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ADVANCED THERMAL BARRIER COATING SYSTEM DEVELOPMENT

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TECHNICAL PROGRESS REPORT

to the

U.S. DEPARTMENT OF ENERGY

Oak Ridge Operations Office

Oak Ridge, Tennessee

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Submitted By

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Advanced Thermal Barrier Coating System Development

Program Objectives

The objectives of the program are to provide an improved TBC system with increased temperature capability and improved reliability relative to current state of the art TBC systems. The development of such a coating system is essential to the ATS engine meeting its objectives.

The base program consists of three phases:

Phase I: Program Planning - Complete
Phase II: Development
Phase III: Selected Specimen - Bench Test

Work is currently being performed in Phase II of the program. In phase II, process improvements will be married with new bond coat and ceramic materials systems to provide improvements over currently available TBC systems. Coating reliability will be further improved with the development of an improved lifing model and NDE techniques. This is being accomplished through according to the following program tasks:

II.1 Process Modelling
II.2 Bond Coat Development
II.3 Analytical Lifing Model
II.4 Process Development
II.5 NDE, Maintenance and Repair
II.6 New TBC Concepts

Phase III of the program will proof test the best of the newly developed TBC systems on airfoil sections in a combustor test passage at the Westinghouse Science and Technology Center.

Technical Progress Report

Task II.2 Bond Coat Development

The Advanced Thermal Barrier Coating System Development program is designed specifically to provide a coating capable of meeting ATS engine operating requirements. Since it is known that there is considerable interaction between the superalloy substrate composition and the coating performance, it is imperative that the coatings be developed and tested on the alloys being considered for the engine. Three alloys are being considered in the program, two blade alloys CMSX-4 and MarM002, and one vane alloy IN-939. CMSX-4 was selected as the base material for this study.

Numerous ingots of the three alloys were cast and received. These were provided in a solution annealed condition. These ingots are being machined to provide test pins for deposition optimization as well as new coating development (figure 1).

Task II.2.1 Bond Coat Deposition Process

Electron beam physical vapor deposition (EB-PVD) and low pressure plasma spray (LPPS) are high temperature vacuum processes for depositing bond coat materials to turbine components. EB-PVD provides a high density coating free of internal oxides. High process temperatures, low chamber pressure and high coating particle velocities in LPPS bond coats provide coatings nearly as good as EB-PVD. Due to high capital equipment costs, however, these processes are inherently expensive. Shrouded plasma spray (SPS), Gator Gard (GG), and high velocity oxy-fuel (HVOF) are three cost effective alternatives to the vacuum processes, however, the coating quality has not been good. In task II.2.1, SPS, GG, and HVOF processes will be optimized for the baseline bond coat material and the performance of the material will be compared directly with the performance of EB-PVD and LPPS bond coats. A statistically designed set of coating depositions parameters has been specified for these processes. The design consists of a two iterations consisting of 6 variables in an the initial study and 4 variables in a second fine tuning study. The variables selected for consideration for the initial coating trials are shown in table 1. Coating quality will be evaluated with respect to coating density, oxide inclusions, surface finish, and deposition rate/efficiency.

Table 1: Optimization Process Variables

SPS	Gator Gard	HVOF
Shroud gas flow	Shrouded/unshrouded	Powder port
Gun distance	Orifice size (velocity)	Fuel/O_2 flow
Anode type	Particle size	Gun geometry
Primary gas flow	Current	Carrier gas flow
Secondary gas flow	Gun distance	Powder size
Current	Primary gas flow	Cooling jets
		Gun Distance
		Gun Speed

Task II.2.2 Evaluate Bond Coat Chemistry

In optimizing blade and vane alloys for high temperature mechanical performance, oxidation and hot corrosion of the base alloy has suffered. To provide the required TBC system life the bond coat chemistries have to possess inherent oxidation resistance, compatibility with the substrate alloy and provide an appropriate surface for ceramic top coat adherence. Bond coat chemistries have been reviewed with Praxair, and seven of the ten program chemistries have been ordered and will be delivered during the next reporting period. The remaining three program chemistries have been identified and are being reviewed in light of processing limitations.

Task II.2.2.8 Sol-Gel Bond Coats

In addition to the conventional plasma sprayed bond coat materials, a sol-gel coating process is being evaluated for depositing a new ceramic bond coat material. Stable sols have been fabricated from organo-metallic monomers. Test sample coating has been accomplished by a simple dip coating process. The large volumetric shrinkage during drying and sintering of the coating, however, led to considerable coating cracking. Deposition trials are continuing to address this issue and will be addressed during the next reporting period.

