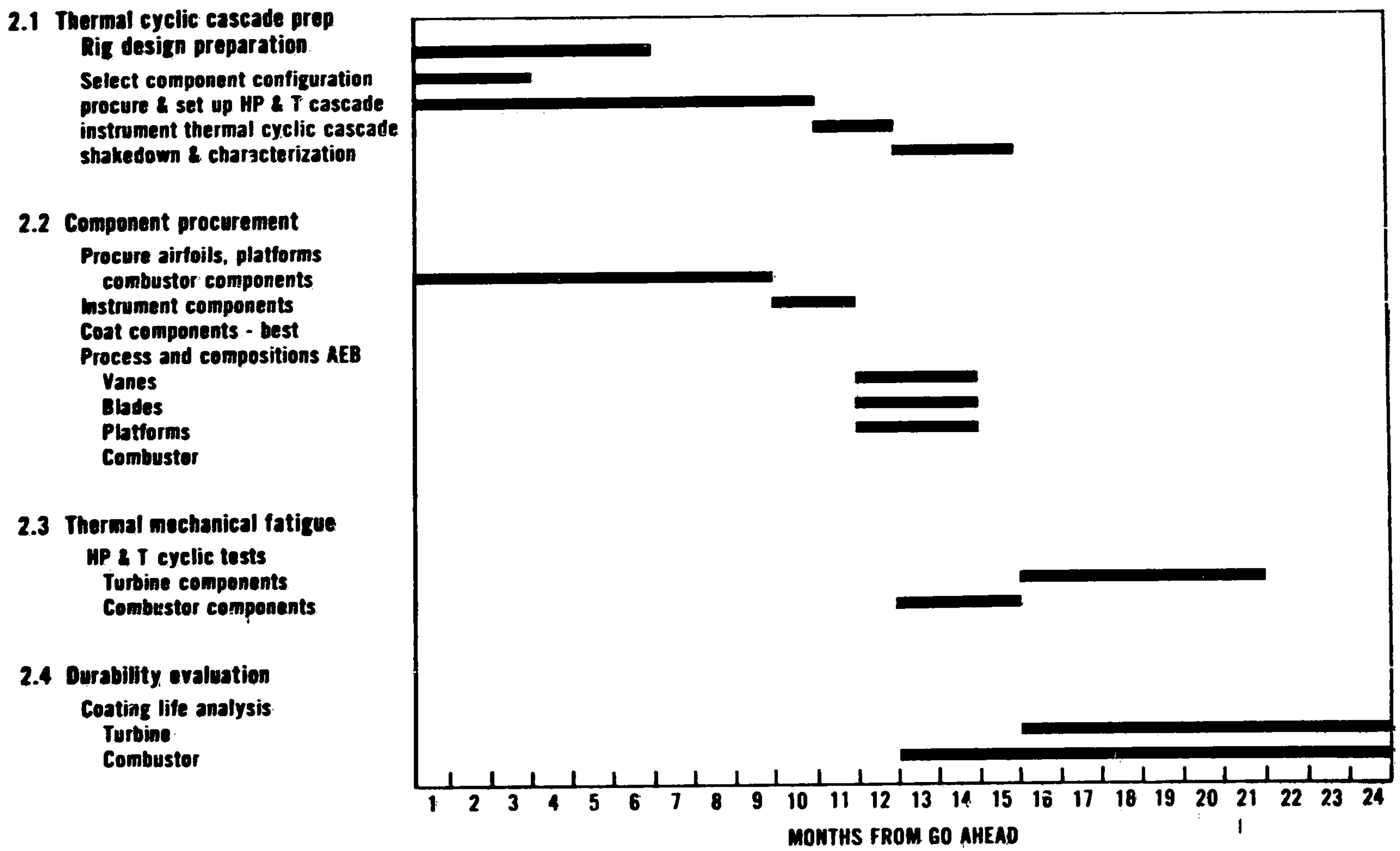


Figure 5-4 Phase II Coating Technology Development, Task 2 Durability Technology

