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THERMAL BARRIER COATING LIFE PREDICTION MODEL

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The objectives of this research were to determine the predominant modes of degradation of a plasma sprayed thermal barrier (TBC) system, and then develop and verify life prediction models accounting for these degradation modes. The TBC system consists of a low pressure plasma sprayed (LPPS) bond coat layer of Ni-22Cr-10Al-0.3Y, an air plasma sprayed (APS) yttria partially stabilized zirconia (ZrO_2-$8Y_2O_3$) top coat on a conventionally cast Rene'80 (Ni-base) substrate.

Thermal cycle testing of TBCs was employed to evaluate the effect of coating edges, bond coat oxidation, bond coat creep, top coat thickness, and bond coat thickness. Two different thermal cycle tests were employed (one utilized an isothermal exposure, while the other imposed a temperature gradient through the ceramic). Increases in life were associated with increases in bond coat creep strength and minimizing the effect of coating edges, while decreases in life were associated with increases in top coat thickness and isothermal pre-exposure damage.

In addition to the thermal cycling, some tests were conducted using coated cylindrical low cycle fatigue specimens in servohydraulic fatigue frames. These specimens were inductively heated and used high temperature extensometers to measure the elongation in the gage section. The first test simply duplicated the thermal cycle of the isothermal exposure test. Subsequent tests then imposed a mechanical strain on the thermal strain and producing the desired thermal-mechanical cycle. The majority of the cycles were in compression (a tensile stress was achieved for only a part of one cycle). Remarkably, in all cases, failure occurred in the substrate prior to detectable coating failure, demonstrating the significant stress tolerance of TBCs.

A time dependent, non-linear finite element model was developed to predict the stresses/strains present in the TBC system. The model was used to evaluate the effects of coating edges, bond coat oxidation, bond coat creep, changes in geometry, and temperature gradient across the TBC system as identified in the thermal cycle tests. The model predicts that TBC life can be extended by minimizing the effect of edges. It also predicts that, although the growth of oxide scale produces strains due to the material addition, it also reduces the strains produced by the thermal expansion mismatch between the bond coat and the top coat.

Property determinations of the bond coat and the top coat have been made. These included tensile strength, Poisson's ratio, dynamic modulus, and coefficient of thermal expansion (1). The properties were required for the modeling work and allow evaluation of material changes in the TBC system.

A TBC Life Prediction Model was developed based on the above tests and finite element analysis. The model relates the ranges of normal and shear strains produced during a thermal cycle (isothermal exposure test) to TBC cycle life as shown by:

$$\Delta\varepsilon_{RZ} + 0.4\,\Delta\varepsilon_{R} = 0.084\,N_f^{-1.445}$$

where $\Delta\varepsilon_{RZ}$ is the shear strain range
$\Delta\varepsilon_{R}$ is the normal strain range
N_f is the cycles to failure

As indicated, the model predicts failure in the TBC due to imposed strains based on the foregoing considerations; hence, changes in substrate and bond coat material, in geometry, in thickness, and the effect of oxidation can be accommodated by this model.

Present work is aimed at evaluating the model's predictive capabilities. Future work will be aimed at incorporating fracture mechanics into the model.

Reference:

1. R.V. Hillery, B.H. Pilsner, T.S. Cook, and K.S. Kim, "Thermal Barrier Coating Life Prediction Model - Second Annual Report," NASA CR-179504, 1986.

Baseline Thermal Barrier Coating System
(Weight Percent)

- **Substrate (Rene'80):** Ni-14Cr-9. 5Co-5Ti-4W-4Mo-3Al-0.17C-0.3Zr-0.015B
- **Bond Coating:** Ni-22Cr-10Al-0.3Y (Low Pressure Plasma Spray)
- **Top Coating:** ZrO_2 - $8Y_2O_3$ (Air Plasma Spray)

