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THERMAL BARRIER COATING LIFE PREDICTION MODEL DEVELOPMENT

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The objective of this program is to develop an integrated life prediction model accounting for all potential life-limiting Thermal Barrier Coating (TBC) degradation and failure modes including spallation resulting from cyclic thermal stress, oxidative degradation, hot corrosion, erosion, and foreign object damage (FOD). This overall program objective will be accomplished in two phases. The goal of the first phase will be to determine the mechanisms and relative importance of the various degradation and failure modes, and to develop and verify the methodology to predict predominant mode failure life in turbine airfoil applications. Phase I will employ an empirically based correlative model relating coating life to parametrically expressed driving forces such as temperature and stress. The effort in this phase will be accomplished in three tasks: failure mode determination (Task I), modeling (Task II), and substantiation testing (Task III). This Phase currently is in the material procurement, specimen preparation and initial testing stages. Phase II will experimentally verify Phase I models and develop an integrated, mechanistically based life prediction model including all relevant failure modes.

The two-layer TBC system being investigated, designated PWA264, currently is in commercial aircraft revenue service. It consists of an inner low pressure chamber plasma-sprayed NiCoCrAlY metallic bond coat underlayer (4-6 mils) and an outer air plasma-sprayed 7 w/o Y_2O_3 - ZrO_2 (8-12 mils) ceramic top layer. The TBC system is shown in figure 1. The composition and structure of this coating are based in part on effort conducted under previous NASA sponsored programs (ref. 1 and 2).

Phase I, Task I - Failure Mechanism Determination

The Phase I, Task I investigation is designed to evaluate the relative importance of various thermomechanical and thermochemical failure modes, focusing on thermal stress cycling, oxidative degradation, and their potential interaction. The primary experimental method to be employed in this investigation is cyclic burner rig testing. Static furnace exposure tests also will be included to evaluate the relative importance of oxidation and other thermal exposure effects. At the conclusion of this task, a preliminary life prediction model will be developed on the basis of the experimental data generated.

Phase I, Task I - Experimental Design and Test Plan

The experimental plan for this Task is based on a thorough review of the literature pertaining to thermal barrier coating degradation and failure modes, and on careful evaluation of damage observed on laboratory and engine-exposed thermal barrier coated hardware. This review identified ceramic spallation resulting from formation of a dominant crack in the ceramic phase, parallel to and adjacent to, but not co-incident with, the metal-ceramic interface, as the primary mode of thermal barrier coating failure. This cyclic cracking failure mode clearly is influenced by thermal exposure effects, as shown by results of experiments conducted to study thermal pre-exposure and thermal cycle-rate effects (ref. 3 through 6). Various mechanisms have been proposed to account for these thermal exposure effects, including oxidation, time-dependent bond coat flow, ceramic sintering, changes of ceramic phase distribution, etc. Oxidation is important, as shown by comparison of inert environment and air pre-exposure effects and by the observation of significant oxidative degradation on failed laboratory test specimens. However, it is also interesting that significantly less oxidation degradation is observed on failed engine test components than on laboratory specimens. Evaluation of engine exposed coatings also shows essentially no ceramic sintering.

The Task I test plans shown in figures 2, 3, and 4 are designed to identify the relative importance of the various potential thermal barrier coating degradation modes discussed above. Included in this test plan are static furnace and cyclic burner rig thermal exposure tests, with the cyclic tests being conducted with both clean and contaminated fuels to assess the relative importance of hot corrosion induced ceramic spallation (ref. 7 through 10). Static furnace tests will be conducted both in air and in a non-oxidizing environment to separate the influence of oxidation from other potential thermal exposure effects. To determine the relative importance of thermal exposure and cyclic thermal stress effects, cyclic burner rig tests will be conducted at two cycle rates, on as-fabricated coatings, and on coatings pre-exposed in oxidizing and non-oxidizing environments. The influence of cyclic thermal stress level will be studied by varying peak test temperature, transient heating rate, and ceramic thickness. Also included in this plan is a fractional exposure test which will involve destructive examination of unfailed coatings exposed for various fractions of the anticipated ceramic spalling life. These observations will provide information about the nature and rate of coating damage accumulation.

