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SURFACE PROTECTION

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INTRODUCTION

The hot section of an aircraft gas-turbine engine presents a severe chemical environment due to the presence of available oxygen and nitrogen under kinetically favorable conditions as well as due to the occasional presence of potentially more aggressive air-borne and fuel-borne impurities which can be collected as corrosive salt deposits. Thus, (as shown in fig. 1) one must consider such phenomena as high-temperature oxidation, corrosion, and erosion of base metals and their protective coatings as well as the materials' creep and fatigue responses to imposed mechanical and thermal loads. The consequences of unexpected severe environmental attack are illustrated in figure 2. However, even less dramatic environmental attack degrades system efficiency, reduces life, and ultimately costs us money.

The chemical response and the mechanical response of hot-section materials are not isolated phenomena. The influence of the chemical response on the mechanical response (and vice versa) must be understood to adequately design a component. Thus, the goal of the surface protection subproject is to develop an integrated, environmental attack, life-prediction methodology for metaland ceramic-coated hot-section components. This scheme will consider environmental attack life prediction as well as the effects of environment and coatings on mechanical response. As illustrated in figure 3, thermal and mechanical loads are inputs, and the analysis methods result from studies of material behavior in laboratory and engine tests. The surface protection subproject consists of three major thrusts:

(1) Airfoil deposition model
(2) Metallic coating life prediction
(3) Thermal barrier coating (TBC) life prediction

The time frame for each of these thrusts and the expected outputs are displayed in figure 4. The airfoil deposition model will predict the location and potential severity of hot-corrosion attack of turbine airfoils by late 1987. The metallic coating life prediction effort will produce models to predict metallic coating life as well as, in conjunction with the fatigue and fracture subproject, the effects of the environment and coatings on mechanical response. Finally, the thermal barrier coating (TBC) life-prediction thrust, which has grown to maturity during the past year, will yield life-prediction tools to permit use of TBC in the performance improvement mode. Such aggressive TBC use places the burden for component integrity on the life of the coating, and therefore progress of this technology is life-prediction-capability critical. Figure 5 gives further details of each thrust insofar as specific element schedules and whether they are being conducted in-house (I), via grant (G), or via contract (C).

AIRFOIL DEPOSITION MODEL

The direction of the airfoil deposition model effort is shown in figure 6. The goal, approach, and status for the airfoil deposition model thrust are as follows:

Goal: To develop and verify a model to predict corrodant deposition quantity and location on turbine airfoils.

Approach:
- Airfoil model development via grant with Dan Rosner of Yale
- Model verification via in-house research with support from S. Gokoglu
  - Mach 0.3 burner rig
  - High pressure burner rig
- Burner rig modernization.
  - Computer data acquisition and limit monitoring
  - Computer control

Status:
- Prodigious output of papers by Rosner and Gokoglu
- Initial turbine airfoil deposition model developed
- CFBL theory documented and verified in burner rigs by accounting for particle impaction

Air-borne and fuel-borne impurities can be collected on stationary or rotating airfoils by vapor deposition and particle impaction mechanisms. Such salt deposits can be depleted by evaporation or by molten salt flow and shedding. The purpose of the deposition model is to account for the local temporal inventory of molten salt as an input to the coating life prediction model. The airfoil deposition model is being developed, via a grant, by Professor Dan Rosner and coworkers at Yale. Model verification is being carried out in-house in Mach 0.3 burner rig and ultimately in a high-pressure burner rig. This effort is supported by the work of Dr. S. Gokoglu of Analex Corporation at Lewis. In parallel with the model development, in-house burner rig facilities are being modernized in support of this and other HOST thrusts.

To date, the work of Rosner, Gokoglu, and coworkers has been documented by numerous publications in the open literature (refer to their workshop papers for references). These papers describe the initial airfoil deposition model and its verification.

The goal, approach, and status of the rig and engine correlation is as follows:

Goal: Provide a unique and relatively inexpensive laboratory facility to aid in the development of environmental attack life-prediction tools for hot-section materials.

Approach: Verify advances made in the life prediction of hot-section materials at pressure levels encountered in gas turbine engines

Verify deposition theory and dew point shift in the deposition of Na_2SO_4 corrodant at elevated pressures

Determine the effect of high heat fluxes on the life of thermal barrier coatings

Status: Checkout nearly complete. Scheduled to be operational this fall

A key feature of the surface protection subproject is the verification of the airfoil deposition model and the thermal barrier coating failure mechanism and life-prediction models in a simulated engine environment. This will be accomplished in the high pressure burner rig facility which is currently under construction at Lewis. Key features of this facility are described in figure 7. This unique facility will be dedicated to materials research and will offer temperatures to 1650° C (3000° F) and pressures to 50 atmospheres.

