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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, oxidation 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 is 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 develop an empirically-based correlative model relating coating life to parameterically expressed driving forces such as temperature and stress. The effort in this phase consists of three tasks: Failure Mechanism Determination (Task I), Modeling (Task II), and Substantiation Testing (Task III). Phase II will experimentally verify Phase I models and develop an integrated, mechanistically-based life prediction model including all relevant failure modes. The program is currently in the final stages of Task I; predominant failure modes have been identified and a preliminary life prediction model is being developed.

The two layer TBC system being investigated, designated PWA264, is currently in commercial aircraft revenue service, on turbine vane platforms in the JT9D and 2037 engines. It is also bill-of-material on turbine vane airfoils in the advanced PW4000 and IAE V2500 engines. The TBC consists of an inner low-pressure chamber plasma sprayed NiCoCrAlY metallic bond coat (4-6 mils) and an outer air plasma-sprayed 7 w/o Y_2O_3-ZrO_2 (8-12 mils) ceramic layer (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

A review of experimental and flight service components as well as laboratory test evaluations indicates that the predominant mode of TBC failure involves thermomechanical spallation of the ceramic coating layer. This ceramic spallation involves the formation of a dominant crack in the ceramic coating parallel to and closely adjacent to the topologically complex metal ceramic interface (figure 2). This cyclic "mechanical" 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. 3-6).

EXPERIMENTAL DESIGN AND TEST PLAN

The Task I, "Failure Mechanism Determination" investigation was designed to evaluate the relative importance of various thermomechanical and thermochemical "damage" modes, focusing on thermal stress cycling, oxidative degradation and their potential interaction. The primary experimental method used in this investigation was cyclic burner rig testing. The cyclic tests were conducted with both clean and

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contaminated fuels to assess the importance of hot corrosion induced ceramic spallation (ref. 7 - 10). Static furnace tests also were performed to evaluate the relative importance of oxidation and other thermal exposure effects. The test matrix (figure 3) was designed to study the influence of various "driving forces" such as temperature, thermal cycle frequency, environment, coating thickness and pre-burner rig test thermal exposure on TBC spalling life. To provide property data required for subsequently described thermal and stress analyses, physical and mechanical property tests are being conducted on monolithic ceramic and metallic specimens fabricated to simulate the composition and structure of the respective coating layers.

CRITICAL EXPERIMENT RESULTS

All burner rig and furnace test specimens exhibited the typical ceramic spallation near the metal-ceramic interface, with a thin layer of ceramic remaining adherent after failure. Examination of the laboratory data clearly shows a strong temperature effect; comparison of these data with typical engine test conditions suggests that "cyclic content", (i.e., relative frequency and severity of engine thermal cycling) also strongly influences TBC spallation life (figure 4). Oxidation damage occurring at the ceramic-metal interface for laboratory testing was found to be somewhat greater than that found for engine exposed failures. This is attributed to the relatively high interface temperature employed in the accelerated laboratory spallation life testing.

In the laboratory tests conducted to study environmental effects, results suggest that bond coat oxidation damage at the metal-ceramic interface contributes significantly to thermomechanical cracking in the ceramic layer. Low cycle rate furnace exposure in air versus exposure in Argon clearly shows a dramatic increase of spalling life in the non-oxidizing environment (figure 5). The results of burner rig testing indicated that static thermal pre-exposure of burner rig test specimens in air causes a proportionate reduction of cyclic thermal spalling life, whereas pre-test thermal exposure in Argon does not reduce cyclic thermal spalling life (figures 6 and 7). Typical respective pre-test microstructures for air and Argon pre-exposed specimens are shown in figures 8a and b.

Laboratory testing was conducted in clean and contaminated (Na, S) fuel environments to evaluate the hot corrosion spallation resistance of the TBC. Corrodant induced failure was observed during cyclic hot corrosion testing at high corrodent levels (35 ppm Na_2SO_4) but not for low corrodent levels (10ppm Na_2SO_4). The failure mode, which has not been observed on engine exposed components, involved "flaking" of small patches of ceramic above the typical failure location.