Phase I, Task I - Instrumentation and Coating Property Measurements

The design of the specimen to be employed for cyclic burner rig testing is shown in figure 5. To provide temperature distributions required for Task I preliminary life prediction modeling, an instrumented specimen will be run at the beginning of each Task I burner rig test. The design of this instrumented specimen, presented in figure 6, provides for temperature measurement at the ceramic surface and at a location approximately 10 mils below the metal-ceramic interface in five equally distributed circumferential locations. These temperature measurements will provide boundary values for transient thermal and structural finite element analyses of coating temperature and strain (stress) distribution.

To provide necessary material properties for thermal and stress analyses, selected mechanical, thermomechanical and physical property tests will be conducted in Task I. These tests will be conducted on bulk ceramic or metallic (bond-coat composition) specimens fabricated by plasma application of thick coating deposits on mild steel panels. These panels will be machined to remove the steel substrate and to form "thick coating" blanks to required test specimen dimensions. Initial ceramic test panels have been fabricated; as shown in figure 7, the structure produced in these panels provides a relatively good approximation of the desired thin coating structure shown in figure 1.

Phase I, Task I - Analysis and Verification Testing

To assess the relative importance of various failure modes studied in the Task I experimental plan, empirically-based correlative life prediction models will be developed to independently predict life for each mode. Using a typical engine mission cycle, these models will be applied to independently predict mission cycle coating life for each failure mode. Predicted lives will be compared to determine the importance of each failure mode.

Based on results of this assessment an interactive prediction model will be developed to account for the predominant modes of coating degradation and failure. This preliminary life prediction system will be based on relatively simple interactive modes such as linear or damage summation.

To verify the preliminary prediction model, additional burner rig tests will be conducted using test parameters and methods which are different from those used to generate the data on which the model in based. The test method will involve exposure of a single rotating specimen located in the center of the burner rig spindle. This will improve and simplify temperature measurement and control, and will eliminate circumferential thermal gradients which are inherent to the multiple specimen configuration used earlier in this task. To improve the simulation of airfoil conditions the specimen will be hollow and incorporate internal cooling, thus providing a steady state thermal gradient across the TBC. Three sets of test parameters will be selected to simulate typical airfoil mission cycles. The specimen geometry has a 1-inch outside diameter (O.D.), with a 1/2-inch inside diameter (I.D.) and is approximately 5 inches long. The specimen geometry is shown in figure 8.

Phase I, Task II - Major Mode Life Prediction Model

The Task II objective is to design, conduct and analyze experiments to obtain data for major mode life prediction model development. Design of the experiments will be based on results of Task I. Test parameters will cover the range of parameters anticipated on thermal barrier coated turbine components. Transient thermal and stress analyses will be conducted for each test condition. The results will be used to construct life prediction models for the predominant failure modes. For this task a minimum of 20 single-specimen, cooled burner rig tests will be conducted to obtain major mode life prediction model development.

The test method will be the same as for Task I verification testing. This method involves clean fuel or ducted burner rig testing of a single tube rotating about its axis, with internal cooling and external burner heating (figure 8). Variables to be studied include maximum surface temperature, thermal gradients, cycle duration, transient rates, ceramic thickness, virgin and pre-exposed ceramic, and clean fuel versus corrosive environment. Test parameters will be varied to cover the range of parameters anticipated on thermal barrier coated turbine components. A combination of thermocouple data and thermal analysis will establish the transient temperature distribution for each combination of test parameters.

Transient thermoelastic analysis will be used to develop a correlative model. Utilizing the MARC program, transient thermal analysis as well as stress analysis will be developed and modified for the rotating tube specimen test. MARC provides elastic, elastic-plastic, creep, large displacement, buckling and heat transfer analysis capabilities. Dimensional analysis of parameters which characterize the

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data base (loading, specimen geometry, material properties, and number of cycles to failure) will be conducted. Multiple linear and nonlinear regression techniques are to be used to obtain the best correlation between the established parameter groups. Analytical studies of the stress increase in the ceramic layer due to oxidation of the bond layer will be conducted to account for the effects of oxidation. Multiple linear and nonlinear regression will be conducted to correlate parabolic oxidation of the bond layer and time to spallation of ceramic as functions of temperatures of bond layer and ceramic. Also, a unified correlation model will be developed so that all failure modes and their ranges are accounted for, with thermal cyclic stress as the main failure mode. Creep and long time exposure, with some periodic cyclic effects, will also be incorporated.

