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THERMAL BARRIER COATING LIFE PREDICTION MODEL DEVELOPMENT*

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Thermal barrier coatings (TBCs) for turbine airfoils in high-performance engines represent an advanced materials technology with both performance and durability benefits. The foremost TBC benefit is the reduction of heat transferred into air-cooled components, which yields performance and durability benefits (Figure 1). To achieve these benefits, however, the TBC system must be reliable. Mechanistic thermomechanical and thermochemical life models are therefore required for the reliable exploitation of TBC benefits on gas turbine airfoils. GTEC's NASA-HOST Program (NAS3-23945) goal is to fulfill these requirements.

This program focuses on predicting the lives of two types of strain-tolerant and oxidation-resistant TBC systems that are produced by commercial coating suppliers to the gas turbine industry (Figure 2). The plasma-sprayed TBC system, composed of a low-pressure plasma-spray (LPPS) or an argon shrouded plasma-spray (ASPS) applied oxidation resistant NiCrAlY (or CoNiCrAlY) bond coating and an air-plasma-sprayed yttria (8 percent) partially stabilized zirconia insulative layer, is applied by Chromalloy (Orangeburg, New York), Klock (Manchester, Connecticut), and Union Carbide (Indianapolis, Indiana). The second type of TBC is applied by the electron beam-physical vapor deposition (EB-PVD) process by Temescal (Berkeley, California).

The overall objective of Phase I of this program is to develop mechanistic mission-analysis-capable life prediction models for the predominant environmental and thermomechanical TBC failure modes for preliminary design analyses. Because the TBC must be considered early in the component design process in order to fully incorporate and exploit its benefits, an additional model goal is to drive the preliminary TBC life model with component thermal analysis data and simple snap acceleration-snap deceleration stress analysis data. This approach permits the designer to economically include TBCs into initial iterations of the blade and vane design process. More refined TBC analyses for final design lives are the subject of Phase II.

A comprehensive strategy to achieve this goal has been developed that includes the analyses of the TBC durability on both the TFE731-5 HP turbine blades (Figure 3) and the burner rig test specimens. Due to the complex nature of the problems involved, the finite element method is deemed to be most effective in promoting the in-depth understanding of the essential overall thermal/mechanical behavior of the TBC systems as well as the interactions between the individual material regimes and the interfacial conditions in the TBC systems. This approach also interfaces efficiently with existing airfoil design methods.

*Work done under NASA Contract NAS3-23945.

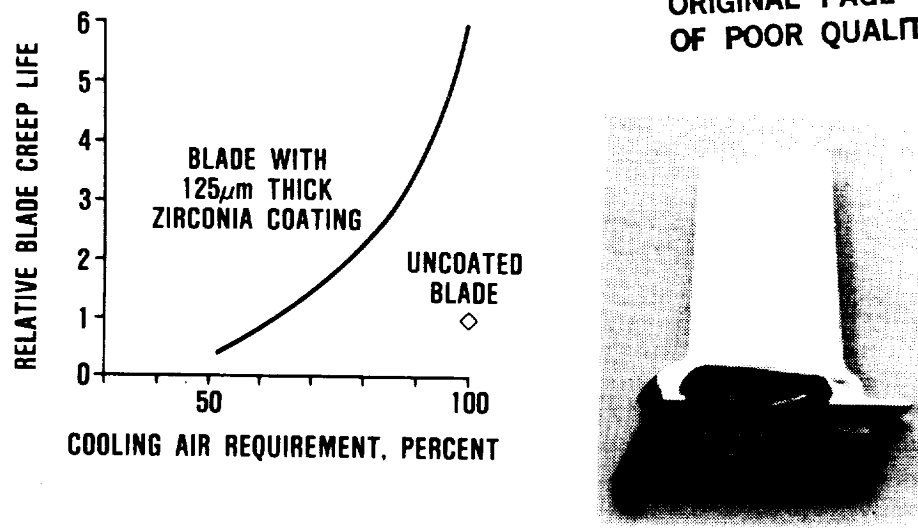

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Figure 1. TBCs Improve Creep Life and Reduce Cooling Air Requirements for the GTEC High-Pressure Turbine Blade.

