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Turbine Cycle Heat Rate Monitoring: Technology and Application

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Turbine Cycle Heat Rate Monitoring: Technology and Application

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PRODUCT DESCRIPTION

Research has been completed on available technology for monitoring turbine cycle heat rate and factors affecting the successful deployment of this technology in fossil generating plants. Information has been gathered from interviews with experienced industry plant staff and vendors. Trends were noted and are described in this report. The report is recommended as guidance for power generation fleets and individual plants seeking to establish a successful program for heat rate reduction.

Results and Findings

Significant advances in heat rate monitoring technologies have been made in the past decade. These improvements parallel the increased processing speed and bulk data storage of computing platforms. Recently, the deployment of monitoring systems on wide area networks has made centralized technical expertise feasible. Analysis systems have gone beyond simple trending to include data-driven models that help reduce the effort needed to pinpoint sources of the increase in turbine cycle heat rate early in the degradation process. In principle, this should enable power companies to sustain effective thermal performance programs even though significant reductions in staffing have occurred since the 1990s. It was found in many interviews that, in practice, the actual staff reductions have been excessive so that even with this technology, heat rate improvement programs are not effective at many plants. Corporate culture and management priorities contribute to this trend.

Challenges and Objectives

Power generating companies today are challenged to reduce operating costs. At the same time, the cost of unit unavailability can be significant in today's power markets. Management focus in the past decade has therefore been on reducing forced outage rates, with less attention paid to thermal performance. Plant owners are challenged to prepare for the impact of future fuel price increases and carbon taxes and consider the value of environmental stewardship. This can be accomplished through effective heat rate monitoring and maintenance activities derived from this information. This report provides a fundamental understanding of the technology and issues surrounding the creation of a successful heat rate improvement program.

Applications, Value, and Use

This report is intended for performance engineers tasked with developing or improving the heat rate programs in their systems. Those who are inexperienced in this area will find the fundamental technical information and a synopsis of commercial systems valuable. The extensive information from interviews of experienced plant staff is also revealing in terms of what is perceived to be successful and unsuccessful from business practice, staffing, and prioritization perspectives.

EPRI Perspective
EPRI has sponsored research in the development and field verification of plant performance monitoring technology. At the component level, recent projects address topics such as the internal efficiency of steam turbines and condenser performance. In anticipation of increased interest in thermal performance, EPRI recommends that companies institutionalize and sustain practices that improve turbine cycle heat rate. The available commercial technology can support this, but it still requires a commitment to prioritize staff resources on a corporate level.

Approach
The information in this report was assembled from interviews with industry experts. This includes representatives of vendor companies supplying commercial technology and end users of this technology.

Keywords
Heat rate
Turbine cycle
Monitoring
Thermal efficiency

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EXECUTIVE SUMMARY

Power generating companies today are challenged to reduce operating costs. At the same time, the cost of unit unavailability can be significant in today's power markets. Management focus in the past decade has therefore been on reducing forced outage rates, with less attention paid to thermal performance. Plant owners are challenged to prepare for the impact of future fuel price increases and carbon taxes and consider the value of environmental stewardship. This can be accomplished through effective heat rate monitoring and maintenance activities derived from this information. This report provides a fundamental understanding of the technology and issues surrounding the creation of a successful heat rate improvement program.

Background

Significant advances in heat rate monitoring technologies have been made in the past decade. These improvements parallel the increased processing speed and bulk data storage of computing platforms. Recently, deployment of monitoring systems on wide area networks has made centralized technical expertise feasible. Analysis systems have gone beyond simple trending to include data-driven models that help reduce the effort needed to pinpoint sources of increase in turbine cycle heat rate early in the degradation process. In principle, this should enable power companies to sustain effective thermal performance programs even though significant reductions in staffing have occurred since the 1990s. It was found in many interviews that, in practice, the actual staff reductions have been so excessive that even with this technology, heat rate improvement programs are not effective at many plants. Corporate culture and management priorities contribute to this trend.

Technology Assessment

To assist readers in developing a fundamental understanding of turbine cycle heat rate monitoring, this report provides the technical approach to converting process data to performance metrics on both a component and unit level. Five commercially available systems that can support the monitoring and diagnostics of turbine cycle heat rate are described in this report in terms of their approach and functionality. There are many similarities among these systems: all systems are easily connected to most plant data sources, all systems are based on a similar set of governing equations described in Section 3, and all systems have built-in trending tools and can export data for further analysis with other software packages. The differences noted include how tightly steam cycle models are integrated into the monitoring systems, the data preprocessing for anomaly detection, the tools for root cause diagnostics, and the automated alarming and reporting tools. Although these systems can leverage the abilities of performance engineers, they do not replace the need for them.

