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

Final Technical Report

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10.0 Acronym Table

a. (TBC) Thermal Barrier Coating

b. (NIR) Near Infrared

c. (RAM) Reliability Availability Maintainability

d. ATS and NGT (Advance Turbine Systems) (Next Generation Turbines)

e. (InGaAs) Indium Gallium Arsenide

On-Line Thermal Barrier Coating (TBC) Monitor for Real-Time Failure Protection and Life Maximization

PUBLIC ABSTRACT

Under the sponsorship of the U. S. Department of Energy's National Energy Laboratory, Siemens Power Generation, Inc proposed 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 Power Generation, Inc. 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.

EXECUTIVE SUMMARY

With On-line blade monitoring, Siemens Power Generation (SPG), under the sponsorship of the U.S. Department of Energy, have 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 Siemens Power Generation's customers.

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 replacements, by implementing this new technology significant cost savings can be achieved.

During the month of October 2-12, 2004, Siemens Engineering successfully installed a commercial On-line TBC Blade Monitor in a W501FD gas turbine at Empire District 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 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 was design with a minimum expected life of 8,000 hours.

This commercial monitoring installation will installed and evaluated the performance of row 1 TBC coated blades of both pressure and suction sides. The tests and demonstration evaluated 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:

- 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.
- 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.
- 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 are equally applicable to smaller land, aero and marine based gas turbines. This opens future global market opportunities for the team to pursue.

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.

TECHNICAL DISCUSSION

1. Scientific and Technical Merit

1.1 Relationship to Overall Program Goals

Responding to the Area of Interest 16, "Advanced Turbines", Siemens Power Generation, Inc., Indigo Systems, and Wayne State University propose a four-year program to develop and demonstrate an on-line thermal barrier coating (TBC) monitor for critical engine components, row 1 turbine blades and vanes. This on-line TBC monitor represents an important advancement toward achieving the program goals of improved reliability availability and maintainability (RAM) of existing and advanced gas turbine power plants by continuously monitoring the health of critical thermal barrier coated parts allowing plant owners to operate the units longer than conservative inspection requirements would allow.

As engines are driven to higher efficiencies (or higher firing temperatures), they require ceramic TBC to protect the thermally challenged base metal of critical components. As a result, the newest engines used today for land based power generation rely heavily on the durability of the TBC. Current operating evidence demonstrates the importance of monitoring the TBC on a frequent basis. Waiting for scheduled down time, even if it is on a basis as for peaking units, would not be frequent enough and would require daily viewing through borescope ports. Because TBC coated components fail primarily by debonding which progresses to spallation, an on-line monitoring system that can detect TBC failure will provide the necessary early detection of premature component failure. Therefore, the on-line TBC monitor will not only significantly extend critical component lives by advising of the need for repair before the component's failure, but also serve as a guard for the safe operation of a turbine engine. One-hundred percent monitoring, when fully implemented, will allow for better scheduling of maintenance outage and operation of the turbine to meet immediate "call for electricity" demands. It will do this by combining the state-of-the-art real-time infrared (IR) sensor systems, component lifing models, engine operational parameters and expert systems into a supervisory system that will oversee and report on component status and recommend best operating practice. It will therefore significantly escalate the current reliability/availability/maintainability (RAM) standard of electric power generation for gas turbines.

In the development process, the work will initially focus on the “F” and “G” class AGT’s. When the technology has been successfully implemented on these designs, we will extend the use to ATS and NGT class gas AGT’s that will be operated at even higher temperatures. All gas turbine engines using TBC coated components will eventually benefit from this on-line monitoring technology. The on-line monitor can be implemented on existing engines with upgraded capability or fully integrated into a new generation AGT’s.

To accomplish our objective, we will team with Indigo Systems Inc., a leader in advanced infrared camera design and manufacturing, and Wayne State University, with 25 years of leadership in the Infrared NDE field.

1.2 Improvements Over Present Technology

Current power generating turbines are equipped with sensors of limited functions such as gas-path temperature measurement and flame detection, providing basic turbine operating conditions. IR spot pyrometers have been used for many years to check local temperatures in turbines but they have limited field of view and scan only one 5mm (.200 inch) radial sweep of the blade. Complex supervisory systems are already installed in many operating plants and have incorporated, in recent years, the input from many advanced sensor systems. Monitoring of in-service parts degeneration during engine operation has not yet been performed. The need for such monitoring has become more critical in recent years as engine gas temperatures have risen and the potential impact of parts failure has grown. In particular, the need to guard against the loss of TBC has become an important factor for predicting operating turbine availability and for providing commercial guarantees. Currently, we have no comparable system. Borescopic inspections are conducted frequently to evaluate TBC quality. Each inspection requires a power down and Cool down cycle of approximately 7 hours to allow the borescope to enter the engine without damage. The examination takes an additional 3 hours to complete and close the unit.