Phase I, Task III - Model Verification

The validity of models developed in Task II will be assessed in Task III through a series of approved benchmark engine mission simulation tests. The basis for judgment of model validity will be how closely the model predicts TBC life for each benchmark engine simulation test. If necessary, recommendations for further research or refinement required for satisfactory engine life prediction methodology will be made.

Phase II - Design Capable Life Models

Phase II objectives (Tasks V through IX) are to develop and verify integrated design-capable life prediction models accounting for all important contributions to coating failure. Continuum and fracture mechanisms life prediction models based on material properties and analysis of load resulting from the coating system, including the effects of thermal exposure on component properties, will be done in Task V. Task VI will develop oxidation and hot corrosion failure models under both steady state and simulated engine conditions. Task VII will generate a data base from which erosion and FOD life prediction models can be developed. Task VIII and IX develop and verify integrated design, causal life prediction models using correlation, continuum mechanics and fracture mechanics methodologies.

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TABLE I
TASK I COATING PROPERTY TESTS

	As Deposited Ceramic	As Deposited Bond Coat
Elastic Constants	4 temperatures (1000°F, 1300°F) (1600°F, 2100°F)	
Thermal Conductivity	3 temperatures (1000°F, 1600°F, 2100°F)	3 temperatures (1000°F, 1600°F, 2100°F)
Specific Heat	3 temperatures (1000°F, 1600°F, 2100°F)	3 temperatures (1000°F, 1600°F, 2100°F)
Stress Rupture (4 point bend)	4 stress/temperature combinations (1000°F, 1300°F) (1700°F, 2100°F)	--
Creep (4 point bend)	9 stress/temperature combinations (1000°F, 1600°F, 2100°F)	-- --
Sintering Shrinkage	2 temperatures (1000°F, 2100°F)	2 temperatures (1000°F, 2100°F)
Isothermal LCF	-------	9 temperature/strain range combinations (1000°F, 1400°F, 2100°F)

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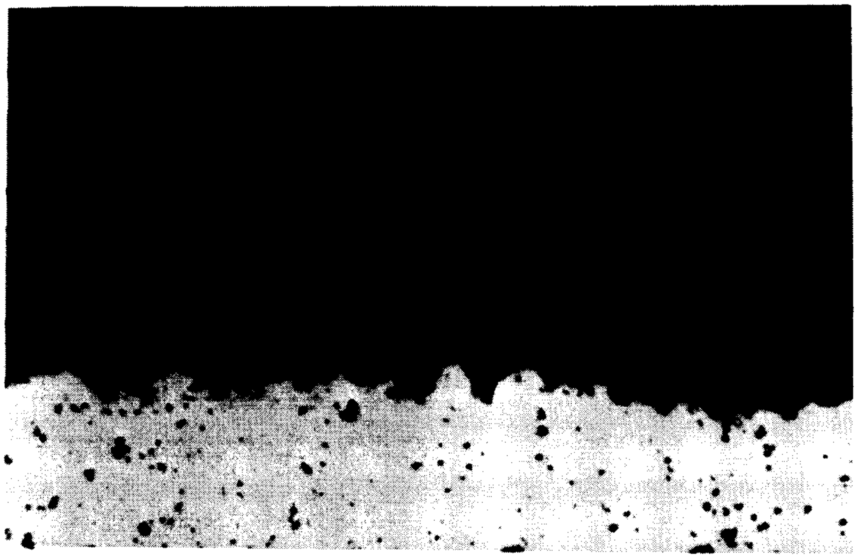