	PLASMA SPRAY	PLASMA SPRAY	ELECTRON BEAM — PHYSICAL VAPOR DEPOSITION
TBC	APS Y_2O_3 (8%) STABILIZED ZrO_2	APS Y_2O_3 (8%) STABILIZED ZrO_2	EB-PVD Y_2O_3 (20%) STABILIZED ZrO_2
BOND COAT	LPPS Ni-31Cr-11Al-0.5Y	ASPS Co-32Ni-21Cr-8Al-0.5Y	EB-PVD Ni-23Co-18Cr-12Al-0.3Y
SUBSTRATE	MAR-M 247 SUPERALLOY	MAR-M 247 SUPERALLOY	MAR-M 247 SUPERALLOY
SUPPLIER	• CHROMALLOY • KLOCK	• UNION CARBIDE	• TEMESCAL

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Figure 2. Life Prediction Models are Being Developed for Plasma-Sprayed and EB-PVD TBC Systems.

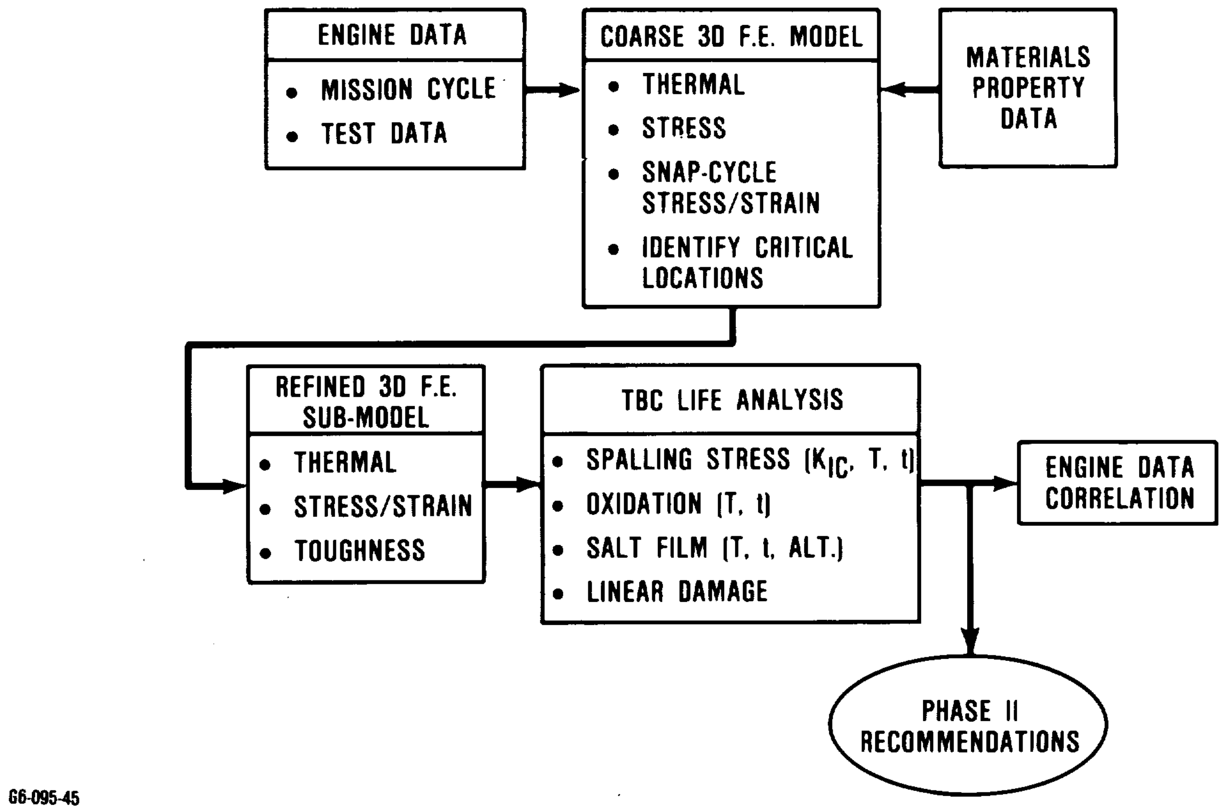

Figure 3. Three TBC Damage Modes are Evaluated in TFE731 Blade Analysis.

