Paper No: 03-IAGT-209

15TH SYMPOSIUM ON INDUSTRIAL APPLICATIONS OF GAS TURBINES

REMOTE CONDITION MONITORING AND DIAGNOSTICS AN INTEGRAL PART OF MACHINERY MANAGEMENT

by

William J. Carpenter
Miguel J. Estupinan
R. Alec Gordon

Of
Solar Turbines Incorporated
Subsidiary of Caterpillar Inc.
San Diego, CA

Presented at the 15th Symposium on Industrial Application of Gas Turbines
Banff, Alberta, Canada - October 13 - 17, 2003
The IAGT Committee is sponsored by the Canadian Gas Association.

Biographies Session 2.9

William Carpenter
15th Symposium on the Industrial Application of Gas Turbines (IAGT) October 13-17, 2003, Paper Title: Remote Condition Monitoring and Diagnostics, Author: William J. Carpenter, Program Manager, Remote Integrated Services. William Carpenter has been with Solar for over 30 years in a variety of positions in engineering, overhaul and field operations. He received his BS and MSME degrees from San Diego State University.

ABSTRACT:

This paper summarizes the Remote Monitoring and Diagnostic program and provides a technical overview of the diagnostics system including details of the system features, design structure and technical development. In addition, technical case studies demonstrating the RM&D system benefits are presented and future development efforts are briefly discussed.

Solar Turbines Incorporated, a subsidiary of Caterpillar Inc, has combined 40 years of turbomachinery design, manufacturing, service and operational experience with proven information technology and technical expertise to develop an automated remote condition monitoring and diagnostic system. The remote monitoring system provides expert diagnostics, enabling machinery management services that extend beyond traditional equipment management and risk management programs. The RM&D system is not a stand-alone system, but is an integral part of a holistic approach to machinery management.

The Remote Monitoring & Diagnostic (RM&D) system incorporates a centralized engine monitoring and diagnostic database with secured communication that allows for the systematic acceptance of multiple unit data. The centralized system allows for decentralized unit and fleet management. Authorized users, with system access, can quickly evaluate automated reports and recommendations in support of engine health and maintenance plans. The RM&D system information is coupled with maintenance history and essential environmental and operational data to effectively manage machinery health and to mitigate machinery risk in order to meet or exceed customer operational objectives. Remote Monitoring & Diagnostic capability is available only in conjunction with a variety of machinery and asset management service agreements.

Presented at the 15th Symposium on Industrial Application of Gas Turbines
Banff, Alberta, Canada - October 13 - 17, 2003
The IAGT Committee is sponsored by the Canadian Gas Association.

INDUSTRY AND MARKET TRENDS

Users need to reduce life cycle cost and mitigate risk within both the Oil and Gas and Power Generation markets, and are increasingly outsourcing non-core business activities and actively restructuring to focus on core business operations. In support of customer needs, Solar's Customer Services has developed machinery management programs that use environmental, conditional and operational data to facilitate condition based maintenance. These programs differ from traditional, timed-based programs and provide a more effective approach to machinery management. These machinery management programs are supported by Solar's Remote Integrated Services. The Remote Monitoring & Diagnostic (RM&D) system is a critical element within the Remote Integrated Services initiative.

PROGRAM AND SYSTEM OVERVIEW

The Remote Integrated Services (RIS) initiative is a market driven program with a holistic approach to engine and package health assessment and maintenance management. Remote Integrated Services offerings provide for equipment risk mitigation through assessment of condition, trend and diagnostic information and their relationship to site environmental data such as oil, air and fuel analysis. They incorporate package and engine maintenance activity that includes borescope inspection and vibration analysis findings into technical recommendations on suitability for continued operation. The RIS offerings are designed to provide optimization of maintenance and inspection plans based on an assessment of the operating environment.

The Remote Monitoring & Diagnostic system is the key aspect of the RIS program and is coupled with live-viewing to facilitate troubleshooting with remote engineers. The primary elements of the Remote Monitoring & Diagnostic system consist of data acquisition and storage, and of performance diagnostic algorithms. The data is automatically filtered and stored where a rule-based diagnostic software application performs automated trending and assessment of engine and package condition. The system offers early warning of incipient faults or failure by employing statistical trending and diagnostic algorithms and provides support personnel with automatic notification of pre-alarm symptoms to enable proactive response. The RM&D system information is integrated with maintenance activity and inspection reports to facilitate equipment condition assessment and drive event notification and recommendations for corrective action. Figure 1 illustrates these capabilities as an integral basis for effective unit and fleet management.