Task II.3 Analytical Lifing Model

TBC Analytical Lifing Model development is being performed in conjunction with Southwest Research Institute. Efforts during the last reporting period include evaluating current TBC lifing models and defining applicable mechanisms and equations for an improved TBC lifing model. The model will take a mechanistic approach following the HOST [1] model. This model has been reviewed in concert with models developed at NASA [2], Pratt and Whitney[3,4,5], Southwest Research Institute[6], and Garrett [7]. The models were analyzed as to the factors that affect coating life. TBC spallation, erosion, and hot corrosion (figure 2) were identified as the primary modes of degradation and for the skeleton of the lifing model. Key parameters and constitutive equations were identified for each mechanism involved in the coating degradation. Mechanisms being addressed include:

a) thermomechanical fatigue,
b) bond coat oxidation,
c) creep and stress relaxation in the bond coat,
d) out-of-plane stress/curvature effects,
e) sintering of TBC,
f) bond coat interdiffusion.

The model will initially focus on TBC spallation. Essential features of the model are described in figure 3. TBC failure mechanisms, the corresponding governing equations, variables, model parameters, and test requirements have been summarized.

Test requirements for supporting the lifing model have been initiated. These tests include determination of oxidation kinetics, low cycle fatigue behavior of the TBC, constitutive property measurement on the TBC, bond coat, and substrate, as well as characterization of the effects of bond coat surface roughness, curvature, and sintering on the LCF behavior of the TBC.

Task II.4 Manufacturing Process Development

Task II.4.2 Cooling Hole Masking Technology

Coating of turbine component surfaces results in a restriction of cooling holes and alters the heat management of the engine. Significant changes in cooling hole dimensions can have catastrophic effects. It is, therefore, necessary to understand the extent of cooling hole restriction accompanying TBC deposition and to 1) account for such restriction in the cooling hole design, 2) prevent cooling hole restriction, or 3) remove coating material which fills in the cooling holes.

Current masking techniques have been identified and are being reviewed. Additional techniques have been suggested for possible development. Table 2 shows a list of masking techniques that are under consideration.

Table 2: Cooling hole masking techniques

Masking Technique	Advantages	Disadvantages	Status
Programmed spray process	no manual mask no contamination	•requires robotics •high cost	contacting vendors
Automated pin insertion	no contamination	•requires robotics •difficult for refurbishing	contacting vendors
Air flow	no contamination no complex automation	•requires optimized air flow •difficult to control	contacting vendors
Tape	easy to apply	•strip of bare metal •sharp edge on tbc	in use for tbcs and bond coats
Bar shadowing	bar built into fixture	•strip of bare metal	in use by vendors on other products
Selectively cured polymers	masks holes only	•requires several polymers and organic solvents	internal discussion
Polymer extrusion	masks holes only	•polymer removal •requires surface grinding	internal discussion
Hole filling(polymer paste)	easy to apply paste	•contamination •requires secondary machining	paste being formulated

The masking techniques can be split into two classes. The first class requires complex automation that may not be readily available for evaluation. The second class requires the use of several complex organic compounds; compatibility and predictable interaction of the components is critical. This list will be down selected and tested.

Two cooling hole test specimens have been designed. A flat plate was designed for initial hole restriction measurements. The flat plate will be useful for several masking and re-machining techniques. A cylindrical pipe design will be used for several masking techniques that require an internal air passage. The pipe also provides a curved survace representative of airfoil curvature. The preliminary designs will be discussed with machining vendor.

Task II.4.3 Hole Re-Drilling

An alternative to cooling hole masking is to redrill the cooling holes after coating. Current machining techniques have been identified and are being reviewed. Table 3 shows a list of techniques that are being evaluated.

Table 3: Cooling hole re-machining techniques

Machining Technique	Advantages	Disadvantages	Status
Water-jet cutting	compatible with non-conductive materials	•current resolution •under cut on angles	contacting vendors
Laser cutting	allows precise positioning of beam	•thermal stresses •heat affected zone •ceramic to metal transition	internal discussion

Task II.5 NDE, Maintenance, and Repair

The term "prime reliant coating" has been adopted to refer to the bond coat / TBC system for the ATS engine. What this means is that for certain components, rapid degradation of the component will ensue if the TBC system fails. Appropriate measures must, therefor, be taken to ensure that the coating meets the Westinghouse quality standards as new equipment and throughout the life of the coating. Since detailed inspection of the coatings is limited and component refurbishment at every inspection interval is impractical, appropriate NDE methods, sensitive to the types of microstructural features that cause failure, and local repair methods must be established. In addition, on-line monitoring of the TBC during engine operation is essential to limit damage in the event of a coating failure.