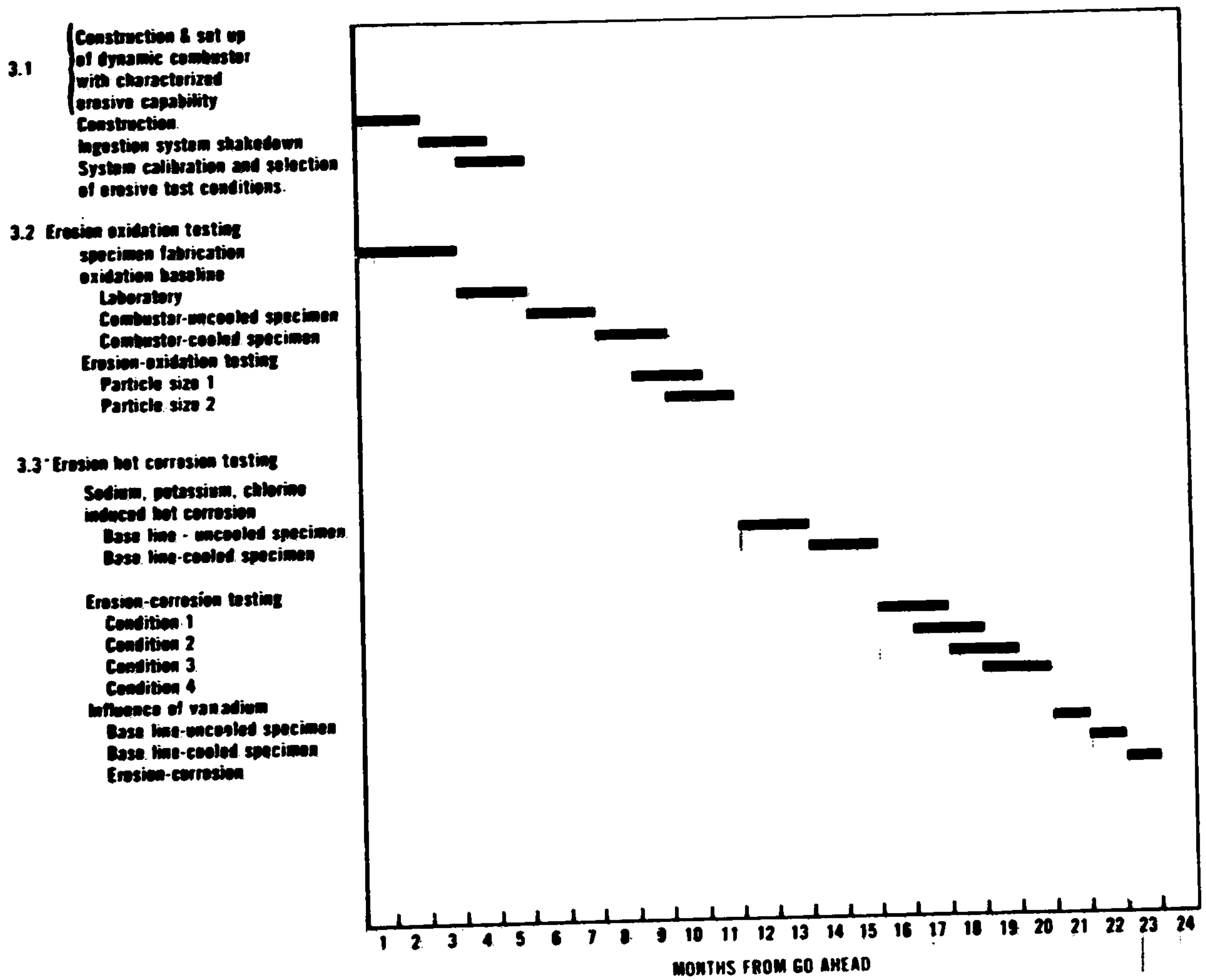


Figure 5-5 *Phase II Coating Technology Development, Task 3 Erosion-Corrosion Technology*