Testing was also conducted to evaluate the effects of ceramic thickness on TBC spalling life. Ceramic thickness was found to have an effect on coating durability (figure 9). Thick coatings were found to decrease TBC life while thin coatings increased it as compared to the "baseline" 10 mil thick ceramic.

PHASE I, TASK I PRELIMINARY LIFE PREDICTION MODEL DEVELOPMENT

The preliminary life prediction model currently being developed focuses on the two major damage modes identified in the laboratory testing described above. The first of these modes involves a mechanical driving force, resulting from cyclic strains and stresses caused by thermally induced and externally imposed loads. The second is an environmental driving force which appears, based on the experimental results, to be related to "oxidation damage", most probably to the in-service growth of a NiCoCrAlY oxide scale at the metal-ceramic interface. Based on the apparently "mechanical" mode of ceramic failure, it is presumed that the growth of this oxide scale influences the intensity of the mechanical driving force. The mechanism(s) of this "interaction" are not presently understood, and no attempt is being made to incorporate interaction effects in the initial model, which will be based on linear damage summation. Interaction effects will be considered in the refined model to be developed in Task 2 of this program.

Mechanical failure of the ceramic layer is presumed to involve accumulation of fatigue "damage". Possible mechanisms for the accumulation of this damage might involve the initiation and propagation of a dominant crack in the ceramic, or possibly the subcritical growth and subsequent link-up of pre-existing microcracks in the ceramic structure. Metallographic examination of specimens removed from burner rig test prior to spallation failure presently is being conducted to identify specific mechanical damage accumulation mechanism(s).

Cyclic inelastic strain range in the ceramic layer will be used to represent the driving force for mechanical damage in the life model. Use of this parameter is based on results of mechanical (reversed bend) tests conducted on monolithic ceramic specimens having a porous, microcracked microstructure representative of the ceramic coating. These results have shown highly non-linear stress-strain behavior with significant stress-strain hysteresis in reversed loading . Finite element calculations of ceramic inelastic strain range are being conducted for each of the Task I burner rig test conditions using transient thermal data obtained from thermocouple instrumented test specimens. It is presently planned to use a relatively simple empirical relationship such as Manson-Coffin to express the functional dependence of mechanical "damage" on ceramic inelastic strain range.

Based on the observation that thermal exposure damage appears to be related to oxidation effects, the relationship between thermal damage accumulation rate and primary exposure parameters (time and temperature) will be based on the accepted parabolic and exponential forms appropriate to oxidation kinetics.

A major shortcoming of the present model is the absence of any provision for interaction between environmental and mechanical damage. The relatively coarse preliminary finite element break-up constructed to represent the substrate coating structure incorporates a planar metal-ceramic interface and predicts essentialy no change of stress level with growth of an interfacial oxide scale. Thus, oxidation effects will be "forced" in the preliminary model using the linear damage summation approach. One approach which will be evaluated in an effort to incorporate interaction effects in the refined Task 2 model will involve an attempt to represent, in a relatively simple geometric form such as that employed by G. C. Chang (ref. 11), the very complex (rough) topological form of the real physical interface shown in figure 1. Other changes to the relatively simple functional forms used in the preliminary Task I model undoubtedly will be suggested by ongoing microstructural damage interpretation and by testing this preliminary model against additional burner rig verification tests to be conducted at the conclusion of Task I.

VERIFICATION TESTING - WORK PLANNED

To verify the preliminary Task I 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 is 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.

