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

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

EXECUTIVE SUMMARY

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 in the field of infrared non-destructive examination (NDE), to complete the program.

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.

KEY MILESTONE UPDATE

Completion of Task 1 – Conceptual Design of System Configuration and Definition

ON-LINE TBC MONITORING – STATUS OF TASK 1 AND TASK 2

Task 1 Conceptual Design of System Configuration and Definition

The objective of this task is to evaluate structural designs and operating conditions of targeted gas turbine engine. They will be thoroughly analyzed in order to establish on-line TBC monitor sensor design criteria (exact sensor attachment positions, the number of total monitoring sensors, etc.).

Subtask 1.1 Design System Configuration

Subtask 1.1.1.1: Structural design

The work being discussed in this review involves the DOE funded program entitled “TBC On Line Monitoring” system. 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. In order to “see” the target area one or more line of sight “viewing tubes” will be installed in a 501FD CT. The intended is to review the mechanical design aspect of the project. The following figures profile the viewing direction and penetration locations into the gas turbine generator.

Engineering have begun drawing layouts 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 will have clear view of row 1 blades from an Axial oblique or Radial oblique viewing direction.

The main issues associated with installing these tubes include finding the optimum path for the tube, so as to see the maximum target area while minimizing interference's between the viewing tube and engine internals and at the same time not violating existing mechanical design criteria. The main component and issue associated here is the combustor transition, which as shown in figures 1 A, B with a single penetration through the inner panel for viewing direction #1. View 3A, it is believed, has few issues associated with it and, in fact, has essentially been done before by MHI at FP&L (501F prototype) without any known problems associated with the radiation pyrometer installation. Figure 2 profiles a 3D model of the 1A viewing penetration direction to the row 1 blades.

Figure 1

Figure 2

Subtask 1.1.2: Establish blade and vane monitor coverage -

The objective of this task will determine the degree of blade coverage that can be realized. These factors include criticality ranking of all blade regions, accessibility determination of blade surfaces, and propensity for degradation for blade surfaces.

A review has been completed that established the order to rank blade coverage, based on historical data of the degradation of TBC and the remaining life coating. Subsequently, the real issue is what can the conceptual sensor resolve vs. specified engineering defect coverage? This development continues in task 2.1 of blade sensor development.

Subtask 1.1.4: Assess vane monitoring sensor(s)-

The overall objective of this task is to assess and provide development direction of a monitor sensitive to TBC coating degradation in Row 1 vanes and, therefore, provide the first indication of over temperature conditions and other problems in the gas turbine engine. On January 22, 2002, a meeting was established to review concepts of a sensor to monitor GT engine vanes for TBC life and prediction model. Development and selection of vane monitor continues in Task 3. The following are some examples of vane monitoring objectives, methodologies and concepts.

Objectives and Methodologies:

The following objectives were developed for the desired monitor to follow TBC condition on first row turbine vanes:

- 1 The method should allow on-line monitoring of row 1 turbine vanes, as well as other turbine vanes for critical failures.
- 2 The method should be specific to row 1 TBC failures. That is, general methods that indicate operating problems without specific knowledge of whether row 1 vanes caused the problem will be less desirable.

3 Methods that are ***spatial and global*** will be preferred for failure detection. ***Integrated global*** indication methods will also be considered. ***Point measurements*** are unlikely to be successful for monitoring vane TBC coating failures. To clarify this categorization of detection methods, refer to the ***spatial global*** temperature distribution that was measured on a hot part by optical pyrometry. In order to detect TBC coating failures, a ***spatial global*** temperature indication measured over the surface of a part provides the most information on the vane's surface condition.

If a failure would impact a significant area of the vanes TBC coating, an ***integrated global*** indication of the overall surface temperature of the vane might also provide useful diagnostic information. Measurement of the integral of temperature over the entire part's surface has the possibility of indicating TBC coating failures because it considers the entire part, and the failure can be on any portion of the part's surface. The ability of an ***integrated global*** measurement to detect a particular localized failure will depend, however, on the sensitivity of the technique. If a small cooling hole is initially plugged, the integrated part surface temperature may not detect this failure until the plugged hole impacts a large fraction of the part's surface temperature. Point temperatures would be the least likely to provide any sensitivity the fault's occurrence.