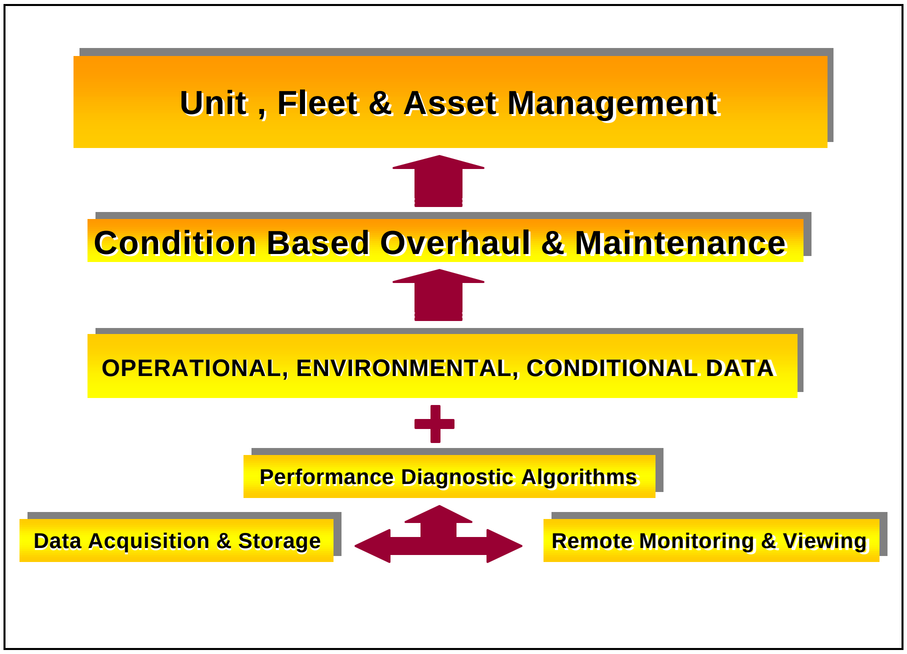

Figure 1. The RM&D System's Role in Unit, Fleet and Asset Management

DESIGN STRUCTURE

The RM&D system leverages the unit's TT4000 Human Machine Interface (HMI) as the central site communication and data collection device. The central monitoring and diagnostic center systematically acquires and processes data from the HMI. Twenty-four data snap shots are taken at hourly intervals. These data are automatically uploaded / transmitted daily through a dedicated line or satellite connection to the central Remote Monitoring & Diagnostics center where the data are sorted and stored in an engine condition database.

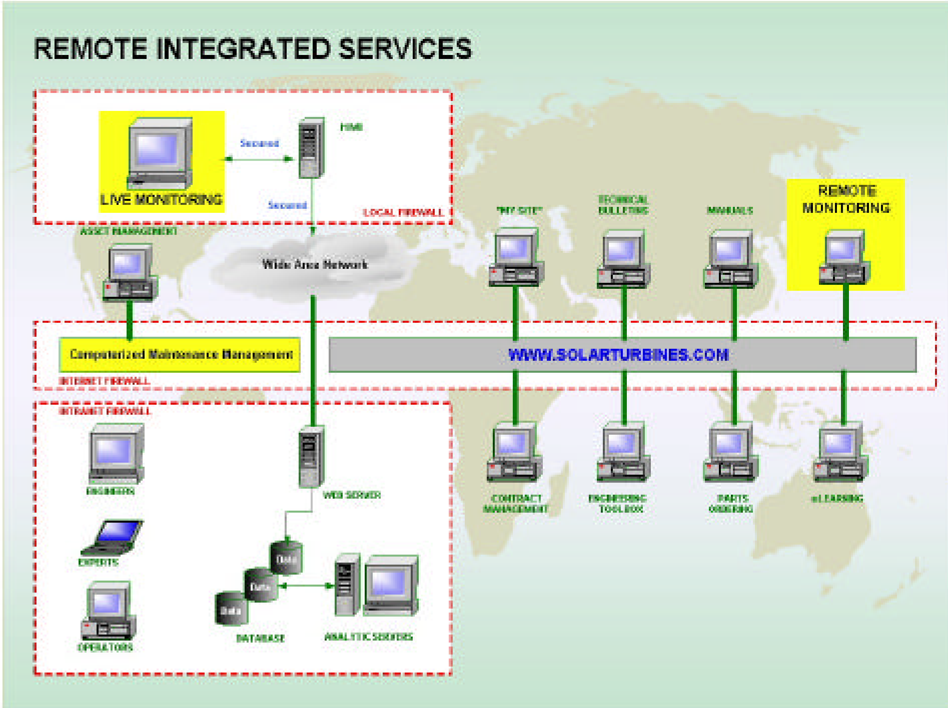

Figure 2. RM&D as part of the RIS Architecture

Reports are automatically generated and formatted for engineering review and are accessible via the Internet, allowing on-line examination of operating units, maintenance logs, component data, equipment details and statistics. Data storage, access and communication architecture is designed to comply with strict security requirements; however, the architecture does include added flexibility to address additional customer security concerns.

Figure 2 details the overall system architecture and highlights individual aspects of the RIS program development such as Remote Monitoring, Live-Viewing and Computerized Maintenance Management.

The secured live-monitoring feature is also made possible by the HMI and serves as an efficient troubleshooting tool. Authorized users can access display screens over the Internet to view real-time status of their equipment operation, allowing multiple users to view information simultaneously. The diagnostic and troubleshooting tools are supported by consolidated environmental and maintenance data, stored in an integrated computer maintenance management system. The computerized maintenance management feature establishes the link between engine operational data, collected and analyzed by the RM&D system, and equipment maintenance activity and inspection records.