METALLIC COATING LIFE PREDICTION

As shown schematically in figure 8, metallic coatings protect structural alloys from the environment by providing a reservoir of a protective oxide-scale-forming element, for example, an aluminum bearing alloy which is selectively oxidized to form aluminum oxide. Aluminum is depleted by oxidation and thermal-cycle-induced oxide-scale spallation. Aluminum is also diluted by interdiffusion with the substrate. Exposure to corrosive salts may lead to accelerated hot corrosion attack of the oxide scale and coating. Finally, the coating must withstand thermal-mechanical loads without degrading system mechanical response.

The metallic coating life-prediction thrust deals with the chemical and mechanical aspects of the problem. The goal, approach, and status for this thrust are as follows:

Goal: To develop a coating life model for oxidation, spalling, hot corrosion, and coating/substrate diffusion and to account for environmental and coating effects on mechanical response.

Approach:

Environment/mechanical property interactions
Support contract efforts managed by fatigue and fracture subproject.

Oxidation/diffusion life prediction (I)
- Integrate cyclic oxidation spalling prediction and coating/substrate interdiffusion models for coated superalloy and verify

Hot corrosion surface chemistry (GE/TRW)
- Assess effects of aging environment and time on hot corrosion life for various coating/alloy systems as a basis for proposing and verifying a life model

Oxidation/hot corrosion dual cycle attack (I)
- Determine feasibility of an empirical linear damage model for oxidation/mild hot-corrosion attack of coated superalloy

Life prediction Verification (C)
- Integrate results into a mission simulation prediction model and verify

Status:

Determined that diffusion model required to predict spalling parameters and breakaway oxidation

Hot corrosion efforts initiated in FY 1983.

An oxidation/diffusion life model is being developed in-house by building on existing interdiffusion and cyclic oxidation/spalling models developed for model systems. This task has proven far more difficult than envisioned due to spall measurement problems. The hot corrosion efforts, one in-house and one under contract with General Electric, were initiated in fiscal year 1983. These three efforts are scheduled to culminate in a contractual life prediction integration and verification effort.

The roles of the environment and coatings on the mechanical responses of isotropic and anisotropic materials are being addressed by our support of contract efforts managed through the fatigue and fracture subproject.

THERMAL BARRIER COATING LIFE PREDICTION

Thermal barrier coatings are presently used in noncritical gas-turbine applications to extend component life. Present coatings suffer from limited coating life and inadequate design capability when considered for more critical applications such as turbine airfoils. Both life prediction and advanced coatings are vital to the future use of TBC on airfoils for large improvements in system performance. Strong HOST support in the life-prediction area is now being provided. The TBC life-prediction thrust has grown during the past year to become the major thrust of the surface protection subproject. The direction of the thrust is shown in figure 9. The goal, approach, and status are described as follows:

Goal: To develop and verify life prediction methodologies for thermal barrier coatings

Approach:

TBC life prediction model development (C)
- Phase I: failure analysis and preliminary model (multiple contracts)
- Phase II: design capable models of TBC's

Mechanical behavior of TBC (G-JIAPP/CSU)
- Fracture mechanisms (C. Berndt, on-site)
- Residual stress modeling (G. Chang, CSU)

Rig/engine correlation (I) - high-heat-flux tests in high-pressure burner rig to
complement contract effort.
- Failure mechanisms
- Model verification

Status:

Grant in place July 1983 and contracts in place April 1984.

The mechanical behavior effort is being conducted through a grant with Professor George Chang and Dr. Chris Berndt of Cleveland State University. The core effort involves parallel, complementary contracts with Garrett Turbine Engine Company, General Electric, and Pratt & Whitney Aircraft. These contracted efforts build on our research and technology base failure mechanisms research and are supported by parallel in-house high-heat-flux tests in the high pressure burner rig facility. Some of the key complementary features of the paralleled TBC life-prediction contracts are illustrated in figure 10. All three contractors are investigating their current advanced plasma-sprayed TBC which consists of a low-pressure plasma sprayed MCrAlY bond coat and an air plasma-sprayed yttria, partially stabilized zirconia ceramic layer. In addition, Garrett is conducting a parallel effort involving a vapor deposited zirconia layer.