4. The method should attempt to provide an early indication of vane TBC problems so that major damage to the vanes and other turbine components can be avoided.
5. The method should, as far as possible, detect failure mechanisms known in the field.
6. The method should feasibly be demonstrated in gas turbines within the next two years.

Vane Failure Mechanisms

In order to facilitate the task of down selecting the appropriate sensors to consider we collected available information on prominent failure mechanisms for vane failures.

Prominent vane 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 caused by strain accumulation, usually a design flaw

This failure list indicates that after gas turbine designs are verified with long operation experience, and after appropriate part inspection and quality control techniques are implemented, the primary on-line monitoring need for vane monitoring will be to inspect TBC coating integrity. Furthermore, the two prime causes of TBC coating integrity faults appear to be plugging of cooling holes and damage from foreign or domestic particles in the engine. This means that monitors for cooling hole plugging and foreign object damage may provide important precursor information for TBC condition failures of Row 1 vanes. These techniques should be considered in developing a monitoring basis.

Vane Failure Detection Options

Options for sensors with promise to allow vane monitoring were developed in a brainstorming session attended by a variety of technical experts. The options suggested can be grouped into three types of sensing concepts: 1) concepts that simply use existing plant instrumentation in better ways to detect gross vane failures, 2) concepts that apply existing sensors in new ways within the turbine to allow detection, and 3) concepts for new sensor development. Each proposed sensing technique will be qualitatively evaluated as to their likelihood of detecting relevant vane faults.

Use current plant instrumentation for vane monitoring:

1. **Blade Path Thermocouples:** Thermocouples located downstream of the blades and vanes may be able to detect changes in Row 1 vane condition if localized gross failures occur.

Apply existing sensors in new ways within the turbine

2. **Fixed thermocouples:** Fixed thermocouples could be installed at special locations within the turbine to obtain more information on vane failures.
3. **Rotating thermocouples:** Rotating thermocouples or a rotating sensor carrier could be applied downstream in the exhaust gas path to obtain additional information on temperature perturbations that could be caused by vane failures.
4. **Flow and pressure sensors:** Standard sensors for detecting flow and temperature may be implemented in new ways within the turbine. For example, one could measure flow or pressure changes within the cooling air passages to detect problems with cooling air plugging.

Developmental Sensors

Developmental sensors that have promise for vane monitoring as indicated by the objectives are being evaluated. We will develop initial test plans to obtain data on these sensors and their feasibility to incorporate in a demonstration test.

Subtask 1.1.5: Assess System Hardware Package and Package Requirements-

The objective of this task is to provide system hardware and hardware packaging requirements. There will be field trial site representatives to assure understanding of the limited space and aggressive conditions of the turbine engine environmental enclosure. Hardware required for signal conditioning, preprocessing and transmission, protective cabinets, conduits, and terminals will be reviewed in preparation for Task 6.

Reviewed Specifications:

Hardware; optics, sensor, integration, data storage, spectral filters, data type for software modeling and hardware packaging requirements.

Experimental testing of hardware were conducted at the DOW facility, which explored the attenuation loss of spectral windows and the development of spectral filters to optimize viewing through gas path. These narrow band-pass filters ranged from 950-1550 nanometers.

Subtask 1.1.6: Assess Computer Controls and Software Needs-

The objective is to define the complete diagnostic system. A system specification will be drafted by all partners for final acceptance to begin system development in Task 4. The details of the form and transfer of data through the ascending hierarchy of combined processing and intelligent systems will be established. The data will be preprocessed and summarized into information from each sensor system prior to introduction into the artificial intelligence system. The artificial intelligence system will be comprised of several complex subsystems to; monitor the engine operating conditions and update the presentation of this information to the supervisory system, continually analyze for TBC degradation rate via the SWPC-developed model, review and compare blade monitor information, review and compare vane monitor information, and reiterate various subsystem interaction scenarios for a continually updated output on immediate or eminent damage, remaining life of TBC's and or recommendations for best operating parameters for a given power demand.