Connectivity

The data used for the diagnostics are taken from a stored file located within the customer's TT4000 HMI system. The TT4000 logs are transferred via phone modem, LAN or satellite connection, as per site agreement and availability, to a parsing program, which feeds into the central database (reference Figure 3). The central database is critical to the RM&D system reliability and maintenance. There are many advantages to this central configuration, including automation, data mining techniques and time to retrieve, analyze, and report on the data.

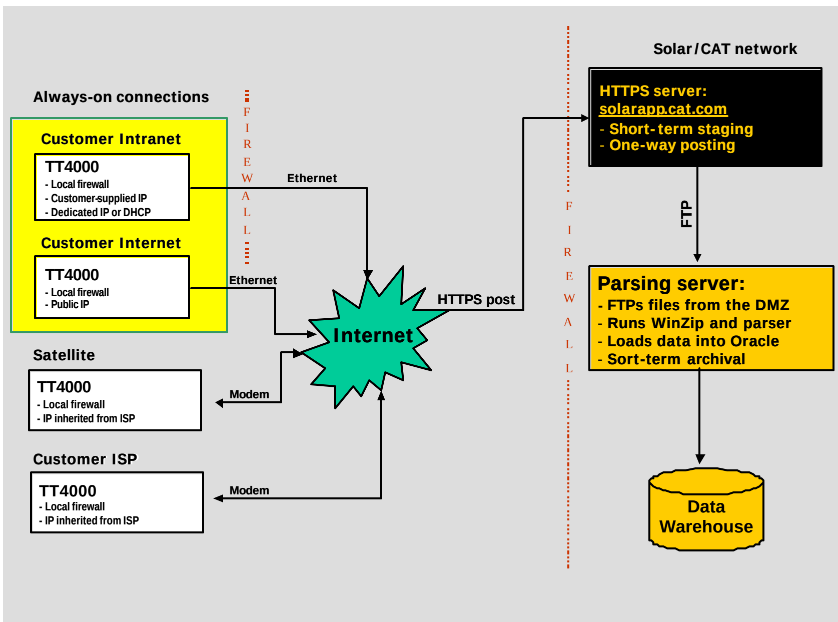

Figure 3. Connectivity

Data Analysis and Presentation

The RM&D system employs a powerful, statistical analysis program with customized algorithms to filter the data, perform the analyses and provide automated report generation. The results are posted to a reporting engine where the final product is stored in hypertext markup language (HTML).

The statistical data analysis software provides various filtering techniques and math subroutines to organize and perform diagnostic evaluation. This capability automates analytical techniques that an equipment expert would normally employ when making maintenance, repair or overhaul decisions. The diagnostic model evaluates calculated variables compared to both theoretical and practical fixed limits and statistical mean-variance criteria. The model detects when process variables approach predetermined or "specification" limits, or if the process is changing in an unexplained fashion, regardless of whether it complies with overall specification. Results are presented in report format, conveying the evaluation of the given data set and the coinciding recommended corrective actions.

Troubleshooting and Data Resolution

The RM&D system collects data once per hour. Troubleshooting capability commands high-resolution data and is available with the Live-View feature. With higher resolution data available for download, engine start-up and shutdown transient data can be verified or compared with correct/typical equipment data, identifying anomalies that may reveal the problem source. For trouble shooting purposes, the data of most interest is contained in discrete event, trigger and historical, one and ten second logs.

DIAGNOSTIC DEVELOPMENT

The primary purpose of instrumentation on gas turbine packages is to facilitate safe start-up, operation and shutdown of the engine and associated package equipment. However, advancements in digital control system technology have significantly improved the resolution and data available from package instrumentation to enable support of engine and ancillary equipment monitoring.

The objective of data trending and early detection of adverse trends and conditions is to pre-empt control system alarms and reduce unscheduled maintenance and downtime. Traditionally, data collection, storage, trending and analysis are seldom accomplished with any degree of consistency or success. A great obstacle exists in that there is no easy way to efficiently analyze operational data and draw conclusions from large amounts of data with respect to engine condition. Typically, an engineer would incur a great deal of time acquiring large data files, importing and exporting them into a format that permits manipulation, and attempting to represent the data graphically. Due to the labor-intensive nature of this analysis, it is often not done or incomplete. Even if methods to represent the data graphically are developed, interpretation of the graphics is a considerable obstacle, requiring significant turbine knowledge and expertise.

RM&D addresses these analysis obstacles, while promoting product performance, technical support, asset management and equipment comparison techniques. By the time a control system alarm is activated, it is probable significant hardware damage has already transpired. The initial symptoms of the problem or condition causing the alarm are in many cases detectible before accrued hardware damage occurs. The primary benefit of trending and diagnostics lies in the potential for condition assessment and thus, notification of incipient control system alarms and shutdowns. This includes specific recommendations or corrective action advisories. For example, the operator will be alerted of a problem and presented with the correct course of action required to pre-empt component failure or vastly reduce future package downtime. The automation of this data trending and condition assessment has obvious value.