1.3 Potential for Scientific /Technical Breakthrough

What is required now is to demonstrate that planar arrays can detect TBC failure related local temperature rises over larger areas. Our recent studies have shown that modern systems are capable of detecting the required defects in real time. The proposed on-line TBC monitor implements state-of-the-art focal plane array (FPA) infrared thermal wave imaging sensor(s) as the primary technique. This sensor captures array images on the blade tip rotating 3600rpm which is equivalent to 400m/s linear speed as demonstrated in Figure 1.3a. These systems do not need cryogenic cooling which is critical for hardware packaging and support. Given that supervisory system structures are already in-place, if monitoring systems can be demonstrated for self scanning blades we still require innovative solutions for: (1) Overcoming the vane sensor limitations identified by developing new sensors, (2) Understanding the working fluid IR characteristics and selecting the best spectrum for TBC observation, (3) Combining sensor outputs with engine parameter outputs and developing a supervisory system to monitor TBC integrity, and (4) Developing and incorporating a TBC remaining life model which requires the development of distributed monitoring systems for stationary vanes in order for complete monitoring. Thus, the initial demonstration that modern, fast IR planar array monitors can detect incipient TBC failures on line would provide the basis for a breakthrough in the development of on-line TBC monitoring

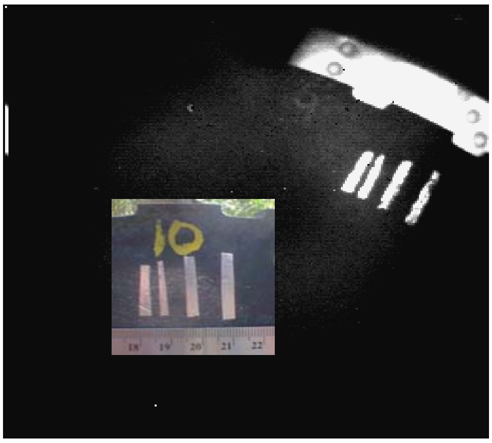

Figure 1.3a – Thermal Snapshot of 2’ Diameter Flywheel with Target Features “White Light Still Frame” in Inset

systems. Monitoring TBC failures on-line appears to be feasible using a thermal imaging system whereby the local temperature variation derived from the precursor structure to spallation is imaged and identified by advanced sensor(s).

1.4 Scientific and Technical Basis and Merit of the Proposed Work

The scientific and technical basis of our work demonstrates that on-line signals from a focal planar array (FPA) IR sensor can be used to detect the precursors of TBC failure. Our in-house preliminary studies have shown that new sensors have the potential to meet these needs. Indigo Inc. has developed an FPA InGaAs detector that has the right characteristics for the proposed application (500nS integration times, 40Mpix/sec processing time. Spectral sensitivity of 0.9 to 1.7 um is equivalent to 200 – 1800C optimum temperature range). These characteristics of speed and spectrum are essential for the success of the on-line monitor due to the high speed, temperature and atmosphere involved.

The initial phase of the work was devoted to establishing the capability of the IR detector to monitor the precursor and growth of TBC defects on blades. Vane monitoring is different from blade monitoring because the vanes, unlike blades, do not all pass in front of the same sensor. Several different potential approaches have been identified and will be evaluated and implemented in the vane monitors.

TBC systems used in land-based turbine engines and aircraft gas turbines are fabricated by either atmospheric plasma spray (APS) or electron beam-physical vapor deposition (EB-PVD). Figure 1.4a shows microphotographs of APS and EB-PVD microstructures. These TBC systems nominally consist of a 0.127mm (0.005in) McrAlY bond coat and a 0.254mm (0.010in) ceramic top coat. The bond coat is needed to prevent oxidation of the substrate material and provide a good ceramic-to-metal bond. Yttria stabilized zirconia (nominally 7wt% Y) is typically

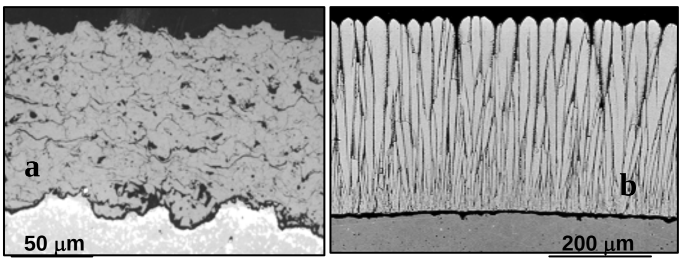

Figure 1.4a. Microstructures of Two different TBC systems. a. APS, b. EB-PVD

used for the ceramic top coat. APS TBC is a bulk coating in which the ceramic contains pre-existing micro-defects. In general, the TBC ceramic layer is in considerable residual compressive stress at room temperature. Crack growth and spalling (far from edges and corners) is predominantly associated with buckling. As briefly discussed, failure mechanisms of APS and EB-PVD TBC systems are different. In general, however, both TBC systems start failing when the imposed stresses exceed the material strength at or near the ceramic-metal interface. APS TBC failure occurs just above the metallic bond coating in the ceramic material. Ceramic delamination cracks initiate very near (or at) peaks in the rough bond coating and propagate along the interface in the ceramic layer as shown in Figure 1.4b. EB-PVD TBC failure appears to occur in the thermally grown oxide (TGO) layer adjacent to the metallic bond.

Thermal barrier coatings (TBC) are a powerful cooling method. Each 0.025mm (0.001inch) of TBC thickness provides 17-33C (30-60F) temperature reduction depending on the TBC ceramic structure and level of convective cooling as seen in Figure 1.4c. Unfortunately, TBC delamination and spalling in hot section components may occur before reaching the component design life requirement. Local TBC spalling introduces a hot spot condition in the substrate which aggravates substrate thermo-mechanical fatigue (TMF) crack initiation. As a result, the full TBC cooling benefit can not be realized.