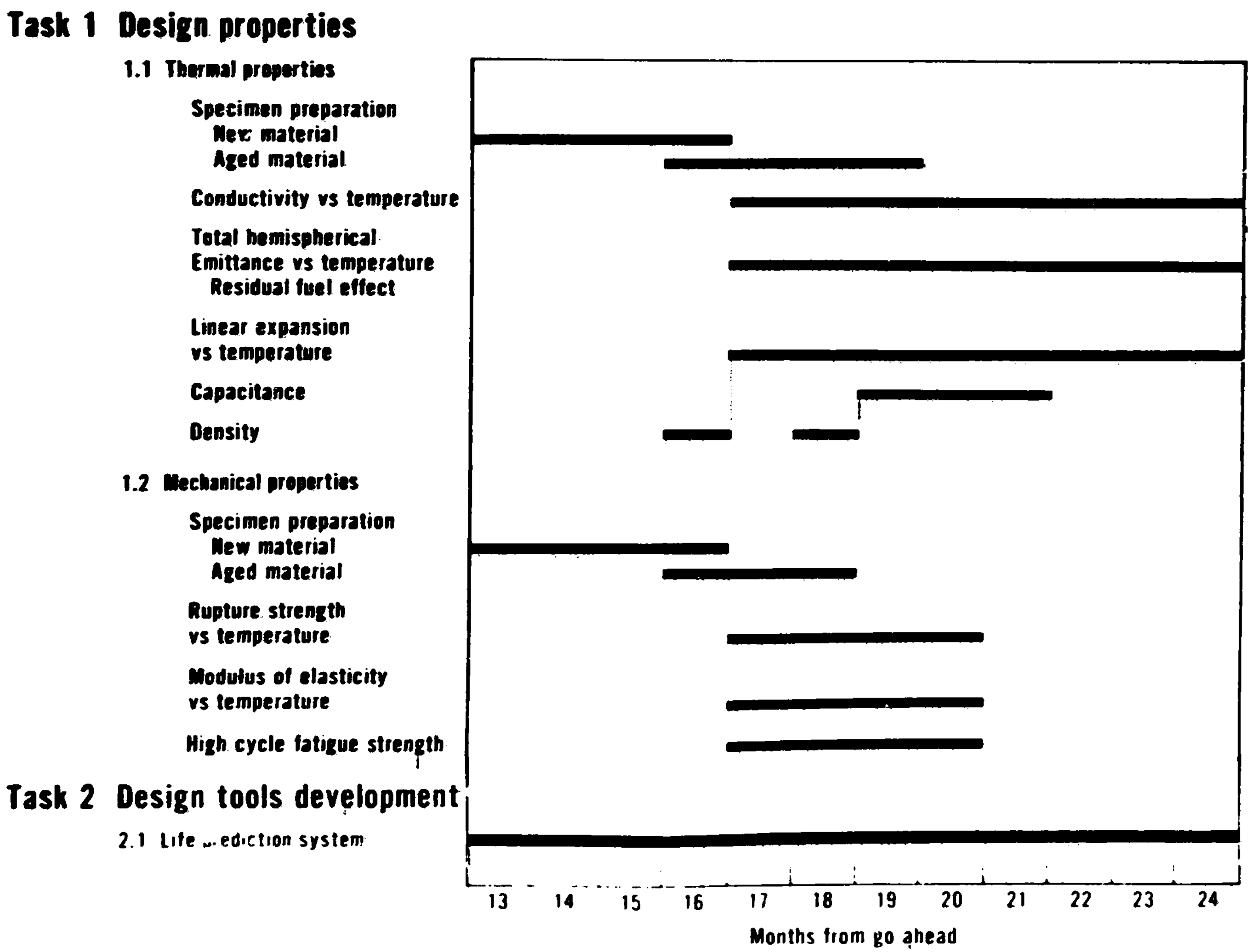


Figure 5-6 *Phase III Design Support Technology*

ORIGINAL PAGE IS
OF POOR QUALITY

5.2 PHASE II – COATING TECHNOLOGY DEVELOPMENT

Coating Technology Development is composed of three significant technology tasks. These are Coating Process Technology, Coating Durability Technology, and Coating Erosion and Corrosion Technology.

5.2.1 Coating Process Technology

The major objectives of the Coating Process Technology are to develop thermal stress control and application techniques for improved coating durability. Arc plasma spray processes now in use for combustor applications are automatically controlled to meet production specifications. The elements of the plasma spray process are shown in Figure 5-7. Coatings on turbine components are generally manually applied and therefore are highly dependent on operator technique. Coating stresses induced during the depositing of coating material are also believed to be operator and process dependent.