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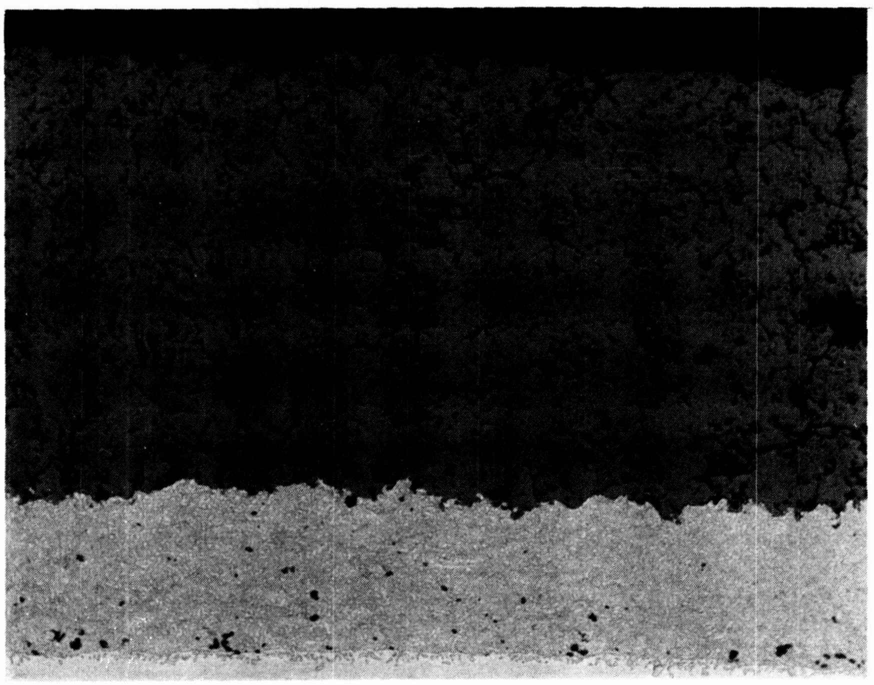

