On-Line Thermal Barrier Coating Monitoring for Real-Time Failure Protection and Life Maximization

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Disclaimer

ABSTRACT

Under the sponsorship of the U. S. Department of Energy's National Energy Laboratory, Siemens Westinghouse Power Corporation proposes a four year program titled, "On-Line Thermal Barrier Coating (TBC) Monitor for Real-Time Failure Protection and Life Maximization," to develop, build and install the first generation of an on-line TBC monitoring system for use on land-based advanced gas turbines (AGT).

Federal deregulation in electric power generation has accelerated power plant owner's demand for improved reliability availability maintainability (RAM) of the land-based advanced gas turbines. As a result, firing temperatures have been increased substantially in the advanced turbine engines, and the TBCs have been developed for maximum protection and life of all critical engine components operating at these higher temperatures. Losing TBC protection can therefore accelerate the degradation of substrate components materials and eventually lead to a premature failure of critical component and costly unscheduled power outages. This program seeks to substantially improve the operating life of high cost gas turbine components using TBC; thereby, lowering the cost of maintenance leading to lower cost of electricity.

Siemens Westinghouse Power Corporation has teamed with Indigo Systems; a supplier of state-of-the-art infrared camera systems, and Wayne State University, a leading research organization.

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ON-LINE THERMAL BARRIER COATING (TBC) MONITOR FOR REAL-TIME FAILURE PROTECTION AND LIFE MAXIMIZATION

EXECUTIVE SUMMARY

With On-line blade monitoring, Siemens Power Generation (PG), under the sponsorship of the U.S. Department of Energy, has developed an innovative way to continuously monitor row 1 and 2 blades in gas turbines. By using a high-speed infrared camera these blades can be kept under surveillance during operation of the gas turbine. The challenge comes when the blades are running they rotate at extremely high speeds and in a hostile environment of a fully operating turbine engine. This unique approach opens opportunities to real condition-based maintenance which can lead to significant cost savings for PG's customers.

The blades in the first two rows of a gas turbine are subjected to high thermal stresses. In order to optimize the life of the blades and to avoid the high costs involved in unscheduled replacement a team at Siemens in Orlando developed the idea of recording the radiation of the hot ceramic blade surface using a high-speed infrared camera. To do this a cooled optical probe, which reaches as far as the moving blade row, is installed in the gas turbine. The camera is attached to the optical probe and mounted outside of the turbine casing. Despite the high speed of rotation, the control software is capable of identifying and recording each individual blade. The images are evaluated automatically, and the entire system can be linked up to remote diagnostics centers.

This monitoring system makes it possible to replace the blades based on their actual condition. Blades will be replaced only when they are worn, such as when the thermal barrier coating is severely damaged. Taking into account the high costs of a row-1 or row 2 replacement, by implementing this new technology significant cost savings can be achieved.

During the period of October 2-12, 2004, Siemens Westinghouse Engineering successfully installed a commercial On-line TBC Blade Monitor in a W501FD gas turbine at Empire Stateline Electrical Company in Joplin, Missouri . This is the first commercial full scale, high temperature, full pressure, blade monitoring system. Blade monitoring is accomplished by both near and mid- wave infrared (IR) high speed cameras. Two access ports were R5 design reviewed and installed to allow two vantage points for viewing the row 1 blades on the W501FD engine. A pair of IR lens trains were designed and built to install optics within the turbine cover. These optics are capable of withstanding the high temperature of the turbine casing with only a small amount of compressor discharge cooling. The cameras are operated via a control station in the engine test room. A TATM blade rotor synchronization system was developed to allow for specific blade(s) viewing. Custom software has been created to operate the camera(s) and select any combination of blade views and view periodicities. The software also operates filter functions, camera motion and skew. The entire camera system is contained in an environmental enclosure that is cooled with a small amount of compressed shop air. The enclosure is self contained and allows multiple adjustments to the optical system from the engine test room. The system has an expected life of 8,000 hours.

This commercial installation will monitor and evaluate the performance of row 1 TBC coated blades of both pressure and suction sides. The tests and demonstration will evaluate the mechanical design of the monitoring viewing ports, mechanical integrity of TBC monitoring system (camera performance, environmental enclosures and spectral filter) and integration and development of system supervisory system and TBC Lifing Model.