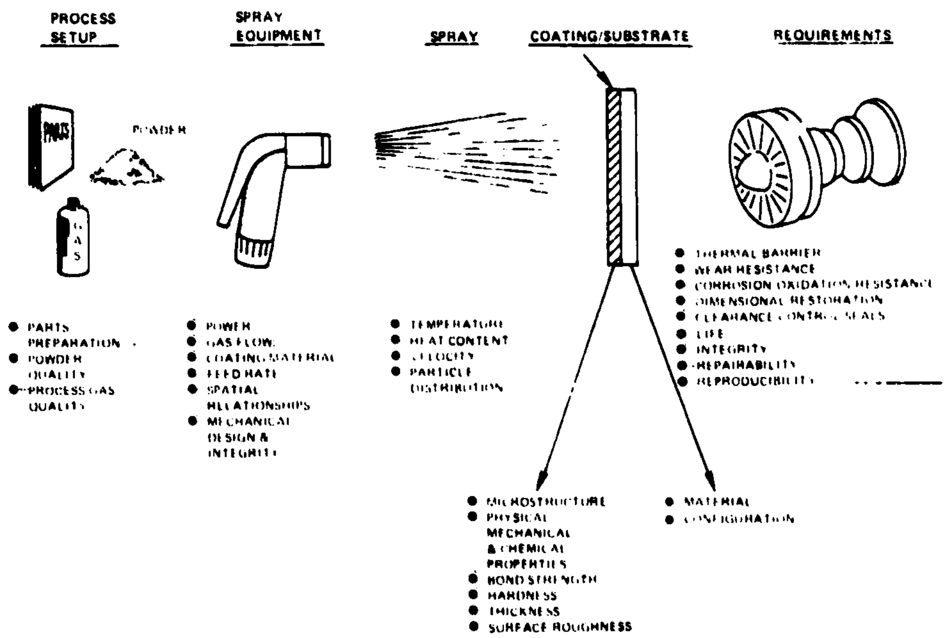


Figure 5-7 Elements of the Plasma Spray Process

Stress calculations using a suitable model of the spray process and the coating/substrate system have indicated that residual coating stresses can be reduced with a time temperature controlled process. Analysis has also indicated the desirability of thermal pre-stressing the coating system in a controlled manner to take advantage of the higher ceramic compressive strength and achieve increased coating thermal fatigue life. It has been demonstrated experimentally as part of the UTC research effort, that temperature control of the substrate will affect the thermal stress levels of the coating during the arc plasma spray process. Precautions must be exercised to prevent overheating and oxidation of the substrate which will reduce coating adhesion. Development of a thermal stress control technique offers potential for significant coating durability improvements. Coating Process Development Tasks 1, 2, and 3 are directed at developing the thermal stress control techniques.

Thermal fatigue specimens will be constructed to simulate airfoil configurations with provisions to readily install instrumentation. Half cylinder shell specimens will be instrumented with thermocouple and strain gages, coated on the convex side and used to evaluate the effects of curvature on coating durability. Specimens made from flat plates are used by P&WA to model vane platforms and evaluate coating durability under thermal cyclic conditions. Thermocouples mounted at the coating interface and the metal plate back surface permit calculation of the heat flux through the coating. Through the use of an analytical model, stresses are calculated based on measured temperatures. These tests are used to screen thermal barrier coatings for platform and airfoil applications.

Task 4 is aimed at developing the coating application techniques. Component size and shape will influence the methods used to apply the arc plasma spray coating. Large components, such as "FT50 type" high temperature turbine components will present processing problems to which solutions must be sought to control residual stresses and coating quality. Coating thickness control is also necessary to minimize stress concentrations, establish a uniform insulation, and maintain specified aerodynamic contours.

A capacity for measuring coating thickness during the plasma spray process is of particular importance in realizing an automatic system. Currently, coating thickness measurements are obtained by interrupting the spray process and manually taking micrometer readings to determine the thickness of coating deposited and then proceeding incrementally until the required coating thickness has been obtained. Improved methods of thickness measurement would contribute significantly to the reproducibility of coating quality by improving the repeatability of conditions under which the coating is deposited, thus eliminating the necessity to interrupt spraying to measure thickness and by improving gradation control for reproducibility to graded coating systems.

Another application technique that requires development is the coating surface finish. Smooth thermal barrier coating gas path surfaces are required for aerodynamic efficiency and minimized convective heat load. Rough surfaces affect skin friction, which causes increased pressure losses and increased heat transfer. Arc plasma sprayed coatings, as currently applied, have adequate smoothness for burner liners; however, improvements are required for use on turbine airfoils.

Surface roughness of the plasma deposited coating is primarily related to the angle of deposition and the powder particle size. Since most of the plasma spraying performed at Pratt & Whitney Aircraft is done perpendicular to the part to be coated, the effect of deposition angle is minimal. Powder particle size, however, will generally have a significant effect upon as-deposited coating roughness. Deposition methods currently used in as-deposited NiCrAlY surface roughness of approximately 6 micrometers (250 micro-inches). This roughness condition is advantageous for the bond layer of a two-layer thermal barrier coating in order to promote adherence of the subsequent ceramic layers.

The surface roughness of the ceramic layer is influenced by the starting powder particle size as well as the roughness of the metallic bond layer and the thickness to which the ceramic layer is sprayed. Generally, a finer ceramic powder particle size will produce a smoother coating surface finish. For this reason, a finer ceramic powder particle size than -200/+325 mesh would be advantageous.