Figure 1 Light Photomicrograph Showing PWA264 Microstructure 200X

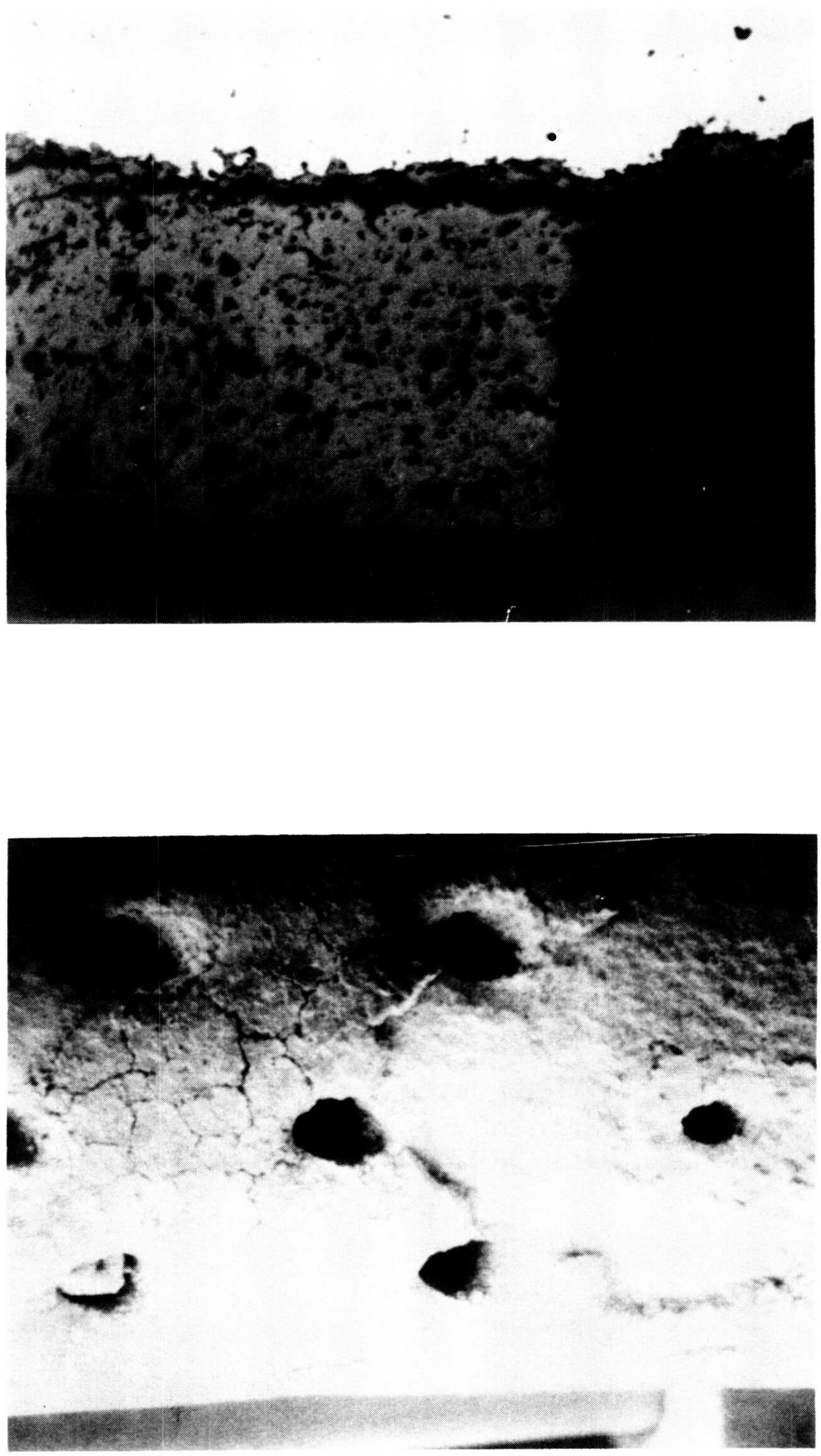

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Figure 2 Typical Thermal Barrier Coating Failure Mode

TEMPERATURE	EXPOSURE	STATIC		CYCLIC						FRACTIONAL EXPOSURE							
	TEST	FURNACE		BURNER RIG						FURNACE		BURNER RIG					
	ATMOSPHERE	OXIDIZING	NON-OXIDIZING	OXIDIZING				HOT CORROSION		OXIDIZING	NON-OXIDIZING	OXIDIZING				HOT CORROSION	
	CYCLE LENGTH			SHORT		LONG						SHORT		LONG			
	HEATING RATE			FAST	SLOW	FAST	SLOW					FAST	SLOW	FAST	SLOW		
	CORRODENT LEVEL							LOW	HIGH							LOW	HIGH
1650								J	H								K
2000				D_2													
2100		A_1	A_2	D_1	E	F				C		G					
2200		B															

CYCLIC OXIDATION BURNER RIG TEST SPECIMEN SET FOR CONDITIONS D1, D2, 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 FOR APPROXIMATELY ½ ESTIMATED BURNER RIG HOT TIME LIFE
2 10 MIL Ar PRE-EXPOSED FOR APPROXIMATELY ½ ESTIMATED BURNER RIG HOT TIME LIFE

