Combustion Turbine (CT) Hot Section Coating Life Management

Semi-Annual Technical Progress Report

Reporting Period Start Date: October 1, 2002

Reporting Period End Date: March 31, 2003

Agreement Number: DE-FC26-01NT41231

Principal Authors:

R. Viswanathan
K. Krzywosz
S. Cheruvu
E. Wan

Subcontractors

Southwest Research Institute
Turbine Technology International

Submitted by

R. Viswanathan
EPRI
3412 Hillview Avenue
Palo Alto, CA 94304
Phone: (650) 855-2450
E-mail: rviswana@epri.com

Disclaimer

“This (describe material) was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC26-01NT41231. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE”.

TABLE OF CONTENTS

	Page
1.0 ABSTRACT	7
2.0 INTRODUCTION	8
3.0 EXECUTIVE SUMMARY	9
4.0 TASK 1: REFINEMENT AND VALIDATION OF HSLMP	11
4.1 Experimental	11
4.2 Results and Discussion	11
4.3 Conclusions	21
4.0 TASK 2: COATLIFE FOR ADVANCED METALLIC COATINGS AND TBCs	22
5.1 Task 2.1: Thermal Barrier Coatings	22
5.1.A Experimental	22
5.1.B Results and Discussion	23
5.1.C TBC Life Algorithm Development	31
5.1.D Conclusions – TBCs	32
5.2 Task 2.2 MCrAlY Coating	32
5.2.A Experimental	32
5.2.B Results and Discussion	33
5.2.C Coating Life algorithm Development	41
5.2.D Conclusions	43
6.0 TASK 3: NDE OF COATINGS	44
6.1 Task 3.1 NDE System Assembly and Testing VIC 3D Eddy Current Modeling	44
7.0 FIELD VALIDATION OF COATLIFE AND NDE	54
8.0 TASK 5: ECONOMIC RISK-BASED DECISION ANALYSIS	54
9.0 REFERENCES	57

LIST OF TABLES

	Page
Table 1	Chemical Composition of GTD-111 and IN-738 Test Materials (wt. %) 22
Table 2	Chemical Composition of CT102 Bond Coating Powder (wt. %) 22
Table 3	Chemical Composition of Ceramic Coating Powder (wt. %) 23
Table 4	Average Aluminum Content and Volume of Fraction of the β -phase In the Coating as a Function of Thermal Cycles Between Room Temperature and 1010°C (1850°F) 35
Table 5	Average Aluminum Content and Volume of Fraction of the β -phase In the Coating as a Function of Thermal Cycles Between Room Temperature and 1066°C (1950°F) 35
Table 6	Relative Test Positions on the Samples 45
Table 7	Estimated Coating Values 46

LIST OF FIGURES

		Page
Figure 1	Details of the S-W W501FC 1 st Stage Bucket That Was Examined	13
Figure 2	Finite Element Model of W501FC 1 st Stage Blade	14
Figure 3	Physical and Elastic Properties of IN738, NiCoCrAlY and TBC	14
Figure 4	Stage Gas Temperature Distribution for W501FC	15
Figure 5	Aero-thermal Procedures for W501FC 1 st Stage Blade	16
Figure 6	Predicted Temperature Distributions for W501FC 1 st Stage Blade	16
Figure 7	Temperature Distributions in the TBC System at 50% Blade Height	17
Figure 8	Temperature Distributions in the TBC System at 50% Blade Height – Higher TBC Conductivity	18
Figure 9	Stress Distributions for the W501FC 1 st Stage Blade at Base Load	19
Figure 10	Stress Distributions in the Platform Region Where Cracks Occurred	20
Figure 11	Optical Micrographs of As-Coated TBC on a NiCoCrAlY Coated GTD-111 Specimen	24
Figure 12	Optical Micrographs of As-Coated TBC on a NiCoCrAlY-coated IN-738 Specimen	25
Figure 13	Optical Micrographs of As-Coated TBC on a Platinum-plated NiCoCrAlY Coating on a GTDI-111 Specimen	26
Figure 14	Optical Micrographs of As-Coated TBC on a Platinum-plated NiCoCrAlY Coating on an IN-738 Specimen	27
Figure 15	Photographs of Specimens Showing the Condition of TBC On the Specimens	29
Figure 16	Optical Micrographs Showing Variation of TGO Thickness	30
Figure 17	Optical Micrographs Showing Variation of Delamination Cracks	31
Figure 18	Summary of the TBCLIFE Code	31
Figure 19	Cyclic Oxidation Behavior of NiCoCrAlY (CT-102) Coating	34
Figure 20	Microstructure of NiCoCrAlY (CT-102) Coated GTD-111 Specimens	36
Figure 21	Optical Micrographs of Transverse Section Removed from the Exposed Specimens	37
Figure 22	Coefficients of Thermal Expansion of NiCoCrAlY (CT 102) and DS-GTD 111 as a Function of Temperature	38
Figure 23	Thermal Strains in NiCoCrAlY Coating During Thermal Cycling Of Coated DS GTD-111 Specimens	39
Figure 24	TMF Data of GT33 Coated DS GTD-111 Compared Against Those of GT33+ Coated DS GTD-111 and the Corresponding TMF Life Models	39
Figure 25	SEM Back Scattered Electron Images of Oxide Scale on the Outer Surface of NiCoCrAlY Coated Specimens after Cyclic Exposure Between 25°C (77°F) and 1010°C (1850°F)	41
Figure 26	Comparison of Computed and Measured Weight Changes Data of NiCoCrAlY at 1010°C (1850°C)	42
Figure 27	Al Depletion Compared Against Experimental Data for NiCoCrAlY at 1010°C (1850°F)	42

Figure 28	Computed Volume Percent of β Phase Compared Against Experimental Data for NiCoCrAlY at 1010°C (1850°F)	43
Figure 29	The Equivalent Circuit of a Real Eddy-Current Probe with $U_p - O$ As the Frequency Goes to Zero (left)	45
Figure 30	Real (left) and Imaginary (right) Plots of the Normalized Impedances from Sample A	46
Figure 31	Comparison of Measured and Calculated Coil Impedance Data	47
Figure 32	Coating Model Based on 8-layer Inversion Program	47
Figure 33	Suction Side of Blade 53 Showing Possible Coating Wear	49
Figure 34a	Transverse Section F – Suction Side	50
Figure 34b	Transverse Section G – Suction Side	51
Figure 35	SEM Photomicrographs of Degraded Substrate Sections	52
Figure 36	SEM Photomicrographs of Degraded Coatings	53
Figure 37	Basic Logic Structure of the Risk-Based Economic Decision Analysis Software	56

Combustion turbine (CT) Hot Section Coating Life Management

1.0 ABSTRACT

The integrity of coatings used in hot section components of combustion turbines is crucial to the reliability of the buckets. This project was initiated in recognition of the need for predicting the life of coatings analytically, and non destructively; correspondingly, three principal tasks were established. Task 1, with the objective of analytically developing stress, strain and temperature distributions in the bucket and thereby predicting thermal fatigue (TMF) damage for various operating conditions; Task 2 with the objective of developing eddy current techniques to measure both TMF damage and general degradation of coatings and, Task 3, with the objective of developing mechanism based algorithms. Task 4 would be aimed at verifying analytical predictions from Task 1 and the NDE predictions from Task 3 against field observations. Task 5 would develop a risk-based decision analysis model to make run/repair decisions. This report is a record of the progress to date on these 3 tasks.

2.0 INTRODUCTION

The objective of this project is to improve the reliability, availability and maintainability (RAM) of combustion turbines (GTs) by developing advanced technology for assessing and managing the life of protective coatings on CT blades and vanes.