The anticipated benefits are listed below:

(1) Use of the on-line TBC monitor will significantly improve plant reliability and availability by extending critical component lives. Damaged TBC can be identified early and repaired before the component's catastrophic failure.
(2) Use of the on-line TBC monitor will significantly increase availability of peaking gas turbines by eliminating down time required for frequent borescope examination of TBC's.
(3) The on-line TBC monitor can be used on all existing and new gas turbines that use TBC to protect critical turbine parts. The fundamental concepts of the on-line TBC monitoring is equally applicable to smaller land, aero and marine based gas turbines. This opens future global market opportunities for the team to pursue.
(4) The financial payback of this technology comes in the form of reduced maintenance costs and having power plants available when they would not have been. All of today's advanced gas turbines can benefit from this monitor. We expect over 600 "F" and "G" class gas turbines to be in service over the next 12 years. The total estimated 12-year life-cycle maintenance cost savings for these 600+ units is expected to be over $600M.

ON-LINE TBC MONITORING – STATUS OF TASK 2

Task 2: Develop On-line TBC Monitor for Blades

PROGRAM PROPOSAL

Subtask 2.1 Determine Temperature-Dependent IR Characteristics of Blade Surface and GT Working Fluid

2.1.1 Measure Spectroscope Properties of GT Working Fluid: Infrared transmission, absorption, and emissivity properties of the turbine engine atmosphere will be determined within the range of operating parameters expected. The high-pressure, high-temperature, high-velocity gas will effect the relationship between radiance and temperature as will the TBC damage.

2.1.2 Measure TBC Coated Blade Emissions as Function of Temperature: Thermal emission characteristics will be determined for several states of the TBC condition. They will include sintering, contamination and defect formation. Characteristics of deteriorating TBCs will be studied. Deteriorating TBC emissions will demonstrate a local step change in emissivity.

2.1.3 Characterize Emissions from TBC Defects (APS): Emissions from critical TBC defects types will be determined. Debond growth and surface temperature changes will influence the radiance and radiant transients. The debond is expected to cause an increase in the absolute temperature of the TBC surface. As the same debond grows, the temperature will increase and the imaged region of the spallation will grow. Basic measurement capabilities will be investigated by building a laboratory model of the TBC blade sensor.

STATUS OF TASK 2, SUBTASK 2.1

This task continues on schedule and meets all milestones.

Ceramic TBC's are used on metal turbine blades and engines to operate at higher temperatures to increase power, improve fuel consumption, and lower emissions into the environment. Studies have shown that ceramics which show promise as TBCs have low, variable emittance and significant reflectance and transmittance at short wavelengths, which leads to increased uncertainties of measurement for short-wave infrared. However, testing conducted on this program has determined that the peak contrast for TBC defect detection is at 1510 nm for shortwave infrared. This can be seen in Figure 1.