A typical as-sprayed ceramic surface has a mean variation that exceeds 7.6 micrometers (300 micro-inches). To achieve smoothness comparable to metallic overlay coatings (less than 1.9 micrometers (75 micro-inches) RMS), the thermal barrier coating surface must be finished with a mechanical or chemical treatment. Several post-coating treatments are available for reducing surface roughness. Possible methods include wire brushing, vapor honing, and glass-bead peening.

5.2.2 Coating Durability Technology

High temperature and pressure thermal fatigue testing of hot section components will be conducted to evaluate coating durability. The best thermal stress control techniques and coating application techniques developed in the process technology task will be demonstrated in component rig tests.

Coating airfoils and platforms will be instrumented and installed in high temperature and pressure cascade rigs to evaluate and develop coating component durability. Data obtained from thermal fatigue cascade testing is expected to provide a good base for developing the life prediction system. The instrumented components will provide infomation for durability evaluations and allow design modifications to achieve increased life.

Piggy backed engine tests are planned to demonstrate the thermal barrier coating system in the engine environment and identify the problems not exposed during rig or laboratory tests. Coated burners, platforms and airfoils must be evaluated to understand the specific problems and failure modes associated with each component and to permit development of a long life design for each component.

5.2.3 Coating Erosion – Corrosion Technology

The purpose of the erosion-corrosion technology task is to identify and develop the resistance mechanisms of the thermal barrier coating system for increased life when operating with residual fuels. The first subtask is identified to set up the dynamic combustor and characterize the thermal environment prior to conducting the oxidation erosion tests and thru the corrosion-erosion tests, subtasks 2 and 3, respectively. Separation of the erosion-oxidation mechanisms from the erosion-hot corrosion mechanisms should provide valuable information for developing increased coating resistance.

A thermal barrier coating's primary function is to reduce surface heat flux thereby allowing either reduced cooling air at a constant substrate temperature or reduced substrate temperature at a constant coolant flow. Most components require coatings such as CoCrAlY to provide protection from the corrosive turbine environment. Thermal barrier coatings must therefore either provide that protection, or be used in conjunction with an environmental protective coating such as CoCrAly. In addition, the thermal barrier coating must itself resist corrosion if it is to remain adherent and otherwise effective.

P&WA experience to date has not shown corrosion of themal barrier coatings to be a major problem; however, sulfur corrosion of magnesia stabilized zirconia has been observed along with oxidation of the grading alloy. The Navy (Naval Ship R&D Center Report 4428) has also observed minor attack of zirconia stabilized with magnesia and yttria by sodium sulfate and has identified the requirement for a protective under layer such as CoCrAly. These reactions have not compromised the thermal barrier coating integrity or bonding on burner liners; however, to insure success on less complaint components such as airfoils, laboratory tests are required to further define the phenomenon and optimize coating resistance.

The oxidation corrosion resistance of ceramics is generally considered to be excellent; however, high temperature reactions involving fuel inpurities and ingested salt can affect their properties. It is well known that sulfur reacts with magnesium oxide to form magnesium sulfate in petroleum based fuel combustion, and this reaction forms the basis for mitigating hot corrosion by treating industrial boiler fuels with magnesium-bearing additives.

Calcia is also reported to react with SO_2. Both MgO and CaO are commonly used as stabilizers for zirconia, and it is anticipated that extended exposure of these materials to gas turbine environments will result in some degree of reaction and an associated undesirable partial destabilization of the zirconia coating. Furthermore, the effect $MgSo_4$ and $CaSO_4$ will have on further corrosion of the insulator, the substrate or grading alloy is not known. Although no service problems have arisen, magnesium sulfate has been observed on burner liner thermal barrier coatings in experimental engines.

Another stabilizer for zirconia is yttria, which is relatively inert with respect to the turbine environment. This property makes yttria a very strong thermal barrier coating compositional candidate.

Laboratory evaluation of the corrosion resistance of thermal barrier systems will permit comparison of candidate materials and selection of a system with a high probability of success on turbine airfoils. Cyclic burner rig testing is proposed which simulates coating temperature distributions and fluctuations representative of the gas turbine. The combined effect of ceramic/metal corrosion and mechanical interaction will be evaluated. Coating modifications will be incorporated based on the test results to improve coating durability.