Figure 1

Specimen Configurations

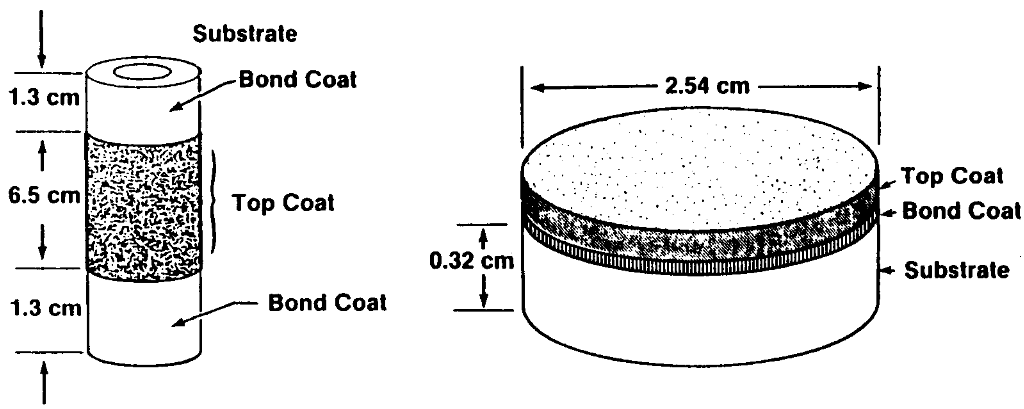


Figure 2

TBC Thermal Cycle Tests

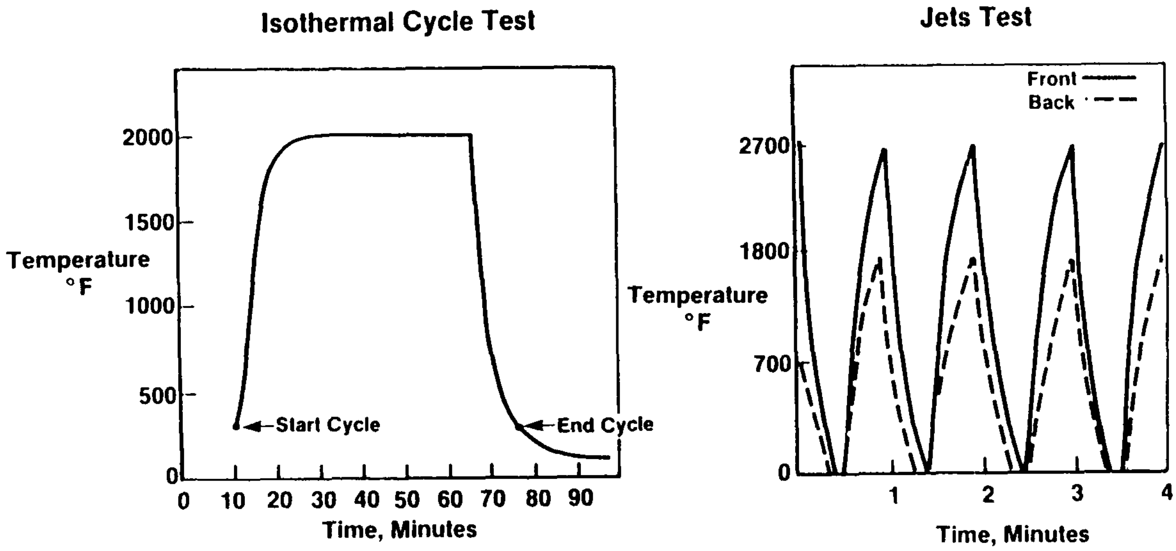


Figure 3

Rapid Temperature Thermal Cycle Test at 2000° F
45 Minute Exposure — 15 Minute Cool Down