Testing at the DOW facility in November 2001 helped determined computer controls and software requirements, which would include data type, data storage and frame rate. Further software development are being reviewed with Wayne State, Indigo Systems and Siemens Westinghouse. This development continues in Task 4 and 5 and will be updated in next semi-annual report.

Technical progress

Task 2: Develop On-line TBC Monitor for Blades

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

2.1.1 Measure Spectroscopy Properties of GT Working Fluid: Infrared transmission, absorption, and emissivity properties (Data report 2) of the turbine engine atmosphere will be determined within the range of operating parameters expected.

Objectives of this task will profile the gas turbine working environment of the gas path. Spectral radiation measurement were taken at DOW within the mid-infrared region and provided detail information of gas path atmosphere. Blade temperature and emissivity were determined at the same time from the multi-wavelength radiation intensity measurements at $3.5 - 4.0 \mu m$. (Data report 1)

Significant Accomplishments:

- **Structural Designs** – Structural design models complete establishing penetration and viewing configurations
 1. Axial, oblique through transition inner panel
 2. Radial access between vane 1 TE and blade 1LE
- **Field Test** – Field test data was acquired at a DOW facility. These tests established proof-of-concept for On-line TBC monitoring program. Testing at DOW facility was very successful.

Blade Monitoring Methodology:

The program objective to monitor, real-time, the thermal barrier coating of row 1 blades is comprised of many approaches to understand the technical methodology and a review of the geometric design will be reviewed during the data analysis of this program.

The W501FD engine was the choice as the targeted engine. We based this on availability of engines that have row 1 blades and vanes coated with TBC, installation cost perspective and penetration feasibility for best “viewing”.

The technical approach to monitoring in real-time, row 1 blades began at a DOW facility in Baton Rouge Louisiana in November of 2001. Technical testing and analysis involved the use of a Land Pyrometer with a spectral response of $0.9-1.6\mu m$ that will measurement the maximum temperature of row 1 blades. Spectrometry analysis with a spectral response of $0.9-3\mu m$ will profile the gas path absorption as a function of temperature and the use of infrared imaging system with a spectral response of $(.9-1.65\mu m)$ that would profile the radiance map of the row 1 blade. The analysis from the instrumented installation and technical experiments will provide proof-of-concept of the critical function and characteristics of the program objective.

Experiments and Work at DOW Facility, Baton Rouge, Louisiana (November 2001)

Objectives:

- 1) Determine camera and data integration time of turbine blades with the camera. It was determined that the Merlin camera with a short integration time of 5 microseconds may provide an image of the row 1 blade. Further analysis demonstrated the Indigo camera might require shorter integration, such that of the Indigo System Phoenix NIR camera.
- 2) Determine transmission of sapphire window during clean and dirty conditions. Determine attenuation loss. The current spectral windows of the DOW facility had not had the window cleaned for some 9 months. It appeared optically that there would be little if any attenuation loss from this condition and it may be a very realistic test.

- 3) Determine best absorption filter for CO and H₂O.
- 4) Determine if the infrared cameras could see through the hot gas path (1700F) to resolve the row 1 blades moving at 3600 rpm.
- 5) Document Temperature profile of gas turbine generator during operations with radiometric camera.

The initial challenge at the DOW facility in Baton Rouge was to identify issues concerning the usage of infrared instrumentation that would provide proof-of-concept of the On-line TBC Monitoring program. Experiments were performed at the DOW facility in Baton Rouge to examine the spectral absorption characteristics of an operational gas turbine gas path.

Figure 4

Figure 5

Theoretical and spectral absorption data was taken on 12/12-14/01, providing sufficient information to perform infrared and spectral filtering experiments. The next experiments would involve the usage of two infrared camera systems, a NIR 0.9-1.65 μ m and a Mid wave would provide analysis of the turbine blade. Infrared instrumentation would synchronize the 3-5 μ m infrared cameras, set with an integration time of 5 microsecond and the turbine blade revolution (approx. 3600-rpm). This then would provide a single freeze-framed image of the rotating blade and provide a radiance map of the turbine blade. Preliminary data from the DOW testing is profiled in Figure 4 and 5. The first tests produced promising results, though further experiments and analysis of the DOW testing will proceed into the following months, the up front information obtained from this testing produced results that will construct test criteria's and safety requirements.