CONCLUDING REMARKS

The past year has been one of significant expansion and progress for the HOST surface protection subproject. Some progress highlights are enumerated here. In the airfoil deposition thrust, the chemically frozen boundary layer (CFBL) theory was documented and extended to multicomponent salts, and particle impaction theory was verified in the Mach 0.3 burner rig. In the metallic coating life prediction effort, field components were analyzed, and service life was directly related to average mission duration. The initial approach for the oxidation/diffusion life model was assessed and alternative approaches developed. Finally, the TBC life-prediction effort matured. Parallel life-prediction development contracts were awarded. Initial results relating TBC degradation to acoustic emission signature were documented, and initial finite-element calculations for stresses near the undulating interface between the ceramic coat and bond coat were completed. Further details of these and other efforts can be found in the subsequent papers covering each of the major program elements.

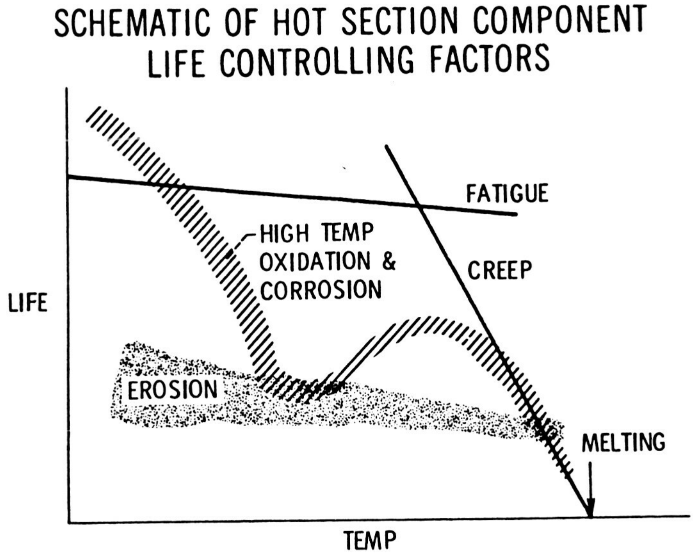
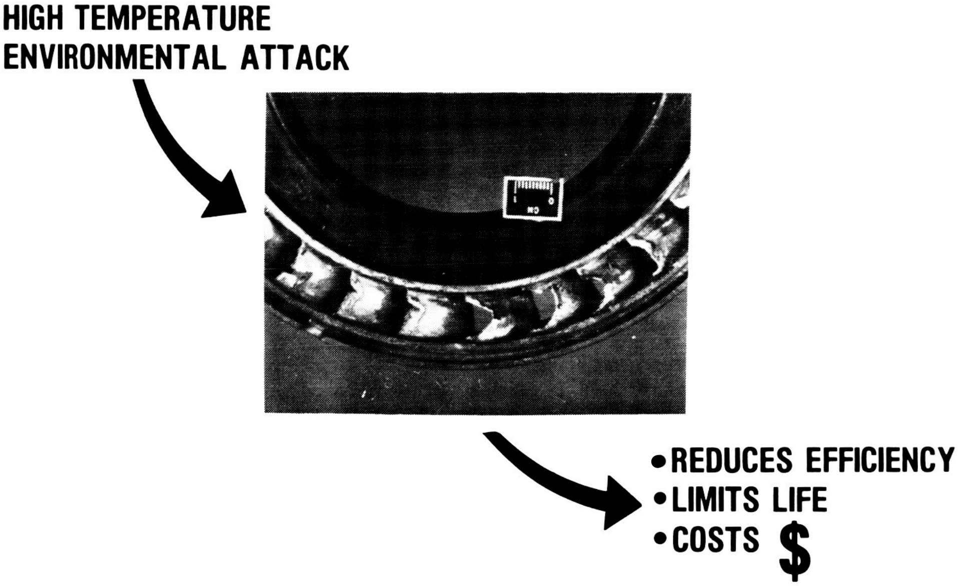


