

*NASA Conference Publication 10170*

# Thermal Barrier Coating Workshop Abstracts

*Abstracts from proceedings of a Workshop  
held at and sponsored by NASA Lewis Research Center  
Cleveland, Ohio  
March 27–29, 1995*



National Aeronautics and  
Space Administration

Office of Management

**Scientific and Technical  
Information Program**

1995

## **FOREWORD**

Thermal barrier coating (TBC) has been the subject of intense interest as a near-term means to meet materials requirements for next generation heat engines. While TBC has been incorporated into engines for over thirty years and is now being used in some advanced applications, much of the development work has been empirical in nature. The multiple challenges of higher operating temperatures, use in critical applications, and increased durability and reliability requirements demand that numerous fundamental issues be addressed. The goals of the Thermal Barrier Coating Workshop are to assess the state of TBC knowledge and specifically identify critical gaps in the knowledge that hinder use in advanced applications. The Workshop goals are addressed through presentations on topics ranging from defining the need for thermal barrier coating to the design of future coatings, and through extensive discussion of the issues facing TBC use. The participation of both speakers and attendees should provide a broad and well informed view of these issues.

This program contains the abstracts for the presentations in the workshop. Workshop proceedings will be mailed to attendees shortly after the workshop.

William J. Brindley  
Chairman TBC Workshop

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**THERMAL BARRIER COATING (TBC) ORGANIZING COMMITTEE**

**William J. Brindley  
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**Woo Y. Lee  
Oak Ridge National Laboratory  
Oak Ridge, Tennessee**

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**John G. Goedjen  
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**AGENDA**  
**Thermal Barrier Coating Workshop**  
**March 27-29, 1995**

**MONDAY, MARCH 27, 1994**

6:00 - 10:00 P.M. Registration - Ballroom Hallway  
 Reception - Canterbury/Dover Ballrooms

**TUESDAY, MARCH 28, 1994**

7:00 A.M. Registration  
 Continental Breakfast - Ballroom Hallway  
 All presentations will be in the Bassett/Bradley Ballrooms

8:00 A.M. Welcome  
 Salvatore J. Grisaffe, Director of Aerospace Technology, NASA Lewis Research Center

8:10 A.M. Opening Remarks  
 W.J. Brindley, NASA Lewis Research Center

8:15 A.M. Keynote Speaker  
 A Design Perspective on Thermal Barrier Coatings  
 F.O. Soechting, Pratt & Whitney . . . . . 3

**Overviews**

8:45 A.M. Thermal Barrier Coatings for Aircraft Engines—History and Directions  
 R.A. Miller, NASA Lewis Research Center . . . . . 5

9:15 A.M. Thermal Barrier Coatings Issues in Advanced Land-Based Gas Turbines  
 W.P. Parks,\* Office of Industrial Technologies, Department of Energy, and W.Y. Lee  
 and I.G. Wright, Oak Ridge National Laboratory . . . . . 7

9:45 A.M. BREAK

10:00 A.M. Measurement Methods and Standards for Processing and Application of Thermal  
 Barrier Coatings  
 S.J. Dapkunas, National Institute of Standards and Technology . . . . . 9

10:30 A.M. Thermal Barrier Coatings for Diesel Engines  
 J.W. Fairbanks, Office of Transportation Technologies, Department of Energy . . . . . 11

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\*Speaker.

**Thermal/Mechanical/Chemical/Physical Properties**

8:00 A.M. Process, Properties and Environmental Response of Plasma Sprayed Thermal Barrier Coatings  
R.C. Novak, Pratt & Whitney Talon, Inc. . . . . 29

8:30 A.M. Thermal Conductivity of Zirconia Thermal Barrier Coatings  
R.B. Dinwiddie\* and S.C. Beecher, Oak Ridge National Laboratory; and  
B.A. Nagaraj and C.S. Moore, GE Aircraft Engines . . . . . 31

9:00 A.M. Mechanical Properties Testing and Results for Thermal Barrier Coatings  
T.A. Cruse\* and B.P. Johnsen, Vanderbilt University . . . . . 33

9:30 A.M. Properties of Plasma Sprayed Bond Coats  
W.J. Brindley, NASA Lewis Research Center . . . . . 35

10:00 A.M. BREAK

10:15 A.M. Thick Thermal Barrier Coatings for Diesel Engines  
M.B. Beardsley, Caterpillar, Inc. . . . . 37

10:45 A.M. Some Aspects of the Hot Corrosion of Thermal Barrier Coatings  
R.L. Jones, Naval Research Laboratory . . . . . 39