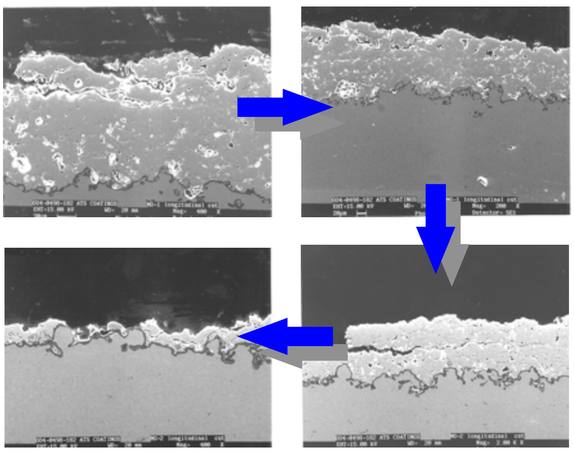

Figure 1.4b. Microphotographs for APS TBC Failure Mechanism.

The work proposed and demonstrated initially focused on on-line monitoring of APS TBC system because it has become the most widely used coating. With successful completion of APS TBC monitor development; this technology could be extended for use on EB-PVD coated components.

The demonstrated NDE technique (Infrared thermal wave imaging sensor) will detect these failure stages (i.e., delamination, and spallation), and submit it to artificial intelligence (AI)-based supervisory system for an immediate action request or to numerical TBC remaining life prediction model for warning how long the component may continue to service until it has to be either repaired or replaced.

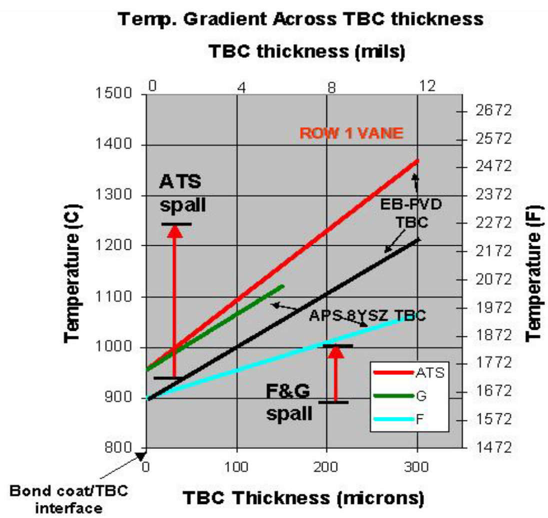

Figure 1.4c. Temperature Gradient Across TBC Thickness

The following Project Tasks are describe in the following report. This report describes the original Tasks and Final Repots as purposed in Program Solicitation No. DE-PS26-01NT41048 for "DEVELOPMENT OF TECHNOLOGIES AND CAPABILITIES FOR DEVELOPING COAL, OIL, AND GAS ENERGY RESOURCES" and Tilted On-Line Thermal Barrier Coating Monitor for Real-Time Failure Protection and Life Maximization - Application No. 1117

The work consists of seven major tasks as shown in Figure 2.1a. Discussions for each of the tasks follow: The following status will describe the original contract task proposal and final reports.

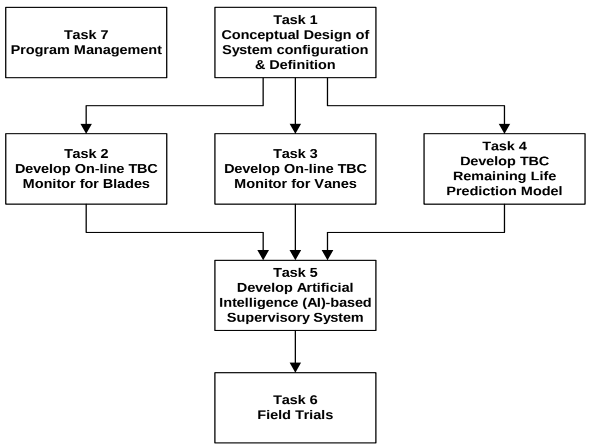

Figure 2.1a. Block Diagram for the Project

1.0 TASK 1: CONCEPTUAL DESIGN OF SYSTEM CONFIGURATION AND DEFINITION

TASK 1 PROGRAM OBJECTIVES

1.1.1 Review Target GT Designs: Structural designs and operating conditions of targeted AGT's 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.).

1.1.2 Establish Blade and Vane Monitor Coverage's: Several factors 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. Critical surfaces as determined by design engineering will mandate coverage. Critical surfaces have been estimated to include the leading edges and the fillet radii. Balance of airfoil surfaces and platform surfaces will be reviewed as well. The accessibility of all blade regions will be determined. Depending on the specific infrared sensors, the coverage of the blade will rely on multiple sensor array detectors. Detectors arranged for forward, retro and/or radial viewing will be considered. Some regions of the blade may have a higher likelihood of damage due to other factors. For example, regions on the platforms have in the past been prone to severe erosion and wastage.

1.1.3 Assess Blade Monitor Sensor(s): The blade sensor uses high speed thermal imaging and computer recognition software to thermally examine each blade as it passes a focal plane array (FPA) sensor. Several candidate sensors will be reviewed for adequacy. Sensor type, style and cooling requirements will be compared against performance and robustness. Sensor elements may be selected for various spectral and energy ranges as well. It is very likely that fiber optics will be used to transmit the radiant information to the sensor. Due to the spectral transmissivity characteristics of the various fiber options, the sensor will have to accommodate the wavelength allowed by the fiber. In the event of using sensor arrays, the aspects of spatial resolution related to using an array will be considered. A parallel effort will characterize the operating conditions that the sensor will be subjected to in the turbine engine. The sensor optics will be introduced into the pressure chamber of the aggressive environment of the turbine section of the engine. These conditions will be fully characterized from the existing design data and literature. The final sensor selection will depend on the best combination of reliability, robustness and sensitivity.