In recent years, gas turbines (GTs) have become the equipment of choice for power generation by both electric utilities and independent power producers. Continuing advances in design concepts and in structural materials and coatings for GT hot-section components have enabled increases in rotor inlet temperature resulting in major efficiency gains. These high temperatures mandate the use of coatings on hot section components (blades and vanes) to protect them from oxidation. Degradation of these protective coatings represents a major profitability challenge for turbine owners. Coating life usually dictates blade refurbishment intervals – which typically are shorter than desired for baseload units. Downtime for coating inspection and replenishment requires dispatch of less efficient generating equipment or purchase of replacement power. Coating failure can lead to rapid, severe damage to the superalloy substrate, warranting blade replacement. Replacement of a conventionally cast alloy blade row can cost up to \$3 million in the case of directionally solidified or single-crystal blades with internal cooling. Unavailability costs can run up to \$500,000 in lost revenues per day for a 500MW combined cycle plant. Blade failures can also cause downstream damage in the turbine, causing prolonged outages and revenue loss. Moreover, losses to electricity customers due to disruption in supply can also be very substantial. A proper life management system for coatings represents a major step in preventing such major losses to the GT owner and to society at large.

The life management activities covered in this project for coatings directly impacts the objectives of increasing RAM of GTs. Accurate life management techniques optimize refurbishment intervals and operating practices, thereby avoiding unplanned outages. Currently, coating refurbishment intervals are dictated by empirical, fleet-specific (rather than unit-specific) manufacturer recommendations based on the concept of “equivalent operating hours (EOH).” The new technology described in this proposal will enable machine-specific calculations of coating remaining life and direct measurements of the same using non-destructive evaluation (NDE) techniques.

The project is intended to develop improved analytical and nondestructive evaluation techniques to assess the consumed life and/or estimated life of protective coatings on CT blades and vanes, and then integrate these techniques with economic risk-based decision-analysis tools to optimize run/repair/replace decisions. The project is defined along five major technical tasks including:

- Task 1. Refinement and Validation of Hot Section Life Management Platform (HSLMP)
- Task 2. COATLIFE for Advanced Metallic Coatings and TBCs
- Task 3. NDE of Coatings
- Task 4. Field Validation of COATLIFE and NDE
- Task 5. Economic risk-based Decision Analysis

This report summarizes results from these tasks.

3.0 EXECUTIVE SUMMARY

In Task 1, the primary objective for this semi annual period was to construct the aero-thermal model for S-W W501FC 1st stage blade with APS TBC. By means of the HSLMP, aero-thermal and structural analyses were performed to provide initial understanding of the thermal-mechanical response for the 1st stage blade coated with TBC. **Preliminary analysis at base load condition was performed successfully and the results provide crucial insights as to the temperature and stress levels in the TBC system.** Also, the platform cracking experienced by the 1st stage blade was found to be associated with pronounced compressive steady state stress predicted at the cracked location. The thermal transients characterizing various operating cycles will be pursued to further assess the TMF damage at critical locations. Assessment of TBC life will be performed based on aero-thermal results and the life model developed by EPRI/SwRI. A generalized creep equation of IN738LC for W501FC 1st stage blade base material has been developed. A creep analysis will be conducted to assess the creep damage based on the accumulated creep strain.

The objective of Task 2 is to develop the capability of COATLIFE to handle spallation life prediction for TBCs that are being used in advanced turbines manufactured by major domestic OEMs and to enhance COATLIFE to cover broader range of MCrAlY coatings for oxidation life prediction. The MCrAlY coating selected for the evaluation was CT102. The chemical composition of the CT102 coating is similar to the nominal chemistry of GE's proprietary NiCoCrAlY coating GT33. Tasks 2.1 and 2.2 deal with the COATLIFE development for TBC and MCrAlY coatings, respectively. The COATLIFE model treats coating degradation mechanisms that are applicable to TBC spallation, and bond coat degradation resulting from loss of aluminum. Isothermal oxidation tests at three temperatures are being conducted on TBC-coated GTD-111 and IN-738 specimens with two different bond coatings. Cyclic oxidation tests were conducted at two peak temperatures on NiCoCrAlY coated specimens to determine the constants for COATLIFE model.

Isothermal oxidation tests at three different temperatures, 1010°C (1850°F), 1038°C (1900°F), and 1066°C (1950°F) have been initiated on the TBC coated specimens. The specimens have been exposed for 6000 hours at 1010°C (1850°F), 5000 hours at 1038°C (1900°F), and for 3330 hours at 1066°C (1950°F) to date. Examination of these specimens revealed no external TBC surface cracking on the specimens exposed at 1010°C (1850°F and 1038°C (1900°F). TBC coating on all specimens spalled after 3330 hours at 1066°C (1950°F). Cyclic oxidation testing of TBC coated specimens at the peak temperature of 1066°C (1950°F) have been initiated and the specimens have been exposed for about 1500 one-hour thermal cycles.

Considering the physical degradation mechanisms, **a mechanistic model has been developed for predicting remaining service lives of TBCs. The predictive capabilities of the model are demonstrated by comparing the model predictions against the results published in the literature for APS TBCs. Preliminary results indicate that model predictions are in good agreement with the experimental data.**

Cyclic oxidation tests on NiCoCrAlY (CT102) coated specimens were conducted at two peak temperatures to determine the constants for the COATLIFE model. At both temperatures, the specimens initially gained weight due to formation of oxide scale with thermal cycles and then the specimen lost weight due to domination of scale spallation with increasing thermal cycles. The β -phase in the coating provides aluminum for the oxide scale formation. The loss of aluminum due to spallation of the protective oxide scale results in coating degradation. Volume fraction of the remaining β -phase and aluminum content in the coating were determined as a function of thermal cycles. The oxides formed on the specimens were also characterized and the results showed that the oxides formed on the coated specimens after thermal exposure varied with thermal exposure. The oxide scale formed on the coated specimens exposed for up to 1000 to 1500 thermal cycles, depending on the peak temperature, was predominantly alumina with dispersion of yttria particles, while the specimens exposed for over 1500 cycles exhibited mixed (aluminum, chromium, and yttrium-rich) oxides at both temperatures.

Considering the formation of chromium, aluminum, and yttrium rich oxides, the constants for COATLIFE were determined based on aluminum depletion in the coating. **The calculated volume fraction of the remaining β -phase in the coating was in good agreement with the measured values of the specimens exposed at both peak temperatures.**

Under Task 3, capability of the frequency-scanning eddy current system to detect, discriminate, and characterize such coating conditions as normal coating, β -phase depletion, and cracked coating was demonstrated on service-aged 7FA first stage bucket with GT33+ coating. In addition, it was possible to quantify based on the built-in inversion program to estimate conductivity values associated with the topcoat, NiCoCrAlY bond coat, and GTD 111 substrate. During the reporting period, additional investigation showed its capability to assess a service-aged bucket coated with CoCrAlY simple coating (GT 29). Due to heavy oxidation of CoCrAlY coating accompanied by diffusion of aluminum into the substrate as columnar AlN and finely dispersed TiN precipitates, no effective base metal protection was provided at selected blade surface areas. In addition to the loss of coating protection, chromium depletion caused the GT29 coating to become magnetic. **By reviewing the normalized coil impedance plots, it was possible to detect and discriminate the β -phase depletion of coating from the base metal corrosion.** In addition, the magnetic characteristic of the coating was identified from the unique impedance plots obtained at low frequency. Due to lack of access to a normally coated bucket, no quantitative analysis was conducted.

Technical work under Task 4 is slated to begin in November 2003.

The purpose of Task 5 is to develop a prototype software package to serve as the user's "front end" to the technology being developed. This decision analysis software will use a Microsoft ExcelTM spreadsheet with the Crystal BallTM add-in for probabilistic Monte Carlo simulations as the basic software architecture.