CYCLE LENGTH

SHORT: 6 MINUTE CYCLE = 4 MINUTES IN THE FLAME + 2 MINUTES FORCE AIR COOLED

LONG: 60 MINUTE CYCLE = 57 MINUTES IN THE FLAME + 3 MINUTES FORCE AIR COOLED

CYCLE RATE

FAST: NOMINAL 60 SECOND HEAT-UP TO MAXIMUM TEMPERATURE

SLOW: NOMINAL 180 SECOND HEAT-UP TO MAXIMUM TEMPERATURE

CORRODENT LEVEL

LOW: 10 PPM Na_2SO_4

HIGH: 35 PPM Na_2SO_4

Figure 3 Task I Test Plan To Evaluate Thermal Barrier Coating Failure Life

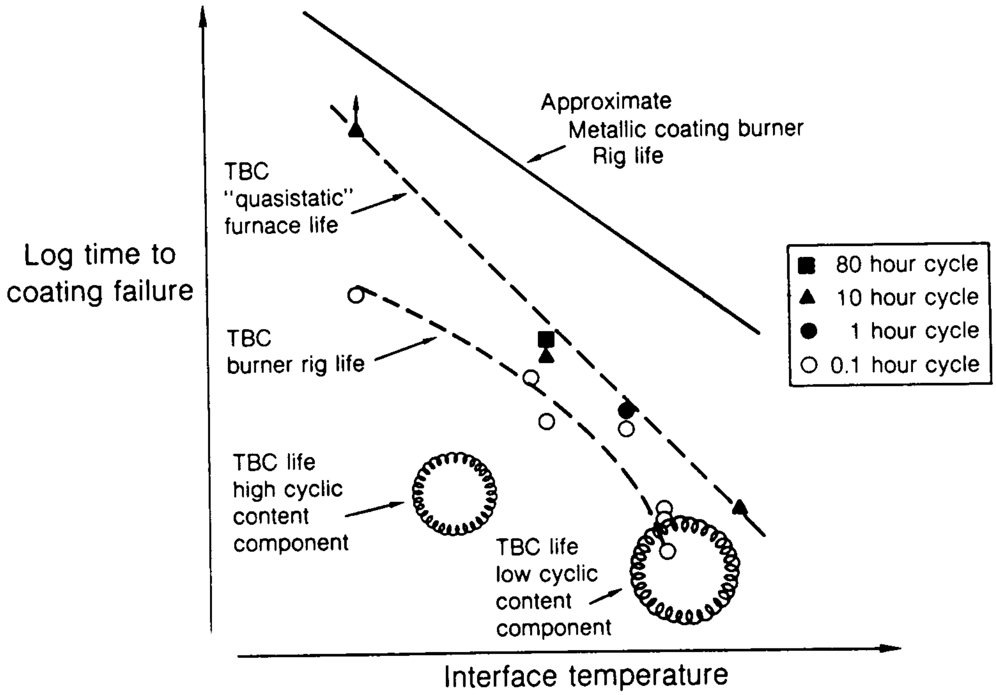

Figure 4 Test Data Showing Coating Life Dependent on Temperature, "Cyclic Content"

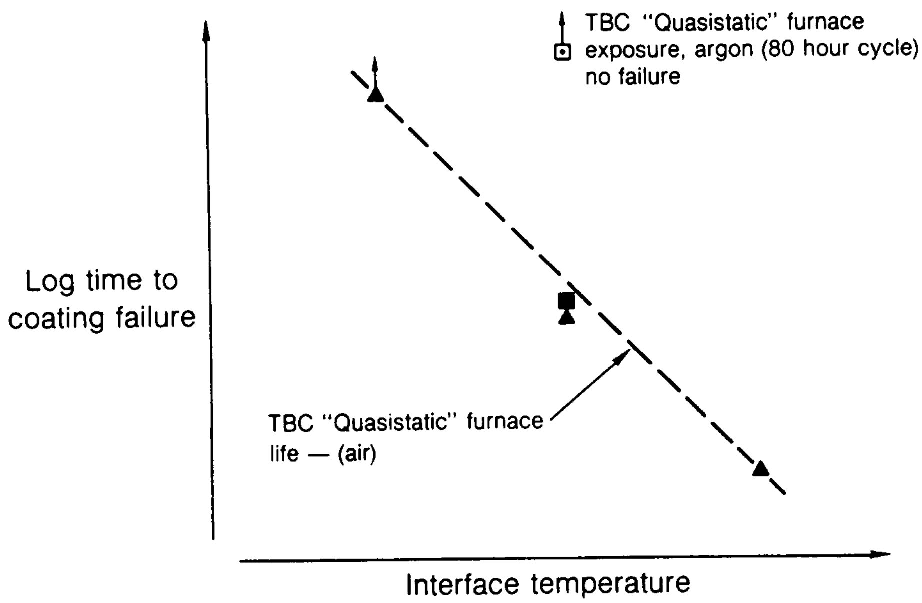

Figure 5 Test Data Showing Thermal Exposure Atmosphere Effects on Coating Durability