An OEM advantage to turbine health assessment lies in actual equipment knowledge and experience. The diagnostic development process began with several studies, including an examination of Field Service repairs and a Failure Mode Effect Analysis (FMEA), performed on the reasons for turbine overhaul. The field service repairs analysis identified those issues most frequently in need of callout support, while the FMEA on overhaul returns identified predominant and reoccurring reasons for overhaul. Additionally, the RM&D team conducted a statistical analysis of engine returns based on operating hours. Figure 4 displays a frequency distribution of time between overhaul (TBO) for engine returns. Each data point represents an individual engine return. The data in this plot provide a basis for empirical methods to quantify the opportunity for TBO extension.

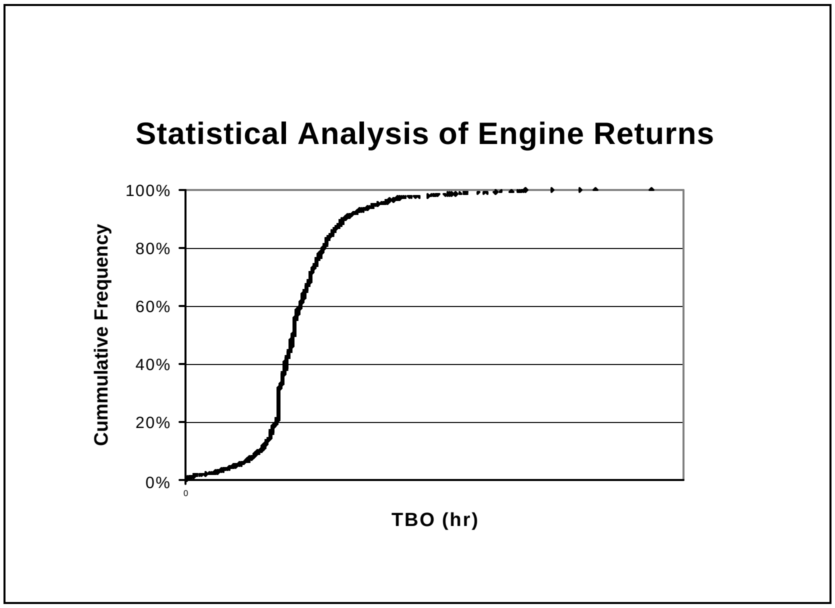

Figure 4. Frequency of Engine Returns versus Time Between Overhaul (TBO)

The results of these analysis techniques reinforce the benefits associated with a condition-based maintenance and overhaul philosophy, and the impact of turbine engine condition assessment on equipment life extension.

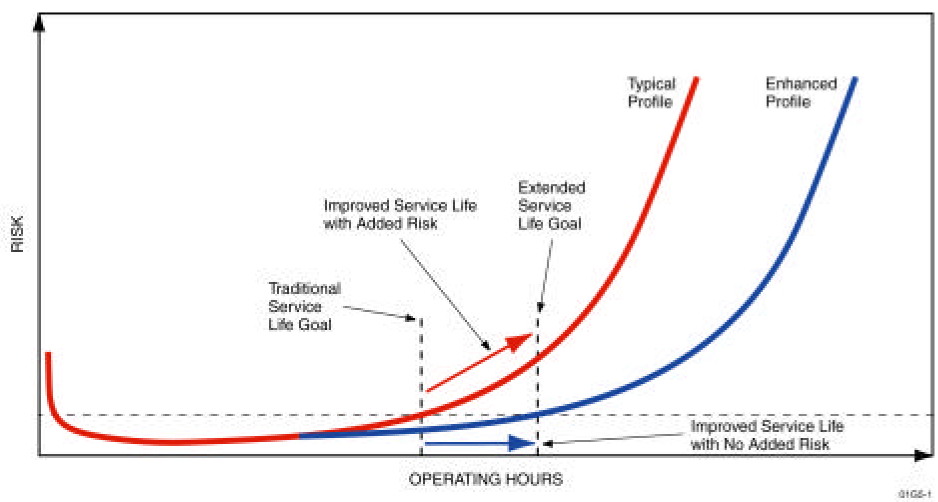

Figure 5. Warranty or "Bathtub" Curve: Failure Rate versus Turbine Operating Hours

Figure 5 shows a "bathtub" curve of failure rate versus time. The curve depicts the life consumption of a gas turbine. In order to achieve highly reliable operation, the routine and/or recommended service must take place before any known failure or wear mechanisms occur. However, extending the service life period by only extending the operating period will result in the operator taking on additional risk (red line). Introducing condition monitoring and analysis in order to drive service and maintenance provides visibility into turbine health and allows for proactive maintenance and engine life extension. The RM&D system is a tool for engine life extension - shifting the typical "bathtub" curve by increasing operating hours for a typical failure rate, or decreasing failure returns for a given operating hour. As the entire curve is shifted to the right, operating periods increase without additional failure risk (blue line).