4.0 TASK 1 REFINEMENT AND VALIDATION OF HSLMP

4.1 Experimental

The S-W W501FC is a 3600 RPM heavy-duty combustion turbine with high efficiencies and rated output about 170 MW for simple cycle units. In parallel with GE F-class machines, the W501FC is featured with advanced cooling strategies for the 1st stage blade and operated at a firing temperature about 2400° F (1316° C). The 1st stage blades are precision cast of IN738 coated with APS TBC. In addition to the TBC, the 1st stage blade also relies on more advanced cooling schemes to compensate for the adoption of IN738 base material [1]. IN738 has lower creep strength comparing to the GTD111-DS used by GE 7FA of similar machine. The 1st stage blade is cooled by a combination of convection techniques (through three serpentine cooling channels) and pin fin cooling in the trailing edge exit slots. Showerhead film cooling on the leading edge and arrays of film cooling on both pressure and suction sides further enhance the overall cooling.

A sample blade was sectioned to obtain the details of external and internal geometry. As shown in Figure 1, the 1st stage blade features with a total of 7 passages on 3 separate cooling channels. The row 1 blade uses a relatively short shank and slanted axial root with 4 serrations. A 3-D finite element model (Figure 2) including a TBC and a bond coat was constructed using the data generated from reverse engineering. The thickness of APS TBC and NiCoCrAlY bond coat was assumed to be 7 mils, respectively. The corresponding physical and elastic properties for IN738 base metal and TBC systems [2] adopted in the aero-thermal model are shown in Figure 3. The thermal conductivity, thermal expansion coefficient and Young's modulus of TBC are noticeably lower than bond coat and base metal, especially in the high temperature regime. The model is designed to effectively handle the enormous amount of surface data resulting from the cooling configuration. This is required in order to predict the interface temperatures and operating stresses within the TBC system. Results will provide critical insights on the strengths and limitations of this advanced coating technique based on its thermo-mechanical behavior and how it deals with the mechanisms that presently affect a 1st stage rotating blade. The model is also being designed to assess the TMF damage in the platform region, which causes premature retirement of 1st stage blade.

4.2 Results and Discussion

The procedure of aero-thermal analysis for a cooled blade involves a through flow analysis, an external gas flow heat transfer analysis, an internal cooling flow heat transfer analysis and a heat conduction analysis to establish the temperature gradient and distribution. A multiple stage through flow model was constructed to improve the prediction of aero-thermal variables for the W501FC 1st stage blade. Based on the turbine inlet temperature profile for the W501D machine [3], the predicted gas temperature profile for the 1st stage blade is shown in Figure 4. Using ANSYS [4] the heat conduction analysis for W501FC 1st stage blade was performed by incorporating the results from external heating and internal cooling heat transfer analyses. A converged solution was achieved by iterating between the heat conduction model and internal cooling flow model. Figure 5 demonstrates the models developed and iterative procedure utilized in the aero-thermal analysis for the 1st stage blade. The predicted temperature

distribution throughout the blade at base load is shown in Figure 6. The pronounced temperature gradient ranging from 600° F to 1800° F was attributed to a colder cooling air and film cooling arrangement on the airfoil surface.

Figure 7 depicts the predicted temperature distribution inside the TBC system. As a result of the lower thermal conductivity of the ceramic coating, a significant temperature gradient of 200° F~400° F was estimated across the TBC system. To evaluate the effect of TBC thermal conductivity on temperature distributions in the coating system, a sensitivity study was performed. This was done by doubling the nominal thermal conductivity of the ceramic coating. As shown in Figure 8, the TBC surface temperature dropped about 50° F~100° F, producing a lower temperature gradient across the TBC. The interface temperature between the TBC and bond coat remained low (maximum near 1500° F) and suggests that oxidation might not be a serious concern for this 1st blade.

A preliminary stress analysis was performed by applying temperatures as body forces, and using temperature dependent material properties for both the base and coating materials. The stress distributions in the blade, and about 50% blade height, are shown in Figure 9. Tensile stresses were calculated at selected regions of the TBC external surfaces. Because these predicted tensile stresses could be crucial in terms of TBC life, they therefore require further investigation.

In the platform, a notably high compressive axial stress was calculated at the cracked location (Figure 10). It is becoming apparent that the extraordinarily high compressive strain (near 0.6% at base load) might be associated with the large crack that developed near the leading edge on the pressure side. A complete transient aero-thermal analysis is planned to further assess the TMF damage for various operating scenarios.

Figure 1 – Details of the S-W W501FC 1st Stage Bucket That Was Examined

Figure 2 – Finite Element Model of W501FC 1st Stage Blade

Figure 3 – Physical and Elastic Properties of IN738, NiCoCrAlY and TBC

Young's Modulus

Tensile Strength

Figure 4 – Stage Gas Temperature Distribution for W501FC

Figure 5 – Aero-thermal Procedures for W501FC 1st Stage Blade

Figure 6 – Predicted Temperature Distributions for W501FC 1st Stage Blade

Figure 7 – Temperature Distributions in the TBC System at 50% Blade Height

Figure 8 – Temperature Distributions in the TBC System at 50% Blade Height – Higher TBC Conductivity

Figure 9 – Stress Distributions for the @501FC 1st Stage Blade at Base Load

Figure 10 – Stress Distributions in the Platform Region Where Cracks Occurred

4.3 Conclusions

- TMF is the predominant life-limiting factor that governs the reliability of the W501FC 1st row of blades operated in a cyclic fashion. Substantial fatigue cracking in the platform can lead to premature retirement of the blade long before the 1st HGPI of 800 cycles. Results of preliminary aero-thermal and stress analyses reveal that the pronounced compressive strain at base load operation could be crucial in terms of the TMF life for this design. Excessive compressive axial stress predicted in the platform was attributed to a significant temperature gradient across the platform, occurring as a result of the colder cooling air and relatively high operating gas temperature.
- Water injection tends to increase conductivity/heat transfer and therefore could further increase the level of thermal stress at critical locations. The effect of water injection will be studied in determining the role it might have played for the observed long crack. A complete transient aero-thermal analysis is planned to assess the TMF damage under various operating scenarios.
- For the airfoil, a significant temperature gradient was predicted across the wall thickness. This was attributed to a colder cooling air and the type of film cooling arrangement present on the airfoil surface. As a result of the lower thermal conductivity of the ceramic coating, a large temperature gradient of 200° F~400° F was estimated across the TBC. The effect of the thermal conductivity for a TBC on temperature distributions in the coating system needs further investigation. It presently appears that oxidation might not be a serious concern for the 1st row blade which uses a TBC, principally because of the low temperature present within the TBC and at the interface between the TBC and bond coat. In addition, the sintering effect (which tends to increase the stiffness and accelerate TMF damage of TBC system) might also be less critical for the 1st stage blade.
- It is currently planned to extend the application of the aero-thermal model to further assist in refining the existing TBC life prediction model developed by EPRI/SwRI [5]. The predicted temperatures and stresses will be evaluated in detail to validate experimental results and refine the module and thereby better describe time-dependent effects of bond coat oxidation and sintering kinetics.
- A creep analysis will be performed to account for the accumulated creep damage. This may be particularly important for base load machines. A generalized creep equation of IN738LC for W501FC 1st stage blade base material has been developed. A creep strain based creep analysis will be performed based on calculated temperatures and mechanical loadings experienced by the blade.

5.0 TASK 2 COATLIFE FOR ADVANCED METALLIC COATINGS AND TBCs

5.1 Task 2.1 Thermal Barrier Coatings

5.1A *Experimental Procedures*

Three shank sections of GTD-111 DS blades and three shank sections of IN-738 blades retired from Frame 5002 engines were procured for machining test coupons. The shank sections operate at a much lower temperature than the airfoil section of a blade and, as a result, the material at the shank section is not expected to degrade during service. The structure and properties of the material at the shank section represent the initial, as heat-treated condition.