1.1.4 Assess Vane Monitor Sensor(s): Whether monitoring engines for catastrophic failure or attempting to extend the time between power plant outages, it will be necessary to have an on-line indication of the condition of Row 1 turbine vanes. Since Row 1 vanes are subjected to the hottest conditions in the turbine, and they are the first to be impacted by foreign objects entering the hot path so monitoring is important. Development of a monitor sensitive to TBC coating degradation in Row 1 vanes may, therefore, provide the first indication of over temperature conditions and other problems in the gas turbine engine. Early indication of Row 1 vanes TBC coating degradation may allow adjustments in engine-operating conditions before major component damage results down stream. Any attempts to extend life beyond normally scheduled outages will need to have assurance of the integrity of Row 1 Vanes. The vanes are stationary and they extend over a large positional area of the turbine, making monitoring of this component quite challenging. In the development process, different approaches will be evaluated in terms of practicality, maturity, accuracy, and flexibility.

1.1.5 Assess System Hardware Package: System hardware and hardware packaging requirements will be considered with 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 activities. A layout of the locations of turbines, monitoring computers and monitoring personnel quarters will be reviewed.

1.1.6 Assess Computer Controls and Software Needs: All team members will be will 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 SPG-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.

Subtask 1.2 Definition of On-line Monitoring System

A conceptual design will be completed to align all parties involved. Technology development partners and subcontractors will be actively involved during this effort. Full documentation and detailed system specifications will be completed and forwarded to the subcontractors.

1.1 TASK 1 FINAL REPORT STATUS – COMPLETE AND FINAL REPORT SUBMITTED

NEAR INFRARED (NIR) ON-LINE MONITOR SYSTEM SUMMARY

Monitoring of mission critical engine parts during gas turbine operation is now possible by combining innovative access port design, high-speed infrared imagery, a tailor-made overall control and image evaluation system, and related Thermal Barrier Coating (TBC) lifing models. The need for such monitoring has become more critical in recent years as engine firing temperatures have risen and the potential impact of part failure has grown. In particular, the need to guard against the loss of TBC has become an important factor for maximizing turbine availability and for minimizing commercial risk. This On-Line TBC Blade Monitor will not only help insure the safe operation of a gas turbine, but also provide the opportunity to extend the life of blades beyond the nominal operating hours, based on real-time and historical images that clearly prove the integrity of the thermal barrier coating. Detection of spallation is important to provide a warning signal of potential blade failure. This report is a comprehensive review of the Online Thermal Barrier Coating Blade Monitor. The system concept is based on a telescopic arrangement consisting of a lens objective head and a series of relay lenses with the final relay acting as the system focus. The system was designed to function in the near infrared (NIR) (~0.9 – 1.65 microns) region. This on-engine real-time monitor measures infrared radiation through a Near Infrared optical lens assembly.

This On-Line TBC Blade Monitoring system is able to capture two-dimensional infrared images of row-1 blades during full engine operation. This system, which was successfully tested on our 200 MW class gas turbine at full load, was developed by a team of Siemens Power Generation Engineering and Diagnostics experts in cooperation with Siemens Corporate Research under the sponsorship of the U.S. Department of Energy's National Energy Laboratory.

Thermal Barrier Coating (TBC) is an important method to increase efficiency of modern stationary gas turbines. Increasingly, ceramic thermal barrier coatings (TBC's) deposited on airfoils are utilized as insulation layers to reduce the heat transfer rate from the hot gas path, which can reach temperatures above the melting point of superalloys, to turbine engine walls and components. Such a reduction in the rate of heat transfer is achieved by creating a path of high resistance to the transfer of thermal energy, thus enabling engine parts to operate at cooler temperatures without excessive cooling air schemes. The most obvious benefit of the IR imaging is that the detector assemblies in focal plane arrays have multiple detector elements on a single detector chip that map directly to the aperture of the optical system. Therefore in addition to providing temperature information of the Blade surface it provides high spatial resolution means the camera can distinguish between two closely spaced items. Watching a part "age" may be of great value to the plant maintenance department in predicting the expected failure date for a machine component. Being able to trend thermal data as a function of time is one way to watch the aging process.

Loss of thermal barrier coating (TBC) reduces the temperature resistance of parts and can cause unscheduled engine failure or engine damage. The trend toward higher combustion temperatures makes TBC more important. Row 1 blades in a stationary gas turbine are of specific interest. Blades on row 1 rotate at high speed and are exposed to high temperatures. It is important to monitor TBC of row 1 blades in stationary gas turbines to avoid unscheduled engine failure or engine damage. It is necessary to replace coated blades (Figure 3) due to the limited lifetime of the TBC.

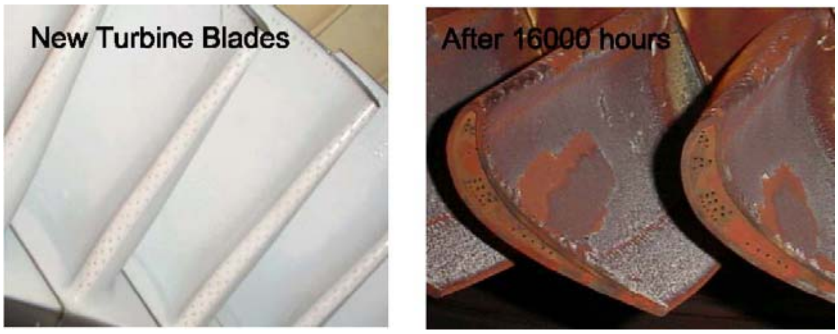

Figure 3. New and Used Row 1 Blades

Figure 3 shows new row 1 blades and used row 1 blades, Monitoring of TBC loss is important to avoid unscheduled engine failure or engine damage. It is necessary to replace coated blades due to the limited lifetime of the TBC.