11:15 A.M. Discussion

12:00 noon LUNCH

**Modeling**

1:00 P.M. Thermal Fracture Mechanisms in Ceramic Thermal Barrier Coatings  
K. Kokini,\* B.D. Choules, and Y.R. Takeuchi, Purdue University . . . . . 41

1:30 P.M. A Software Tool to Design Thermal Barrier Coatings  
G. Petrus\* and B.L. Ferguson, Deformation Control Technology, Inc. . . . . 43

2:00 P.M. Thermal Barrier Coating Life Modeling in Aircraft Gas Turbine Engines  
D.M. Nissley, Pratt & Whitney . . . . . 45

2:30 P.M. Discussion

3:15 P.M. Wrap up/identify critical issues and directions

3:45 P.M. Adjourn

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\*Speaker.

# ABSTRACTS

## A DESIGN PERSPECTIVE ON THERMAL BARRIER COATINGS

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1-15-2001  
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This technical paper addresses the challenges for maximizing the benefit of thermal barrier coatings for turbine engine applications. The perspective is from a customer's viewpoint, a turbine airfoil designer, who is continuously challenged to increase the turbine inlet temperature capability for new products while maintaining cooling flow levels or even reducing them. This is a fundamental requirement to achieve increased engine thrust levels. Developing advanced material systems for the turbine flowpath airfoils is one approach to solve this challenge; such as high temperature nickel based superalloys or thermal barrier coatings to insulate the metal airfoil from the hot flowpath environment. The second approach is to increase the cooling performance of the turbine airfoil, which enables increased flowpath temperatures and reduced cooling flow levels.

Thermal barrier coatings have been employed in jet engine applications for almost 30 years. The initial application was on augmentor liners to provide thermal protection during afterburner operation. However, the production use of thermal barrier coating in the turbine section has only occurred in the past 15 years. The application was limited to stationary parts, and only recently incorporated on the rotating turbine blades. This lack of endorsement of thermal barrier coatings resulted from the poor initial durability of these coatings in high heat flux environments. Significant improvements have been made to enhance spallation resistance and erosion resistance which has resulted in increased reliability of these coatings in turbine applications.

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THERMAL BARRIER COATINGS FOR AIRCRAFT ENGINES—  
HISTORY AND DIRECTIONS

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Thin thermal barrier coatings for protecting aircraft turbine section airfoils will be examined. The discussion focusses on those advances that led first to their use for component life extension and more recently as an integral part of airfoil design. It will be noted that development has been driven by laboratory rig and furnace testing corroborated by engine testing and engine field experience. The technology has also been supported by performance modeling to demonstrate benefits and life modeling for mission analysis.

Factors which have led to the selection of the current state-of-the-art plasma sprayed and physical vapor deposited zirconia-yttria/MCrAlY TBCs will be emphasized as will observations fundamentally related to their behavior.

Current directions in research into thermal barrier coatings and recent progress at NASA will also be noted.



THERMAL BARRIER COATINGS ISSUES IN ADVANCED  
LAND-BASED GAS TURBINES

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The Department of Energy's Advanced Turbine System (ATS) program is aimed at fostering the development of a new generation of land-based gas turbine systems with overall efficiencies significantly beyond those of current state-of-the-art machines, as well as greatly increased times between inspection and refurbishment, improved environmental impact, and decreased cost. The proposed duty cycle of ATS turbines will require the use of different criteria in the design of the materials for the critical hot gas path components. In particular, thermal barrier coatings will be an essential feature of the hot gas path components in these machines. While such coatings are routinely used in high-performance aircraft engines and are becoming established in land-based turbines, the requirements of the ATS turbine application are sufficiently different that significant improvements in thermal barrier coating technology will be necessary. In particular, it appears that thermal barrier coatings will have to function on all airfoil sections of the first stage vanes and blades to provide the significant temperature reduction required. In contrast, such coatings applied to the blades and vanes of advanced aircraft engines are intended primarily to reduce air cooling requirements and extend component lifetime; failure of those coatings can be tolerated without jeopardizing mechanical or corrosion performance. A major difference is that in ATS turbines these components will be totally reliant on thermal barrier coatings which will, therefore, need to be highly reliable even over the leading edges of first stage blades. Obviously, the ATS program provides a very challenging opportunity for TBCs, and involves some significant opportunities to extend this technology.