Figure 1



HIGH TEMPERATURE ENVIRONMENTAL ATTACK

- **REDUCES EFFICIENCY**
- **LIMITS LIFE**
- **COSTS $**

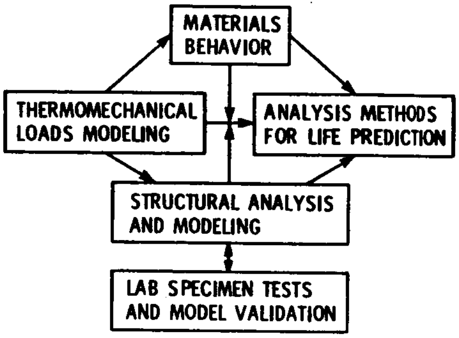
Figure 2

SURFACE PROTECTION-IT'S ROLE IN HOST

GOAL

DEVELOP AN INTEGRATED ENVIRONMENTAL ATTACK LIFE PREDICTION METHODOLOGY FOR METAL AND CERAMIC COATED HOT SECTION COMPONENTS

PROGRAM INTEGRATION



PROGRAM ELEMENTS

- AIRFOIL DEPOSITION MODEL
    - AIRFOIL MODEL
    - MODEL VERIFICATION
    - RIG/ENGINE CORRELATION
    - BURNER RIG MODERNIZATION
- METALLIC COATING LIFE PREDICTION
    - ENVIRONMENT/MECH. PROP. INTERACTIONS
    - OXIDATION/DIFFUSION
    - HOT CORROSION SURFACE CHEMISTRY
    - OXIDATION/CORROSION ATTACK
    - LIFE PREDICTION VERIFICATION
- THERMAL BARRIER COATINGS
    - THERMAL BARRIER LIFE PREDICTION
    - TBC MECHANICAL BEHAVIOR
    - RIG/ENGINE CORRELATION

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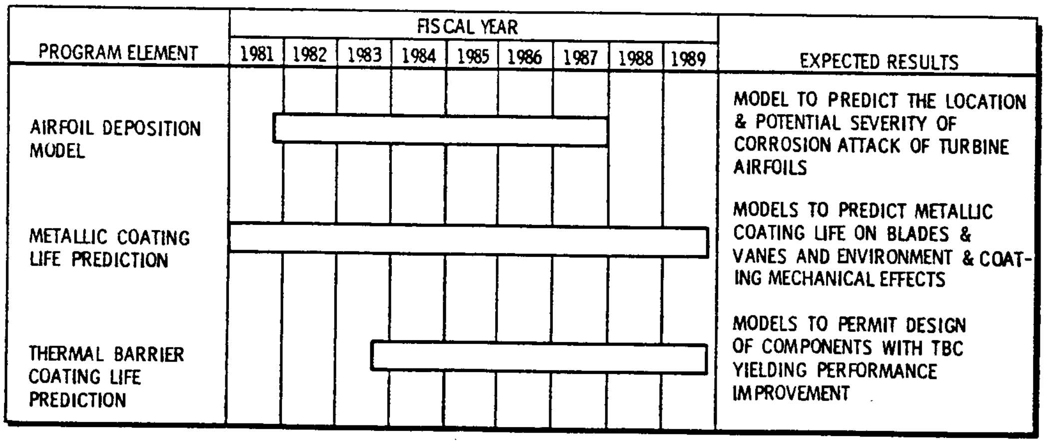
Figure 3

SURFACE PROTECTION



MODEL TO PREDICT THE LOCATION & POTENTIAL SEVERITY OF CORROSION ATTACK OF TURBINE AIRFOILS

MODELS TO PREDICT METALLIC COATING LIFE ON BLADES & VANES AND ENVIRONMENT & COATING MECHANICAL EFFECTS

MODELS TO PERMIT DESIGN OF COMPONENTS WITH TBC YIELDING PERFORMANCE IMPROVEMENT

Figure 4

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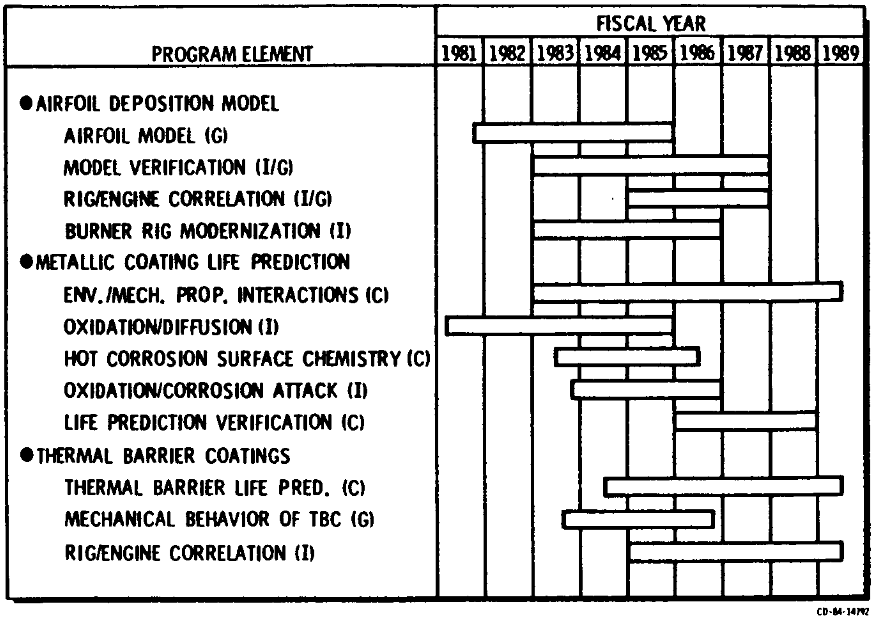