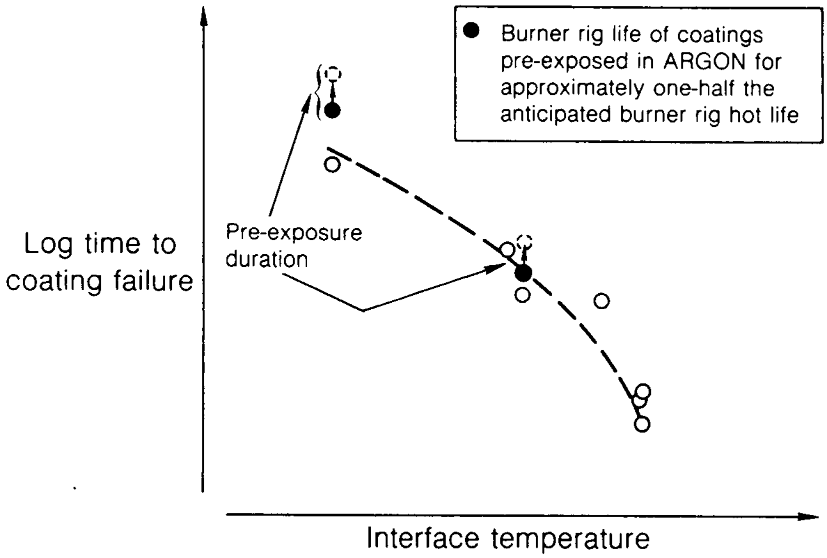

Figure 6 Test Data Showing "INERT" Pre-Exposure Does Not Effect Coating Performance