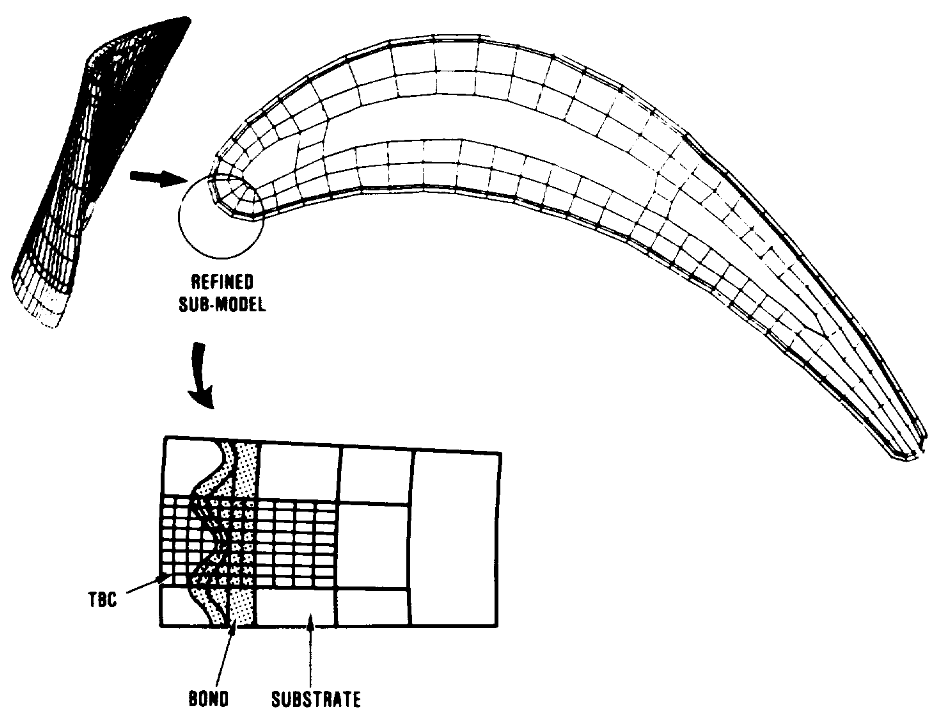

Figure 4. TFE731 HP Turbine Blade F.E. Model Incorporates Bond Coating and Zirconia Layers.

For computational efficiencies, typical preliminary design (PD) finite element models were first constructed to analyze the bulk behavior of the TBC systems on the airfoil component (Figure 4). Critical locations, in terms of temperatures, stresses, and strains or their combinations, can be identified from these PD models. Refined sub-models are then constructed for analysis of critical locations. Detailed thermomechanical and thermochemical behaviors of the TBC systems and the interactions between the individual material regimes and the interfacial conditions are being analyzed via these refined sub-models. Major analysis work in this program is being performed with ANSYS, a commercially available general purpose finite element code.

For preliminary component design analyses (Phase I), TBC lives are being independently calculated for three operative damage modes:

- o Bond coating oxidation
- o Molten salt film damage, and
- o Thermomechanical stress induced spalling

Computation of the oxidation life of a TBC system in the preliminary design model is driven by the component thermal analysis and engine power requirements during a mission cycle.

Molten salt film damage life is calculated using the component thermal analysis, engine power requirements during a mission, and aircraft altitude (salt ingestion).

Zirconia spalling associated with thermomechanical stresses is calculated based on the analysis of the snap-cycle thermal transients as well as the steady-state condition and the rotational loads in a mission cycle. Calculated snap-cycle interfacial tensile stresses and the largest pre-existing flaw diameter (determined by NDE or calculated from bond strength tests) are used to estimate a stress intensity factor that the coating must endure without spalling. As indicated in subsequent paragraphs, the fracture toughness of the zirconia or the bond coating-zirconia interface is dependent upon exposure temperature and time. Time and temperature dependent changes in the zirconia or interfacial toughness are calculated based on the thermal analysis results of the component and a linear cumulative damage model to account for variations in a mission cycle.

Figure 5 is a schematic of the TBC life model that illustrates these three failure modes and the respective temperatures regimes at which these failure modes are likely to occur. Figure 6 illustrates parameters that affect each of these three major failure modes.