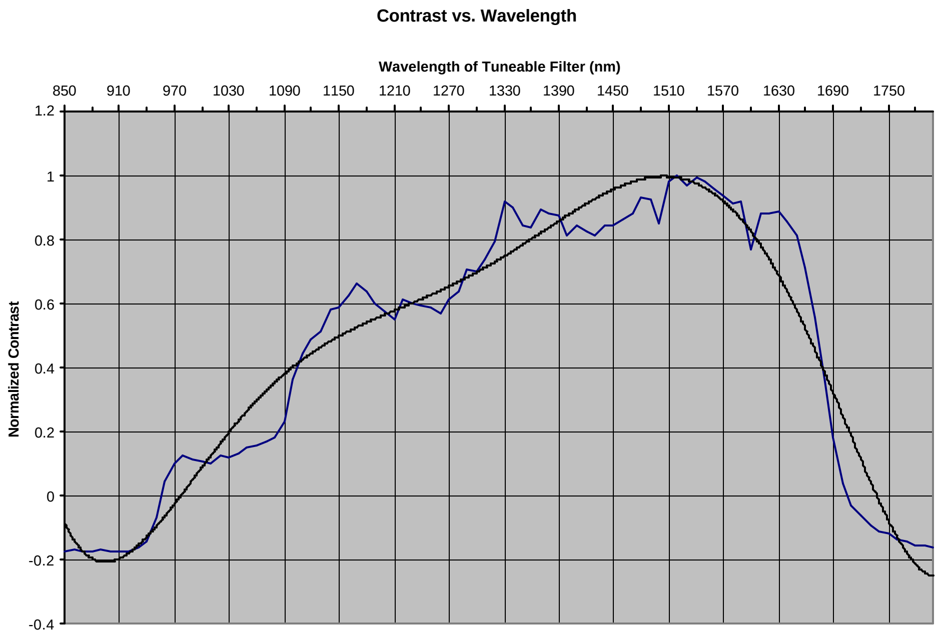

Figure 1

The radiative properties of the TBC samples were measured by Advance Fuel Research (AFR) with a Benchtop Emissometer. Samples placed in the Emissometer were irradiated from all directions by energy from a near-blackbody source, and reflected and transmitted energies collected at directional near-normal take-off angles with an FTIR spectrometer. Thus, spectral hemispherical-directional reflectance and spectral hemispherical-directional transmittance are measured, and conservation of energy (closure) provides the spectral directional emittance (E=1-R-T). A liquid nitrogen cooled MCT detector was used to measure the 20-1.2 micron spectral region. The detector has low sensitivity as it approaches the 1.2 micron region and this is observed as increased "noise" in plotted data. Torch heating in air on the backside of a sample is performed to achieve requested high temperatures for measurement. The strongest absorption band of torch generated carbon dioxide gas at ~4.1 microns presents itself as a fairly narrow band interference in the spectral data. Table 1 indicates the types of detectors employed and their ranges.

Table 1 – Detectors employed in the Emissometer

Detector	Spectral Range
Mercury-Cadmium-Telluride (MCT) (liquid nitrogen cooled)	500 cm^{-1} - 8,500 cm^{-1} or 20 µm - 1.18 µm
Silicon-Photodiode (ambient temperature)	8,500 cm^{-1} - 12,500 cm^{-1} or 1.18 µm - 0.8 µm

In order to collect data over the wide spectral range at a specific temperature, measurements were taken sequentially for both detectors while maintaining a constant temperature on the surface.

EMITTANCE OF AIR PLASMA SPRAYED (APS) COATING

Sample Preparation

Test samples of free standing 8YSZ on a graphite substrate were supplied to Advance Fuel Research for measurements of spectral emittance. The temperatures requested were 1000C, 1100C, 1200C, 1300C, and 1400C. The temperature range was achieved by heating the back surface with an oxy-acetylene torch.

Results and Discussion

Results for this test are for clean TBC surfaces and measured at wavelengths nominally from 1.1µm – 14µm. The results of the data has concluded that emissions from Near Infrared and Mid Infrared exhibit low emittance and high emittance in the Long wave Infrared. Additional laboratory experiments are being performed to measure the thermal contrast during the progression of defect formation. Preliminary results has profiled the maximization thermal contrast for defect detection with an infrared focal plane array detector at 1550nm. Further experiments will profile these contrast measurements in test results from data at the Forschungszentrum Julich Research Facility, Julich, Germany. The results of the emittance measurements of clean TBC are summarized in Table 2.

Table 2 – Summary of Emittance

Sample – 8SYZ	1000C initial	1100C	1200C	1300C	1400C	1000C final
Near Infrared .9-1,65µm						
Emittance – 1.1µm	0.12	0.11	0.14	0.18	0.22	0.08
Emittance – 1.2µm	0.09	0.10	0.15	0.18	0.22	0.08
Emittance – 1.3µm	0.12	0.12	0.15	0.18	0.22	0.09
Emittance – 1.4µm	0.11	0.10	0.14	0.17	0.21	0.07
Emittance – 1.5µm	0.11	0.11	0.14	0.18	0.22	0.09
Emittance – 1.6µm	0.12	0.12	0.15	0.18	0.22	0.10
Emittance – 1.65µm	0.12	0.11	0.14	0.18	0.22	0.09