Diagnostic techniques employ data reduction, filtration, and normalization and incorporate statistical methods for data smoothing and trending in addition to adverse trend recognition. *Control* or *Pre-Alarm* limits are predetermined and depicted graphically based on statistical mean-variance criteria or technical expertise. When a control limit is traversed, the trend line color changes to red to draw attention to the deviation and an alert is posted to the *Alert Summary Report.* It is important to note that the predetermined alert or control limit is below the alarm level set in the on-site turbine package control system, thereby providing advanced notification of impending faults.

The RM&D remote format presents up to six months of data with powerful viewing and reporting techniques and allows for the quick identification and isolation of problems. This includes a number of specific system reports with detailed diagnostic and trend plots. Machinery technicians are able to review the RM&D data in conjunction with the site data such as maintenance activity and fuel, oil and vibration analysis reports. With this abundance of data readily available, analysis and response time is minimized, while maintenance and repair is proactive.

CASE STUDIES

Multiple RM&D case studies have been prepared in conjunction with field service repair reports and failure analyses to validate RM&D algorithms. The following case studies provide an examination into the specific systems under Remote Monitoring and Diagnostic observation. Figures 6, 7 and 8 investigate the source of deviation of a typical turbine combustor thermocouple temperature profile. The thermocouple spread (TC Spread) measures the difference between the highest and lowest thermocouple reading. When compared with and correlated to additional engine instrumentation measurements, this simple measurement represents a powerful indicator of turbine condition.

Figure 6 shows a gradual decrease in thermocouple spread occurring at 3236 hours of operation (6a). This decrease corresponds to a significant step change in the data and is followed by a sudden increase in thermocouple spread at 3546 hours (6b). The trend progresses past the established RM&D system pre-alarm limit (red dotted line) and triggers the automated pre-alarm notification, driving condition assessment and potential recommendations for action. The preliminary assessment and pre-alarm notification in this case indicates potential fuel injector blockage. At a minimum, this scenario calls for further investigation.

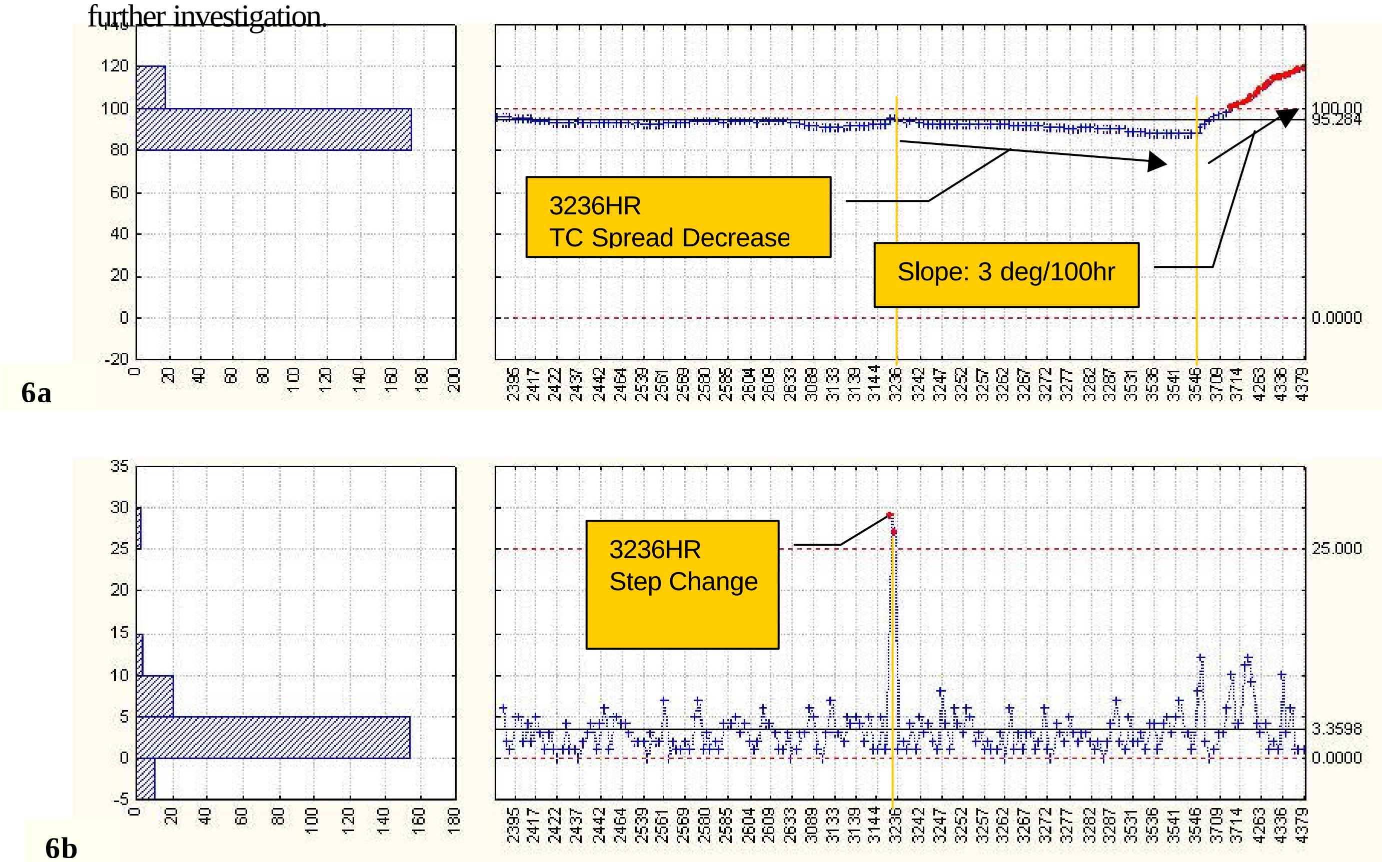

Figure 6a. Combustor Thermocouples: ***Temperature Spread Versus Operating Hours***