Compositional measurements were made at selected locations on the GTD-111 and IN-738 blade shank sections using energy dispersive X-ray spectroscopy (EDS). The composition of the blade materials is given in Table 1.

Table 1. Chemical composition of GTD-111 and IN-738 test materials (wt. %).

Blade	Al	Ti	Cr	Co	Mo	Nb	Ta	W	Ni
GTD-111	3.2	5.2	14.4	9.2	2.1	—	4.0	3.2	Bal
IN-738	3.8	3.6	16.0	8.3	1.9	1.1	2.1	2.2	Bal

About 150 cylindrical specimens (0.36 inch diameter and 1.5 inches long) were removed from the GTD-111 and IN-738 blade shank sections using an electro-discharge machining process. The specimens were ground and polished to remove the recast layer. Turbine Airfoils, Coatings, and Repairs (TACR) applied bond and yttria stabilized zirconia coatings. A low-pressure plasma spray process (LPPS) was used to apply NiCoCrAlY (CT102) coating to all specimens. The composition of the powder is given in Table 2. The composition of the powder is comparable to the nominal chemistry of GE's proprietary coating GT33. After application of the coating all specimens were given a vacuum diffusion treatment at 1121°C (2050°F) for two hours. An approximately 10 µm thick layer of platinum was applied by electroplating on half of the NiCoCrAlY coated specimens. The Pt plated NiCoCrAlY was selected because Siemens Westinghouse uses the platinum-plated CT102 as a bond coating for TBC-coated parts of advanced turbines. Following electroplating, the specimens were given a vacuum diffusion heat treatment at 1121°C (2050°F) for two hours. All CT102 and platinum-plated CT102 specimens were then given an aging treatment at 843°C (1550°F) for 24 hours prior to the application of the top ceramic coating, a standard yttria stabilized zirconia, by using an air plasma spray (APS) process. The chemical composition of the ceramic coating powder is given in Table 3.

Table 2. Chemical composition of CT102 bond coating powder (wt%).

Al	Co	Cr	Ni	Y
8.0	Balance	21.0	32.0	0.5

Table 3. Chemical composition of ceramic coating powder (wt.%).

Al_2O_3	Fe_2O_3	SiO_2	TiO_2	Y_2O_3	HfO_2	ZrO_2
0.13	0.02	0.27	0.09	7.69	1.85	Balance

Isothermal Tests

Multiple TBC-coated GTD-111 and IN-738 specimens with two different bond coatings are being aged in three different furnaces, which are maintained at three temperatures: 1010°C (1850°F), 1038°C (1900°F), and 1066°C (1950°F). One specimen from each substrate/coating system is being removed at predetermined intervals for metallurgical evaluation.

5.1B Results and Discussions

Microstructure of As Coated Specimens

Typical microstructures of the bond and ceramic coatings in the as-deposited condition are presented in Figures 11 through 14. Among all the specimens, thickness of the CT102 bond coating varied approximately 130 μm (0.005 inch) to 155 μm (0.006 inch). A thin layer of platinum is evident in Figures 13 and 14 between the CT102 and top ceramic (TBC) coating. The bond coating on all specimens was dense and exhibited a microstructure consisting of fine β -phase (NiAl) in a matrix of γ (Ni-Cr-Co solid solution). The outer surface of the bond coating on all specimens exhibited irregular surface topography, which is normal for the LPPS processed coatings. The rough surface is required for the adhesion of air plasma TBC. The thickness of the TBC on the specimens varied from about 250 to 375 μm (0.010 to 0.015 inch). Examination of the bond coating/TBC interface revealed a thin and discontinuous thermally-grown oxide (TGO) scale in isolated areas and a few micro-delamination cracks at the interface. These cracks were parallel to the interface and were about 50 μm (0.002 inch) long. Propagation of these cracks during isothermal or thermal cycling exposure could lead to TBC spallation. The microstructure of the TBC exhibited a layered structure resulting from the splatting of the powder particles during the deposition process. The pores/voids and microcracks were seen in the coating, which is normal for an APS-processed TBC.

Figure 11. Optical micrographs of as-coated TBC on a NiCoCrAlY coated GTD-111 specimen. The arrows point to delamination cracks at the TBC/bond coat interface.

Figure 12. Optical micrographs of as-coated TBC on a NiCoCrAlY -coated IN-738 specimen. Arrows point to delamination cracks at the TBC/bond coat interface.

Figure 13. Optical micrographs of as-coated TBC on a platinum-plated NiCoCrAlY coating on a GTD-111 specimen. Arrows point to delamination cracks.

Figure 14. Optical micrographs of as-coated TBC on a platinum-plated NiCoCrAlY coating on an IN-738 specimen. Arrows point to delamination cracks at the TBC/bond coat interface.

Isothermal Exposure Testing

Isothermal exposure testing of the TBC-coated specimens at 1010°C (1850°F), 1038°C (1900°F), and 1066°C (1950°F) has been initiated. The specimens have been exposed for 6000 hours at 1010°C (1850°F), 5000 hours at 1038°C (1900°F), and for 3330 hours at 1066°C (1950°F) to date. Examination of these specimens revealed no external TBC surface cracking on the specimens exposed at 1010°C (1850°F) and 1038°C (1900°F).

A crack was seen on the TBC coating on only one of the four specimens (IN-738 with MCrAlY bond coating) after 2785 hours of exposure at 1066°C (1950°F). TBC coating almost completely spalled on all four specimens after 3330 hours at this temperature. The spallation was more severe on the specimens with a platinum interlayer between the MCrAlY (CT-102) and the ceramic coating, as illustrated in Figure 15.

Figure 15. Photographs of specimens showing the condition of TBC on the specimens after a) 2785 hours (note a crack on Specimen # 2) and b) 3330 hours of exposure at 1066°C (1950°F) (note the specimens were severely oxidized).

Microstructure of Exposed Specimens

Metallurgical mounts were prepared from the samples removed after 600, 1000, 1500, and 2000 hours exposure at 1066°C (1950°F). The results showed that the TGO scale thickness increased with exposure time and temperature. The extent of delamination at the TGO/TBC interface also increased with the exposure temperature and time. Variation of TGO thickness and delamination cracking at the TGO/TBC interface as a function of exposure time is shown in Figures 16 and 17, respectively.

Figure 16. Optical micro graphs showing variation of TGO thickness (a) after 600 and b) after 2015 hours exposure at 1066°C (1950°F)

Figure 17. Optical micro graphs showing variation of delamination cracks (a) after 600 and b) after 2015 hours exposure at 1066°C (1950°F).

5.1C TBC Life Algorithm Development

A life prediction model for TBC was developed to treat bond coat oxidation, sintering and spallation of the TBC, as well as effects of coating thickness and substrate curvature on TBC spallation. Figure 18 summarizes the essential features of this TBC lifing model, which is called TBCLIFE.

Figure 18. Summary of the TBCLIFE code.

Parametric Calculations

A parametric study of the various key variables in the TBC model has been performed, using air-plasma-sprayed (APS) TBC and MCrAlY bond coat as an example. The effect of the peak temperature, sintering, and the curvature has been determined. The TBC life was found to decrease with increasing temperature and with decreasing radius of curvature. Sintering of TBC also decreases the TBC life. The calculated results of TBC life are compared against the results published in the literature. The details of these results were presented in a previous report.

51.D Conclusions-Thermal Barrier Coatings

- Isothermal and cyclic exposure testing of TBC coated specimens at different temperatures was initiated. The preliminary results showed that the TGO thickness and delamination cracking at the TGO/TBC interface increases with increasing exposure time.
- TBC degradation and failure mechanisms included, oxidation sintering, spallation, and TMF cracking
- Considering all pertinent failure mechanisms, a preliminary TBC lifing model was developed. Parametric studies of key variables showed that the TBC life decreases with increasing temperature and decreasing radius of curvature.