Sample – 8SYZ	1000C initial	1100C	1200C	1300C	1400C	1000C final
Mid Infrared 3-5µm						
Emittance – 3.0µm	0.13	0.12	0.15	0.18	0.22	0.10
Emittance – 3.5µm	0.13	0.12	0.16	0.19	0.23	0.10
Emittance – 4.0µm	0.18	0.18	0.21	0.24	0.27	0.17
Emittance – 4.5µm	0.31	0.32	0.34	0.37	0.39	0.30
Emittance – 5.0µm	0.47	0.48	0.50	0.52	0.54	0.47

Sample – 8SYZ	1000C initial	1100C	1200C	1300C	1400C	1000C final
Long Infrared 3-5µm						
Emittance – 8.0µm	0.96	0.96	0.96	0.96	0.97	0.96
Emittance – 8.5µm	0.97	0.97	0.97	0.98	0.98	0.97
Emittance – 9.0µm	0.98	0.98	0.98	0.98	0.98	0.98
Emittance – 9.5µm	0.98	0.98	0.98	0.98	0.98	0.98
Emittance – 10.0µm	0.99	0.99	0.99	0.99	0.99	0.99
Emittance – 10.5µm	0.99	0.99	0.99	1.00	1.00	0.99
Emittance – 11.0µm	0.99	1.00	1.00	1.00	1.00	0.99
Emittance – 11.5µm	0.99	0.99	0.99	1.00	1.00	0.99
Emittance – 12.0µm	1.00	0.99	1.00	1.00	1.00	1.00
Emittance – 12.5µm	0.99	0.99	0.99	0.99	0.99	0.99
Emittance – 13.0µm	0.98	0.98	0.98	0.98	0.99	0.98
Emittance – 13.5µm	0.96	0.96	0.96	0.96	0.97	0.96
Emittance – 14.0µm	0.91	0.91	0.92	0.92	0.93	0.91

TASK 2.2 DEVELOP IR MONITOR FOR TBC COATED BLADES

This subtask consists of the following components: (1) select/develop IR sensors; (2) determine data types, transmission rate, and formats, (3) design data analysis scheme for the GT-TBC monitor inputs, (4) determine control interface and blade sensor attachment, and (5) develop blade surface condition monitor. Two possible embodiments considered for the blade sensors are:

(1) Rectangular array designed for direct, line-of-sight viewing of blade region of interest.

(2) Rectangular array designed for coherent fiber bundle for non line-of-sight viewing of blade region of interest.

The array detector will be a state-of-the-art, cooled, solid state, infrared detector. Work conducted in Task 1 shall determine the best combination of atmospheric spectral window and maximum TBC system information. Once determined, the detectors will be designed within these spectral windows. The detector spectral selection used for embodiment 2 shall have the additional consideration of fiber optic transport. The fiber optic system must be rugged in the AGT environment and allow remote detector location outside of the AGT enclosure, if possible. The fiber optic device shall be designed to allow replacement of the fiber bundles, including gas-exposed viewing optics without disassembling any AGT components. The closest location for detector installation is outside of the shell of the turbine.

Future embodiments may allow complete gas path viewing fiber and detector replacement without shutting the turbine down, an internally installed optical directly involved in this activity. Design Engineering will determine the optimum sensor vantage points with the following considerations: pressure boundary control, serviceability, viewing optics protection, critical region viewing, viewing regions, and sensor installation minimization. This activity will establish guidelines and limitations for sensor type, placement and attachment. The Program Manager along with SWPC Design Engineering will publish an installation requirement complete with specifications, attachment requirements, and modified and approved AGT drawings demonstrating penetrations and detailed pressure boundaries. They will be responsible for approving all sensor attachments and installation procedures.

STATUS OF TASK 2, SUBTASK 2.2

The intent is to develop a system for real-time viewing and, recording of a Thermal Barrier Coated gas turbine component experiencing the onset of TBC spallation. The overall program involves continuously viewing a row 1- turbine blade surface via an infrared camera system. Figure 1 profiles the viewing layout.

Engineering have completed drawing layouts and design reviews with the intent of viewing both internal path and any potential obstructions and interference's external to the engine casing such as piping, brackets and other features. These drawings have clear view of row 1 blades from a radial oblique viewing direction. The following figure profiles the viewing direction and penetration locations into the gas turbine generator.