Summary:

Experimental tests at the DOW facility provided up front details and data analysis for proof-of-concept of the On-line TBC monitoring program. The testing at this facility did have some restrictions such as; thermally the W501A is a cooler operating engine than the targeted W501F. The viewing path was setup for pyrometer measurements and the turbine blades

were not coated and uncooled. The two engines do have similar atmospheric gas path characteristics. The experiments at DOW were very successful in viewing through the hot gas path and examining a single turbine blade as captured by an infrared camera to view the radiance of the blade. Additional testing and experiments will determine the emittance of TBC coating as a function of wavelength.

Status of Milestones

Current program milestones are on or ahead of schedule

Communications / Visits / Travel

Siemens Westinghouse Manufacturing Facility in Hamilton Ontario, on November 18, 2001

Site testing at DOW Facility in Louisiana, on December 13, 2002

Testing preparation at Waltz Mill Plasma Center in Pittsburgh, PA, on February 12, 2002

On – Line TBC Monitoring for Real-Time Failure Protection and Life Maximization

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Dow Facility, December 12 – 14, 2001

1. Spectral radiation intensity measurement

One scan file has 6000 frames of spectrum, and the average spectrum of 6000 frames is shown in Fig. 1. Three distinct absorption bands are shown in Fig. 1. H₂O gas bands are located at 1.75 and 2.7 μm . CO₂ gas band is located at 4.3 μm , and hydrocarbon band is shown at 3.3 μm . The spectral radiations at gas bands are shown as dips because of presence of cold gas layer in the line of sight. If hot gas layer is dominant in the line of sight, the bands radiation would show peaks on top of continuous radiation. The spectral radiations from 3.56 to 3.95 μm are free of gas band absorption/emission; so we can use this band to deconvolute temperature and emissivity of the turbine blade.

The optical alignment was quite freaky, it is important to check the repeatability of the data. The Fig.2 shows mean radiation intensities for different scan files. The dataset taken before 10:40 AM is very similar to each other. However, the dataset taken after 11:11 AM were down more than 20 % as shown in Fig. 2. This change can only happen when the optical alignment is changed. It was noticed that the signal was changed quite a bit by just touching the tripod. The change in optical alignment causes some changes in the transmittance of the sapphire window, therefore, the deconvolution for the dataset after 11:11 AM were not conducted.

The Fig. 1 is an average of 6000 frames of data. To see the details of individual blade, each frame of data should be considered. The Fig. 3 is 3D-color plot for the spectral intensities over time. The frame rate for the spectrometer is 1320 Hz, and the turbine is running at 61 Hz and the number of blades are 90; therefore, the one frame of data from the spectrometer is average of 4.16 blades since

$$61 \times 90 / 1320 = 4.16 \quad (1)$$

The intensities in Fig. 3 are varying with time. The difference in the turbine blade temperature could contribute to the variation, and some random noise also contributed to the variations. The Fig. 4 shows time variation of radiation intensities at 3.88 μm . The RMS of intensity variation is about 0.06.

Nine dataset were taken at every five minutes from 11:13:13 to 11:53:13 on Dec. 14, 2001. The time variations of spectral intensities at four wavelengths are shown in Fig. 5.

The figure shows that radiation intensity is highly correlated to the operating condition of the gas turbine.

2. Deconvolution for temperature and emissivity

Spectral transmittance of the sapphire window is crucial to the determination of the temperature and emissivity of the turbine blade. The sapphire window not only cut down the overall radiation intensity level, but also changes the spectral information of the measurement since the transmittance of sapphire is not uniform over the wavelength. A typical spectral transmittance for 3-mm thickness window is shown in Fig.7. The window for the DOW turbine was 3/8 inch thick and its transmittance was not measured. Since the spectral transmittance for the sapphire window was now known, approximate transmittance was used for the deconvolution of temperature and emissivity. The transmittances of sapphire, which were used in the deconvolution, are shown in Fig. 6.