5.2 Task 2.2 MCrAlY Coating

5.2A Experimental Procedures

Materials and Coatings

Flat rectangular specimens were machined from the shank sections of GTD-111 buckets using an electro-discharge machining process for thermal cycling tests at two peak temperatures. TACR applied CT102 coating on these specimens using an LPPS process. Following application of the coating, the specimens were given a vacuum diffusion heat treatment at 1121°C (2050°F) for two hours and an aging treatment at 843°C (1550°F) for 24 hours.

Metallurgical Evaluation of Coated Specimens

For metallographic evaluation, a transverse section was removed from coated specimens. The sections were mounted in a conductive mounting media, polished using standard metallographic techniques, and examined under optical and scanning electron microscopes to characterize the coating structure and to determine the chemical composition of the coating either in the as-coated or post-exposed condition. The composition of the phases in the coating was determined using Energy Dispersive Spectroscopy (EDS) and the volume fraction of β -phase in the coating was determined using quantitative metallographic techniques.

Cyclic Oxidation

Cyclic oxidation tests were conducted using a facility designed and fabricated at Southwest Research Institute. The test facility consists of a furnace, a forced air cooling system, a coated superalloy frame for suspending test specimens, and a computer controlled moving arm that transfers specimens in and out of the furnace and to the cooling system. For cyclic oxidation testing, coated specimens were inserted into the furnace, which was maintained at a desired peak temperature and held at that temperature for 55 minutes prior to moving them into the cooling system. Following cooling the specimens for 5 minutes, to room temperature, the specimens were then reinserted back into the furnace. The tests were interrupted at predetermined intervals to weigh the specimens.

5.2B Results and Discussions

Cyclic Oxidation

Cyclic oxidation testing at two peak temperatures, 1010°C (1850°F) and 1060°C (1950°F), was completed. The weight change results at the two peak temperatures are presented as a function of thermal cycles in Figure 19. At both temperatures, the specimens initially gained weight due to formation of oxide scale with thermal cycles, up to approximately 200 thermal cycles and then specimen lost weight due to domination of scale spallation with increasing thermal cycles. The scatter in the weight loss data also increased with increasing thermal cycles. Variation of uncoated areas on the edges of the specimens is, in part, presumably responsible for this scatter. A small bolt was tack welded to one of the edges of each specimen to facilitate rotation of the specimen during the coating application. The tack welded regions were ground prior to cyclic oxidation testing. Variation of oxide scale spallation from these uncoated regions among the specimens can result in a pronounced weight changes.

Figure 19. Cyclic oxidation behavior of NiCoCrAlY (CT-102) coating

Microstructure of Exposed Specimens

Metallurgical mounts were prepared from all the specimens exposed at 1010°C (1850°F) and 1066°C (1950°F). The mounts were examined in optical and scanning electron microscopes for coating degradation. Typical microstructure of the coating as a function of thermal cycles is shown in Figure 20. The results showed that the β -phase in the coating decreased with increasing thermal cycles. The volume of fraction of the β -phase and the aluminum content in the coating were determined in all exposed specimens. The results are presented Tables 4 and 5. The volume of fraction of the β -phase in the coating after 4500 cycles exposure at 1010°C (1850°F) dropped to 9% from the original value of 40%, while the β -phase was almost consumed after 2000 cycles at 1066°C (1950°F), as shown in Figure 10 d. These results are used to develop COATLIFE algorithm.

Table 4: Average aluminum content and volume of fraction of the β -phase in the coating as a function of thermal cycles between room temperature and 1010°C (1850°F)

Specimen	Cycles	Average Aluminum Content		Average vol. Fract. of β -phase in the coating, %
		Wt. %	At %	
X-17	0	8.3	16.1	40
X-17-2B	800	7.9	15.4	35
X-17-5B	1500	7.4	14.4	26
X-17-3B	2000	6.7	13.2	21
X-17-4B	2750	6.2	12.3	15
X-17-6B	3486	5.6	11.0	12
X-17-1B	4500	5.0	10.1	9

Table 5: Average aluminum content and volume of fraction of the β -phase in the coating as a function of thermal cycles between room temperature and 1066°C (1950°F)

Specimen	Cycles	Average Al Content		Average β -phase in the coating, %
		Wt%	At%	
X-17	0	8.3	16.1	40
X-17-6	280	8.0	15.5	38
X-17-1	600	7.3	14.3	32
X-17-4	1000	6.7	13.3	18
X-17-5	1500	5.3	10.7	8
X-17-2	1750	5.1	10.3	7
X-17-3	2000	4.7	9.6	1.1

(a)

(b)

Figure 20. Microstructure of NiCoCrAlY (CT-102) coated GTD-111 specimens showing variation of β -phase in the coating as a function of thermal cycles between room temperature and 1066°C (1950°F) after: (a) 280 cycles, (b) 1000 cycle, (c) 1500 cycles, and (d) 2000 cycles.

Metallurgical examination of the specimens also showed localized oxidation (pitting like) attack on the outer surface of the coating. The specimens exposed at a higher peak temperature were free cracks. At a lower peak temperature, no cracks were seen in the specimens exposed for up to 2700 thermal cycles. However, thermomechanical fatigue (TMF) cracks were observed in the coating on the specimens after 3486 and 4500 thermal cycles between room temperature and 1010°C (1850°C). These TMF cracks were analyzed by computing the thermal strain ranges in the coated specimens during thermal cycling. Figure 21 shows the coefficient of thermal expansion (CTE) of NiCoCrAlY (CT 102) coating and DS GTD-111. The CTE of NiCoCrAlY coating increases linearly with increasing temperature, while the CTE of DS GTD-111 is a nonlinear function of temperature.

c)

Figure 21. Optical micrographs of transverse section removed from the exposed specimens after a) 2700 cycles, b) 3486 cycles, and c) 4500 cycles. Note TMF cracks in specimens after 3486 and 4500 thermal cycles exposure.

The TMF strain, ϵ_{mech} , induced during heating or cooling from T_o to T_1 was computed according to the expression given by

$$\epsilon_{mech} = \int_{T_o}^{T_1} (\alpha_s - \alpha_c) dT$$

with

$$\alpha = \alpha_o + \alpha_1 T + \alpha_2 T^2 + \dots + \alpha_n T^n$$

where α is the coefficient of thermal expansion and the subscripts s and c denote substrate and coating, respectively. The regression coefficients, α_n , are shown in Figure 22 for GT33 and DS GTD-111. The TMF strains associated with heating and cooling of NiCoCrAlY coated GTD-111 are presented in Figure 23, which also shows the TMF strain ranges for the total cycle. The computed TMF strain ranges were used to correlate with the number of thermal cycles at which TMF coating cracks were observed in NiCoCrAlY-coated GTD-111 specimens. These results are compared against TMF data for GT33+ coated GTD-111 and NiCoCrAlY coated GTD-111 in Figure 14, which shows the GT33 data just lie outside the 2x line for GT33+ coated GTD-111. It should be noted that in Figure 24, the data for NiCoCrAlY corresponds to the formation of TMF cracks in the coating, while those for GT33+ and NiCoCrAlY coated GTD-111 corresponding to TMF failure of the coated specimens (including the coating and the substrate). Thus, the TMF data of the coated cyclic oxidation and the coated TMF specimens are consistent and are

comparable to those for GT33+ coated GTD-111. The results for NiCoCrAlY (CT-102) are also in agreement with those reported for RT122 by ERA (M.I Wood, D. Raynor, and R.M. Cotgrove, "Thermomechanical Fatigue of Coated Superalloys for Gas Turbine Blading," ERA Technology, Surrey, UK,. ERA Report 96-1088, 1999.). RT122 and NiCoCrAlY (CT-102) coatings have comparable compositions.