The preliminary design TBC life is assessed via a linear damage rule, composed of damages from these three modes during each of the mission cycles, assuming no interactions between these failure modes; that is

$$\text{Life} = [(\text{Life}_{oxid})^{-1} + (\text{Life}_{salt})^{-1} + (\text{Life}_{stress})^{-1}]^{-1}$$

TBC LIFE MODEL

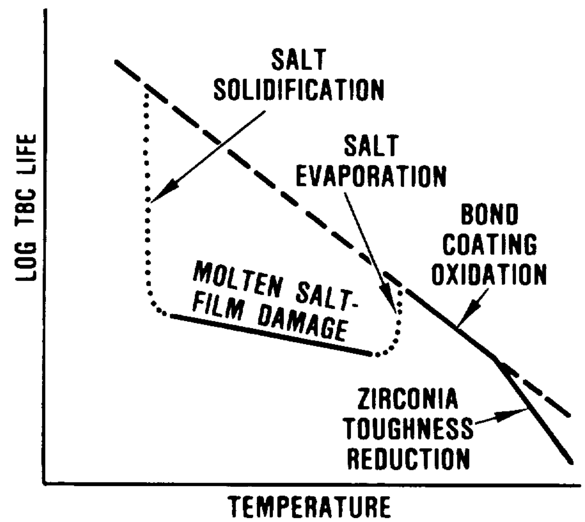

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Figure 5. TBC Life Model Has Three Failure Modes.

TBC DEGRADATION RATE = F_1 (MECHANICAL) + F_2 (OXIDATION) + F_3 (SALT DEPOSITION)

F_1 (MECHANICAL)

- COATING STRESSES
- TEMPERATURE
- MATERIAL SYSTEM
  - K_{IC}
  - FLAW SIZE
  - ELASTIC MODULUS
  - SPALLING STRAIN

F_2 (OXIDATION)

- TEMPERATURE
- CYCLE SEGMENT LENGTH
- MATERIALS SYSTEM

F_3 (SALT DEPOSITION)

- ALTITUDE (SALT INGESTION)
- TURBINE PRESSURE
- SALT EVAPORATION
- SALT SOLIDIFICATION
- TEMPERATURE
- GAS VELOCITY
- AIRCRAFT LOCATION
- MATERIALS SYSTEM

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Figure 6. TBC Life is a Function of Engine, Mission, and Materials System Parameters.

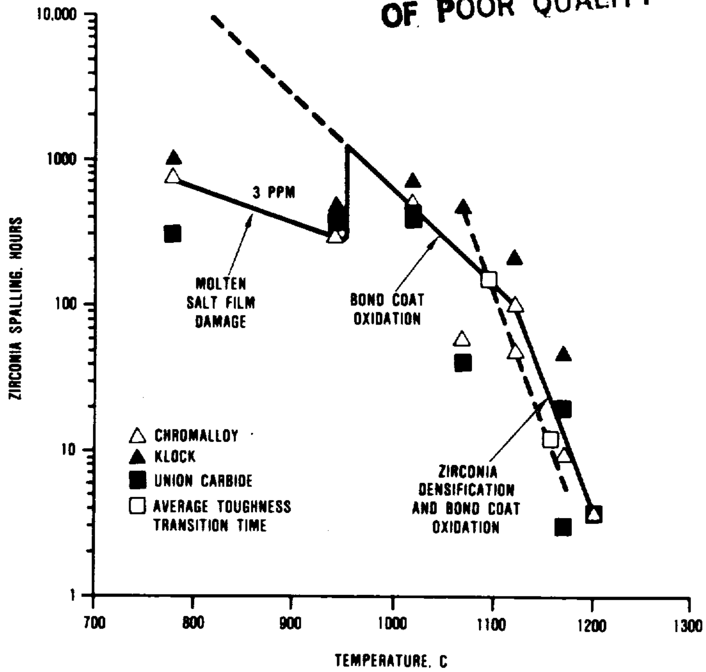
However, the refined sub-models are being constructed to be sufficiently flexible and detailed to analyze the interactions between these models. Subsequent improvements in Phase II of the program will incorporate failure mechanism interactions into the life prediction model.

Burner rig and mechanical property data have been obtained to quantify the capabilities of each of the TBC systems for each major mode of degradation. Burner rig test data are illustrated in Figures 7 and 8 for plasma-sprayed and EB-PVD TBC coating systems. These data indicate that bond coating oxidation, high temperature zirconia densificiation (sintering), and molten salt film damage at intermediate temperatures significantly affect TBC life (Figure 7). The length of the heating cycle must also be considered when computing a coating life (Figure 8).