Figure 6b. Combustor Thermocouples: ***Temperature Step Change by Operating Hour***

Figure 7 illustrates an avenue for further investigation of the previously discussed combustor temperature event. This plot represents the combustor thermocouple temperature profile at the radial position for the same turbine, during the same timeframe of operation.

Thermocouple position #12 displays a shift to a lower operational temperature. This shift corresponds to approximately 3314 hours of operation, soon after the thermocouple temperature event on the previous plot occurred (3236 hours). This evidence supports the original condition assessment and isolates the problem to the specific thermocouple. The operator is then able to identify the exact radial injector position within the combustor corresponding to thermocouple #12. Once again, further investigation is possible.

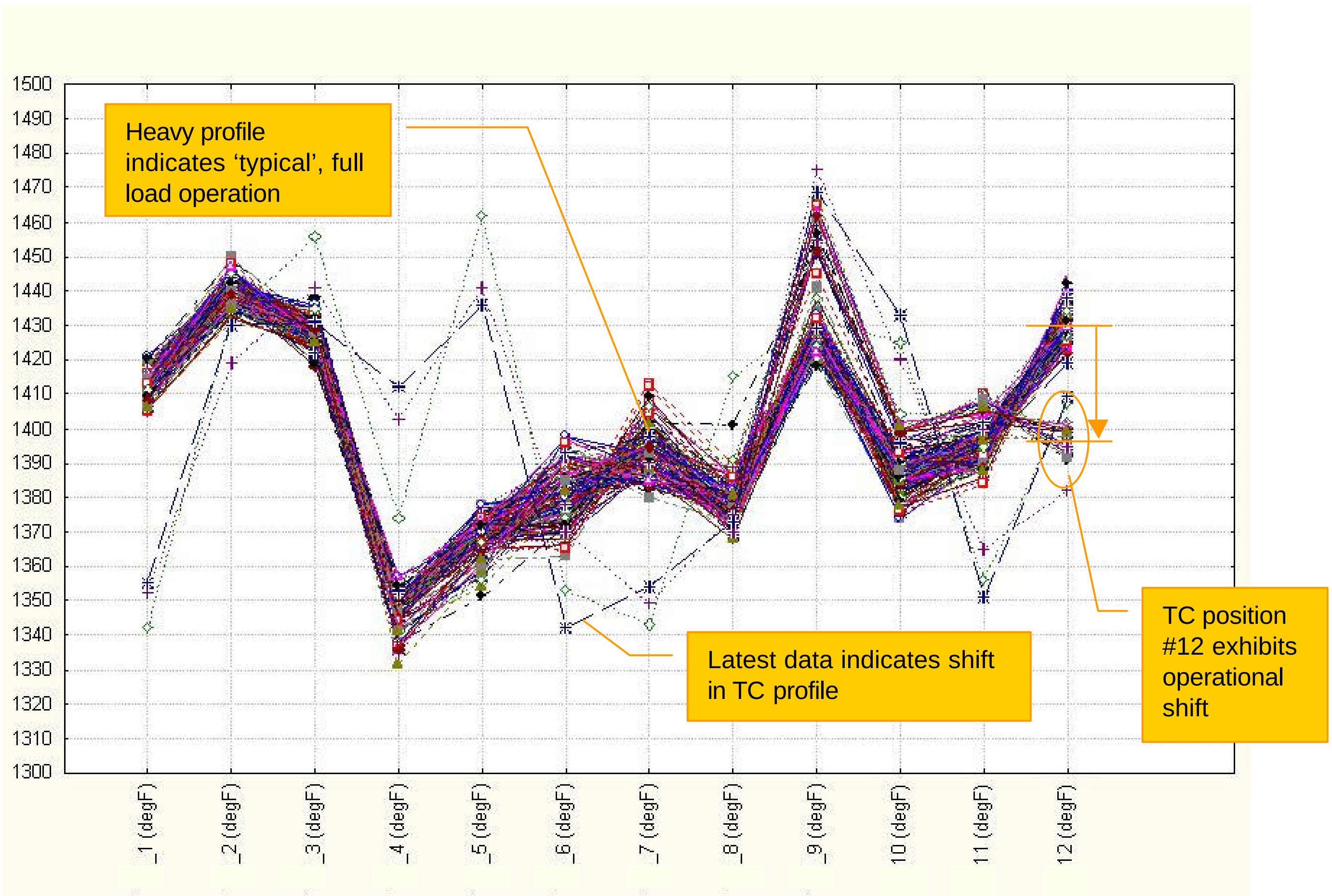

Figure 7. Combustor Thermocouple Profile: ***Thermocouple Position Versus Temperature***