Using MLE (Maximum Likelihood Estimate) method, the temperature and emissivity were deconvoluted. The temperature was 1275 K and the emissivity was 0.85. Measured and deconvoluted radiation intensity profile is shown in Fig. 8. The two profiles closely matched. At two wavelength regions, 3.536-3.753 and 3.754-3.971 μm , the emissivity for each region is assumed to be constant. The calculated emissivities for both regions are found to be almost same.

The calculated temperature (1285) is slightly higher than expected blade temperature (1200 K) and the calculated emissivity (0.85) is similar to the measured emissivity at ambient condition (0.85). This discrepancy in blade temperature is expected since the spectral transmittance of the sapphire window was assumed. An additional uncertainty came from the fact that field of view of the spectrometer was bigger than the diameter of the opening tube. This fact causes two problems in the measurement. The spectrometer not only sees averaged intensity over entire tube cross section, and also sees some reflection from the tube wall, which is dependent upon the tube wall condition.

Deconvolution was conducted for all frames of data without averaging, and the deconvoluted temperatures are shown in Fig. 9. The temperatures are scattered between 1100 K to 1400 K. This random variation in temperature is largely due to random noise in the measurement. Since the temperature is quite sensitive to noise in the measurement, proper averaging over time must be performed to obtain stable temperature for each blade. Time averaging could be based on the phase of blade rotation and spectrometer frequency. In the current measurement, since there is no synchronization mechanism, time averaging was not devised.

3. Conclusions and suggestions

The spectral radiation measurement within the mid-infrared region provides detail information for turbine blade. Blade temperature and emissivity can be determined at the same time from the multi-wavelength radiation intensity measurements at 3.5 – 4.0 μm .

To determine the temperature and emissivity accurately, the transmittance of the sapphire window must be determined prior to the measurement. This can be done by simple transmittance measurement using a blackbody. Proper optical arrangement needs to be provided to measure intensity from the spot of the blade rather than entire tube cross section.

Synchronization mechanism with rotation of turbine blade should be provided to monitor individual blades.

Fig. 1 Mean spectral radiation intensity measurement (blade.scn).

Fig.2 Mean radiation intensity profiles at different times.

Figure 3. Spectral radiation intensities for 1000 frames (blade.scn).

Fig. 4 Time variations of radiation intensities at $\lambda = 3.88 \mu m$ (blade.scn).

Fig. 5 Mean intensity at four different wavelengths for the dataset taken every five minute.

Fig. 6 Spectral transmittance of 3 mm sapphire window.

Figure 7. Spectral transmittance of the 3/8 inch Sapphire window.

Figure.8 Measure and deconvoluted radiation intensities (blade.scn).

Figure 9. Blade temperature for all frames (blade.scn).

Radiative Property Measurements

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The radiative properties of the TBC samples were measured with AFR's Benchtop Emissometer. Samples placed in the Emissometer are irradiated from all directions by energy from a near-blackbody source, and reflected and transmitted energies are each 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.

AFR's Benchtop Emissometer was designed, constructed and patented during an Air Force sponsored Small Business Innovation Research (SBIR) project to meet the need of the Air Force to measure the high temperature spectral radiative properties of aircraft skins and space shuttle skins. The prototype was delivered to the Arnold Engineering Development Center at Arnold Air Force Base in 1993. An R & D 100 award was received by AFR in 1994. A replica was constructed by AFR for service measurements for a number of companies on materials such as metals, ceramics, silicon wafers, and optical materials. The first measurements on TBCs for gas turbine engines were reported at a NASA sponsored conference in 1994, and recent measurements at an international ceramics conference in 2002.

Christiansen Emittance as a Function of Temperature for Sample #D0

References

"A Benchtop Instrument for Simultaneously Measuring Surface Spectral Emittance and Temperature," Rev. of Sci. Instr., 64,(9), 2515-2522 (1993).

"High Temperature Radiative Properties Of Advanced Turbine Materials," proceedings of the NASA Remote Temperature Sensing Workshop (1994), NASA publication 10167.

"Infrared Radiative Properties of YSZ Thermal Barrier Coatings," proceedings of the 26th Annual International Conference on Ceramics & Composites, Jan. 2002, Cocoa Beach, FL.