Management Support of Heat Rate Programs

To evaluate how on-line monitoring systems are currently being used in heat rate improvement programs throughout the electric power industry in the United States, 13 interviews were conducted with plant and corporate staff of major power producing companies. Most performance engineers interviewed had close to two decades of experience with thermal performance monitoring of coal-fired power plants. The company names are not identified in the interview summaries. Because of their lengthy experience, the experts contacted have been involved long enough to see the changes in both technology and the management perspective on the importance of heat rate. The insight from these interviewees is valuable and can be a basis for successful management strategies going forward. Key points from the discussions include the following:

- The resources that a company commits to thermal performance are driven by management support and company culture. Companies with more extensive heat rate programs were typically managed by personnel with performance engineering backgrounds and significant experience in coal-fired power plant performance.
- Success requires long-term commitment by management to create an environment that sustains ongoing thermal performance improvement. Education is a key component of this commitment.
- The regulatory environment in which a company operates does not necessarily determine the characteristics of its thermal performance program. The move toward deregulation has not, in general, motivated companies to be more thermally efficient.
- Effective thermal performance programs require personnel engaged at the plant level. Fleetwide thermal performance monitoring is an effective strategy for leveraging limited personnel resources, but it requires plant-level resources to effectively implement heat rate improvement recommendations.
- Reducing short-term financial obligations by eliminating personnel is easy to quantify and will provide a measurable and immediate decrease in a plant's production costs. However, sustaining a thermal performance program requires that long-term objectives are not sacrificed for short-term cost reductions.
- With the move to a deregulated power market, staffing levels for thermal performance have decreased dramatically since the early 1990s. This reduction in staff parallels a lowered emphasis on thermal performance. There does not appear to be any immediate and significant shift in the U.S. power industry for promoting the thermal efficiency of coal-fired plants.

Recommendations

This research indicates the importance of both technology and management decisions in creating and sustaining an effective heat rate improvement program. It is recommended that companies that do not currently have comprehensive programs for assessing and improving thermal performance consider the high benefit to cost inherent in this activity. Power producers also need to look into the future at emerging trends in factors such as fuel cost, environmental impact, and carbon tax to understand the direct benefit that can be derived from plant efficiency improvements. Companies that are considering building their capability in performance monitoring should note the success paths followed by leading companies in the industry. These include not only selecting the appropriate technology but also creating an organizational structure that ensures that actionable information is used. This could mean combining centralized monitoring and/or expertise with site support staff with clear responsibility and management support. It is recommended that plant thermal performance goals be integrated into corporate incentive plans and the resources required to meet these goals are provided.

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1 INTRODUCTION

In the past few decades, a computer hardware and software technological revolution has occurred. A few decades ago, most power companies' computer systems consisted of mainframes that had both limited storage and limited computing power. As a result, minimal archival and online process data were available. Today, computers are orders of magnitude faster and have orders of magnitude more storage. In addition, almost every employee in a company has ready access to a computer. Instrumentation has also seen enormous improvements in hardware technology. As a result, most power companies have tremendous quantities of both online and archival process data available to operators and performance engineers.

The first report in which EPRI demonstrated on-line monitoring technologies was published in 1986 [1]. This involved a comprehensive program of installing advanced instrumentation and monitoring systems on Potomac Electric Power Company's (PEPCO) Morgantown Unit 2 with the overall objective of improving the unit's heat rate. As part of this project, a turbine cycle performance analysis system was created. This provided the capability to track overall turbine cycle heat rate, turbine performance, condenser performance, and feedwater heater performance. Since this project was completed, turbine cycle heat rate monitors have evolved into a very mature technology and are widely available commercially.

The U.S. electric power industry has also undergone fundamental changes since EPRI's demonstration project. In 1986, the industry was almost entirely regulated, whereas today many areas of the country are either deregulated or moving toward a deregulated power market. In the 1980s utilities had much larger staffs. For example, it was not uncommon for a power company to have 10–20 engineers and technicians in its central staff with 2–3 additional employees at each plant whose primary responsibilities were thermal performance. Significant industry-wide downsizing occurred in the late 1980s and 1990s, and it is currently not uncommon for a central staff with primary duties of thermal performance to be either nonexistent or limited to one or two employees with no additional support at the plants.

1.1 Project Objective

Heat rate improvement is a process that requires both technology and a dedicated focus by management. This report describes the data analysis methods and commercially available systems for performing on-line turbine cycle heat rate monitoring in large central station generating plants. A description of current trends in the industry regarding staff resource allocation and management prioritization follows. By investigating both the industry trends and the technology for on-line turbine cycle heat rate monitoring, a better insight can be gained into the gaps that prevent achieving improved thermal performance in fossil plants.

1.2 Scope of Report

The intent of this report is to describe the technology, human resources, and management support needed to conduct an effective heat rate reduction program. The following specific topics are presented:

- The economic and political drivers for improved thermal performance in the electric power industry
- An overview of advances in commercial technology that have occurred with on-line monitoring in the past few decades
- A historical overview of key legislation that has molded the current regulatory environment
- The calculations and techniques commonly used in turbine cycle performance monitoring systems
- Several commercially available on-line turbine cycle performance monitors
- Case histories obtained from discussions with performance engineers having significant experience in managing thermal performance in coal-fired plants
- Gaps that exist with technology and management practices for implementing effective thermal performance programs

1.3 List of Acronyms, Abbreviations, and Symbols

1.3.1 Acronyms and Abbreviations

ACM	Advanced Condition Monitor
ASME	American Society of Mechanical Engineers
Btu	British thermal unit
CCW	condenser cooling water
DCA	drain cooler approach
DCS	distributed control system
EFOR	equivalent forced outage rate
EPACT	Energy Policy Act
EWG	exempt wholesale generator
FERC	Federal Energy Regulatory Commission
GPA	Global Performance Advisor
HEI	Heat Exchange Institute
HP	high pressure
IP	intermediate pressure
IVM	Input Validation Module
kg	kilogram
kJ	kilojoule