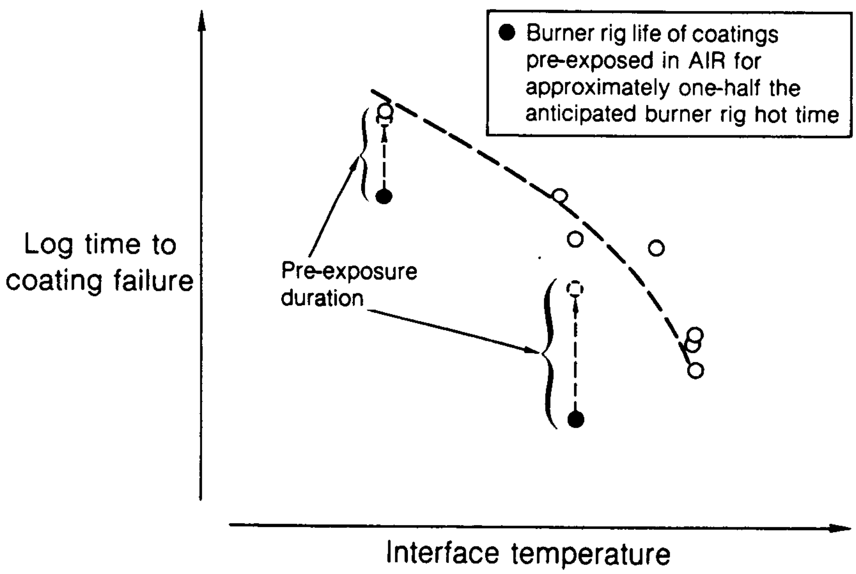

Figure 7 Test Data Showing Air Pre-Exposure Degrades Cyclic Life

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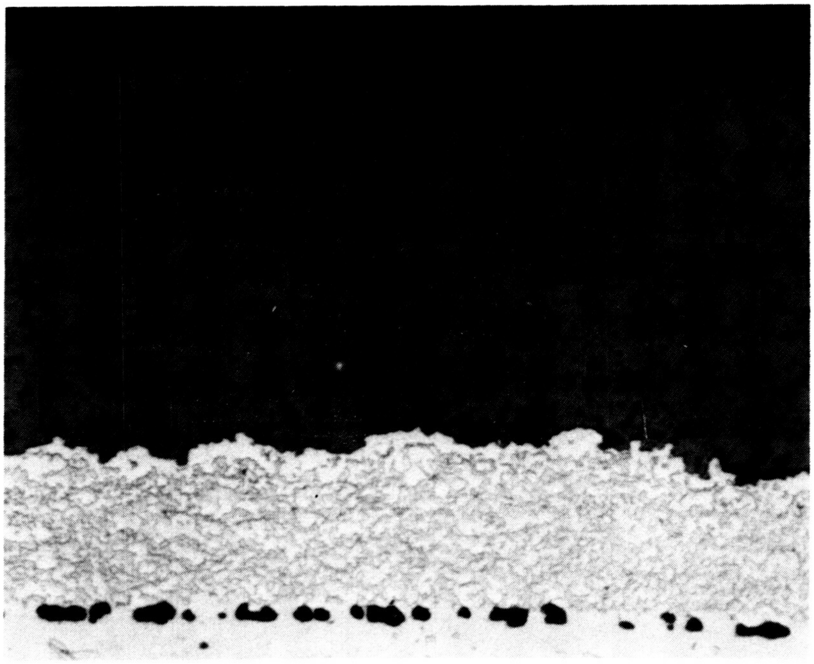
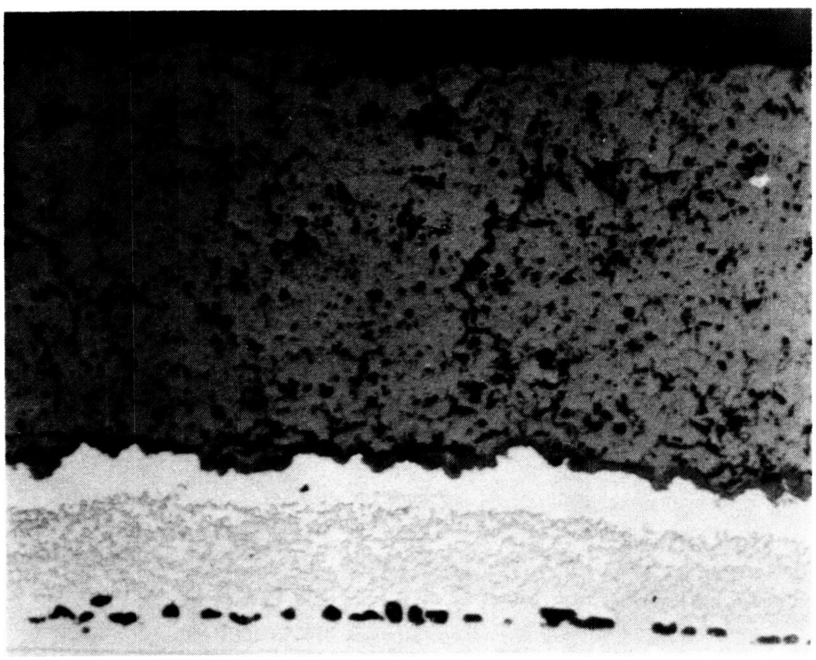


(a)



(b)

Figure 8a and b Microstructural Variations for Pre-Test Thermal Exposure Atmospheres, (a) Argon and (b) Air

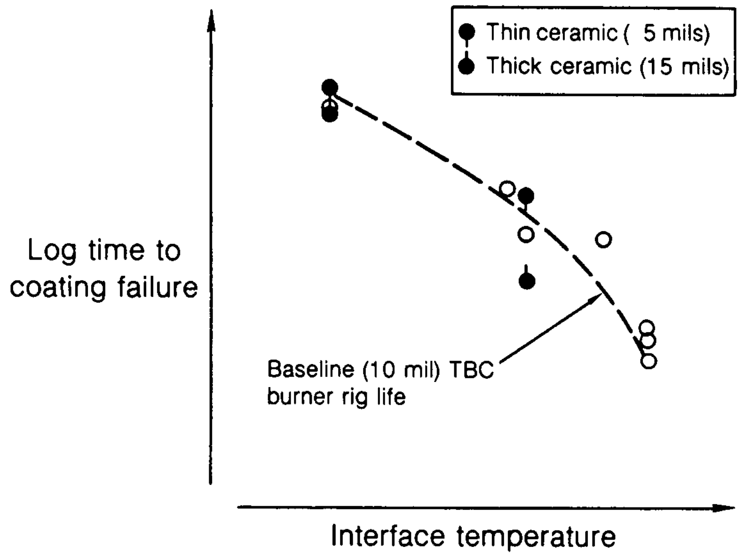


Figure 9 Test Data Showing Ceramic Thickness Effects