Figure 1 Light Photomicrograph Showing PWA264 Microstructure 200X

	OXIDIZING ATMOSPHERE		NON-OXIDIZING ATMOSPHERE	
TEMPERATURE	STATIC FAILURE	FRACTIONAL EXPOSURE	STATIC FAILURE	FRACTIONAL EXPOSURE
2200°F (T_3)	(1) B	(2) X	(3) X	(4) X
2100°F (T_2)	(5) A_1	(6) C	(7) A_2	(8) X

MINIMUM OF TWO (2) COUPONS PER BLOCK

TEST CONDITIONS SHOWN THUS: ☐ X NOT TO BE EVALUATED

Inspection Interval		Hours
B	=	10
A_1	=	10
A_1	=	80
A_2	=	80

Figure 2 Task I Furnace Exposure Test Plan to Evaluate Thermal Barrier Coating Static Failure Life

MAXIMUM CYCLE TEMPERATURE	TRANSIENT HEATING RATE	SHORT CYCLE		LONG CYCLE	
		CYCLE TO FAILURE	FRACTIONAL EXPOSURE	CYCLE TO FAILURE	FRACTIONAL EXPOSURE
2050°F (T_2)	FAST (60 SEC.)	(9) D_1	(10) G	(11) F	(12) X
	SLOW (180 SEC.)	(13) E	(14) X	(15) X	(16) X
1950°F (T_1)	FAST (60 SEC.)	(17) D_2	(18) X	(19) X	(20) X
	SLOW (180 SEC.)	(21) X	(22) X	(23) X	(24) X

CONDITION D,E,F — 12 SPECIMENS PER TEST:

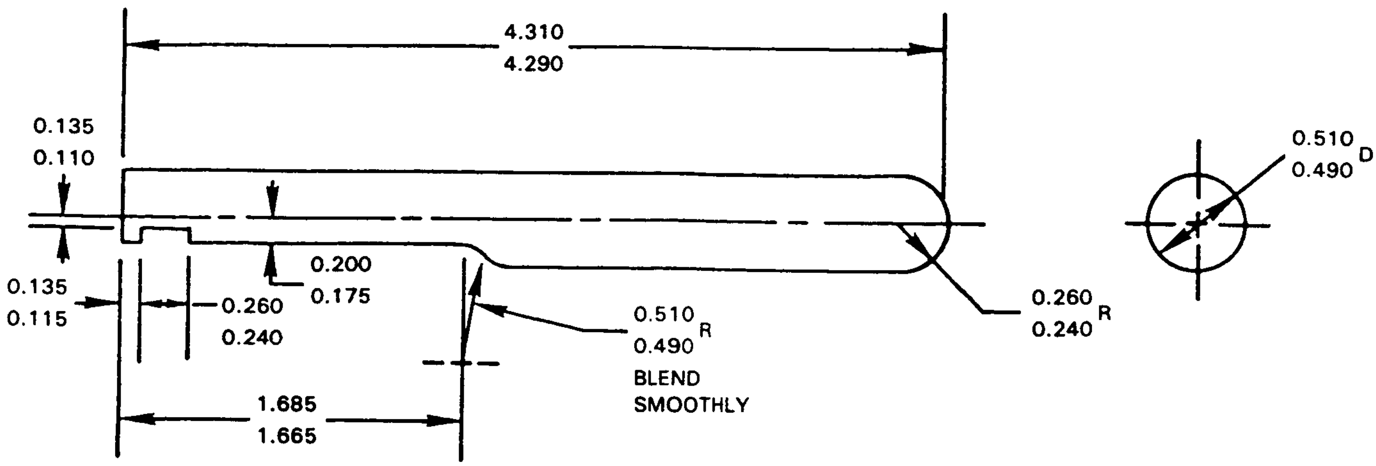
4 — 10 MIL VIRGIN CERAMIC ("BASELINE" COATING)
2 — 5 MIL VIRGIN CERAMIC
2 — 15 MIL VIRGIN CERAMIC
2 — 10 MIL AIR PRE-EXPOSED CERAMIC
2 — 10 ARGON PRE-EXPOSED CERAMIC
12 TOTAL

CONDITION G: FRACTIONAL EXPOSURE TEST – See Text For Explanation.