KPI	key performance indicator
lb	pound
LDS	Leak Detection Services
LOI	Loss on ignition
LP	low pressure
MHZ	megahertz
MIPS	millions of instructions per second
Mt	metric ton
MT	million tons
MW	megawatt
kW	kilowatt
NERC	North American Electric Reliability Council
OPC	object linking and embedding for process control
PC	personal computer
PCS	Performance Consulting Services
PdM	predictive maintenance
PEPCO	Potomac Electric Power Company
PEPSE	performance evaluation of power system efficiencies
PI-SDK	PI Software Development Kit
PJM	Pennsylvania-New Jersey-Maryland Independent System Operator
PMW	Performance Monitoring Work Station
PTC	Performance Test Codes
PUHCA	Public Utility Holding Company Act of 1935
PURPA	Public Utility Policies Regulatory Act
SEC	Securities and Exchange Commission
SQL	Structured Query Language
TTD	terminal temperature difference
VWO	valves wide open

1.3.2 Symbols

A_i	inside area of condenser tube
A_o	outside area of condenser tube
C	empirical constant relating tube velocity to theoretical conductance
c_p	heat capacity of water
DCA	drain cooler approach
f_i	water-side convective heat transfer coefficient
f_o	steam-side convective heat transfer coefficient
h	enthalpy

H	head
h_{att}	attemperation enthalpy
h_{crh}	cold reheat enthalpy
h_{ext}	feedwater heater extraction steam enthalpy
h_{fw}	feedwater enthalpy at entrance to boiler
h_{hrh}	hot reheat enthalpy
h_{ms}	main steam enthalpy
h_{ueep}	steam enthalpy at the used energy end point
k	condenser tube thermal conductivity
K	unit conversion constant relating power to head and flow
l	length of condenser tube
$TCHR$	turbine cycle heat rate
p	pressure
P_{gen}	unit power generation
P_{in}	power input
P_{loss}	generator power losses
P_{out}	power output
Q	flow
Q_{att}	attemperation flow
Q_{ccw}	condenser cooling water flow rate
q_{cd}	condenser duty, heat rejected by condenser
Q_{exh}	low pressure turbine exhaust steam flow
Q_{ext}	feedwater heater extraction steam flow
Q_{hrh}	hot reheat steam flow
Q_{ms}	main steam flow
r_i	inside radius of condenser tube
r_o	outside radius of condenser tube
R_s	steam-side condenser tube fouling resistance
R_{total}	total heat transfer resistance of a condenser tube bundle
R_w	water-side condenser tube fouling resistance
s	entropy
t	temperature
t_{dcex}	temperature of water exiting drain cooler
t_{fwex}	temperature of water leaving feedwater heater
t_s	condenser steam-side temperature
t_{sat}	extraction steam saturation temperature
TTD	terminal temperature difference
U_{act}	actual conductance of condenser tube bundle

U_{th}	theoretical conductance of condenser tube bundle
v	specific volume
V_{tube}	water velocity in a condenser tube
z	elevation
η_t	turbine enthalpy drop efficiency
η_p	pump efficiency

Subscripts

1	inlet conditions
2	exit conditions

2 BACKGROUND

This section describes the economic and political incentives for implementing a heat rate improvement program. After that, a brief overview of the technical advances in turbine cycle performance monitoring technology that have occurred over the past two decades is described. A history of legislation follows describing the drivers that have shaped the current regulatory environment for the U.S. electric power industry.

2.1 The Business and Political Drivers for Improved Thermal Efficiency

Improving the efficiency of the coal-powered fleet is important today, and its value will increase given global trends in energy usage. For example, a typical 500-MW baseloaded unit with a capacity factor of 80% and a net heat rate of 9,500 Btu/kWH (10,023 kJ/kWH) burns 1.45 million tons (1.32 MT) of coal per year at a fuel cost of $67 million. This example assumes 11,500 Btu/lb (26,750 kJ/kg) higher heating value and a $2 million Btu fuel price. Many performance engineers estimate that a 2% improvement is readily achievable with most coal-fired units given current thermal performance management practices. This would save 28,900 tons (26,200 MT) of coal per year with an annual energy savings of $1.3 million. Other benefits achieved with improved unit efficiency include reduced emissions, improved unit reliability, improved unit capacity, and the extension of the life of the global energy supply. The revenue associated with each of these benefits is significant. For example, most actions that produce a 2% improvement in heat rate provide an additional 2% capacity addition. Increased power production can be more important than saving fuel, in which case the improved heat rate could be used to provide additional power given the same fuel input. A 2% capacity improvement is worth $3.1 million per year for the 500-MW baseloaded unit described previously (average energy price of $45 per MW).