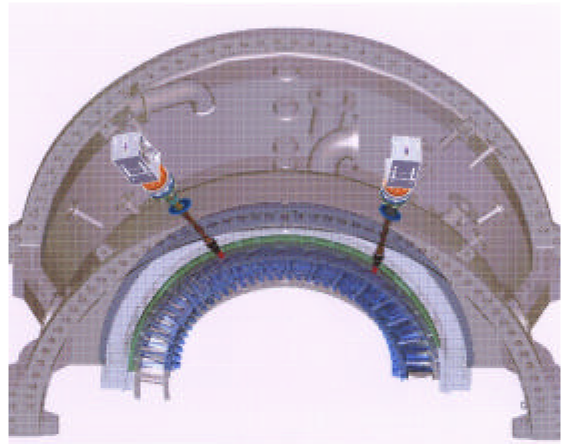

Figure 2

The conceptual design will allow the implementation of the concept to more thoroughly assess practical issues of the sensors implementation and cost. Along with the conceptual design, some additional verification tests or analysis will be performed on the concept to allow a better assessment of the monitoring system. Dual high-speed infrared cameras operate with a spectral response of 0.9-1.65µm and 3-5µm and integration or shutter speed on the order of 1µm. These cameras with a blade position sensor allow viewing of a single blade surfaces during engine operation. Both systems have state-of-the-art real-time infrared (IR) sensors that captures images on the blades rotating at 3600rpm which is equivalent to 400m/s linear speed.

ON-LINE TBC MONITORING – STATUS OF TASK 5

TASK 5 : DEVELOP TBC REMAINING LIFE PREDICTION MODEL

PROGRAM PROPOSAL

SWPC will develop the supervisory software for the TBC diagnostic system utilizing a rule-based logic. The system will store all the processed data coming from the blade and vane temperature sensors. The data will be supplemented by key thermal data produced by the performance monitoring package. The sensor data will then run through a rule-based expert system to determine the probability of TBC coating failure.

Raw signals from both the blade and vane monitors will have to be preprocessed before the data is analyzed. Preprocessing will also be performed to eliminate spurious indications. Blade monitor signals will include high-speed radiance scans of the blades. Data will be processed into a meaningful form to demonstrate changes or excursions that require reporting to the control software. The decisions that guide in this selection will be made throughout the program.

The control software will interpret the reported trends or excursions and notify or alert the operator of the finding. Different types of preprocessing logic will be used to identify excursions or trends. Raw data signals will be processed as collected. Some preprocessing steps will include a continually updated running average with statistical significance for ongoing data collection. This will establish a baseline for comparison of each refreshed data set. Excursions from this baseline will be brought to the attention and disposition of the artificial intelligence (AI) system. Historical averages will be periodically stored for long-term trending and AI disposition. The system will report information in the following categories: Temperature maps, Remaining life of TBC, Recommendations for optimizing specific parameters, and Emergency alert.

By continually monitoring the operating conditions, the remaining life for future operating conditions will also be forecasted. Using the advice given by the control system, an operator will have the ability to balance power output and TBC life expense rate. This will ultimately optimize power output and outage scheduling for maximum operator control. Other engine performance and parameter inputs will also be accessed by the advisory system as identified throughout the program. The system will also provide alarms for critical TBC loss situations. The alarms will notify operators only in the event of eminent damage or failure. The system will also provide alarm signals for connection to standard tripping control devices for the option of automatic tripping.

STATUS OF TASK 5

This task continues on schedule and meets all milestones

SWPC will develop the supervisory software for the TBC diagnostic system utilizing a rule-based logic. The system will store all the processed data coming from the blade and vane temperature sensors. The data will be supplemented by key thermal data produced by the performance monitoring package. The sensor data will then run through a rule-based expert system to determine the probability of TBC coating failure.

Results: SWPC has successfully demonstrated the functionality of a new developed software, thus be called Blade Inspector. The Blade Inspector has completed validation of operation by obtaining data from two (2) infrared camera while gas turbine was operating at operating. The image processing functions covers the spectrum of image preprocessing, segmentation, feature extraction, evaluation and classification required to inspect the thermal barrier coating. The inspection result will include an estimate of the blade's TBC characteristic and an estimate of the percentage of affected blade surface. conditions.