Figure 3 Cyclic Burner Rig Test Matrix

	LOW CORRODANT LEVEL	HIGH CORRODANT LEVEL
CYCLE TO FAILURE	(25) J	(26) H
FRACTIONAL EXPOSURE	(27) X	(28) K

Figure 4 Cyclic Hot Corrosion Testing Matrix



All Dimensions Shown In Inches

Figure 5 Cyclic Burner Rig Specimen

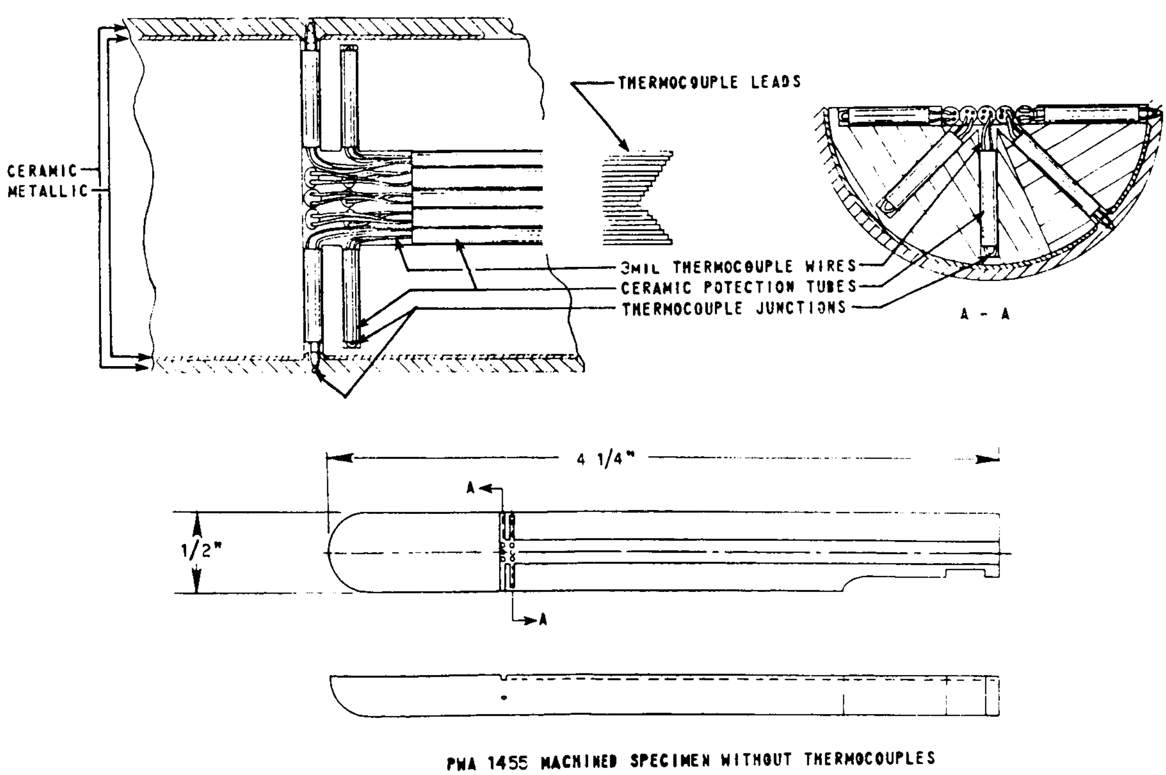


Figure 6 Thermocoupled Calibration Specimen Geometry

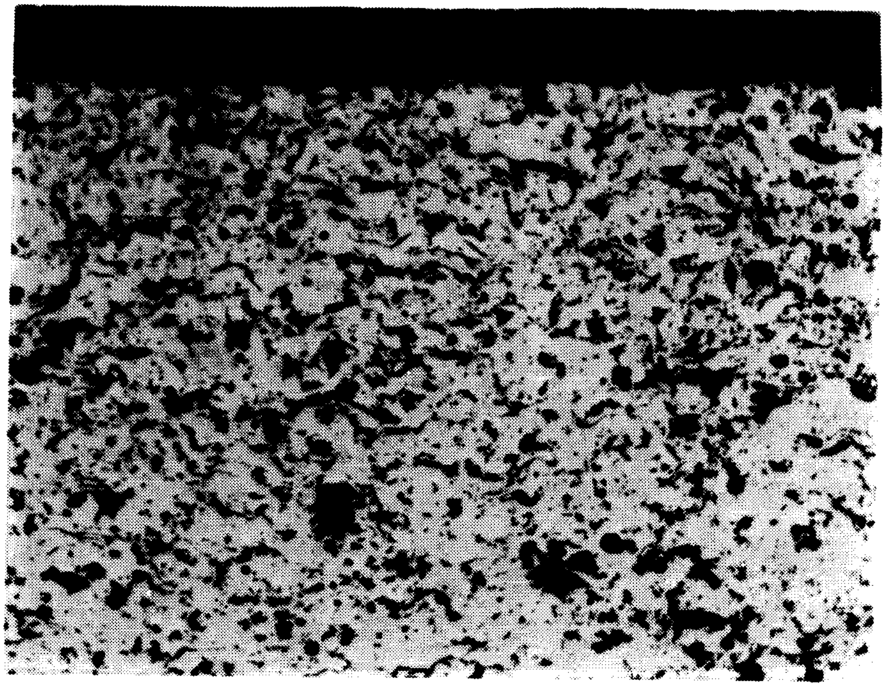


Figure 7 Bulk Specimen Microstructure 200X

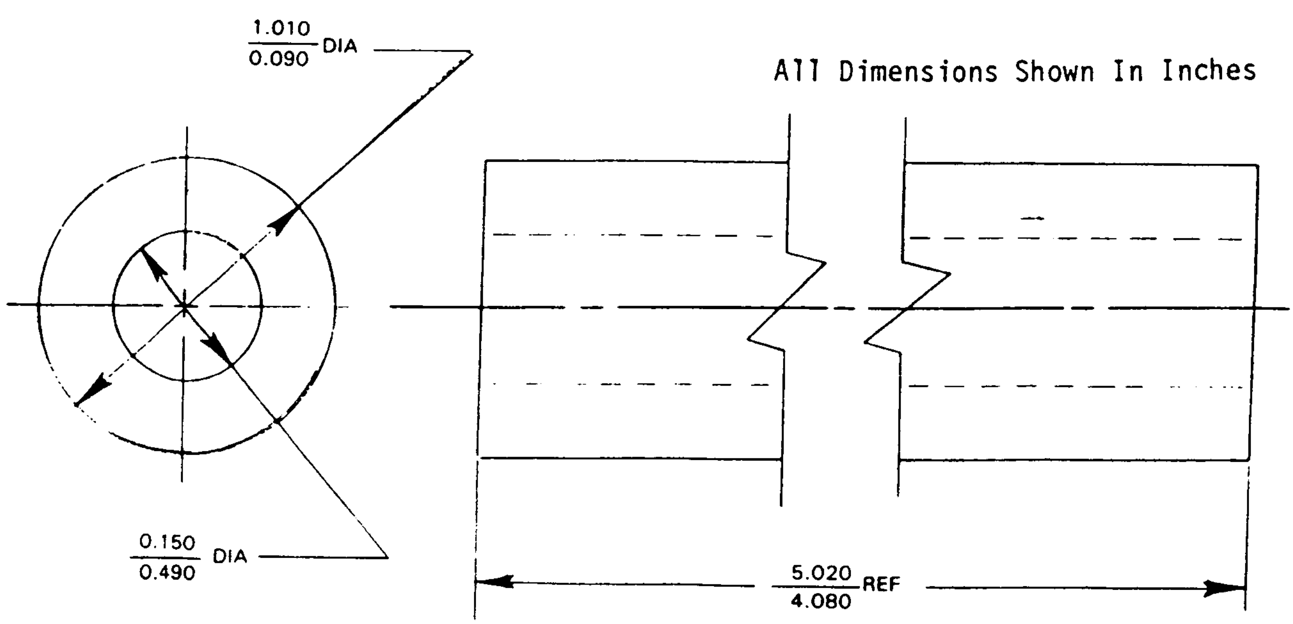


Figure 8 One-Inch Hollow Single Rotating Internally Specimen Geometry