MEASUREMENT METHODS AND STANDARDS FOR PROCESSING AND  
APPLICATION OF THERMAL BARRIER COATINGS

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Application of thermal barrier coatings deposited by thermal spray, physical vapor and possibly other methods is expected to be extended from aircraft gas turbines to industrial and utility gas turbines as well as diesel engines. This increased usage implies the participation of greater numbers of processors and users, making the availability of standards for process control and property measurement more important. Available standards for processing and evaluation of thermal barrier coatings are identified as well as those needed in the future but currently unavailable.

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## THERMAL BARRIER COATINGS APPLICATION IN DIESEL ENGINES

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Commercial use of thermal barrier coatings in diesel engines began in the mid 70's by Dr. Ingard Kvernes at the Central Institute for Industrial Research in Oslo, Norway. Dr. Kvernes attributed attack on diesel engine valves and piston crowns encountered in marine diesel engines in Norwegian ships as hot-corrosion attributed to a reduced quality of residual fuel. His solution was to coat these components to reduce metal temperature below the threshold of aggressive hot-corrosion and also provide protection.

Roy Kamo introduced thermal barrier coatings in his "Adiabatic Diesel Engine" in the late 70's. Kamo's concept was to eliminate the engine block water cooling system and reduce heat losses. Roy reported significant performance improvements in his thermally insulated engine at the SAE Congress in 1982.

Kamo's work stimulates major programs with insulated engines, particularly in Europe. Most of the major diesel engine manufacturers conducted some level of test with insulated combustion chamber components. They initially ran into increased fuel consumption. The German engine consortium had Prof. Woschni of the Technical Institute in Munich. Woschni conducted testing with pistons with air gaps to provide the insulation effects. Woschni indicated the hot walls of the insulated engine created a major increase in heat transfer he refers to as "convection vive." Woschni's work was a major factor in the abrupt curtailment of insulated diesel engine work in continental Europe. Ricardo in the UK suggested that combustion should be reoptimized for the hot-wall effects of the insulated combustion chamber and showed under a narrow range of conditions fuel economy could be improved.

The Department of Energy has supported thermal barrier coating development for diesel engine applications. In the Clean Diesel - 50 Percent Efficient (CD-50) engine for the year 2000, thermal barrier coatings will be used on piston crowns and possibly other components. The primary purpose of the thermal barrier coatings will be to reduce thermal fatigue as the engine peak cylinder pressure will nearly be doubled. As the coatings result in higher available energy in the exhaust gas, efficiency gains are achieved through use of this energy by turbochargers, turbocompounding or thermoelectric generators.

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THERMAL BARRIER COATING EXPERIENCE IN THE GAS TURBINE ENGINE

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Thermal Barrier Coatings (TBC), provide thermal insulation and oxidation resistance in an environment consisting of hot combustion gases. TBCs consist of a two layer system. The outer ceramic layer provides good thermal insulation due to the low thermal conductivity of the ceramic coatings used, while the inner metallic bond coat layer provides needed oxidation resistance to the underlying superalloy. Pratt & Whitney has over a decade of experience with several generations of TBC systems on turbine airfoils. This paper will focus on the latest TBC field experience along with a proposed durability model.

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## PVD TBC EXPERIENCE ON GE AIRCRAFT ENGINES

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The higher performance levels of modern gas turbine engines present significant challenges in the reliability of materials in the turbine. The increased engine temperatures required to achieve the higher performance levels reduce the strength of the materials used in the turbine sections of the engine. Various forms of Thermal Barrier Coatings (TBCs) have been used for many years to increase the reliability of gas turbine engine components. Recent experience with the Physical Vapor Deposition (PVD) process using ceramic material has demonstrated success in extending the service life of turbine blades and nozzles. Engine test results of turbine components with a 125  $\mu\text{m}$  (0.005 in) PVD TBC have demonstrated component operating temperatures of 56-83  $^{\circ}\text{C}$  (100-150  $^{\circ}\text{F}$ ) lower than uncoated components.

Engine testing has also revealed the TBC is susceptible to high angle particle impact damage. Sand particles and other engine debris impact the TBC surface at the leading edge of airfoils and fracture the PVD columns. As the impacting continues the TBC erodes away in local areas. Analysis of the eroded areas has shown a slight increase in temperature over a fully coated area, however, a significant temperature reduction was realized over an airfoil without any TBC.