A fundamental requirement to sustain the Unites States and world economies is plentiful and affordable energy in which enhanced energy efficiency will play a critical role. The importance of energy is clearly seen in the recent political dialog concerning the United States' energy security. One of the key topics in this debate is the dependence on foreign oil from countries for which foreign relations have become increasingly volatile. For example, in 2005 the United States imported 5 billion barrels of oil, 40.74% of which was supplied by OPEC nations. Venezuela supplied 11.15% of the oil received from OPEC [2]. Global demand for energy might cause additional stability problems with the energy supply and will increase global energy prices. For example, China is currently undergoing unprecedented industrial expansion that will create a commensurate increase in China's energy demand.

The United States has a large domestic supply of coal and consumes a significant quantity each year. The U.S. Energy Information Administration estimates that United States' coal consumption will increase by 1.1% per year from 2004 to 2015 and then increase at the rate of 2.0% from 2015 to 2030 [3]. Based on these projections, the coal consumption in 2030 will increase by 50% relative to 2004. Figure 2-1 shows the breakdown of energy sources for electricity production in the United States in 2005, of which coal provides the largest percentage.

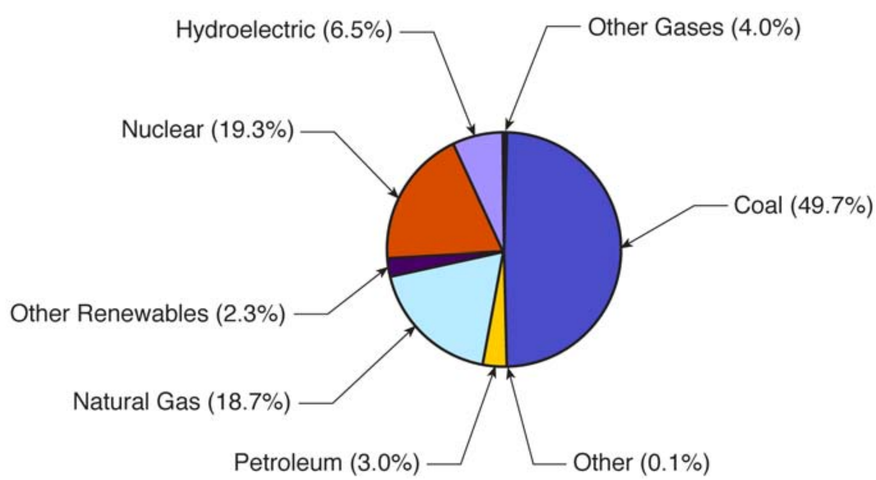

Figure 2-1
U.S. Electric Power Industry Net Generation

2.2 Improving Thermal Efficiency: Advances in Technology

This section of the report describes several EPRI projects for which the objective was improving fossil plant efficiency. One project, Power Plant Performance Monitoring and Improvement [4], provided a detailed description of determining the benchmark heat rate of a coal-fired unit. When computer technology advanced to the point that on-line monitoring became readily achievable, EPRI performed a project at Morgantown Unit 2 that investigated how on-line systems and advanced instrumentation could be used to improve unit heat rate. These reports investigated several topics that included on-line boiler efficiency monitoring, sensitivity of incremental heat rate, on-line turbine cycle heat rate monitoring, and optimized economic dispatch [1, 5, 6, 7].

As part of the Morgantown project, an on-line turbine cycle heat rate monitor was installed [6]. The on-line monitoring system consisted of a distributed computing system connected by a data highway. The computers used in the system were a Prime 750 minicomputer for general computing resources, a GE-PAC 4020 computer used to scan over 400 instruments, input-output boxes that linked process measurements to the data highway, and computers for the engineer and operator stations. The Prime 750 contained fewer than 1.5 gigabytes of storage and operated at 1 million instructions per second (MIPS), which, depending on how many instructions are implemented with each clock cycle of the computer, is roughly equal to 1 MHZ. The data highway connecting the computers supported a data transfer rate of 10 million bits per second.

Since the Morgantown Project, computer technology has improved by several orders of magnitude. For example, personal computers (PCs) that are currently commercially available support processing speeds of a few gigahertz, an improvement of three orders of magnitude relative to the Prime 750. The cost of data storage is currently $1 per gigabyte as compared with $36 per megabyte in 1989 [8], representing a cost reduction of over four orders of magnitude.

The calculations implemented in the turbine cycle heat rate monitoring system at Morgantown were overall turbine cycle efficiency, turbine performance, condenser performance, feedwater heater performance, and boiler feedpump performance. The calculations in current systems are very similar to the calculations implemented in the Morgantown system.

Although the basic methodology for turbine cycle heat rate monitoring has not changed, advancements in technology are important for implementing these systems. The improvements in processor speeds, data storage media, and software make these systems easier to use and more affordable. Most power companies now have a great deal of process data considering the wide implementation of distributed control systems (DCSs) and advancements in instrumentation. Turbine cycle heat rate monitoring systems are now widely used in the electric power industry and include both commercially available systems and custom systems developed within many different companies.

2.3 The Changing Regulatory Environment

Since EPRI initiated the Morgantown project, the power industry has undergone significant changes. A brief overview of major energy legislation is provided to give insight into the changing regulatory requirements of the electric power industry.