Cohesive and interfacial toughness data have also been measured for plasma-sprayed and EB-PVD TBC systems (Figure 9). It has been observed for both types of coating systems that toughness is reduced by exposure at high temperatures. A step transition in toughness, which is associated with sintering shrinkage, is illustrated for plasma-sprayed TBC systems as a function of exposure time at 1100C in Figure 10. The transition to lower toughness levels correlates well with high temperature burner rig test data, as indicated in Figure 7.

Lives of these TBC systems are being predicted for TFE731 high-pressure turbine blades for factory engine test conditions, as well as business aircraft mission. Thermal analysis of the turbine airfoil (Figure 11) indicates that the bond coating oxidation degradation mode results in minimum predicted lives of approximately 7300 hours with the plasma-sprayed TBC system for the business aircraft missions and 1000 hours for the factory engine test conditions. Lives for other failure modes for the plasma-sprayed as well as the EB-PVD TBC systems are currently being analyzed.

This program is now in the third year of Phase I. The program schedule is provided in Figure 12.



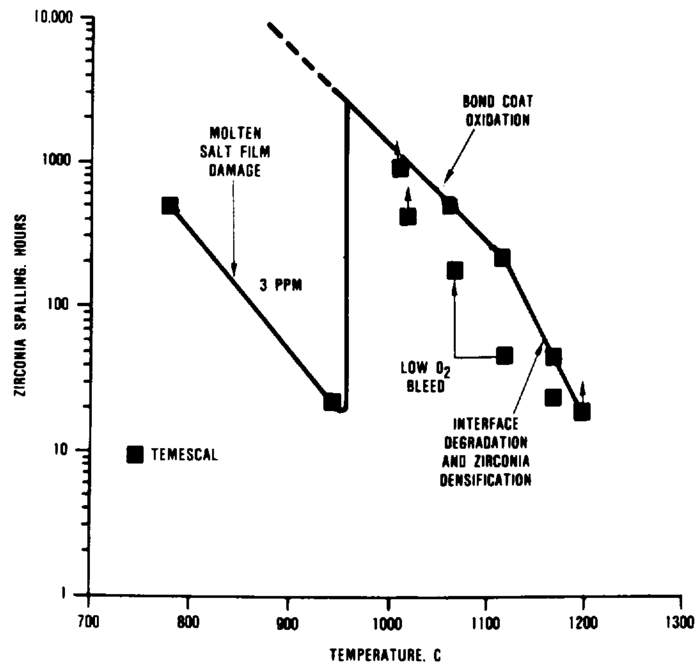


Figure 7. Three Degradation Modes Affect the Durability of Plasma-Sprayed and EB-PVD TBC Systems.