Figure 22. Coefficients of thermal expansion of NiCoCrAlY (CT 102) and DS-GTD 111 as a function of temperature

Figure 23. Thermal strains in NiCoCrAlY coating during thermal cycling of coated DS GTD-111 specimens.

Figure 24. TMF data of GT33 coated DS GTD-111 compared against those of GT33+ coated DS GTD-111 and the corresponding TMF life models.

Characterization of oxides

Figure 25 shows SEM backscattered electron images of the oxide scale of formed on the coated samples after 800, 2000, and 4500 cycles between room temperature and 1010°C (1850°F). EDS was on several locations on the oxide scale on each sample. The results showed that the oxide scale after 800 thermal cycles is comprised mostly of aluminum with some yttrium. In contrast, the oxide scale formed after 1500 thermal cycles consisted of a mixture of alumina, yttria, and chromia.

a) after 800 cycles

b) after 2000 cycles

c) after 4500 cycles

Figure 25. SEM back scattered electron images of oxide scale on the outer surface of NiCoCrAlY coated specimens after cyclic exposure between 25°C (77°F) and 1010°C (1850°F).

5.2C Coating Life Algorithm Development

The model constants for NiCoCrAlY at 1010°C were finalized based on the cyclic oxidation data generated in this program. Figure 26 shows a comparison of the computed and observed weight change curves. The observed weight changes are larger than those predicted by the model after 1000-2000 thermal cycles. The corresponding Al contents and volume fraction of β phase are shown in Figure 27 and 28, respectively. In both cases, the computed values of the Al content and the volume fraction of β phase are lower than the experimental data when the thermal cycle exceeds 2000. This finding indicates that Al and β -phase depletion occur at lower rates than model prediction. Chemical analyses of oxides formed on the surface specimens indicated that the oxide layer contained a mixture of alumina, yttria, and chromia when the number of thermal cycle exceeded 2000 cycles. In addition, oxidation pits, which are indicative of localized oxidation, were observed in specimens after 3500 thermal cycles. The discrepancy between model prediction and experimental data was therefore due to the absence of a continuous alumina scale on the oxidized surfaces.

Figure 26. Comparison of computed and measured weight changes data of NiCoCrAlY at 1010°C (1850°C). Deviations of computed and measured weight changes for thermal cycles greater than 2000 cycles were caused by the formation of alumina, yttria, and chromia in the experimental data, rather than a continuous layer of alumina as assumed in the model .

Figure 27. Al depletion compared against experimental data for NiCoCrAlY at 1010°C (1850°F)

Figure 28. Computed volume percent of β phase compared against experimental data for NiCoCrAlY at 1010°C (1850°C).

5.2D Conclusions

- Microstructure of the NiCoCrAlY (GT 33) coating exhibited a duplex microstructure consisting of β -phase in a matrix of γ . The β -phase in the coating decreased with increasing thermal cycles at both peak temperatures.
- The oxides formed on the coated specimens after thermal exposure varied with thermal exposure. The oxide scales formed on the coated specimens exposed for up to 1000 thermal cycle was predominantly alumina with dispersion of yttria particles. The specimens exposed for over 1000 cycles exhibited mixed (aluminum , chromium and yttrium-rich) oxides.
- TMF cracks were observed in the coating after 3400 cycles exposure at 1010C (1850F). The TMF cracking in these specimens are consistent with the published data for coated GTD-111 material.
- Considering the formation of chromium, aluminum, and yttrium rich oxides, the constants for COATLIFE were determined based on aluminum depletion in the coating.
- The calculated volume fraction of the remaining β -phase in the coating was in good agreement with the measured values of the specimens exposed at both peak temperatures.
- COATLIFE algorithm was validated for NiCoCrAlY (CT-102) coating

6.0 TASK 3. NDE OF COATINGS

6.1 Task 3.1 NDE System Assemblies and Testing

VIC 3D Eddy Current Modeling

EPRI received VIC-3D eddy current NDE software from Victor Technologies. VIC3D provides a convenient interface that allows the user to configure test object geometries, probes, flaws, frequencies, and other inspection parameters to model eddy current coil signal responses. This forward model allows an operator to visualize eddy current signal outputs based on given input system parameters and test material conditions. The modelled outputs from VIC-3D can be compared directly with the laboratory or field-generated eddy current outputs.

A separate inverse program involving a coating characterization module has been developed for inclusion in the software. Basis for this work stems from the error minimization program involving comparison of forward model-derived eddy current coil response to empirically acquired eddy current coil response.

Because there are no commercially available eddy-current instruments that operate in the frequency range of up to 50 MHz, a Hewlett-Packard HP 3577A Network Analyzer that is designed to operate over the frequency range of 5Hz to 200 MHz was used. This instrument measures the reflection coefficient of a one-port network (namely, the loaded coil), from which the impedance data are determined.

There are several steps to be carried out during the testing. First will be to characterize the probe in free-space, then to collect the impedance data, and finally to invert the normalized data with a '12-layer algorithm.' The coil used is a Zetec Z0000595-1 ultra high frequency pancake coil that is designed to operate in the range of 10 to 100 MHz. Its dimensions are 0.090-inch outer diameter, 0.025-inch inner diameter, 0.008-inch height and is wound with 19 turns over two layers. The measured dc resistance was $R_0 = 0.741\Omega$ and the measured dc inductance was $L_0 = 0.462\mu\text{H}$. Using the quoted coil parameters, **VIC-3D**[®] computed a value of $L_0 = 0.436\mu\text{H}$. For the purpose of this demonstration, the coil was housed in an acrylic block, and the test pieces were laid on the block, over the recessed coil. The probe coil was assumed to be an ideal inductor that carries a uniformly distributed current within a rectangular window. In practice, any real coil exhibits self-capacitance and resistance, as well as additional capacitance associated with coaxial cables or other connections to the coil.

A real eddy-current probe can be modeled by the equivalent circuit of Figure 29, in which L_0 and R_0 are the (low-frequency) inductance and resistance of the probe, Z_w is the impedance of the work piece, coupled back into the probe circuit, and Y_p is the parallel admittance that accounts for the remainder of the probe and its connecting cable. For example, Y_p could be the self-capacitance of the coil, which would account for the resonant behavior of the probe. In any case, it is assumed that $Y_p \rightarrow 0$ as $f \rightarrow 0$.

Figure 29. The equivalent circuit of a real eddy-current probe with $Y_P \rightarrow 0$ as the frequency goes to zero (left). In reality, the self-capacitance of the probe is present (right) which accounts for the resonant behavior of the probe.

The acquired data consisted of normalized coil impedance data – real and imaginary- from three transverse cut out samples, A', B, and E from Blade 5 of 7FA 1st stage bucket.

Using the HP network analyzer and the Zetec coil, the reflection coefficient, S_{11} , of the loaded coil, from one to fifty MHz, in one-MHz step, was recorded for each of the test samples. However, due to the flat coil holder configuration, only one location on the suction side was selected for testing. This location is outlined in Table 6.

Table 6: Relative test positions on the samples.

Sample	A'	B	E
Test spot from leading edge (in)	4.5	3.5	3.0
Total chord length from leading edge (in)	7.5	6.5	5.75
Percent of test spot to chord length	60	54	52

S_{11} is recorded as magnitude and phase (in degrees). Z_W , the change in normalized impedance due to the work piece, is then computed from the scattering coefficients. (By 'normalized' mean that the true data at each frequency have been divided by the reactance of the probe coil in free space at that frequency.) The real and imaginary parts of the normalized impedances from one of test samples are shown in Figure 30.

Z_W is recorded as a change in resistance (real part) and a change in reactance (imaginary part). The change in reactance is always negative (due to Lenz' law), whereas the change in resistance is positive.

Figure 30. Real (left) and imaginary (right) plots of the normalized impedances from Sample A'.