Limited real-time information about the condition of turbine blade temperature barrier coating were available during engine operation in the past. Blade pyrometry measurements, for example, are usually limited to single point or line scanning measurements. Siemens Power Generation has proposed a four year program for ”On-Line Blade Monitoring for Real-Time Failure Protection and Life Maximization”. The goal of the Siemens Power Generation project, co-funded by the U.S. Department of Energy’s National Energy Technology Laboratory (DOE), was to develop, build and install the first generation of an on-line TBC monitoring system for use on land-based gas turbines. The system operates with combine state-of-the-art, real-time, high speed infrared (IR) camera systems, component lifting models, engine operational parameters and image evaluation expert systems into an overall supervisory system.

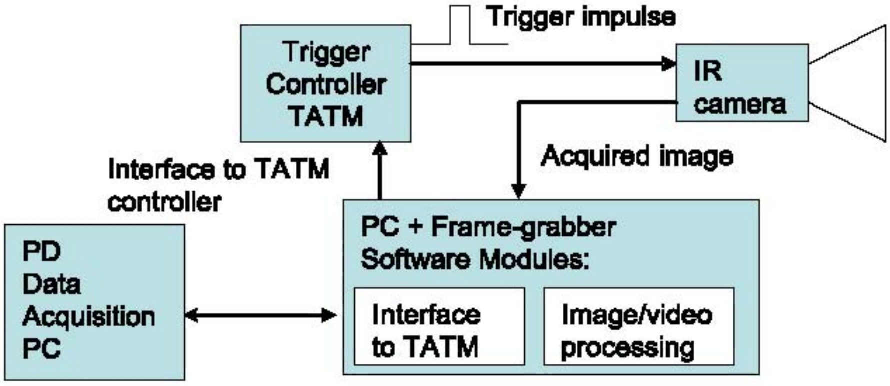

Figure 4. Concept Diagram for Initial Onsite Evaluation System

Siemens Power Generation has teamed up with several internals Siemens groups and external organizations to accomplish the goals. The entire program contains several aspects, such as preliminary studies, material analysis, wavelength analysis, experimental tests, mechanical port designs, enclosure design, and lens designs.

The system concept is based on a telescopic arrangement consisting of a lens objective head and a series of relay lenses with the final relay acting as the system focus. The system was designed to function in the near infrared (NIR) region of 0.9 µm to 1.6 µm.

For the purpose of the testing, a Near-infrared sensor head from FLIR Systems with a 320 x 256 Indium Gallium Arsenide (InGaAs) focal plane array (FPA) was used. InGaAs detectors are highly sensitive to energy in the near-infrared (NIR) and shortwave-infrared (SWIR) wavebands from 900 to 1700 nanometers.

The 320 x 256 InGaAs photodiode arrays produced at Indigo Systems are mated with Indigo's ISC9809 ROIC. The 320 x 256 element FPA is constructed with the pixels on a 30 mm pitch. This FPA will support a wide range of system requirements from very low background applications (nightglow) to daytime high illumination conditions. To accommodate the wide scene dynamic range requirements, two selectable integration capacitors are used to control the input circuit transimpedance gain. A 0.01pF integration capacitor is used for low noise and low flux levels down to 10^{-5} ft Lambert corresponding to approximately $2x10^{10}$ photons/cm^2/sec for 0.9 to

1.7micron spectral band using f/1.5 optics assuming a 2856 Kelvin blackbody distribution. For higher flux levels, a 0.21pF integration capacitor can be selected thereby providing over a factor of 20 dynamic range. A capacitive feedback transimpedance amplifier (CTIA) provides a low noise detector interface circuit capable of operating at low input currents without frame-to-frame image lag. A sample and hold capacitor is also part of the input unit cell architecture which allows the FPA to be operated in full frame snapshot mode and provides the maximum integration time available. The integration time is electronically controlled (gated) by an external clock pulse and is adjustable from 0.5msec to approximately the frame time of 33.3msec for 30 Hz operation. This provides an additional factor of 66,000 to the total system dynamic range. Additional features include programmable operating modes such as dynamic image transposition, dynamic windowing, selectable number of outputs, variable signal gain, input charge skimming and on-chip power adjustment. Performance specifications of the ISC9809G InGaAs FPA are summarized in table 1 below.

Parameter	**Performance**
Array Configuration	320 (H) by 256 (V)
Pixel Pitch	30μm x 30μm
Well Capacity Cint = 0.01pF Cint = 0.21pF	 175K Electrons 3.5M Electrons
Input Current Range Minimum Maximum	 <1fA >1μA
Operating Temperature	Room Temperature to , 80 Kelvin
Total Readout Noise Room Temperature	High Gain Mode ~ 50 electrons Low Gain Mode ~475 electrons
Number of Outputs	Selectable 1, 2, or 4
Maximum Frame Rate (Full Frame) One Output Two Outputs Four Outputs	 110 FPS 200 FPS 350 FPS
Power Dissipation Minimum (One Output) Nominal (One Output, 10 MHz Output Pixel Rate) Maximum (Four Outputs, 10 MHz Output Pixel Rate)	 < 15 mW < 75 mW < 159 mW
Output Voltage Swing	2.7 V
Non-Linearity	< 0.1 %
Integration Time Minimum Maximum	 0.5 μsec (0.25 μsec at 80 Kelvin Operating Temperature) ~ Frame Period
Quantum Efficiency	> 90% 0.9μm – 1.7μm
Uncorrected Non-Uniformity	<5%, 3.5% typical
Operability	>99.5%, 99.99% typical

