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**ADVANCED THERMAL BARRIER
COATING SYSTEM DEVELOPMENT**

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TECHNICAL PROGRESS REPORT

to the

U.S. DEPARTMENT OF ENERGY

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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 will be accomplished by conducting the following program tasks:

- II.1 Process Modeling (deleted)
- 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 representative sections in a test passage at the Westinghouse Science and Technology Center.

Technical Progress Report

Task II.2 Bond Coat Development

- Work was initiated to deposit bond coats with improved resistance to substrate-bond coat interdiffusion. Two chemical systems were selected based on prior Westinghouse experience. Raw materials have been ordered and coating deposition is planned during the next quarter.
- Cyclic furnace evaluation of new bond coat chemistries under "nominal" conditions continued throughout this quarter. As was found in the accelerated test, IN-939 remains the most difficult substrate to coat. For IN-939, two of the new chemistries appear most promising and are recommended for further study. The coating life average coating life was increased by more than a factor of 2 with greater than a 3X increase in minimum coating life. Several new bond coats have exceeded the baseline on MarM002 substrates. Testing is continuing on MarM002 and CMSX-4 substrates.
- Work on the effect of controlled atmosphere heat treatments prior to TBC deposition was completed. Modest differences in coating life, as determined by cyclic furnace exposure, was experienced through the range of processing considered. Most heat treat treatments degraded the coating performance by up to 1/3. The best performance fell within the scatter of the data for the baseline coating on CMSX-4.
- A paper entitled "The Effect of Slurry Modified Bond Coats on TBC Performance" is being prepared for the 1998 ITSC.

Task II.3 Analytical Lifting Model

- The TBC lifting model code developed in phase II has been supplied by SwRI to Westinghouse. The model has not been validated, and will require validation and revision/fine tuning before its implementation.
- The validation process for the lifting model developed in phase II has begun. The first packet of data has been sent to SwRI. This packet includes failure and oxidation data for a spectrum of APS and EB-PVD TBC systems subjected to cyclic oxidation tests in laboratory furnaces.

Task II.4 Manufacturing Process Development

Task II.4.2 Cooling Hole Masking Technology

Application of coatings to industrial gas turbine component surfaces can cause restriction of cooling holes. The restriction can lead to increased metal temperatures and can shorten the life of turbine components. Trials were run to demonstrate the applicability of several techniques for eliminating cooling hole restriction.

It was previously demonstrated and reported that polymer masking can significantly reduce cooling hole restriction. Initial efforts to transfer the masking technique to turbine hardware was, however, unsuccessful. A number of problems were identified and addressed during the current reporting period including measures to ensure proper polymer curing and cooling of components during coating.

- Two masking configurations were evaluated relative to an unmasked condition. The first configuration was a single masking prior to bond coat application. The bond coat and TBC were subsequently applied. As a result of polymer burnout during the HVOF bond coat process, some hole restriction did occur. Reduction in diameter was significantly less than that seen for unmasked holes. The coating appeared to be well adhered in the areas adjacent to the holes. It is recommended that durability tests be performed to see how well masked components perform relative to unmasked parts.
- The second configuration included a double masking approach. Application of the initial masking was followed by bond coat application. The masking material was then reapplied, and the TBC was deposited. While blockage of the cooling holes was minimal for this configuration, problems with the TBC were evident. Residual masking contaminants on the bond coat surface appeared to prevent TBC build up during the initial spray passes. As a result, the TBC was thin in the area adjacent to the cooling holes. Before this double masking configuration is considered for use, additional work in surface cleaning and preparation techniques is required.
- The data that was obtained previously for the masking, machining, and spray pattern trials is being tabulated. The data from the spray pattern trials is being formatted for use in the future design of cooling holes. A final report on the progress made under Task II.4 will be completed during the next quarter.

Task II.5 NDE, Repair and Maintenance

Task II.5.1 Repair and Maintenance

- The best minor repair technique was selected and applied to a series of coupons for further testing. Minor repairs were demonstrated on both APS and EB-PVD coated coupons. Accelerated cyclic furnace test results indicate that repaired samples achieved approximately 82% of the baseline sample life. Lower temperature furnace testing is ongoing.

As a result of mechanical damage followed by high temperature thermal exposure, recrystallization of coated single crystal superalloys has been observed. In light of the possible effect of recrystallization on the mechanical integrity of turbine components, a study was initiated to identify if the thermal history associated with the coating process

will result in recrystallization. Issues such as coating heat treatments, substrate property degradation, service induced mechanical strain, and surface recrystallization are considered. During this reporting period,

- As-cast sections have been MCrAlY coated, stripped, and recoated according to Westinghouse specifications. Samples were later sectioned, aged, and examined for surface recrystallization and changes in microstructure.
- Single crystal mechanical test specimens have been machined and MCrAlY coated. Mechanical testing, which simulates the strain cycles calculated for the row 1 vane, will be completed in October.