Erosion & Impact Resistance – Good erosion resistance is required for durable thermal barrier coatings since the loss of insulation material by this mechanism will reduce the coating barrier efficiency. Thermal barrier coatings do not suffer from erosion damage in burner liner applications. However, the erosion susceptibility of turbine blades may be more severe since gas velocities are higher and the particle impingement angles are less favorable than in burner liners. Laboratory evaluation of the erosion resistance of candidate thermal barrier coating materials is required for selection of the best system. The thermal barrier coatings/airfoil system will be designed to subject the substrate to minimal corrosion susceptibility in the event of foreign object damage.

5.3 PHASE III – DESIGN SUPPORT TECHNOLOGY

The tasks of Phase III are the measurement of materials design properties, and the development of design tasks such as computer analysis programs and development of a coating life prediction system.

5.3.1 Material Design Properties

The measurement and correlation of thermal barrier coating mechanical and thermal properties is necessary to support the design effort aimed at achieving a durable turbine system with good performance characteristics. Materials design properties acquisition is planned in the as-processed new material state and in an aged material state. Since this is a requirement to burn residual fuels, the effects of contaminents in the fuel and their influence on materials design properties must be experimentally evaluated.

5.3.1.1 Thermal Properties

The basic material properties required for the heat transfer analysis are thermal conductivity, heat capacity, and density. Other thermal properties required for heat transfer and structural analysis of hot section components are radiative absorptivity and linear expansion.

Thermal Conductivity – The thermal conductivities of arc plasma spray deposits of both ceramic and metallic thermal barrier coating materials are known to vary with temperature level and high temperature aging. In addition, the arc plasma spray process produces materials whose conductivity is significantly lower than that of conventionally processed metals and ceramics. Therefore, it is necessary to measure the thermal conductivity of the coating constituents over the temperature and life of intended application.

Heat Capacity – Heat capacity is expected to be less dependent on the coating deposition process than thermal conductivity; however, many of the ceramic materials which are candidates for thermal barrier coating constituents are prone to phase de-stabilization with attendant phase transitions occurring with temperature transients. The heat of transformations (when applicable) and heat capacities of the various coating constituents must be evaluated, particularly in the case of the ceramic materials.

Density – Room temperature density measurements combined with thermal expansion properties are adequate to define the density of thermal barrier coated materials. Permanent changes of densities (up to 20%) resulting from relaxation of the initial deposits will be assessed during the thermal expansion testing.

Thermal Radiative Absorptivity – The optical properties of turbine and burner liner surfaces play an important role in the overall heat transfer when there is direct exposure to flame generated thermal radiation. Under certain operating conditions, the radiative heat load may be greater than the convective heat load. The radiative heat load is a function of temperature, flame luminosity, surface thermal radiative absorptance, and coupling or geometry factor. Coal derived fuels are expected to produce flames with very high luminosity because of the increased particulate content. Accurate knowledge of the spectral normal absorptivity of the proposed coatings over the frequency range of maximum flame radiative power is required.

Thermal Expansion -- The thermal expansion of arc plasma spray (APS) deposited materials is basically similar to that of conventionally processed materials, but there are several significant differences. APS coatings characteristically have high internal energy which arises from the quenching inherent in the coating process. Depending on the material, there is usually anisotropic non-reversible shrinkage (or expansion) which occurs during the initial equilibration of the coating during engine exposure or thermal expansion testing (or other heat treatments). In addition, since the material is quenched from a liquid phase, any phase which is in equilibrium for a given composition from the liquidus to room temperature may be initially present in the coating depending on the kinetics of phase transformation and overall cooling rate. Transition of these metastable phases during the initial equilibration of the coating may have a strong effect on the initial thermal expansion. Currently successful coatings are known to undergo phase changes and non-reversible dimension changes, but to insure the successful application of new materials, this behavior must be understood.

5.3.1.2 Mechanical Properties

Stress analysis of the coating substrate system is required to achieve a successful design and predict conditions of coating delamination or fracture. Stresses result from mechanical loading, thermal transients, and discontinuities in material properties which are presented in certain multi-phase materials and coating systems. An understanding of these mechanisms is based on the thermal properties, the mechanical environment, and the elastic and strength properties which are central to all stress oriented failure analyses.

Elastic moduli and strength are strong functions of coating morphology. Porosity and material discontinuities such as cracks resulting from the coating process or phase transformation or thermo-mechanical stresses determine the strength and elastic behavior of the materials. These properties are known to vary with time and temperature and should be measured after an appropriate heat treatment to bring the structure to equilbrium.

Modulus of Elasticity – The modulus of elasticity will be determined in four-point bend testing of coating specimens representative of the ceramic and the graded ceramic/metallic materials. Ambient temperature and a series of intermediate temperatures up to the maximum estimated operating temperature will be tested.