The power of the RM&D system lies in automation. Investigation into each of the previous plots was prompted by an automated pre-alarm notification. This automation also facilitates further detailed investigation. Figure 8 is a least-squares interpolation of combustor thermocouple temperature. This "Contour Plot" is a two-dimensional representation of the cylindrical combustion chamber. The temperature profile at the radial position for each thermocouple is plotted over time and the temperature between thermocouples is interpolated. This graph provides insight into relative thermocouple temperature consistency and variations. The gradual decrease in temperature spread at 3236 hours is undetectable in this plot, however, thermocouple #12 displays a shift to a lower temperature at 3547 hours.

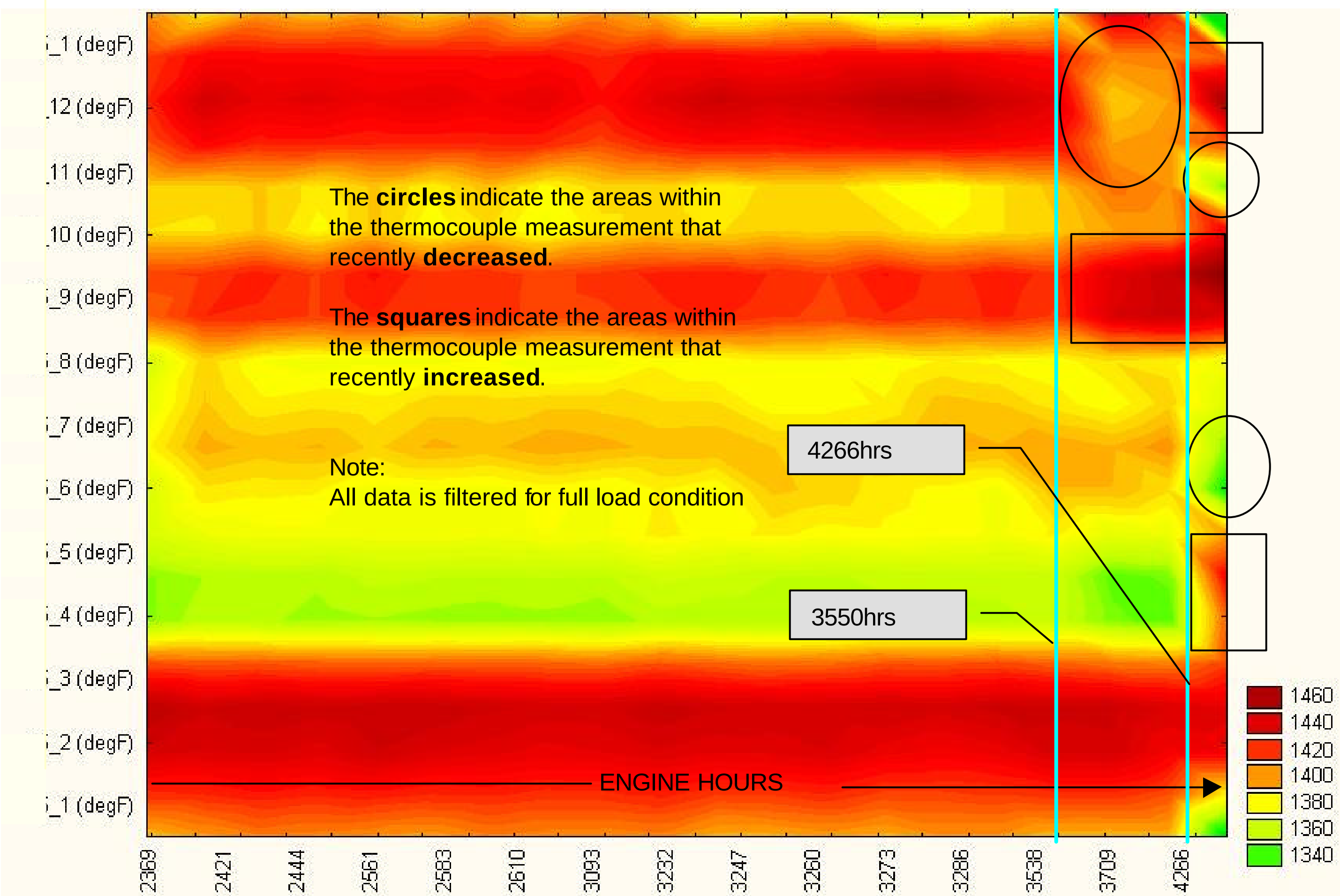

Figure 8. Combustor Temperature Contour Interpolation: ***Thermocouple Temperature versus Time***

This investigation isolated a fouled injector and determined the cause of failure to be injector blockage from a liquid fuel transfer at approximately 3236 hours, confirming operational data and coinciding with RM&D system assessment. The dates of transfer and duration of liquid fuel operation could also be extracted from the plots.