## TBC EXPERIENCE IN LAND BASED GAS TURBINES

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This paper summarizes prior and on-going machine evaluations of TBC coatings for power generation applications. Rainbow testing of various TBCs on turbine nozzles, shrouds and buckets are described along with one test on combustor liners. GEPG has conducted over 15 machine tests with TBC coated turbine nozzles of various coatings. Rainbow test times generally range between 10,000 to 24,000 hours. TBC performance has been quite good and additional testing, including TBC's on shrouds and buckets, is continuing. The results show that TBCs have the capability of surviving in power generation machines for the times required. The earlier rainbow tests which evaluated various top coat compositions resulted in confirmation of the superiority of YSZ and especially the 6-8 YSZ composition. On-going tests are more focused on TBC process and property variations. The prevalent failure modes seen thusfar in the various rainbow tests are erosion, foreign object damage and buildup of deposits. Additional post test analysis is required to investigate bond coat oxidation and other time/temperature dependent changes to the system.

Included is a brief comparison of TBC requirements for power generation and aircraft turbines.

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PERSPECTIVE ON THERMAL BARRIER COATING FOR INDUSTRIAL  
GAS TURBINE APPLICATIONS

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Thermal Barrier Coatings (TBC's) have been used in high thrust aircraft engines for many years, and have proved to be very effective in allowing higher turbine inlet temperatures. TBC life requirements for aircraft engines are typically less than those required in industrial gas turbines. The use of TBC's for industrial gas turbines can increase if durability and longer service life can be successfully demonstrated.

This paper will describe current and future applications of TBC's in industrial gas turbine engines. Early testing and applications of TBC's will also be reviewed. Areas of concern from the engine designer's and materials engineer's perspective are identified and evaluated. This paper focuses on the key factors that are expected to influence utilization of TBC's in advanced industrial gas turbine engines. It is anticipated that reliable, durable and highly effective coating systems will be produced that will ultimately improve engine efficiency and performance.

OVERVIEW OF THERMAL BARRIER COATINGS IN DIESEL ENGINES

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An understanding of delamination mechanisms in thermal barrier coatings has been developed for diesel applications through nondestructive evaluation, structural analysis modeling and engine evaluation of various thermal barrier coatings. This knowledge has resulted in improved thermal barrier coatings which survive abusive cyclic fatigue tests in high output diesel engines. Significant efforts are still required to improve the plasma spray processing capability and the economics for complex geometry diesel engine components.

Data obtained from advanced diesel engines on the effect of thermal barrier coatings on engine fuel economy and emissions has not been encouraging. Although the underlying metal component temperatures have been reduced through the use of the thermal barrier coating, engine efficiency and emission trends have not been promising.

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## THERMAL SPRAY PROCESSING

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Thermal spray processing has been used for a number of years to cost-effectively apply TBCs for a wide range of heat engine applications. In particular, bond coats are applied by plasma spray and HVOF techniques and partially-stabilized zirconia top coats are applied by plasma spray methods. Thermal spray involves melting and rapid transport of the molten particles to the substrate, where high-rate solidification and coating build-up occur. It is the very nature of this melt processing that leads to the unique layered microstructure, as well as the apparent imperfections, so readily identified with thermal spray. Modeling the process, process-induced residual stresses, and thermal conductivity will be discussed in light of a new understanding of porosity and its anisotropy. Microcracking can be understood using new approaches, allowing a fuller view of the processing-performance connection. Detailed electron microscopic, novel neutron diffraction and fracture analysis of the deposits can lead to a better understanding of how overall microstructure can be controlled to influence critical properties of the deposited TBC system.

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PVD TBC APPLICATIONS AND PROCESS DEVELOPMENT FOR AIRCRAFT ENGINES

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JET ENGINE APPLICATIONS FOR MATERIALS WITH  
NANOMETER-SCALE DIMENSIONS

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The performance of advanced military and commercial gas turbine engines is often linked to advances in materials technology. High performance gas turbine engines being developed require major material advances in strength, toughness, reduced density and improved temperature capability. The emerging technology of nanostructured materials has enormous potential for producing materials with significant improvements in these properties. Extraordinary properties demonstrated in the laboratory include material strengths approaching theoretical limit, ceramics that demonstrate ductility and toughness, and materials with ultra-high hardness. Nanostructured materials and coatings have the potential for meeting future gas turbine engine requirements for improved performance, reduced weight and lower fuel consumption.

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PROCESS, PROPERTIES AND ENVIRONMENTAL RESPONSE OF PLASMA  
SPRAYED THERMAL BARRIER COATINGS

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Experimental results are shown which demonstrate that the properties of plasma sprayed fully stabilized zirconia are strongly influenced by the process parameters. Properties of the coatings in the as-sprayed condition are shown to be additionally influenced by environmental exposure. This behavior is dependent on raw material considerations and processing conditions as well as exposure time and temperature.