Table 1. Performance of the Indigo ISC9809G 320 x 256 Focal Plane Array

The near infrared (NIR) system is designed to operate in the spectral range of 0.9μm to 1.6 μm. Optical radiation emanating from the tilted object passes through an aperture and onto the objective head system. The light is then imaged onto the first of four image planes of the system. Three relay sections, each comprising of six lenses, bring the optical signal to the focal plane array (FPA) of the camera, with the final lens set acting as the system focus. The sapphire window is the boundary between the turbine and the external environment. All NIR optical elements were coated to allow maximum transmission at 1.3 μm. The sapphire window was not coated. The optical elements are kept at their respective distances by a series of spacers. Tube spacers separate the relay components while ring spacers are used to separate the lens elements in the objective and the relay lens set. Three ring spacers are needed for the objective and two ring spacers are needed for each of the two relay lens sets in the relay unit.

The mechanical design of the On-Line Monitor System purposed two (2) viewing concepts for purposes of viewing row 1 turbine blades. The first design view or (radial view) would provide viewing of leading edge, pressure side, platform and a portion of suction side of blades. This view would observe approximately 70 % of total surface of blades. The second design view or (radial oblique) would provide viewing of pressure side and leading. This view is very common by pyrometry measurements.

For the purpose of developing a robust monitoring system that would endure 8,000 hrs of operation at a commercial host site an additional pro-type was developed and installed at the Siemens AG Berlin Test Bed facility. This prototype installation helped develop process procedures for the future commercial installation.

2.0 TASK 2: DEVELOP ON-LINE TBC MONITOR FOR BLADES

TASK 2 PROGRAM OBJECTIVIES

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. These effects require understanding so that they may be negated.

At atmospheric pressure NIR bandpasses can be chosen that match the near-blackbody wavelength region for TBC's so as not to overlap with the NIR emission/absorption signature of the major combustion gas products, carbon dioxide (CO_2) and water (H_2O). However, as pressure is increased the gas signatures broaden to result in significant interference that is path length dependent. NIR TBC turbine blade temperature measurements corrections are be applied to account for the combustion gases in the optical beam path etc. The wavelength dependent emission/absorption features for H_2O and CO_2 as a function of temperature. Software correction could be used with the interference over the distance from the optical probe and accounting for the changing distance due to blade curvature).

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. These normal changes are gradual, and therefore are expected to cause gradual and accountable changes in the emission of a normal TBC.

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.

<u>2.2 Develop IR Monitor for TBC Coated Blades</u>

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 installations 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.

SUMMARY AND CONCLUSION FOR TASKS 1 AND TASK 2 - FINAL REPORT STATUS – COMPLETE AND FINAL REPORT SUBMITTED

3.0 TASK 3: DEVELOP ON-LINE TBC MONITOR FOR VANES

TASK 3 PROGRAM OBJECTIVES

The objectives for Row 1 TBC vane coating monitor is to detect TBC coating degradation of the hottest location in the expander to provide an early warning for degradation of TBC coating in the hot gas path. Monitoring information from the Row 1 vane will also be integrated into TBC lifing models to allow outage planning and maximization of availability. In order for the Row 1 Vane monitor to meet these objectives, it will need to have the following criteria:

- The monitoring system should be capable of providing real-time data, and the sensors should have life capability in excess of normal outage times at operating conditions.
- The monitor will need to be an early indication of TBC coating condition changes.
- The monitor will need to monitor the vane globally so that deterioration of particular areas of the vane will be detected.

There are no current sensors that meet all of the above criteria. Mature techniques for sensing (e.g., thermocouples) can be used to locally detect Row 1 vane problems, at least after the problem advances to the point where damage has occurred in the TBC coating and the vane. This program will evaluate some emerging technologies for potential application to this problem. At the same time, mature technologies will be used as a back up in the testing, serving to baseline the interpretation of the TBC coating life sensing system. The result of the program will be the development of a vane TBC coating life detection system that incorporates the state-of-the art methods of detecting coating failures.

During the initial brainstorming amongst experts, a number of vane monitoring techniques were discussed for potential applications. Candidate techniques included (1) blade path spread (temperature) measurement by thermocouples;

(2) temperature and pressure measurement inside the vane by thermocouples and pressure sensors; (3) optical measurement; (4) acoustic guided waves; (5) Bragg filters; (6) chemical sensors; (7) electrostatic monitors; (8) system's RF monitors. In the development process, these candidate techniques will be down-selected in two stages considering various evaluation criteria such as the technique's practicality, accuracy, and maturity.

Subtask 3.2 Design and Fabricate Full Scale Vane Sensor(s)

The selected vane monitor technique(s) will be implemented into the program and the associated vane monitor sensors will be fabricated in a full scale for final performance test on an actual test engine. This subtask consists of (1) determine control interface and vane sensors attachment, and (2) design/fabricate full scale vane sensors.