In inverting the GT33+ coating problem for Samples A', B and E, the N-layer algorithm was not used initially because it was easier to use **VIC-3D**® to generate impedance data. These data were then compared to the measured coil impedance data. The reason for this approach is that there were only three parameters to fit into the GT33+ model, namely Z2, the thickness of the Al₂O₃ layer, and the conductivity (σ) of β^+ and β . Furthermore, this allowed how closely the computed/measured data fit the GT 33+ coating system, where β^+ and β thick nesses were fixed at 100 microns. This also allowed an evaluation of the thickness of the Al₂O₃ layer and the β^+ σ values at higher frequencies, while determining the σ of the β layer at lower frequencies. Therefore, a number of test models were computed using **VIC-3D**® and then plotted the best fits with the measured data over the entire frequency range. This not only provided the answer to the coating-thickness question, but also indicated the quality of the fit over the wide frequency range that was used. The comparative results of measured and calculated results based on assumed values of Z2, β^+ , and β from Sample A' are shown in Figure 31. Similar approach was used to obtain the desired results from Samples B and E. Table 7 shows the range of calculated values associated with Z2, β^+ , and β .

Table 7. Estimated Coating Values

	Z2 (Al ₂ O ₃ Oxide Layer)	β^+ (Topcoat Conductivity)	β (Bond coat Conductivity)
A'	55 microns	7-8E5 S/m	6E5 S/m
B	15 microns	5-7E5 S/m	5-7E5 S/m
E	30 microns	1-1.2E6 S/m	8.4E5 S/m

Figure 31. Comparison of measured and calculated coil impedance data

Less than normal σ estimates were obtained from Samples B. The measurement point was affected by crazed cracking, thus providing below normal readings. Sample A measurement point corresponded to depletion of beta-phase particles and this lead to inaccurate assessment of bond coat σ value. Sample E showed normal coating condition at the point of measurement, thus allowing estimates of topcoat and bond coat σ values. These results show that more than one measurement is necessary to estimate valid coating conductivity values. Using the normal coating area of Sample E, the N-layer algorithm was next applied to obtain independently the values of Z2, β^+ and β layers.

Inverting the impedance data, for example, via the 8-layer algorithm means assigning a value to L_0 , the thickness of the top layer of Figure 32, and assigning σ to the remaining seven layers, each of which has the same thickness, L , that defines the resolution of the reconstruction. This was done by a process of nonlinear least squares, in which the eight variables are chosen to give the best fit to the impedance data. The inversion is done in several steps, starting with the computation of a table of data, from which the final solution is determined by interpolation.

Figure 32. Coating model based on 8-layer inversion program.

The following discussion and subsequent results were based on the 12-layer algorithm that was used to assess the GT33+ coating system. The following initial conditions were used: L_0 , the thickness of the Al_2O_3 layer was 30 microns, and the thickness of the β^+ and β layers were 100 microns each. Each of the eleven layers within the 33+ coating system was assigned a value of 24 microns, which resulted in the total thickness range of up to 264 microns. The liftoff of the coil was estimated to be 1 mil (= 25.4 microns), which was the actual depth of the coil within the acrylic box that was used in the GT33+ experiments.

The numerical experiment was run at 33 different frequencies (in MHz): 0.684, 0.81, 0.947, 1.094, 1.252, 1.421, 1.6, 1.79, 1.991, 2.202, 2.424, 2.656, 2.899, 3.153, 3.418, 3.693, 3.979, 4.275, 4.582, 4.9, 5.228, 5.567, 5.917, 6.278, 6.649, 7.03, 7.422, 7.825, 8.239, 8.663, 9.098, 9.544, 9.999. These are the same frequencies, which were used in the swept-frequency eddy current system from CESI.

The **VIC-3D**[®] run produced the following results:

Variable No.	1	2	3	4	5	6	7	8	9	10	11	12
σ ($\times 10^5$)	9.85	12.3	12.8	11.7	10.3	9.03	8.05	7.33	6.82	6.47	6.24	54.4 μm
Scatter ($\times 10^{-4}$)	4.74	5.92	7.57	9.85	12.7	16.3	20.6	25.8	32.2	39.9	49.3	1.30

The first eleven variables represent σ of the eleven layers (from top to bottom), and the twelfth variable is the thickness of the aluminum-oxide layer, including the liftoff of the coil. When the liftoff value is subtracted, 29 microns of the oxide coating remain. The third row lists the ‘scatter coefficients’ of the solution. Suffice it to say that the smaller the scatter the more sensitive is the solution at that particular location. Hence, the solution is most sensitive to the thickness estimate of the oxide coating, with decreasing sensitivities to σ estimates at deeper layers.

In order to determine σ of the β^+ and β layers, the respective results were normalized over a 100-micron thick coating layer. Based on the each layer being 24-micron thick, the following σ values were obtained from the β^+ and β layers.

$$24 \times (9.85 + 12.3 + 12.8 + 11.7) + 4 \times 10.3 = 1160.6 = 100 \times \beta^+$$

$$20 \times 10.3 + 24 \times (9.03 + 8.05 + 7.33) + 8 \times 6.82 = 846.4 = 100 \times \beta$$

From this, σ values of the β^+ and β layer are 11.61×10^5 S/m and 8.46×10^5 S/m, respectively. These results are tabulated below:

	11-layer Inversion	Model/Empirical Inversion
β^+ Topcoat	1.16 MS/m	1.2 MS/m
β Bond Coat	0.85 MS/m	0.84 MS/m
Al_2O_3 Layer	29.0 microns	30 microns

The comparative results showed that two inversion programs were comparable. These σ results matched closely with the frequency-scanning eddy current-based σ estimates.

Frequency-Scanning Eddy Current Testing of Frame 9 Second Stage Bucket

It was reported in our last semi-annual report that this frequency-scanning eddy current tester (F-SECT) was able to discriminate and characterize normal coating, beta-depleted coating, and cracked coating made of GT 33+ duplex coatings. In addition, by relying on the built-in inversion software program, the following respective σ values were obtained from the topcoat, bond coat, and GTD 111 substrate: 1.04 MS/m, 0.81 MS/m, and 0.77 MS/m.

To evaluate this system's flexibility and capability, F-SECT was tested on a Frame 9 second stage bucket coated with CoCrAlY (GT 29) simple coating. Visual inspection showed areas of possible coating wear after 12,000 hours of operation. Figure 33 shows visual appearance of the blade bucket, where wear (highlighted by blue dye mark) was noted at approximately 50% of the blade height.

Figure 33. Suction Side of Blade 53 showing possible coating wear. This area is highlighted by blue dye mark.

This F-SECT system was used to quickly scan the areas of interest after marking bucket with $\frac{3}{4}$ -inch square grids. Grids were marked A through K along the blade height starting from the platform up to the blade tip. Similarly, they were numbered 1 through 8 from the leading edge to trailing edge along the curvature of the blade chord. The following eddy current displays are shown as Figures 34a and b from the areas of interest represented by transverse cross sections F and G.

Figure 34a. Transverse Section F – suction side

Figure 34b. Transverse Section G – suction side

All of the transverse sections showed some degree of coating degradation with degradation peaking at positions F4, G4, and H4. Outside of these grids, normal coating degradation – beta phase depletion -was noted from the rest of the F, G, and H transverse sections. What is interesting is the shape of the normalized impedance curves at these grid 4 positions. In the F section, a slight increase in the coil impedance values at 1.5 MHz was noted before they started to fall. Similar increase in the coil impedance values was noted at Position 4 of G section at around 3 MHz. Similar but less pronounced increase and decrease in the coil impedance values was noted from Position 4 of H section at around 1.0 MHz. Most pronounced decrease in the coil impedance was noted at F4, followed by G4 and H4.