Process control methodology is described which can take into consideration these complex interactions and help to produce thermal barrier coatings in a cost effective way while meeting coating technical requirements.

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## THERMAL CONDUCTIVITY OF ZIRCONIA THERMAL BARRIER COATINGS

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Thermal barrier coatings (TBCs) applied to the hot gas components of turbine engines lead to enhanced fuel efficiency and component reliability. Understanding the mechanisms which control the thermal transport behavior of the TBCs is of primary importance. Physical vapor deposition (PVD) and plasma spraying (PS) are the two most commonly used coating techniques. These techniques produce coatings with unique microstructures which control their performance and stability. The PS coatings were applied with either standard powder or hollow sphere particles. The hollow sphere particles yielded a lower density and lower thermal conductivity coating. The thermal conductivity of both fully and partially stabilized zirconia, before and after thermal aging, will be compared. The thermal conductivity of the coatings permanently increases upon exposed to high temperatures. These increases are attributed to microstructural changes within the coatings. Sintering of the as fabricated plasma sprayed lamellar structure is observed by scanning electron microscopy of coatings isothermally heat treated at temperatures greater than 1100°C. During this sintering process the planar porosity between lamella is converted to a series of small spherical pores. The change in pore morphology is the primary reason for the observed increase in thermal conductivity. This increase in thermal conductivity can be modeled using a relationship which depends on both the temperature and time of exposure. Although the PVD coatings are less susceptible to thermal aging effects, preliminary results suggest that they have a higher thermal conductivity than PS coatings, both before and after thermal aging. The increases in thermal conductivity due to thermal aging for partially stabilized plasma sprayed zirconia have been found to be less than for fully stabilized plasma sprayed zirconia coatings. The high temperature thermal diffusivity data indicate that if these coatings reach a temperature above 1100°C during operation, they will begin to lose their effectiveness as a thermal barrier.

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MECHANICAL PROPERTIES TESTING AND RESULTS FOR  
THERMAL BARRIER COATINGS

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Thermal Barrier Coatings (TBC's) provide a significant challenge in the evaluation of their mechanical properties in ways that provide data that is not specimen dependent. The paper reviews various developments of the principal author over the past several years for both plasma sprayed and physical vapor deposited (PVD) materials, as well as new data on the fatigue behavior of one material system. The test methods that have been employed address tensile and compressive modulus and ultimate strength, tensile and compressive fatigue strength, and interfacial strength, which testing is now underway.

Property testing is especially difficult for TBC's owing to the limitation on fabrication thickness of the coating. Bending tests are not used as these tests do not provide sufficiently uniform states of strain for property evaluations. Test specimens with uniform states of axial stress have been devised for each material system. The results show that the material property results between various experimentors and experimental methods are not yet consistent. However, the results provide critical design data at a suitable level of accuracy for life prediction.

The paper will review both tensile and compressive mechanical testing of uniaxial specimens showing property dependencies on material density and temperatures for both material systems. Successful test results for both tensile and compressive fatigue loadings will be given. The test data shows that the fatigue strength of the TBC's is highly stress dependent in both loading conditions and is likely to depend on stress range and not mean stress. The fatigue strength of the plasma sprayed TBC's appears to increase with elevated temperatures in a range of temperatures below the creep activation temperature for the materials. The plasma sprayed TBC materials have been confirmed to have cyclic hysteresis at all temperature levels down to room temperature. Limited failure analysis data for various specimens suggest that the failure modes are driven by normal geometric discontinuities in the TBC's.

PROPERTIES OF PLASMA SPRAYED BOND COATS

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Increasing bond coat oxidation resistance has been clearly linked to increasing durability of the ceramic layer of TBCs. However, recent studies have shown that significant differences in TBC life can be achieved for different bond coats that have little or no difference in oxidation behavior. These results suggest bond coat properties other than oxidation resistance can also influence TBC life. A determination of which properties affect TBC life and an understanding of how these properties affect TBC life could be valuable in designing new, more durable TBCs. Unfortunately, there is little existing information on the physical and mechanical properties of bond coat materials and there are fewer comparative studies that can be used to determine which properties are important to TBC life. This paper compares the properties of three bond coat compositions that have similar oxidation behavior but different TBC lives. Analysis of the properties indicates that the coefficient of thermal expansion and stress relaxation (creep) behavior of the three alloys are strongly correlated to the observed differences in TBC life.