Task II.5.1 Repair and Maintenance

Localized repair and maintenance of TBC coatings involves determination of the extent of coating damage, localized TBC and bond coat stripping, base metal inspection, re-application of the bond coat and TBC and final blending and inspection of the component. Techniques have already been established for repairing some conventionally cast and directionally solidified alloys. These techniques have not been demonstrated on the ATS vane alloy IN939 and no repair techniques has been established for components made from the single crystal blade alloy CMSX-4. Repair methods for both alloys are under investigation.

The coating repair system has been identified and will be an overlay CoNiCrAlY bond coat with an 8% yttria stabilized APS top coat. The attributes to be evaluated are:

- local repair size,
- location limitations,
- thermal properties,
- bond quality,
- mechanical integrity,
- substrate interaction.

Although the program is not intended to make a field repair method, field adaptability will be evaluated as it has potentially significant cost implications.

In order to produce a controlled experiment, foreign object and thermal damage must be simulated on test coupons. Alternatives for simulating damaged coatings are being reviewed with coating vendors.

Task II.5.2 Out of Frame NDE

Thermal wave imaging (TWI) has been identified as a promising technique for examining bond coat and TBC integrity. In order to assess the applicability of TWI to TBC defects, reference coupons are being designed to simulate potential life limiting defects. Three types of reference coupons have been identified.

1. Simulated TBC debond - leads to localized hot spot and TBC overheating
2. Bond coat oxidation coupons - excessive oxidation leads to interface stresses
3. TBC thickness coupons - non-uniformity results in excessive TBC or metal tempertures.

TWI will be coupled with existing NDE techniques to examine coatings and determine limits of applicability.

Task II.6 New TBC Concepts

Yttria-stabilized zirconia is the mainstay of the aero and industrial gas turbine TBC coating industries. Significant differences in the operating mode of an IGT relative to an aero engine exist. The long time at temperature in an IGT, has created significant concerns as to whether current zirconia TBC's are capable of operating under ATS conditions.

Task II.6.1 New TBC Chemistry
The emphasis of New TBC Concepts is to evaluate alternate ceramic materials for TBC coatings. The following criteria was applied to candidate ceramic materials as a means of selecting TBC compositions.

- High melting Temperature >1700°C
- Does not decomposition on melting
- Low CTE <4W/mK at 1000°C
- High CTE, preferably >9ppm/°C
- Hot corrosion and acid resistant
- Phase stable (operating temperature to room temperature)
- Sintering resistant, microstructurally stable
- Non-reactive toward MCrAlY or alumina passivation scale
- Erosion resistant

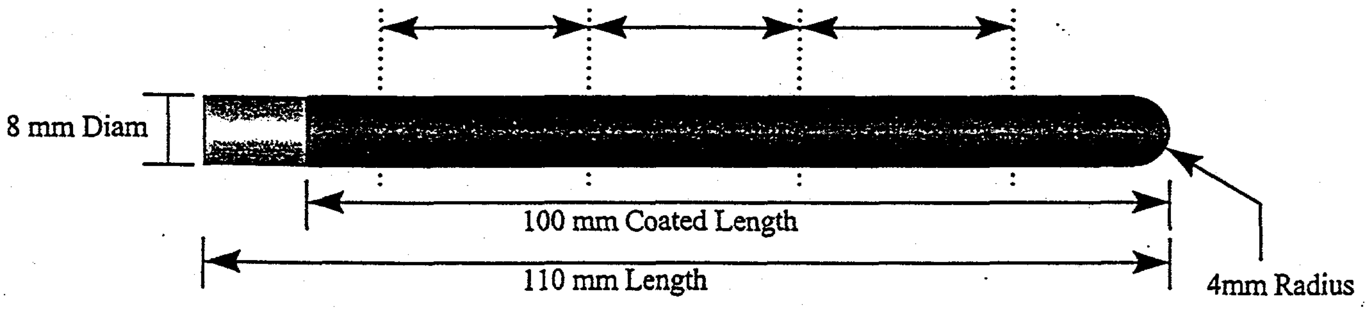
These are the baseline requirements. Literature data is limited for most compositions of interest.