For most coating degradation caused by beta-phase depletion of the GT33+ coating, the coil impedance slopes stay flat or extend slightly into negative values. Any dramatic decrease in the coil impedance from the GT 33+ coating was attributed primarily to cracked coating. Since this second stage bucket came out of a base-loaded plant, no cracking was expected. Thus, it was suspected that observed decrease in the eddy current coil impedance was caused possibly by the damaged blade substrate from the loss of protective coating.

Figure 35 confirms the eddy current findings.

Figure 35. SEM photomicrographs of degraded substrate sections

Figure 35 clearly shows oxidation of CoCrAlY coating accompanied by diffusion of aluminum into the base metal. This diffusion process into the base metal is shown as columnar AlN and finely dispersed TiN precipitates. As will be shown later from the chemistry of coatings by weight percent, aluminum is decreased to 10% along with chromium, which is also down to 8.4%. The oxygen concentration, however, is high at 24.5%. The coatings from F4 and G4 sections are heavily oxidized and offer no protection to the base metal. These precipitates in the substrate lead to weakening of the base metal alloy due to high residual stresses.

In contrast, no base metal precipitates were noted from F5 and G7 cross-sections (see Figure 36).

a) F5 cross-section

b) G7 cross-section

Figure 36. SEM photomicrographs of degraded coatings

Within top coating, no obvious oxidation of the coating was noted except for the oxide deposits on top of the top coating. The average measured deposit thickness at F5 and G7 cross-sections was around 35 microns and 55 microns, respectively. Also, it is possible to see darker β -phase (CoAl) particles dispersed unevenly within gray-colored γ -phase solution. The average coating thickness was 60 microns each for both F5 and G7. They represent the conditions of β -phase depletions. Based on the EDS results in weight percent, the aluminum content was reduced to 12.5% at F5 and 10.5% at G7.

The next question involved the explanation for the characteristic “hook” pattern observed at lower frequency. It should be noted that higher frequency provide more information about coating conditions, while lower frequency generating deeper eddy current penetration depths offers more information about the GTD 111 substrate conditions. This characteristic dip in the normalized coil impedance at lower frequency is attributed to permeability variation. This condition, associated to magnetic characteristic of the coating, was confirmed by the attraction of a small magnet placed alongside each of the outlined grid squares. The areas such as F4 and G4 exhibited stronger attractions than other outlined grid areas. Since the nickel-based GTD-111 substrate alloy is not magnetic, this magnetic behavior is caused more likely to depletion of chromium, which results in chromium oxide deposits. The chemical composition by weight percent for chromium in CoCrAlY coating, based on a literature survey, showed a range of 25-33%. According to the EDS results, the chromium content averaged 8.4% at F4 to 19.9% at G7. The resultant oxide can be found both on the top scale, which can spall off, and in the diffusion interface. The F5 cross-section showed presence of deposit approximately 35 microns thick. The spectrum analysis by weight percent of deposit at F5 showed 40% carbon, 21% cobalt, 13% chromium, 10% aluminum, 9% nickel, and 7% oxygen. Based on the spectrum analyses of the coating and diffusion interface, the respective chromium content was found to be 8.4% and 10% at F4 and 10.6% and 23.2% at G4.

7.0 TASK 4. FIELD VALIDATION OF COATLIFE AND NDE

Objective

The objective of this task is to validate the predictive capabilities of COATLIFE and the eddy current NDE methodology on field-operated coated turbine buckets. This task is scheduled to begin in Nov 2003.

Results

A few utilities were contacted to procure blades, but no blades were procured to date. Blade procurement under this task started in January 2002. Technical work is slated to begin in November 2003.

No progress to report

8.0 TASK 5. ECONOMIC RISK-BASED DECISION ANALYSIS

Objective

The objective of this task is the development of an Economic-Risk-Based Decision Analysis package that shall integrate the various technologies for coating and substrate damage analysis, aerothermal and structural analysis, and nondestructive evaluation into a common system.

$$\text{Future Value} = \text{Present Value} \times (1 + \text{interest rate per period})^{\text{[number of periods]}}$$

For a majority of economic analyses, the value function is the net present value (NPV). To perform the NPV analysis, cost and benefit streams are identified for each year of the analysis. The costs and benefits each year are subtracted to yield a net value for each year. This stream of net values for future years is then transformed using the above equation into present values, thus producing a net present value. NPV analysis has become so common-place that it has become institutionalized within the federal government and is the method of analysis dictated for all federal departments, agencies, and programs by the Office of Management and Budget in OMB Circular A-94. More specific guidelines germane to the present project are given in "Standard Life-Cycle Cost-Savings Analysis Methodology for Deployment of Innovative Technology" issued by the U.S. Department of Energy, Office of Environment Management.

Concept of Decision Analysis

The current statement of work involves the application of economic analysis and risk-based techniques to support management decisions involving the best course of action for the operation and maintenance of gas turbines using coated blade technology. The COATLIFE™ computer program incorporates failure models for coated hot section turbine blades for both oxidation life and thermomechanical fatigue. COATLIFE produces a graphical output graph showing the predicted time to failure of the blade based on prior operating history, coating type, and other factors.

For the purpose of an effective decision analysis, sufficiently accurate economic analysis should be performed to support a “correct” decision to some predetermined level of confidence. The confidence level in the recommendation will not, in general, be better than the confidence in the underlying data. For example, it would be unrealistic to expect a 95% confidence in the correctness of the recommended decision if the input information into the risk-based approach was at worst only 70% confident. This is a key point in decision support.

The confidence interval on the expected value (result) is controlled by the confidence intervals in the underlying data.

In this context, the goal of the decision analysis process is to make the best decision based on the uncertainty of the input data, and not necessarily to seek either accuracy or precision in the economic analysis beyond that supported by the accuracy of all other inputs. For example, a predicted probability of failure or remaining life that is only 70% accurate may only require cost and benefit values estimated to the nearest thousand or tens of thousands of dollars for mathematical consistency and optimal recommended decision to either continue operating, conduct a detailed non-destructive examination, or replace the hot section blades.

Software Architecture

After some consideration, the architecture for the Risk-Based Economic Decision Analysis software has been selected to be the Microsoft Excel™ spreadsheet software with the addition of the Crystal Ball™ add-in to support probabilistic Monte Carlo simulations. Other options considered were stand-alone software programmed for the Windows™ environment using Microsoft Visual Basic™, stand-alone Windows software programmed using Fortran, and an Excel spreadsheet using the @Risk add-in for Monte Carlo simulations. The architecture was decided based on ease of programming, speed of execution, and interface with COATLIFE. When all factors were weighed, the Excel/Crystal Ball combination was the optimal architecture, though suffering from some performance and user interface penalties. The performance issues are being minimized by careful coding and considerable amounts of Visual Basic for Applications (VBA) code should enhance the user interface.

Program Structure

The program structure is still evolving, but the basic structure is illustrated in Figure 37.

Figure 37 Basic Logic Structure of the Risk-Based Economic Decision Analysis Software

Task 5 is ahead of the planned schedule. Subtask 1 for the definition of the software architecture was completed and Subtask 2 for the establishment of costs, consequences and uncertainties will be completed on schedule at the end of April 2003. Subtask 3 for the detailed design and assembly of the spreadsheet model was begun early in February 2003 and should likewise be completed earlier than the planned end of calendar year 2003.

9.0 REFERENCES

1. A. Scalzo, et al. *"A New 150MW High Efficiency Heavy-Duty Combustion Turbine"*, 88-GT-162.
2. J. DeMasi, K. Sheffler and M. Ortiz, *"Thermal Barrier Coating Life Prediction Model Development- Phase I Final Report"*, NASA CR-182230, 1989.
3. A. Scalzo, G. Howard and P. Holden, *"Field Test of the W501D – A 100 MW Combustion Turbine"*, 83-GT-174.
4. *ANSYS User's Manual*, ANSYS Inc., Revision 5.6, 2000.
R. Viswanathan, "Blade Life Management: Coating Systems", EPRI Report 1006608, 2002.