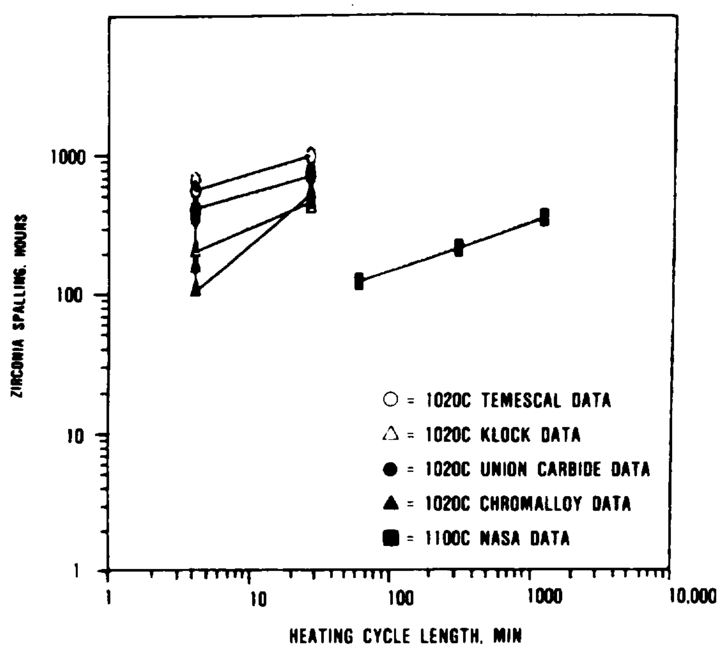
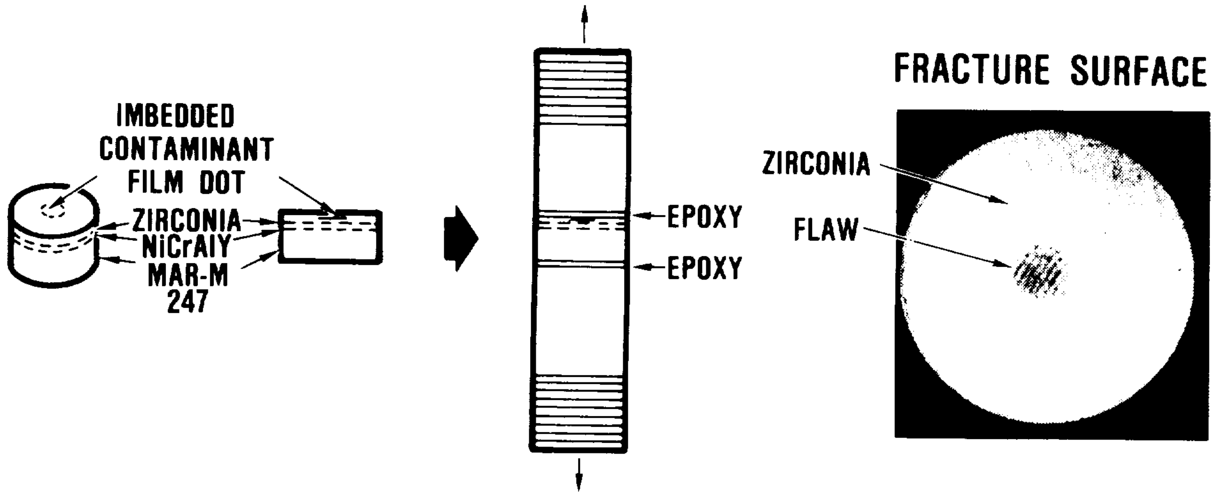


Figure 8. TBC Life Decreases with a Shorter Heating Cycle.



COHESIVE (INTERFACIAL) TOUGHNESS TEST

$$K_{IC} = 2/\sqrt{\pi}\ \sigma_F\ \sqrt{C/2}$$

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FIGURE 38

Figure 9. Cohesive and Interfacial Toughness are Determined with Modified Bond Strength Test.