From its earliest stages, the electric power industry has been recognized as a natural monopoly. With one company owning and operating the generation, transmission, and distribution of electricity, competition was generally nonexistent, creating a monopoly that was outlawed with the Sherman Antitrust Act [9, 10]. To prevent possible abuses from these monopolistic systems, state regulatory agencies were created, the first of which were the New York and Wisconsin agencies in 1907. By 1920, two-thirds of the states had established regulatory agencies.

Parallel with the establishment of state regulatory agencies, holding companies acquired an increasing number of electric companies. A holding company is a parent company that owns stock in subsidiary companies and thereby has control over the subsidiary. By 1921, 94% of all electricity generation was provided by private utilities; by the late 1920s, 75% of U.S. electricity generation was owned by 16 companies.

With the consolidation of the utilities, the state agencies had difficulty regulating the holding companies because they were operating in multiple states and the rate of growth of these companies outpaced the regulators' abilities to keep up with the changes. There was also limited federal oversight of these holding companies. The holding companies abused their power and lack of oversight by sometimes artificially inflating the price of electricity. In addition, captive rate-paying customers from an electric utility provided a guaranteed revenue stream. The holding companies leveraged these guaranteed revenues by investing in potentially much higher profit, and much riskier, nonutility schemes. In 1929, the holding companies went bankrupt, thereby causing the subsidiaries to become bankrupt as well. This was the beginning of the Great Depression.

Having the fate of electric utilities closely linked with other less stable financial sectors was considered to be unsound for the continued economic well-being of the United States. Therefore, the U.S. government drafted the Public Utility Holding Company Act (PUHCA), which was enacted in 1935. Key provisions of the legislation were to limit the geographic area of an electric utility and to prohibit any company owning an electric utility from investing in other financial sectors. The utilities thereby became much smaller and were largely regulated by state public service commissions. In addition, the Securities and Exchange Commission (SEC) provided the oversight to ensure that holding companies owning multiple utilities did not own companies in other financial markets.

The regulatory environment created by PUHCA remained largely unchanged until 1978 when the Public Utility Policies Regulatory Act (PURPA) was passed. A major intent of this law was to encourage the development of more energy efficient and environmentally friendly generation facilities. With the passage of this law, utilities were required to purchase energy from qualified facilities (for example, cogeneration, solar, and wind facilities) at the avoided cost of power. The qualifying facilities were exempt from oversight of the SEC as required by PUHCA and were also exempt from many FERC and state regulations to streamline the process of getting these facilities in operation.

A few years after PURPA was passed, spokespeople in the energy industry began discussing unbundling the generation, transmission, and distribution of a vertically integrated utility to create a more competitive environment, according to John Howes [11]. With PURPA, competition was limited because open access to the transmission system was not guaranteed. The move toward a competitive energy market led to the Energy Policy Act (EPACT) of 1992. Key provisions of this act included guaranteed access to the transmission system and the establishment of exempt wholesale generators (EWGs). The establishment of EWGs, which were exempt from PUHCA restrictions, enabled a single company to own generating assets in different regions of the country. In addition, utilities were no longer required to purchase power from independent generators at the avoided cost of the power but rather could purchase the power at competitive wholesale prices. These two provisions, open access to the transmission system and the establishment of EWGs, are key components of a deregulated power market.

Since the energy legislation of 1992, additional rules have been implemented affecting the regulatory structure of the electric power industry. In 1996, the Federal Energy Regulatory Commission (FERC) passed Rulings 888 and 889, which extended the provisions for ensuring that any generating facility had open access to the transmission system. In 2005, energy legislation was passed that essentially repealed all limitations imposed by PUHCA.

Energy legislation has led to the current power markets, which can generally be described as either regulated or deregulated. Regulated utilities are governed by either a state public service commission or a federal level board, in the case of federal utilities that control power prices charged by utilities. The price includes the utilities' total costs of generation (fuel costs, operating costs, capital costs, and so on) and a negotiated rate of return. In a regulated environment, fuel costs incurred by the utility are passed directly to the customer.

In contrast to cost-based pricing, deregulated markets rely on laws of supply and demand to determine the price of power. This system requires several independent components, such as generation, transmission, distribution, and retail. It also requires that a wholesale market for electricity be established that governs the interaction between the energy generators and the energy retailers. With a wholesale market, the profit is determined by a generator's total cost of generation and the price received for power. Fuel costs are part of the total cost of generation and are not passed directly to the consumer.

Currently, power is sold by generators to the wholesale market through either bilateral transactions or power exchanges, which were created in the mid 1990s. For example, the Pennsylvania-New Jersey-Maryland Independent System Operator (PJM) provides a wholesale power exchange that includes many eastern states. PJM is also a regional transmission operator with the responsibility of operating several transmission systems to ensure that power is delivered from the area where it was produced to the area that purchased the power.

The structure of the electricity market can have a major influence on how power companies manage thermal efficiency. In a regulated market, the public service commission governs utility rates and can provide independent oversight of a power company's thermal performance practices. For example, a rate increase requested by a power company can be influenced by how the company is managing heat rate. A disadvantage with this approach is that the rate case would probably be decided on secondary indicators of how a company is managing thermal performance (capital improvements or staffing levels). Evaluating a company's thermal performance program based on a heat rate measurement would be challenging, given the difficulty in measuring heat rate accurately.