Figure 5

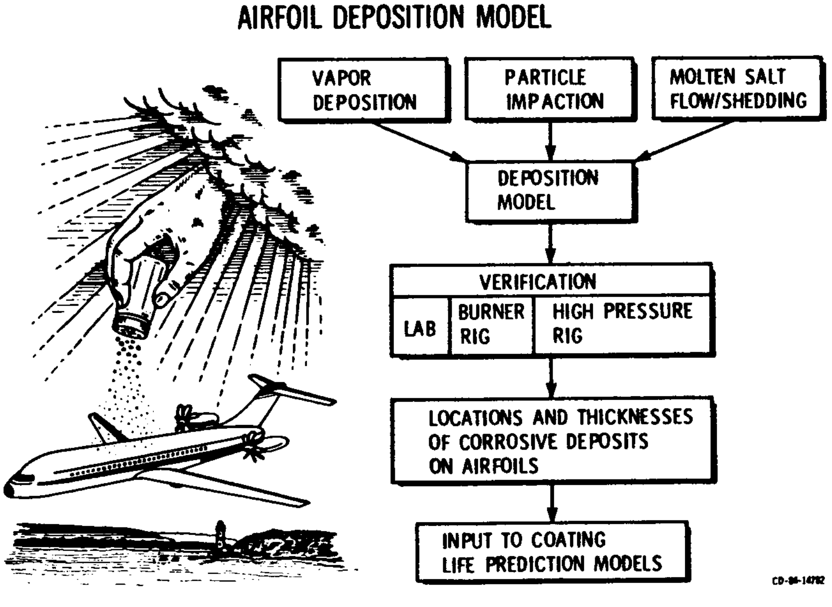
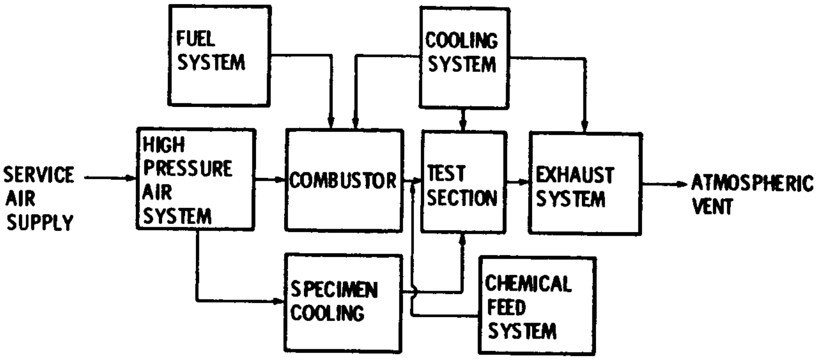


Figure 6

HIGH-PRESSURE BURNER-RIG FACILITY



TEST SECTION SPECIFICATIONS

- 1800 TO 3000° F
- 3 TO 50 ATM
- MACH 0.3 TO 1.0
- 8-SAMPLE CAPACITY
- CYCLIC CAPABILITY
- INDEPENDENT SAMPLE TEMPERATURE CONTROL
- MASS FLOW RATE, 2 lb/sec, max.