The next phase will test and validate the functionality of the supervisory systems. The phase will include a Tatum trigger controller interface model and image based numerical inspection functions. The software package will be integrated on a PC with frame-grabber. The numerical inspection functions will be evaluated by using labeled images of TBC examples.

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ON-LINE TBC MONITORING – STATUS OF TASK 6

TASK 6 : FIELD TRIALS

Subtask 6.1 Field trials for blade monitor.

In the final task of the program, the packaged system will be installed on an AGT at one of Siemens Westinghouse's long-term-program (LTP) sites to assess its performance under real plant conditions. A specific turbine engine type and the site for the field trials will be identified during the development process. The engine will be modified as needed for sensor penetrations and installations. Siemens Westinghouse design engineering will be heavily involved with all aspects of the engine changes. Standard engineering practices will assure safe and effective sensor installation.

Status of Task 6

FIELD TRIALS – PROTOTYPE INSTALLATION
SHORT TERM SITE BERLIN, GERMANY

Siemens Westinghouse Engineering has successfully installed an on-line TBC Blade Monitor in a W501FD gas turbine at Empire Stateline Electrical Company in Joplin Missouri. This is the first commercial full-scale, high-temperature, full-pressure, system that is capable of real-time infrared imaging of rotating blades. The monitor is capable of observing 85% of the blade surface, and has a spatial resolution to sufficiently image very small design features. The unit was installed during a normal scheduled outage during October 2 - 12, 2004. Blade monitoring is accomplished by using both near- and mid-wave infrared (IR) high speed cameras. This commercial installation will monitor and evaluate the performance of row 1 TBC coated blades of both pressure and suction sides. The tests and demonstration will evaluate the mechanical design of the monitoring viewing ports, mechanical integrity of TBC monitoring system (camera performance, environmental enclosures and spectral filter) and integration and development of the system supervisory system and TBC Lifting Model.

The results of On-Line TBC Monitoring will significantly improve plant reliability and availability by extending critical component lives. Damaged TBCs can be identified early and repaired before the component's catastrophic failure, and thus will significantly increase availability of peaking gas turbines by eliminating down time required for frequent borascope examination of TBC's. The on-line TBC monitor can be used on all existing and new gas turbines that use TBC to protect critical turbine parts for all applications, to include the use of synthesis gas in Integrated Gasification Combined Cycle operations. The fundamental concepts of the on-line TBC monitoring are equally applicable to smaller land, aero and marine based gas turbines. This opens future global market opportunities.

The installation of the viewing port were installed per drawing # 2346J30 (option 3A). This view looking with flow on the right side of the engine would view the about 90% of the Airfoil height of the leading edge and pressure side of the blade. Figure 3

The installation of the viewing port were installed per drawing # 2346J37 (option 4). This particular viewing port intentionally looks down at the platform and lower airfoil. Figure 4.

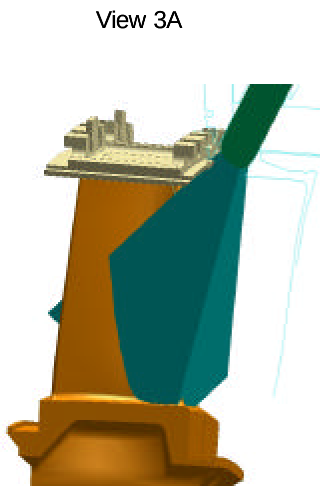

Figure 3

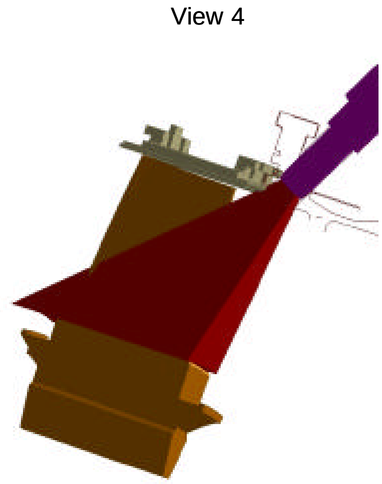

Figure 4

The objective and prominent blade failures occurring in the field are:

1. TBC loss caused by:
    - Erosion of TBC Coating
    - Plugged cooling holes
    - FOD Damage
2. TBC spalling caused by:
    - Sintering at over temperature (cooling hole plugs)
3. Delamination of APS coating caused by manufacturing defects
4. Cracks cause by strain accumulation, usually a design flaw

This task continues with a installation at a long term host site during the 3rd quarter of 2004. This task continues on schedule and meets all milestones

Key Milestone Update

Current program milestones are on or ahead of schedule.