In a deregulated marketplace, there is no independent oversight of a power company's thermal management practices. The amount of profit a company makes on a given plant increases as the plant becomes more efficient and fuel costs are reduced for a given amount of power output. An advantage of this approach is that it provides a direct incentive for thermal efficiency improvement. However, managing and improving the thermal efficiency of a power plant, especially for a coal-fired unit, is difficult and requires a long-term investment in personnel. Unit heat rate is also difficult to measure directly and can have an error of several percentage points. Therefore, a power company could choose not to make a long-term, and somewhat risky (if the heat rate program is unsuccessful), investment to improve thermal performance. Rather, reducing production costs by eliminating personnel is easy to measure, would likely cause no measurable short-term increase in heat rate, and could provide an immediate increase in the plant's perceived value. The perceived value is relevant because power plants can be bought and sold in a deregulated market. These factors could contribute to behavior that increases a plant's value in the short term but would have significant consequences for thermal performance.

3 COMPONENTS AND CALCULATIONS OF TURBINE CYCLE HEAT RATE MONITORING SYSTEMS

Gaining the maximum benefits from on-line monitoring systems requires that they be integrated into a sustained and systematic heat rate improvement program. The staff resources and management support are equally if not more important than the technology employed. The components and monitoring techniques of a heat rate improvement program for improving overall unit heat rate are well described by the Energy Information Agency, American Society of Mechanical Engineers (ASME), and General Physics Corporation [3, 12, 13]. The benefits of improving a unit's heat rate are significant. Improved heat rate reduces fuel costs, improves unit capacity, and improves unit reliability.

Commercially available software provides tools for streamlining many of the tasks associated with a heat rate improvement program. Heat balance codes are commonly used to compute the best achievable performance of a unit, given the changes that have taken place in the unit from the initial design. On-line monitoring systems continually calculate the performance of a unit with a level of detail and uncertainty that depend on how many sensors are installed and to what extent the software is configured for performing and displaying data and calculations. When information from an on-line monitoring system is strategically integrated into the management structure of a power company, it can lead to a sustainable program that promotes timely actions for improving a plant's thermal performance.

An effective turbine cycle heat rate monitoring program requires process data and an efficient means to transform the data into actionable information. The section that follows describes calculations generally used in on-line performance monitors for transforming data into information that quantifies the thermal performance of a component. The next section then describes techniques for summarizing large amounts of thermal performance information with performance indicators.

3.1 Transforming Data to Information

Almost all power plants have numerous data that are continuously archived in historians. A primary reason for installing an on-line monitoring system is that it facilitates the transformation of these process data into higher level, actionable information. On-line monitoring systems enable engineers to track the overall performance of the turbine cycle in addition to each of the components, which include the turbines, condenser, boiler feed pumps, and feedwater heaters. In general, most calculations provided in commercially available systems are based on procedures defined in ASME Performance Test Codes (PTC) [14, 15, 16, 17]. A description of the calculations generally used for each of the components in the turbine cycle is provided in this section.

3.1.1 Turbine Cycle Heat Rate

The turbine cycle heat rate is a key indicator for evaluating the overall performance of a generating unit. Turbine cycle heat rate is computed by dividing the generator output by the total heat added to the turbine cycle. For example, for a typical reheat unit, the turbine cycle heat rate can be calculated with Equation 3-1:

$$TCHR = \frac{Q_{ms}(h_{ms} - h_{fw}) + Q_{hrh}(h_{hrh} - h_{crh})}{P_{gen}} \quad \textbf{Eq. 3-1}$$

Measurement of each of the enthalpy values in Equation 3-1 requires a pressure and temperature measurement.

When tracking the turbine cycle heat rate, the following factors should be considered:

- **Instrumentation accuracy and repeatability.** The accuracy of the instrumentation should be evaluated within the context of both the decision being made and the time period the data represent. For example, when trending turbine performance over a period of several months for determining when to schedule an overhaul, absolute accuracy is essential because small temperature changes can produce significant changes in efficiency. However, when monitoring changes in performance over a period of hours or days to detect changes in performance, it is only necessary that the instrumentation have high repeatability.
- **Testing at the same operating condition.** Turbine cycle heat rate varies with the operating conditions of the unit. The main parameters are main and reheat steam temperatures and pressures, condenser pressure, and valve position of the high pressure (HP) turbine. A recommended test point is at valves wide open (VWO) because it is easy to measure and set a unit repeatedly at this point.
- **Establishing a benchmark.** Benchmark values for turbine cycle heat rate can be obtained from various sources. Acceptance test results can provide a good starting point. However, for many units, acceptance tests were not performed. Other sources of less accurate information are design data, operating data deemed to represent the unit in a good operating condition, and acceptance tests on identical units. It is important that any changes made to the unit be reflected in the expected performance. For example, if condensers or feedwater heaters have been retubed with a material different from the original material, the benchmark performance should reflect these changes.

3.1.2 Steam Turbines

Steam turbine efficiency has a significant impact on turbine cycle heat rate. For example, a 1% decrease in HP turbine efficiency produces approximately a 0.17% increase in unit heat rate. The effect on heat rate is slightly lower for an intermediate pressure (IP) turbine and increases significantly to approximately 0.5% for the low pressure (LP) turbine. The LP turbine heat drop is large, and any energy not used by the LP turbine is rejected as waste heat in the condenser. Therefore, maintaining a low turbine cycle heat rate requires that the turbines be monitored closely, according to K. C. Cotton [18].