II.5.2 Off-Line NDE

- We are continuing to pursue methods of creating *controlled* debonds for NDE standards. This effort has proven to be the technical challenge of the NDE program. A parallel effort is underway to produce the debonds pursuing two completely different manufacturing technologies. One method has demonstrated a controlled means of producing debonds and the simple standards have been forwarded for TBC coating with intentionally located debonds. The simple standards are expected to be complete by October, with NDE demonstration of delectability to follow before year end. NDE methods are expected to differentiate between debonds within layers of the coating system. The primary NDE method to support this work will be thermal wave imaging. Eddy current work will also be conducted on this training set.

II.5.3 On-Line NDE

- A thorough review of the draft final report submitted by Southwest Research Institute was completed. The report demonstrated a strong effort on the behalf of Southwest Research Institute, however, a letter of comments was sent for consideration upon completion of the final report. The final report is currently in the works at Southwest Research, and is expected in October. Once the final report is completed and again reviewed, Westinghouse conclusions and recommendations will be provided.
- This is the first work using real time fiber optic techniques that could be developed into real time remote measurements in aggressive environments on coated specimens. Raman scattering demonstrated useful and measurable spectrum information. This gives hope to measuring key operating parameters or material properties on-line.

Task II.6 New TBC Concepts

- The TBC coating surface is expected to be significantly hotter than the bond coat surface. As a result, any attempt to evaluate TBC stability on the bond coat is limited by the allowable bond coat surface. To circumvent this problem, APS coatings were deposited on carbon substrates followed by relatively low temperature furnace exposure to burn out the carbon. The resulting free standing coatings can then be evaluated at temperatures up to those encountered at the surface of the TBC. Three of the new ceramic compositions were so fabricated and subjected to thermal aging at

ATS relevant temperatures for 1 to 10 days. Two of these materials showed only minor changes in phase composition as a result of aging. Longer term exposures are planned. The third composition, however, showed significant phase changes and was therefore eliminated from further consideration.

- Accelerated cyclic furnace testing of one thermal sprayed TBC, deposited using 16 different processing conditions, continued in the last quarter. The testing identified a set of optimized spray parameters which were used to coat pins for further testing. In the initial optimization series, the new ceramic showed coating life comparable to the baseline YSZ. When the optimum conditions were replicated on a larger set of test pins, the performance was very poor. The discrepancy between the optimization runs and the larger set was the result of a difference in coating microstructure with the poor performance corresponding to an unusually dense microstructure. An error in the processing could not be identified. These samples were resprayed and the microstructure appears similar to that in the original optimization. Cyclic furnace testing is on-going. Thermal conductivity and heat capacity were also measured for this TBC.
- Four TBC chemistries, previously selected for EB-PVD deposition were sent for ingot fabrication. Powder pressing and sintering trials were performed on small pellets to baseline processing conditions. One of the chemistries lost weight during the sintering trials and was therefore eliminated from further consideration. Baseline conditions were established for the remaining three chemistries. PVD ingots, compatible with the Chromalloy coater were pressed into ingots. One ingot from each of the chemistries is being fired to ensure proper sintering. The ingots are expected to be completed in September and ready for PVD deposition in the next quarter.

Blade and Vane TBC Monitor - Feasibility Study

The adherence of the TBC to the row 1 blade and vanes is absolutely critical to obtaining 60% efficiency in the ATS engine. With the life of the component dependent on the coating, early detection of failure is necessary to ensure safe operation and enable component refurbishment.

- Feasibility studies were initiated on concepts for blade and vane TBC monitors. The Vane monitor study is being conducted by Westinghouse. The blade monitor study has been subcontracted to Wayne State University. Information was collected on the respective sensor environments and forwarded to the respective researchers.

Phase III Bench Test

- The construction phase of the Westinghouse High Heat Flux Test Facility was completed. The ability to meet ATS conditions was clearly demonstrated using TBC coated samples. Capacity is being expanded through further increases to sample cooling.

- The test rig has operated successfully in the manual mode and is being transitioned to unattended, full automatic operation. Figure 1 shows the thermal history of the TBC surface, and substrate mid-wall temperature for an APS TBC coated sample. Ten minutes cycles were used and were regulated by the automated system. Testing has been initiated on APS TBC samples to provide data for the TBC Lifing model. Additional samples are being fabricated from IN738, IN939, MarM002 and CMSX-4. Bench testing will continue through the remainder of 1997 and into 1998.

Figure 1: TBC surface and mid wall time-temperature profile for a 12 mil APS TBC tested in the Westinghouse High Heat Flux Test Rig. ATS bond coat and TBC surface temperature objectives are met for this sample.