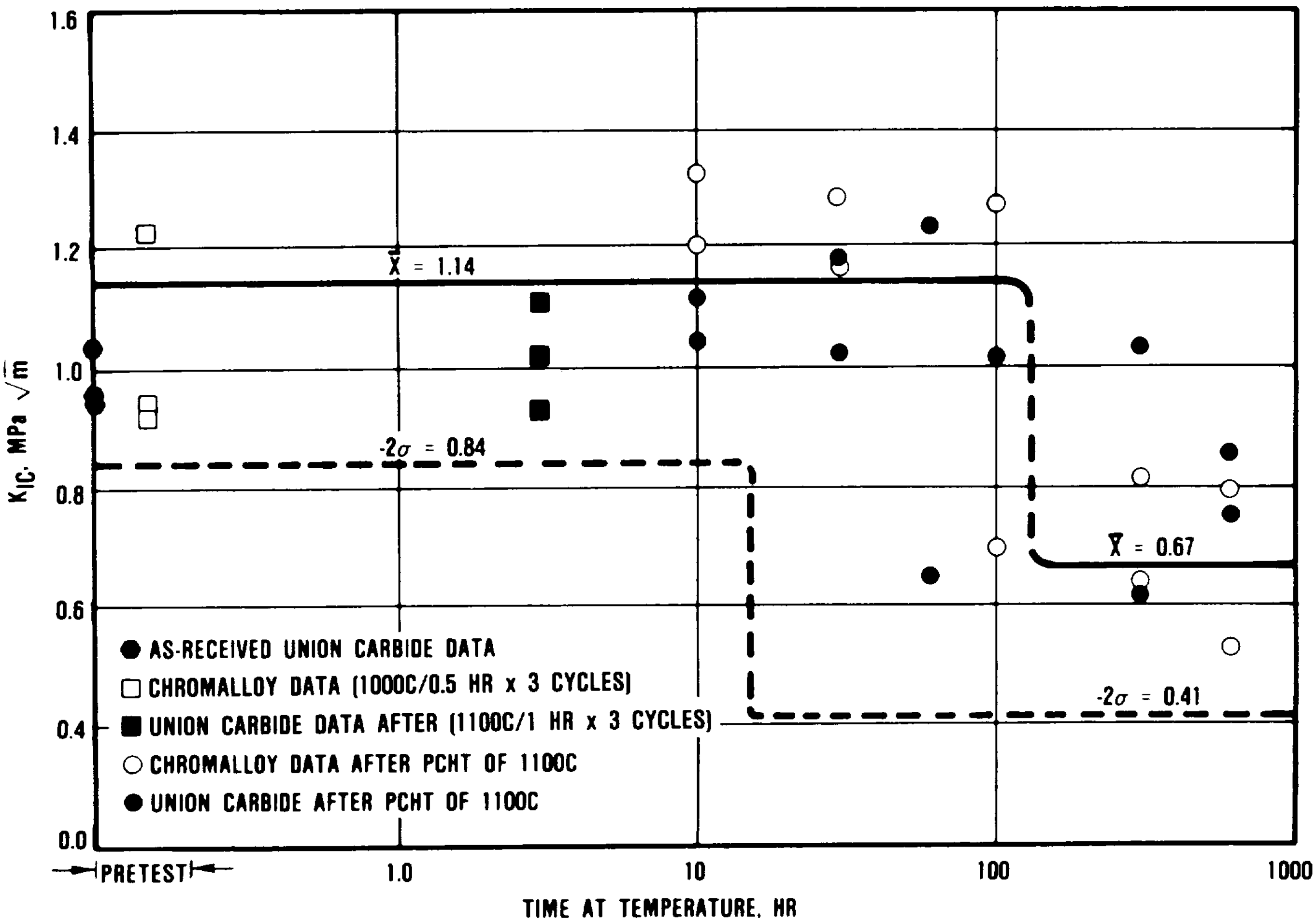

Figure 10. Fracture Toughness of Plasma-Sprayed Yttria (8 percent) Stabilized Zirconia is Reduced After Long Exposures at 1100C.