Because both the HP and IP turbines operate entirely with superheated steam, it is possible to calculate their enthalpy drop efficiencies with measurements of the steam inlet and exit temperatures and pressures. The enthalpy drop efficiency is computed as follows with Equation 3-2:

$$\eta = \frac{h(t_1, p_1) - h(t_2, p_2)}{h(t_1, p_1) - h(s_1, p_2)} \qquad \textbf{Eq. 3-2}$$

By trending HP and IP enthalpy drop efficiencies, performance changes can be detected. When measuring HP enthalpy drop efficiency, it is always critical to conduct the tests at the same conditions, which includes ensuring that the control valves are at the same position. VWO is an easily repeated test point that can remain constant from one outage to the next. If VWO is not attainable, it is important to ensure that the valves are at the same operating point from one test to the next. Measurement of valve stroke provides one means to accomplish this. Another means is to plot HP turbine efficiency versus load and gradually ramp unit load. A valve position will be the point at which the HP enthalpy drop efficiency reaches a local minimum.

LP steam turbine efficiency is not easily measured because the steam leaving the turbine is wet. An accurate, on-line steam wetness measurement is currently neither commercially available nor is it easily implemented. Because of these difficulties, a heat balance must be performed by summing all the energy flowing in and out the turbines. A representative heat balance for a regenerative cycle is as follows in Equation 3-3:

$$Q_{ms}(h_{ms} - h_{fw}) + Q_{hrh}(h_{hrh} - h_{crh}) - \sum Q_{ext} h_{ext} - (P_{gen} + P_{loss}) - Q_{exh} h_{ueep} = 0 \qquad \textbf{Eq. 3-3}$$

The enthalpy of the exhaust steam at the used energy end point state can be computed from Equation 3-3 because all other terms can be determined with temperature, pressure, flow, and power measurements on the turbine cycle. The enthalpy at the LP turbine exit (expansion line end point) can then be computed by adding the losses that occur between the expansion line and used energy end points. These losses are typically computed from curves provided by the turbine manufacturer. After the enthalpy at the expansion line end point has been determined, LP turbine efficiency can be computed, as specified in Equation 3-3. Obtaining an accurate trend of LP steam turbine efficiency requires a much more significant effort than for the HP and IP turbines because of the extensive instrumentation that is required to determine all necessary flows and enthalpies.

3.1.3 Condensers

A primary factor that affects the efficiency of the Rankine steam cycle is the temperature at which the waste heat is rejected to the environment. The waste heat is rejected to the environment by the condenser, and any performance deficiencies in the condenser have a significant impact on the overall turbine cycle heat rate. One of the largest heat rate deviations in turbine cycle heat rate is produced by fouling of the condenser tubes, which causes the condenser pressure to increase. For typical condenser operation, an increase in condenser pressure produces an increase in turbine cycle heat rate.

An increase in condenser pressure can be caused by several factors, such as high condenser air in-leakage, condenser tube microfouling, and condenser macrofouling. High condenser air in-leakage is generally caused by vacuum leaks in the condenser. This can be detected by trending the flow rate of the air ejector pump. Condenser microfouling is caused by biological growth or silt that adheres to the water side of the condenser tubes, thereby impeding the heat transfer. This section presents calculations for evaluating microfouling. Macrofouling is caused by larger objects (mussels, weeds, or fish) that adhere to the condenser tubesheet face and restrict the water flow rate through the condenser. Methods for computing macrofouling are described in the paragraphs following the microfouling description.

Computing condenser microfouling requires that the actual and expected conductance of the condenser tubes be computed. Measurements from on-line systems in conjunction with basic heat transfer relations provide the necessary input to compute condenser performance.

The actual conductance of a condenser tube bundle can be determined in several ways, depending on which measurements are available. The first parameter required is the condenser duty, which is the waste heat load that the condenser is rejecting to the cooling water. One means for determining condenser duty is by performing a heat balance on the turbine cycle. The primary heat inputs are provided by the main and reheat steam flows. The rate of energy removed from the cycle includes the shaft power supplied to the generator, the energy in the flow returning to the boiler, and the heat rejected by the condenser. All energy inputs and outputs can be readily measured, which makes it possible to compute the condenser duty with a heat balance, as shown in Equation 3-4.

$$q_{cd} = Q_{ms}(h_{ms} - h_{fw}) + Q_{hrh}(h_{hrh} - h_{crh}) + P_{bfp} - P_{gen} - P_{loss} - Q_{att}h_{att} \qquad \textbf{Eq. 3-4}$$

Each of the terms on the right side of the equation can be measured with temperature, pressure, flow, and power measurements. A problem with this approach is that several measured parameters are required, some of which might not be available for a typical unit.