## THICK THERMAL BARRIER COATINGS FOR DIESEL ENGINES

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Caterpillar's approach to applying Thick Thermal Barrier Coatings (TTBCs) to diesel engine combustion chambers has been to use advanced modeling techniques to predict engine conditions and combine this information with fundamental property evaluation of TTBC systems to predict engine performance and TTBC stress states. Engine testing has been used to verify the predicted performance of the TTBC systems and provide information on failure mechanisms.

The objective Caterpillar's subcontract with ORNL is to advance the fundamental understanding of thick thermal barrier coating systems. Previous reviews of thermal barrier coating technology concluded that the current level of understanding of coating system behavior is inadequate and the lack of fundamental understanding may impede the application of TTBC's to diesel engines.

Areas of TTBC technology being examined in this program include powder characteristics and chemistry; bond coat composition; coating design, microstructure, and thickness as they affect properties, durability, and reliability; and TTBC "aging" effects (microstructural and property changes) under diesel engine operating conditions. Methods to evaluate the reliability and durability of TTBCs have been developed that attempt to understand the fundamental strength of TTBCs for particular stress states.

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SOME ASPECTS OF THE HOT CORROSION OF THERMAL BARRIER COATINGS

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This paper provides a pro tem review of the hot corrosion of zirconia-based thermal barrier coatings for engine applications. Emphasis is placed on trying to understand the chemical reactions, and such other mechanisms as can be identified, that cause corrosive degradation of the thermal barrier coating. The various approaches taken in attempts to improve the hot corrosion resistance of thermal barrier coatings are also briefly described and critiqued.

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THERMAL FRACTURE MECHANISMS IN CERAMIC THERMAL  
BARRIER COATINGSK. Kokini, B.D. Choules, and Y.R. Takeuchi  
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Ceramic thermal barrier coatings represent an attractive method of increasing the high temperature limits for systems such as diesel engines, gas turbines and aircraft engines. However, the dissimilarities between ceramics and metal, as well as the severe temperature gradients applied in such systems, cause thermal stresses which can lead to cracking and ultimately spalling of the coating. This paper reviews the research which considers initiation of surface cracks, interfacial edge cracks and the effect of a transient thermal load on interface cracks. The results of controlled experiments together with analytical models are presented. The implications of these findings to the differences between diesel engines and gas turbines are discussed. The importance of such work for determining the proper design criteria for thermal barrier coatings is underlined.

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A SOFTWARE TOOL TO DESIGN THERMAL BARRIER COATINGS

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This paper summarizes work completed for a NASA Phase I SBIR program which demonstrated the feasibility of developing a software tool to aid in the design of thermal barrier coating (TBC) systems. Toward this goal, three tasks were undertaken and completed. Task 1 involved the development of a database containing the pertinent thermal and mechanical property data for the top coat, bond coat and substrate materials that comprise a TBC system. Task 2 involved the development of an automated set-up program for generating two dimensional (2D) finite element models of TBC Systems. Most importantly, Task 3 involved the generation of a rule base to aid in the design of a TBC system. These rules were based on a factorial design of experiments involving FEM results, and were generated using a Yates analysis. A previous study has indicated the suitability and benefit of applying finite element analysis to perform computer based experiments to decrease but not eliminate physical experiments on TBC's. This program proved feasibility by expanding on these findings by developing a larger knowledgebase and developing a procedure to extract rules to aid in TBC design.

THERMAL BARRIER COATING LIFE MODELING IN AIRCRAFT  
GAS TURBINE ENGINES

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4/2/95  
4/2/95

Analytical models useful for predicting ceramic thermal barrier coating (TBC) spalling life in aircraft gas turbine engines are presented. Electron beam-physical vapor deposited (EB-PVD) and plasma sprayed TBC systems are discussed. TBC spalling was attributed to a combination of mechanisms such as metal oxidation at the ceramic-metal interface, ceramic-metal interface stress concentrations at free surfaces due to dissimilar materials, ceramic-metal interface stresses caused by local radius of curvature and interface roughness, material properties and mechanical behavior, transient temperature gradients across the ceramic layer and component design features. TBC spalling life analytical models were developed based on observations of TBC failure modes and plausible failure theories. TBC failure was assumed to occur when the imposed stresses exceeded the material strength (at or near the ceramic-metal interface). TBC failure knowledge gaps caused by lack of experimental evidence and analytical understanding are noted. The analytical models are considered initial engineering approaches that capture observed TBC failure trends.