TASK 3 FINAL REPORT STATUS – COMPLETE AND FINAL REPORT SUBMITTED

3.1 CONCLUSIONS

1. The AWG sensor system is uniquely capable of acoustic interrogation of an object in a harsh environment (vane in an operating CT) while the electronics and signal-processing instrumentation is located in a benign environment (outside the pressure shell).
2. In field-testing the AWG system was used to interrogate, in real time, several first row vanes in an operating turbine at full speed base load (FSBL). No part of the sensor system is exposed to the hot gas path nor does it contact the TBC.
3. Signal processing and hardware improvements over the last year have permitted retrieval of the AWG signal with amplitudes of several hundred mV. Using the burst pulse technique and signal averaging, all four vanes have been successfully interrogated many times.

4. The AWG transmitting and receiving wires are welded to the outer body of the vane. The attachment method launches a type of surface acoustic wave, which is very sensitive to strain conditions in the TBC and BC.
5. Removal of small amounts of TBC and wearing of the TBC change the strain levels in the surface layers, which can be detected by the AWG sensor.
6. While a simple measure of the tuned burst-pulse maximum signal can provide a measure of TBC condition and strain, we believe that using frequency spectrum analysis we can define other critical conditions from changes in the frequencies of resonance peaks. These could be plugged cooling holes and structural defects such as cracks and weld failures.

4.0 TASK 4: DEVELOP TBC REMAINING LIFE PREDICTION MODEL

TASK 4 PROGRAM OBJECTIVES

The objectives of task 4 are (1) monitor failure progression of TBC's under high heat flux conditions (Subtasks 4.1) and (2) develop a numerical model to describe the failure progression as a function of the loading regime (Subtask 4.2).

Subtask 4.1 Conduct High Heat Flux Tests for Monitoring TBC Failures

The high heat flux testing rig (HHFTR) at Westinghouse Plasma Corporation (WPC), Madison, PA, will be upgraded to allow monitoring of failure progression under engine-like temperature conditions. The NDE monitoring device proposed in the program to evaluate TBC reliability during engine service will be incorporated on a sub-scale level into the test chamber of the available test rig. WPC has a unique world-class facility for testing coated samples in a thermal fatigue-thermal gradient.

A tubular specimen with APS thermal barrier coating is subjected to the high heat flux with active cooling. A uniform surface temperature of > 1350ºC will be maintained at the thermal barrier coating outer surface. A large temperature gradient across the TBC layer will be created such that the TBC-to metal interface temperature is held at < 1000ºC while the outer surface is at the high temperature mentioned above.

A cyclic operation with heating cycle durations of 3 minutes to > 8 hours can be achieved.

The monitoring device will capture the TBC failure progression during testing period. Thereby, it is able to detect and quantify delamination as well as vertical crack growth. In addition to the testing regime proposed in our response to DOE solicitation DE-PS26-01NT41048 titled "Life Cycle cost reduction through EB-PVD model development", testing will continue beyond the initial detection of TBC spallation in order to derive a database on failure progression as a function of the applied temperature and cycle regime.

Modify current high heat flux test rig: The test chamber and the data acquisition system of the high heat flux test rig will be modified to monitor the specimen condition during high heat flux testing. A test chamber will be designed and manufactured such that NDE devices can easily monitor the rotating test specimen. Image analysis software will also be incorporated into the data acquisition system to obtain quantitative results of the failure progression.

Perform high heat flux tests on TBC coated specimens (APS): TBC coated specimens will be tested under cyclic thermal loads (of actual engine operating condition) until TBC spallation occur at an area greater than the critical size. Both APS and EB-PVD coated specimens will be tested as-deposited and pre-oxidized conditions. Pre-oxidized specimens will also be tested for the effect of TGO thickness on the failure evolution under a given loading scheme. Test specimens will be pre-oxidized in a box furnace under isothermal, cyclic conditions.

Subtask 4.2 Develop Remaining Life Prediction Model

A numerical model will be derived and the model predictions will be correlated with the experimental results: i.e., the observed failure progression under given temperatures and cyclic conditions during the high heat flux testing. Classical theories for sub-critical crack growth under cyclic or static load will be employed to derive a numerical model for the remaining life prediction of TBC as functions of the loading condition and the loading history.

TASK 4 - SUMMARY AND CONCLUSION - FINAL REPORT STATUS – COMPLETE AND FINAL REPORT SUBMITTED

5.0 TASK 5: DEVELOP ARTIFICIAL INTELLIGENCE (AI)-BASED SUPERVISORY SYSTEM

TASK 5 PROGRAM OBJECTIVES

This task consists of two separate subtasks: (1) AI-based supervisory system for blades, and (2) AI-based supervisory system for vanes. 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.

TASK 5 FINAL REPORT STATUS – COMPLETE AND FINAL REPORT SUBMITTED

5.1 TASK 5 RESULTS AND SUMMARY

Siemens Corporate Research has supported the effort of Siemens Power Generation to complete the four year program for"On-Line Blade Monitoring for Real-Time Failure Protection and Life Maximization" in various aspects, with software development for system control and on-line system operating, experimental data acquisition and evaluation for the remaining TBC life modeling, and system test installation in Berlin, Germany and Joplin, MO. The team was successfully able to acquire images of stationary gas turbine blades at engine base load. Scene based image non-uniformity correction in addition to standard camera non-uniformity correction has significant increased image quality. A large software package was developed to control and operate all components of the on-line monitoring system, and to acquire, process and store images of blades from stationary gas turbines on a systematic basis. Various image processing function for non-uniformity correction of IR images; TBC defect detection and estimation of defect size or auto focus were developed and evaluated. Siemens Corporate Research has helped to present this program at the Siemens Power Generation Engineers' Technology Showcase week 2004 in Orlando, FL. The program was selected as the most innovative program of the year in 2004.