Modulus of Rupture – The modulus of rupture or bend strength will be measured in four-point bending by straining the modulus of elasticity samples until failure. Data will be taken at both ambient and the maximum estimated temperature levels. The modulus of rupture will be calculated and the strain to failure also reported. A linear dependence of modulus of rupture with temperature will be assumed to calculate intermediate temperature stress levels and safe strain limits.

Mechanical Fatigue – Mechanical high cycle fatigue testing of thermal barrier coated rotating components is required to identify any possible reduction in substrate fatigue strength or changes in resonances which would compromise an engine design. High cycle isothermal fatigue tests will be conducted to establish coating HFF strength.

5.3.2 Design Tools Development

This section discusses research and development work which will be funded by the United Technologies Corporation.

5.3.2.1 Analytical Tools

Coating stresses and coating interactions with the airfoil configurations and platform interfaces must be evaluated to design structures with minimum stresses. Three dimensional analysis techniques are best suited to evaluate such complex structural or material problems. Three dimensional methods are not used, however, for routine designs where appropriate assumptions and judgements can be made to avoid the higher costs associated with complex computer analysis. Current turbine design programs must be modified to handle multi-material systems and airfoils with thick coatings, i.e., coatings thicker than 0.13 mm (0.005 inch). Both airfoil structural and heat transfer design decks must be modified to meet the requirements of thermal barrier coatings and permit evaluation of coating/structural interactions.

5.3.2.2 Life Prediction System

The development of a coating life prediciton system is based on the study and correlation of results from a well planned devleopmetn program including related experience. IR&D work has been directed at obtaining the data necessary to build the prediciton system. Preliminary failure theories have been postulated based on thermal fatigue specimen testing during the past two years. Also, fundamental materials properties programs in the thermal, mechanical and chemical areas have been initiated. However, these materials designs data must be coupled with component rig and engine test results to establish design criteria for the life prediction system. Continued development work is necessary to verify, complete or extend life analysis concepts.

5.4 PHASE IV – ENGINE PROGRAMS

The demonstration of the thermal barrier coating in a commercial industrial gas turbine will require planning, coordination, and design activities. The use of the FT-4 industrial gas turbine as a test vehicle offers several advantages. Installation of thermal barrier coated components in some of the numerous FT-4 engines currently operating in the industrial environment will provide an excellent source of field data. Another advantage of the FT-4 is that it currently uses convectively cooled turbine components which are readily adaptable to the thermal barrier coating. Although a redesign effort will be required to accommodate aerodynamics and possible cooling flow changes, the modifications are feasible. The preparation for an engine program will require component design modifications, procurement, fabrication and assembly tasks prior to conducting the thermal barrier coating tests and service evaluation. The engine demonstration is planned to follow the durability technology tasks. It is therefore not fully defined, allowing program flexibility to take advantage of the durability technology developed.

APPENDIX A

COATING PROPERTIES AND FUEL SPECIFICATIONS

THERMAL BARRIER COATING PROPERTIES

Radiative Properties

Figures A-1 and A-2 present the measured normal spectral emittance of yttria stabilized zirconia and commercially pure zirconia, respectively. The emittance in both figures is similar and show very low emissivity (0.2 – 0.3) for short wavelength radiation. Figure A-3 shows the radiation flux from a high temperature source concentrated in the shorter wavelengths (i.e., < 10 microns), therefore the predicted absorptivity for the selected thermal barrier coatings is 0.2 – 0.3 for a new clean surface absorbing radiation from the flame source.