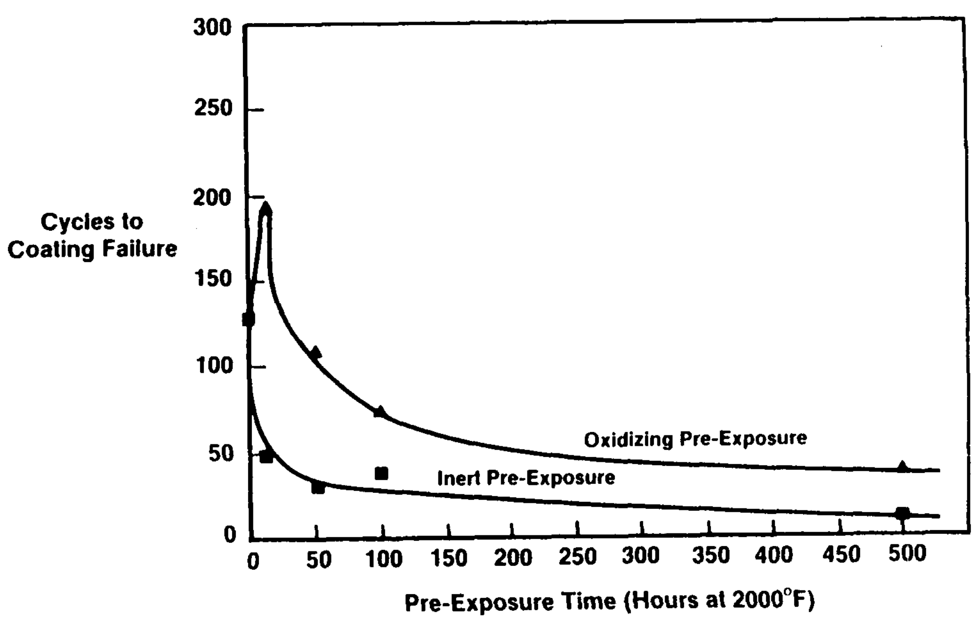
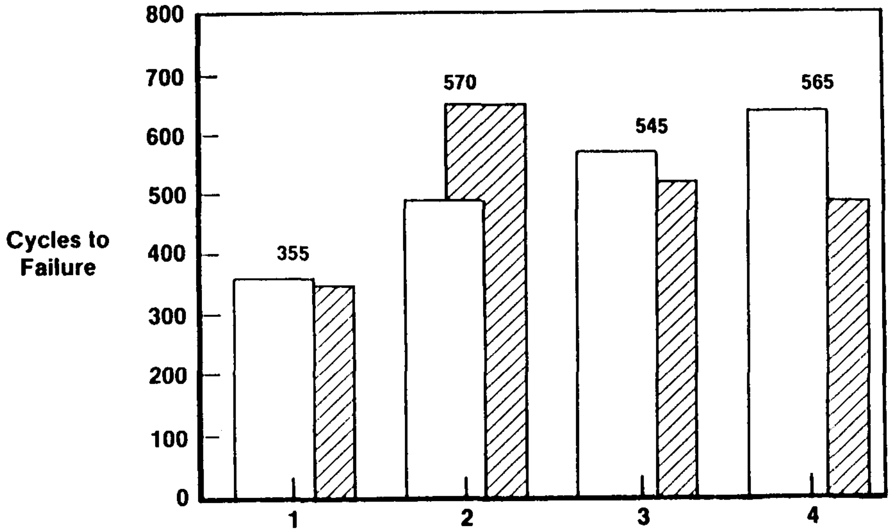


Figure 4

Effect of Bond Coat Creep Strength on TBC System Failure



1 Ni-22Cr-10Al-0.3Y
2,3,4 Modified NiCrAlY Bond Coats

Figure 5

Jets Test Thermal Cycle Results (10% Failure Criterion)

	Bond Coat Thickness (Mils)	Top Coat Thickness (Mils)	Specimen Diameter	Cycles
• Baseline	5	10	1"	21,000
	5	20	1"	4,000
	5	30	1"	2,000
	5	10	1.25"	— *
	5	10	1.50"	— **