6.0 TASK 6: FIELD TRIALS

TASK 6 PROGRAM OBJECTIVES

In the final task of the program, the packaged system will be installed on an AGT at one of Siemens Power Generation'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 Power Generation design engineering will be heavily involved with all aspects of the engine changes. Standard engineering practices will assure safe and effective sensor installation.

Subtask 6.2 Field trials for vane monitor.

For field trials for vanes, either the same LTP site as blade monitor or different site will be identified depending on the availability of the facilities at that time. We are targeting a site located near the engineering headquarters in Orlando.

TASK 6 – SUMMARY AND CONCLUSION - FINAL REPORT STATUS – COMPLETE AND FINAL REPORT SUBMITTED

7.0 SUMMARY AND CONCLUSION

An innovative new system that continuously monitors operating blades in gas turbines has surpassed over 8,000 hours of operation, confirming that the technology is ready for commercialization.

Developed by Siemens Power Generation, with funding from the U.S. Department of Energy, the online monitor makes it possible for operators to replace turbine blades based on their actual condition, when the thermal barrier coating is worn or damaged. This capability optimizes the life of the blades, avoids the high cost of unscheduled replacement, and extends the time between preventative maintenance periods, increasing the availability of the plant.

The first full-scale high-temperature, full-pressure commercial system was installed in a Westinghouse 501FD gas turbine at Empire Stateline Electrical Company in Joplin, Mo., during a scheduled outage last October to demonstrate its capabilities in capturing real-time infrared images of rotating blades. Siemens Power Generation engineers are monitoring the performance of the first row of thermal-barrier-coated blades on both pressure (front) and suction (back) sides.

The demonstration will evaluate the mechanical design and integrity of the blades' thermal barrier coating. The high speed infrared camera is integrated into a smart supervisor system developed by Siemens Corporate Research, the life model then predicts when the thermal barrier coating on a blade will fail.

Turbine blades operate in an exceptionally hostile environment; they rotate at more than 3,600 revolutions per minute, with a linear tip speed of 800 mph, under very high pressure (220 psi, nearly 15 times the force of gravity) and extremely high temperature (in the range of 2,600 ºF, about the melting point of steel).

To operate in these conditions, Siemens Westinghouse developed a cooled optical probe that is installed in the gas turbine reaching down to the moving blades. A near- and mid-wave infrared high speed camera is also situated in a cooled housing and connected to the probe outside of the turbine. Despite the high speed of rotation, the control software can identify and record 85 percent of the blade surface and has the spatial resolution to capture very small design features. The images are evaluated automatically, and the entire system can be linked to remote diagnostic center.

The ongoing success of this commercial demonstration is garnering keen interest by the energy industry and the military. Siemens Power Generation has already ensured that this technology will be available on its next generation of gas turbines, and online blade monitor retrofits are currently being marketed for existing gas turbines.

Commercialization of the technology is expected in future months for gas turbines, and the versatility of the technology may not yet be fully realized. By successfully operating in the most complex environment, the technology has proven it could monitor the performance of components in additional hostile areas of the turbine, such as combustor baskets and stationary vanes.

While DOE involvement in the demonstration is scheduled to end in September 2005, Empire Stateline will continue to use the blade monitoring technology at its Joplin plant. The site will serve as a test bed to expand commercialization of the online monitor for gas, steam, and other types of turbines.

8.0 THE MAJOR ACHIEVEMENTS AND CONCLUSIONS OF THIS DEVELOPMENT PROGRAM ARE:

- The use of On-line monitoring by Siemens Power Generation design can be related to TBC condition based monitoring.

- The robust design with proper installation can provide On-Line Real Time Monitoring of TBC blades. The design system which survived 8000 hrs of operation has provided engineering and designs a new method of analysis during turbine operations and provides a basic lifing model.

- Siemens Engineering demonstrated a new and potentially very important area in remote diagnostics by installation and demonstration of prototype TBC monitor on a Siemens Power Generation turbine engine in Berlin. This pro type design was installed into a Long Term commercial turbine.

- The value of the designed On-Line TBC Monitoring system has proved to be of value for monitoring other important parameters; e.g., cooling hole blockages, platform rubs, spallation and delamination of TBC coated blades

- The development of software named "Blade Inspector" developed by Siemens Corporate Research has evolved a monitoring system that has the ability to image every blade from row 1 and 2 combustion area. With software development for system control and on-line system operating, experimental data acquisition and evaluation for the remaining TBC life modeling, and system test installation in Berlin, Germany and Joplin, MO. The team was successfully able to acquire images of stationary gas turbine blades at engine base load. Scene based image non-uniformity correction in addition to standard camera non-uniformity correction has significant increased image quality. A large software package was developed to control and operate all components of the on-line monitoring system, and to acquire process and store images of blades from stationary gas turbines on a systematic basis.

- The Optical system design is a unique concept and based on a telescopic arrangement consisting of a lens objective head and a series of relay lenses with the final relay acting as the system focus. The system was designed to function in the near infrared (NIR) region of 0.9 μm to 1.6 μm.

- The TBC Lifting calculation of the driving force (applied energy release rate) of typical interfacial TBC defects has been explained. Simulation results are presented and discussed as function of thermal loading conditions and initial defect size. As a result the defect growth rate was predicted at room-temperature assuming a sub-critical defect growth mode to be activated.

- On-line TBC monitor with the Siemens Power Generation design 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 are equally applicable to smaller land, aero and marine based gas turbines. This opens future global market opportunities for the team to pursue.