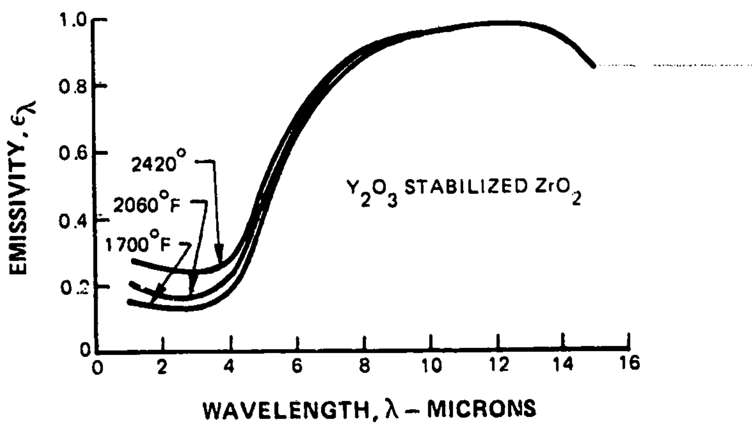


Figure 1 Measured Normal Spectral Emittance of Yttria Stabilized Zirconia

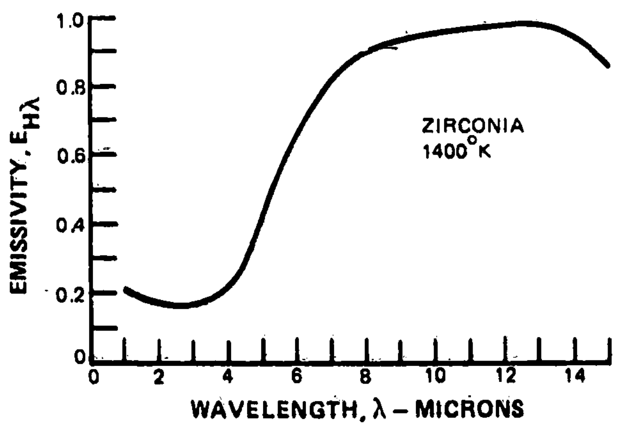


Figure 2 Normal Spectral Emittance of Commercially Pure Zirconia at 1400K

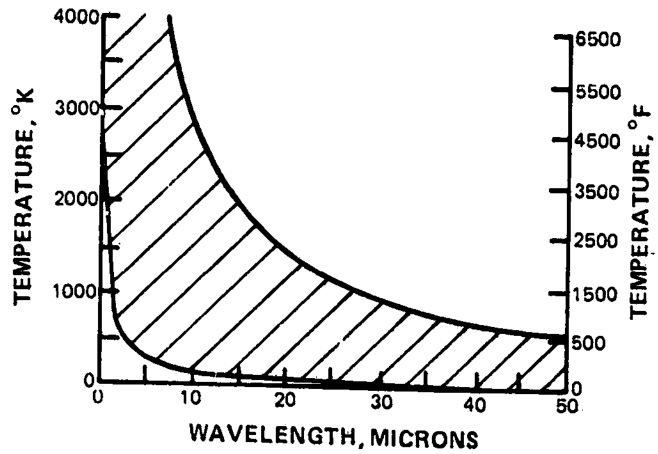


Figure 3 *Wavelength Limits Encompassing 99 Percent of the Fluz Emitted by a Blackbody Radiation at the Indicated High Temperature*

Thermal Properties

The thermal properties for the selected thermal barrier coating are listed in Table A-1.

TABLE A-I

THERMOPHYSICAL PROPERTIES OF PLASMA-SPRAYED COATINGS

Y_2O_3 Stabilized ZrO_2

Thermal conductivity:

$$k(W/m\text{-}K) = 0.00022\ T(K) + 1.09$$

Speeific heat:

$$670\ \frac{J}{Kg\cdot K}$$

NiCrAlY

Thermal conductivity:

$$k(W/m\text{-}K) = 0.0083\ T(K) + 6.7$$

Specific heat:

$$670\ \frac{J}{Kg\cdot K}$$

FUEL SPECIFICATIONS

The fuel specifications used in the study are listed in Table A-II.

TABLE A–II

TURBINE FUEL SPECIFICATIONS TO BE USED IN THERMAL BARRIER SYSTEMS STUDY

Property	"Clean" Light Distillate	"Typical" Residual Fuel
Gravity, °API, Min.	30	18.5
Kin. Visc., cs, 100°F, Min.	2.0	5.8
Kin. Visc. cs, 100°F, Max.	4.3	--
Kin. Visc., cs, 122°F, Max.	--	638
Flash Point, °F, Min.	100	150
Dist. Temp., °F, Min.	540	--
Dist. Temp., °F, Max.	640	--
Pour Point, °F, Max.	20	*
Carbon Res. (10% Bot.), Wt. %, Max.	0.35	--
Ash, Wt. %, Max.	0.01	0.03
Trace Metals, ppm, Max.		
Vanadium	0.5	200
Sodium Plus Potassium	0.5	10
Calcium	0.5	10
Lead	0.5	5
Water and Sediment, Vol. %, Max.	0.05	1.0
Sulfur, Wt. %, Max.	0.5	1.0
Nitrogen, Wt. %, Max.	0.06	0.20
Hydrogen, Wt. %, Max.	13	11
Higher Heating Value, Btu/lb	19,350	18,500
Cost, $\$10^6$ Btu	2.60	2.15

*Assume fuel preheating required