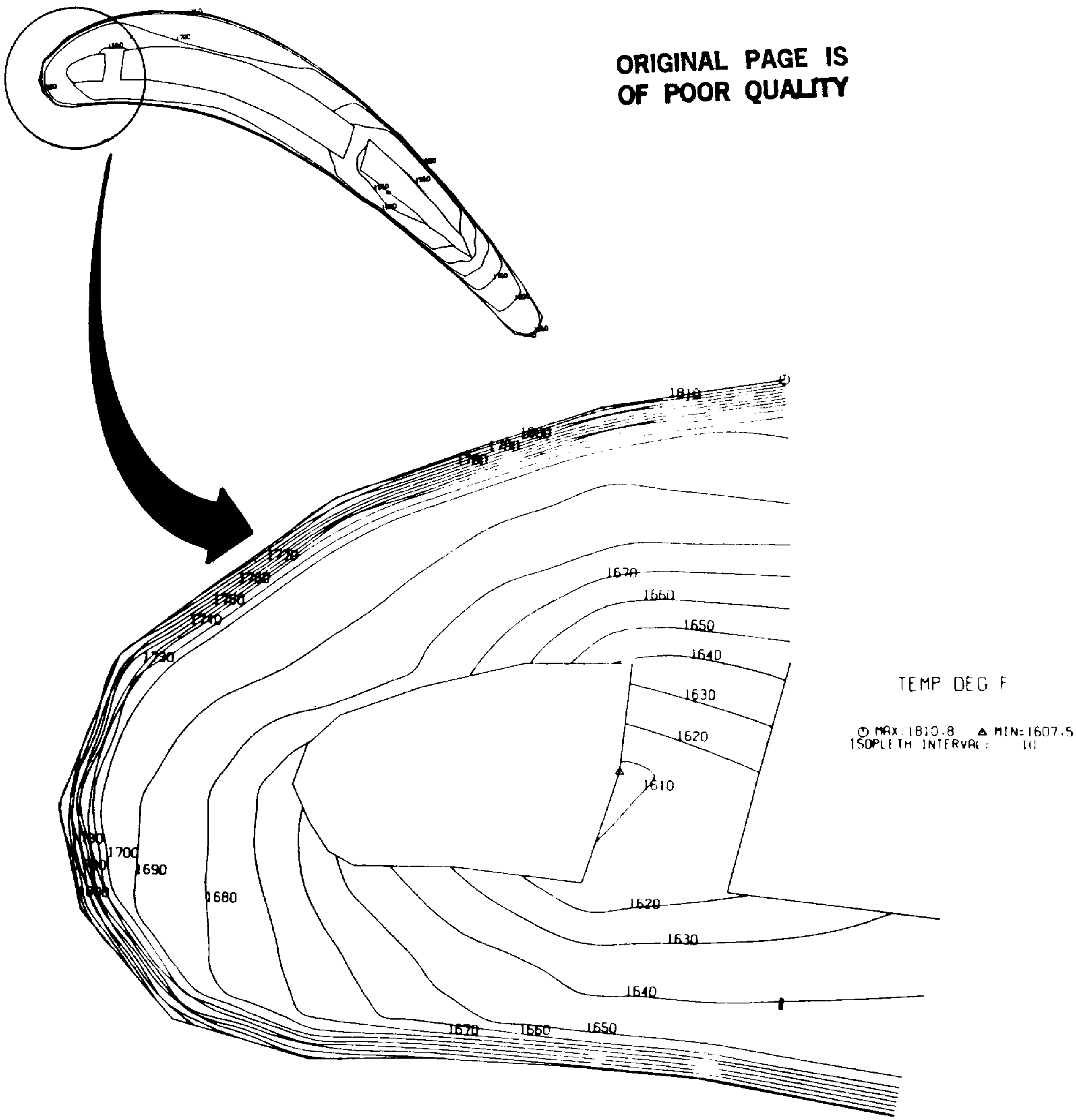

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Figure 11. Thermal Analysis of TBC-Coated Blade has been Conducted.

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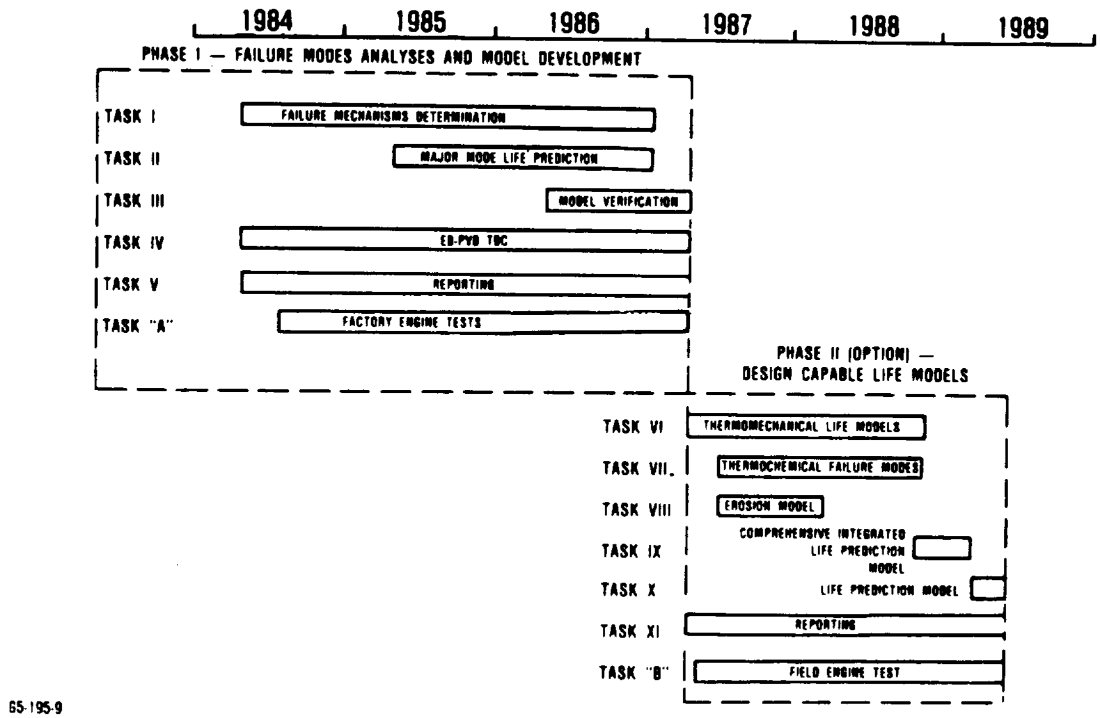

Figure 12. TBC Life Prediction Schedule.