Pre-alarm notifications provide recommendations for further analysis and corrective action. In this case, recommendations included further investigation into site fuel type/quality changes leading to fuel injector blockage. An investigation into maintenance and environmental events corresponding to the particular operational period was also recommended and possible with the system.

Figure 9 provides insight into both cross-product analysis and instrumentation calibration. This graph is a visual representation of a diagnostic measurement taken from the same instrumentation, within the same system, on two identical packages, installed at the same site and

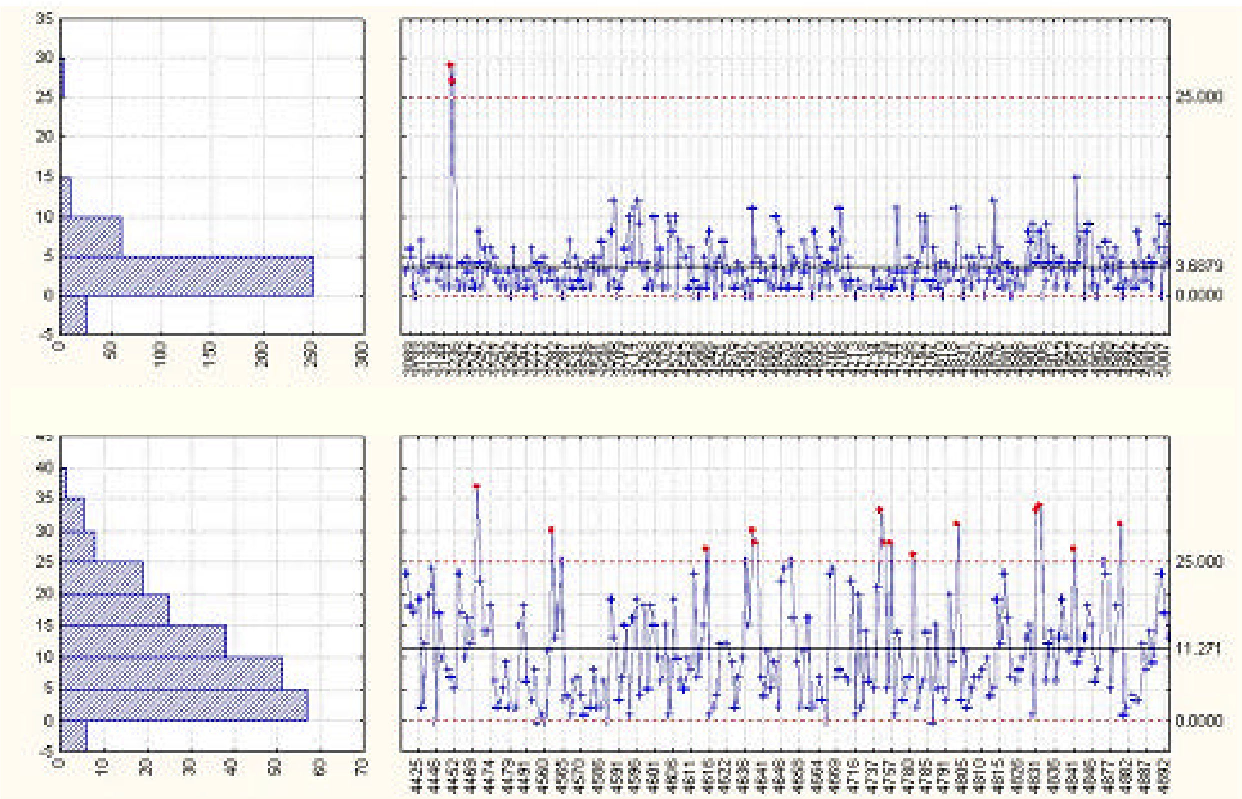

Figure 9. Cross-Product Analysis and Instrumentation Calibration

subjected to identical environmental and operating conditions. The capability for direct comparison of identical or disparate trends among the same product line represents a valuable cross-product analysis tool. With respect to the specific system in Figure 9, these identical units demonstrate significantly different operational characteristics. The variation in the bottom graph is a result of an instrumentation failure, resulting in several RM&D pre-alarms, which may or may not be detected by the control system. Cross-product comparison techniques are intuitive and often successful in field evaluation, but are limited due to the complexity and time involved in the analysis. Although this instrumentation calibration issue may not be apparent within the control system or even by evaluating the individual plot, when the plots are compared to each other, the added value of cross-product comparison with automated trending and diagnostics is evident, specifically with respect to these "sister units."

FUTURE DEVELOPMENT (Smarter Diagnostics)

New and increasingly accurate measurement associations are expected with the magnitude of data being monitored and trended by the RM&D system. Although field units reside in a typically highly dynamic and uncontrolled environment, the RM&D system provides the ability to compare product-to-product, application-to-application and site-to-site data trends. The system will further ascertain common trends and cause and effect relationships to aid in diagnostic development, drive additional package instrumentation and improve product design. The diagnostic development will ultimately result in algorithms being incorporated back into the system to establish automated self-learning.