* 4% Spallation Through 27,000 Cycles
** No Spallation Through 27,000 Cycles

Figure 6

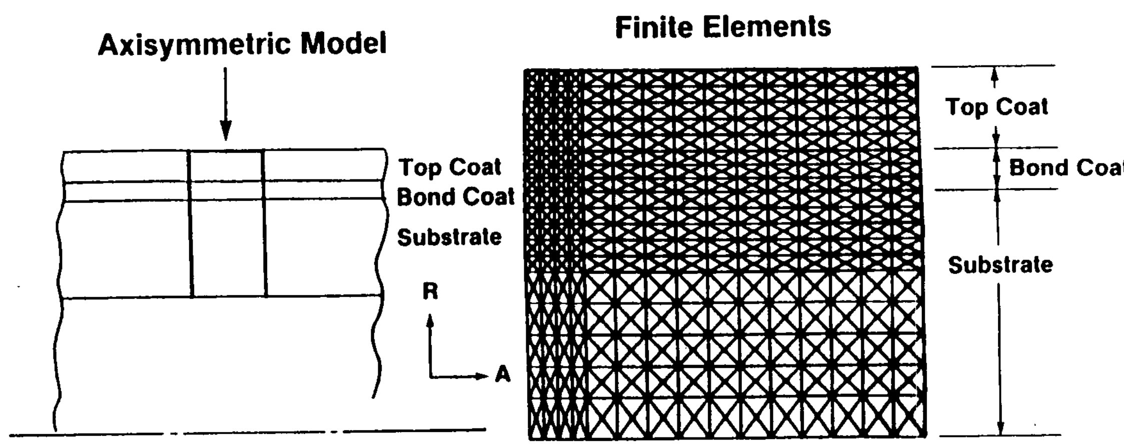


Figure 7

Variation of Effective Stress in Temperature Gradient Cyanide Analysis

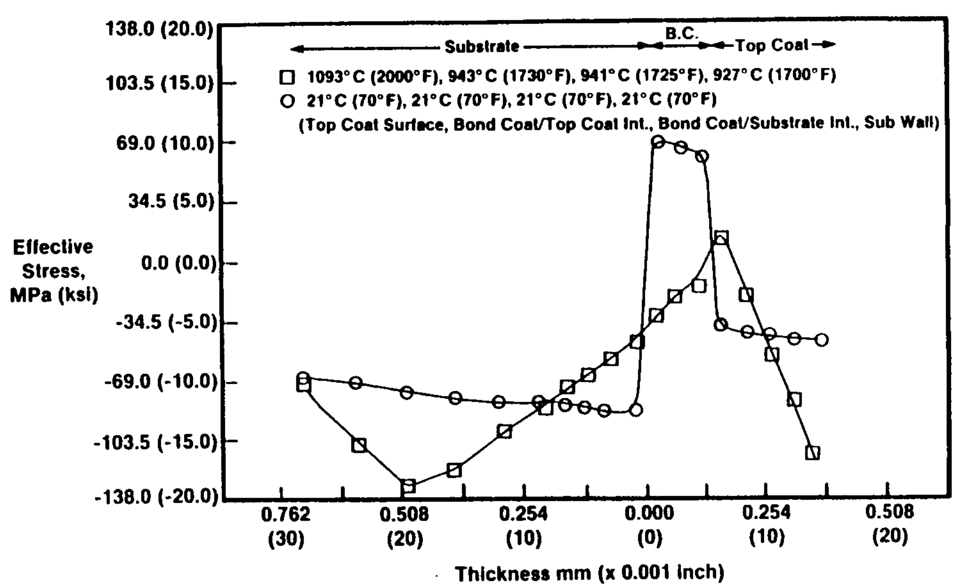
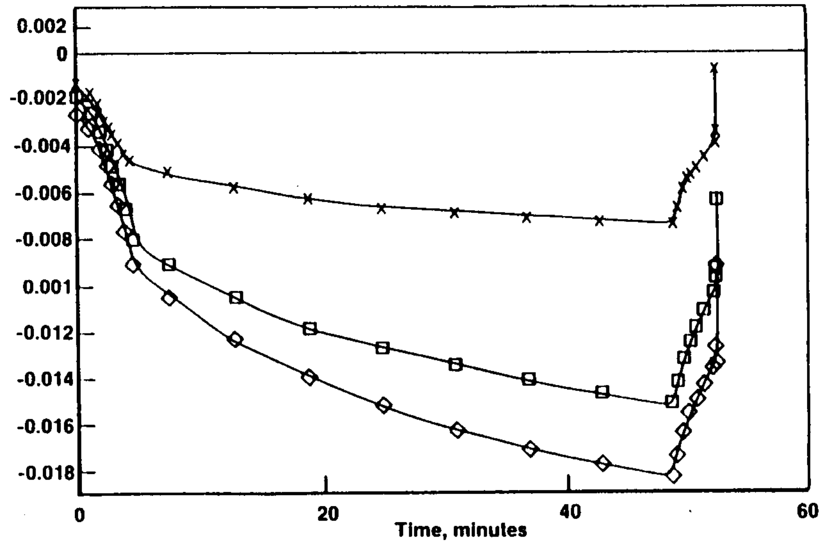


Figure 8

TBC Cylinder
Variation of RZ Total Strain



□ = .010 Top Coat
0 Scale
.005 Bond Coat

x = .010 Top Coat
4 Mic Scale
.005 Bond Coat

◇ = .030 Top Coat
0 Scale
.005 Bond Coat

Figure 9

TBC Life Prediction Model

- $\Delta\varepsilon_{RZ} + 0.4\ \Delta\varepsilon_{R} = 0.084\ N_f^{-1.445}$

  Where:

  - $\Delta\varepsilon_{RZ}$ is the Shear Strain Range
  - $\Delta\varepsilon_{R}$ is the Normal Strain Range
  - N_f is the Cycles to Failure

Figure 10