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Figure 7

METALLIC COATING LIFE PREDICTION

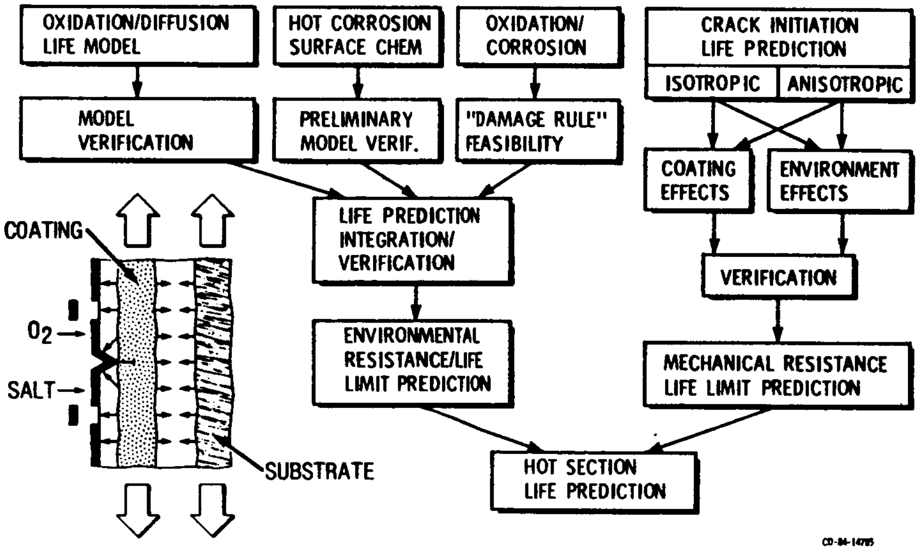

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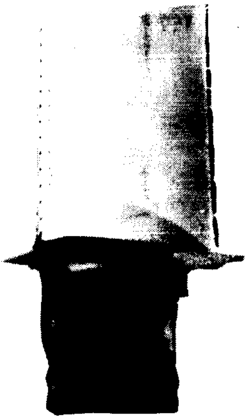
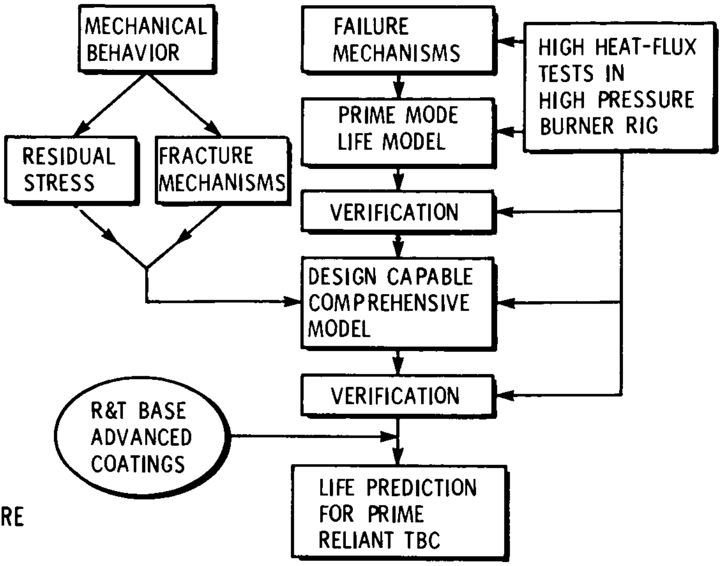
Figure 8

THERMAL BARRIER COATING LIFE PREDICTION





MECHANICAL BEHAVIOR

RESIDUAL STRESS

FRACTURE MECHANISMS

FAILURE MECHANISMS

PRIME MODE LIFE MODEL

VERIFICATION

DESIGN CAPABLE COMPREHENSIVE MODEL

VERIFICATION

HIGH HEAT-FLUX TESTS IN HIGH PRESSURE BURNER RIG

R&T BASE ADVANCED COATINGS

LIFE PREDICTION FOR PRIME RELIANT TBC

- EXTEND LIFE
- INCREASE TEMPERATURE
- REDUCE COOLING

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Figure 9

MULTIPLE CONTRACTS INCORPORATE BEST FEATURES OF MULTIPLE APPROACHES FOR TBC LIFE PREDICTION

	GARRETT	GE	P&W
MULTIPLE VENDORS	*		
ENGINE TESTS	*		
NDE	*		
QUALITY CONTROL			*
FAILURE MODE SEPARATION		*	
HOST INTEGRATION/CONTINUUM MODEL		*	
EROSION			*
FOREIGN OBJECT DAMAGE			*
STATISTICAL MODEL			*
FRACTURE MECHANICS	*		
HOT CORROSION MODEL	*		
MECHANICAL PROPERTIES		*	
MODEL INTEGRATION			*

Figure 10