The literature search for new TBC compositions was restricted to oxides. A list of compositions has been generated and four of these are in the process of being fabricated. Delivery of these new compositions is expected during the next reporting period. The remaining two program ceramic compositions will be finalized shortly.

Task II.6.3 Process Optimization
Discussions were also held to identify a means for optimizing the APS deposition of YSZ. Through optimization of the ceramic particle size distribution, TBC microstructures can be optimized and deposition efficiency improved. YSZ powder modifications are being finalized.

Advanced TBC System Development

Test Pin Dimensions and Sectioning



Substrates

- CMSX 4
- MarM002
- IN 939

Figure 1: Test pin geometry used for bond coat and TBC deposition studies.

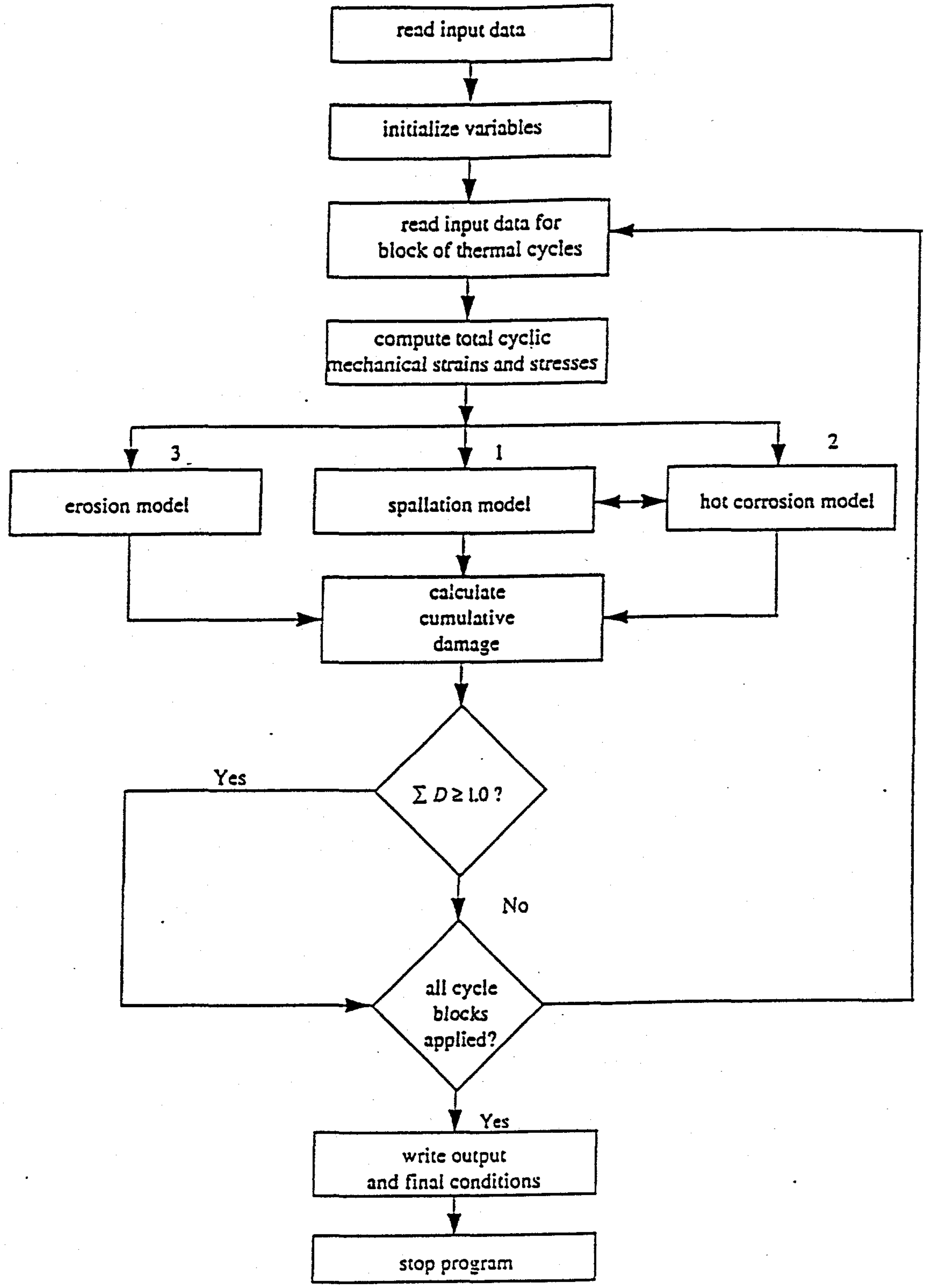


Figure 2: A flow chart for the proposed TBC life prediction model

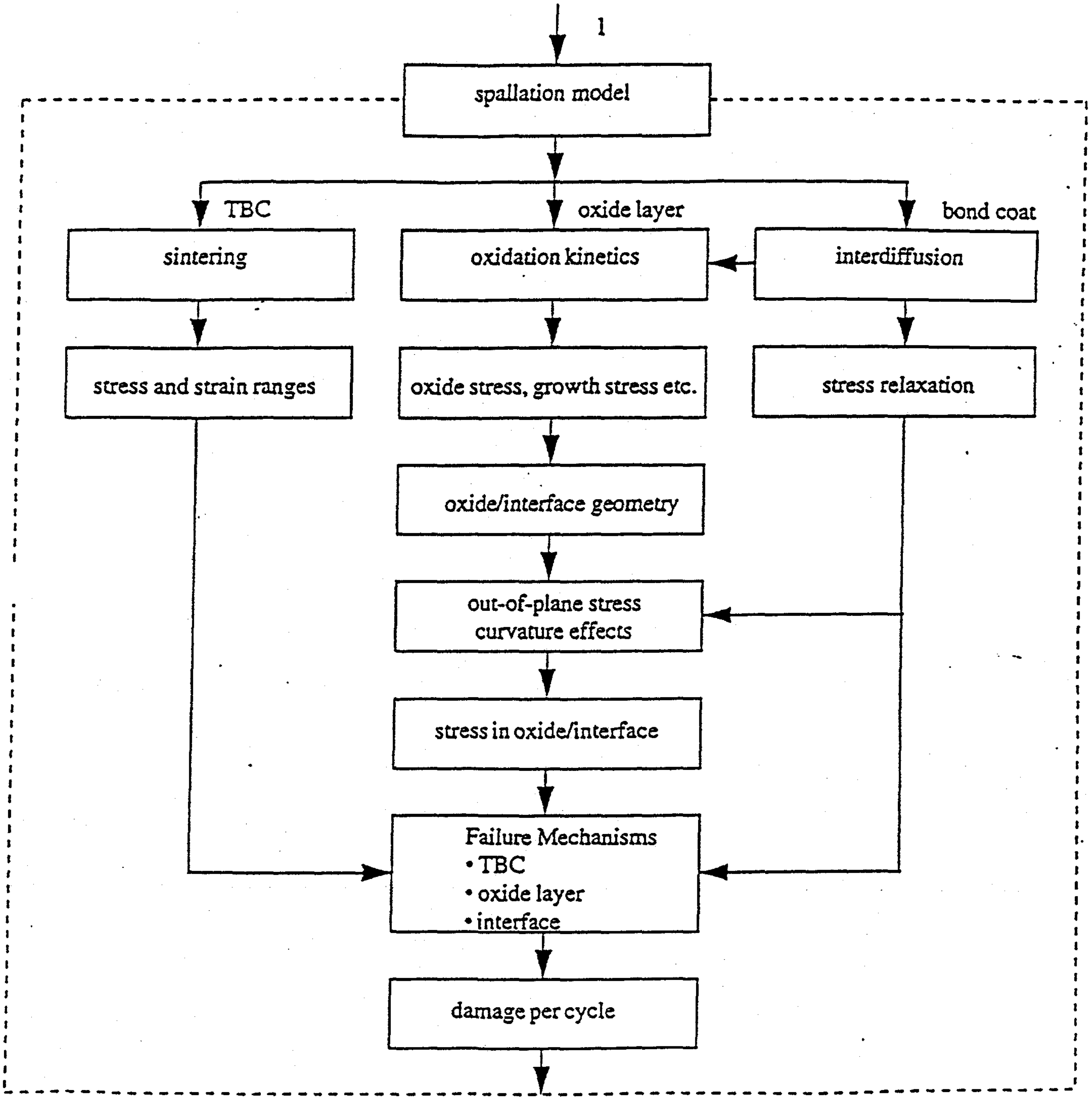


Figure 3: A flow chart for the proposed TBC spallation model