TECHNICAL PROGRAM ACHIEVEMENTS

Achievements from 10/01/01 – 09/30/04

- DOW Proof-of-Concept Testing, November 2001
- 3D Model Scoping penetration location and direction, 3 of 4 models complete
- Westinghouse Plasma Center HHFTR Modification, Completion May 2002
- Spectroscopy measurements of GT working fluids, DOW Test, November 2001
- Purchase of NIR Infrared Data Acquisition system and rental agreement of Infrared camera head
- Siemens Westinghouse Power Corporation Program review, Completion March 28, 2002
- Select Infrared Hardware, Milestone completion April 2002
- Siemens Westinghouse Power Corporation Program review, Completion May 28, 2002
- Siemens Westinghouse Power Corporation Program review, Completion September 27, 2002
- R5 Design Review for Radial Penetration, Completion January 2003
- On-Line TBC Monitor system installation in working gas turbine, January 2004 (Berlin, Germany)
- Successfully installed an on-line TBC Blade Monitor in a W501FD gas turbine at Empire Stateline Electrical Company in Joplin, Missouri.

Milestone Completion, 2002

- Develop Proof of Concept of Infrared Sensor, Complete 12/10/2001
- Select/Develop infrared sensors - The final selection for the core of the blade monitor, the focal plane array, Complete 3/12/02
- Conduct lab prototype experiments on selected vane sensors - The vane sensor elements and concept will be evaluated in a lab environment, Complete 8/30/2002
- Assess computer controls and software needs - This effort will complete the statement of computer and software needs anticipated to input, update and archive the data generated by both the blade and vane monitors. Complete 8/30/2002
- Modify current high heat flux test rig - The High-Heat Facility rig test will be retrofit for Blade monitor simulation. Complete 6/6/2002

Milestone Completion, 2003

- Modification of high temperature test rig and TBC Lifing tests, Complete 12/01/03
- Installation of On-line Monitor View Ports for Row 1 blades, Complete 11/01/03

Milestone Completion, 2004

- First infrared images from row 1 blades in the operating W501FD test bed engine in Berlin, under base load, 01/27/04 (Berlin, Germany)
- Identify available blade test facility, Completed 09/01/04
- Complete AI supervisory software/hardware integration into the system operating software, completed 05/31/04
- Complete implementation of TBC remaining life prediction software, completed 06/30/04
- Successfully installed an on-line TBC Blade Monitor in a W501FD gas turbine at Empire Stateline Electrical Company in Joplin, Missouri.

Presentations & Publications

Title: On-Line TBC Monitoring for Real-Time Failure Protection and Life Maximization
Date: September 28th & 29th 2004
Location: Barcelona, Spain
Presenter: Dr. Hans-Gerd Brummel
File: EVI-GTI Conference – On-line TBC Monitoring Presentation.ppt

CONCLUSION

During the period of October 2-12, 2004, Siemens Westinghouse Engineering successfully installed a commercial On-line TBC Blade Monitor in a W501FD gas turbine at Empire Stateline Electrical Company in Joplin Missouri . This is the first commercial full scale, high temperature, full pressure, blade monitoring system. Blade monitoring is accomplished by both near and mid- wave infrared (IR) high speed cameras. Two access ports were R5 design reviewed and installed to allow two vantage points for viewing the row 1 blades on the W501FD engine. A pair of IR lens trains were designed and built to install optics within the turbine cover. These optics are capable of withstanding the high temperature of the turbine casing with only a small amount of compressor discharge cooling. The cameras are operated via a control station in the engine test room. A TATM blade rotor synchronization system was developed to allow for specific blade(s) viewing. Custom software has been created to operate the camera(s) and select any combination of blade views and view periodicities. The software also operates filter functions, camera motion and skew. The entire camera system is contained in an environmental enclosure that is cooled with a small amount of compressed shop air. The enclosure is self contained and allows multiple adjustments to the optical system from the engine test room. The system has an expected life of 8,000 hours.

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