An alternate approach for determining condenser duty is with a direct measurement of condenser cooling water (CCW) flow rate, CCW inlet temperature, and CCW exit temperature. Condenser duty is then computed with Equation 3-5.

$$q_{cd} = Q_{ccw}c_p(t_2 - t_1) \qquad \textbf{Eq. 3-5}$$

A fundamental problem with measuring condenser duty with this approach is that the water leaving the condenser is thermally stratified. Measuring the CCW exit temperature near the condenser waterbox requires a grid of sensors to obtain an accurate average exit temperature measurement. An alternate approach (if access can be gained to the CCW pipe) is to measure the temperature at points farther downstream from the condenser exit to ensure that the CCW flow is mixed.

Once condenser duty has been determined, the actual conductance of the tube bundle is computed with Equation 3-6:

$$U_{act} = \frac{q_{cd}}{A_o \Delta t_{lm}} \qquad \textbf{Eq. 3-6}$$

Where Δt_{lm} is the log mean temperature difference and is defined by Equation 3-7.

$$\Delta t_{lm} = \frac{(t_2 - t_1)}{\ln\left(\frac{t_s - t_1}{t_s - t_2}\right)} \qquad \textbf{Eq. 3-7}$$

The theoretical conductance can be computed with two different techniques. A commonly used method is found in a standard published by the Heat Exchange Institute (HEI), which provides an empirical equation to estimate the theoretical conductance of a condenser tube bundle [19]. Using this approach, the theoretical conductance is computed with Equation 3-8:

$$U_{th} = C\sqrt{V_{tube}} \qquad \textbf{Eq. 3-8}$$

An advantage of the HEI approach is that it is easily applied. However, it is an empirical relation intended for use as a design standard and is generally not as accurate as using first principles relations.

An alternate approach is to use the resistance-summation method, which is a set of equations based on fundamental heat transfer principles. With this approach, as described by Incropera and DeWitt [20], the total heat transfer resistance is computed by summing the individual heat transfer resistances, the inside boundary layer, the inside fouling, the condenser tube, the outside boundary layer, and the outside fouling. The total resistance is computed with Equation 3-9.

$$R_{Total} = \frac{A_o}{A_i f_i} + \frac{A_o \ln \frac{r_o}{r_i}}{2\pi kl} + \frac{1}{f_o} + R_w + R_s \qquad \textbf{Eq. 3-9}$$

The theoretical conductance is then computed by taking the reciprocal of the total heat transfer resistance.

The actual and theoretical conductance of a condenser tube bundle can be used to compute performance indicators of a condenser. A common measure is to ratio the two conductances and compute a percentage to calculate an apparent cleanliness factor. Another common measure is the tube-side microfouling resistance. If one assumes that the steam-side conditions are not changing, the water-side fouling resistance is computed by Equation 3-10:

$$R_w = \frac{1}{U_{act}} - \frac{1}{U_{th}} \qquad \textbf{Eq. 3-10}$$

Condenser performance is often adversely affected when debris in the CCW flow adheres to the tube sheet face and reduces condenser flow rate. Typical debris can consist of weeds, sticks, fish, and mussels. With the appropriate measurements, this type of fouling can be easily differentiated from other factors, as explained by Almquist and March [21]. The required parameters consist of differential pressure measurements from the inlet to the exit waterboxes and from the exit waterboxes to the exit CCW water pipes. A ratio of these measurements provides a measure of macrofouling. An additional advantage to this approach is that measurement of the differential pressure from the outlet waterbox to the outlet water pipe provides a relative measurement of the CCW flow rate. As the flow accelerates as a result of the constriction from the exit waterbox to the exit water pipe, a differential pressure is produced that is proportional to flow rate. This is the same principle used in venturi, orifice, and nozzle flowmeters. If this method is used, it is important that the geometry of the flow path near the pressure measurements in the exit water pipe remains constant. For example, this flow measurement would be adversely affected if the pressure measurements were obtained near cooling water valves that changed position during routine condenser operation. This method can be calibrated with an absolute flow measurement technique (for example, a dye dilution test) to provide an absolute CCW flow measurement.

3.1.4 Feedwater Heaters

Most generating units have a string of both HP and LP feedwater heaters that preheat the feedwater using the heat available in turbine extraction steam. There are three zones that comprise feedwater heaters, a desuperheating zone, a condensing zone, and a drain cooler zone. The desuperheating section contains superheated steam; the condensing zone contains saturated steam; the drain cooler zone contains liquid water in contact with the tubes. A given feedwater heater might contain all three zones or contain only one or two of the zones.

The two most commonly used measures of feedwater heater performance are the terminal temperature difference (TTD) and the drain cooler approach (DCA). The terminal temperature defined in Equation 3-11 is the difference between the saturation temperature of the extraction steam and the temperature of the feedwater exiting the heater.

$$TTD = t_{sat} - t_{fwex} \qquad \textbf{Eq. 3-11}$$

For feedwater heaters with desuperheating sections, it is common to achieve a negative terminal temperature difference.

The drain cooler approach temperature defined in Equation 3-12 is the difference between the temperature of the water exiting the drain cooler and the temperature of the feedwater entering the heater.

$$DCA = t_{dcex} - t_{fwin} \quad \textbf{Eq. 3-12}$$

Expected values for both the TTDs and DCAs are typically obtained from heat balance diagrams because they are readily available and easily configured in an on-line monitoring program

A more rigorous approach is to use the manufacturer design data in conjunction with basic heat transfer relationships to compute expected TTDs and DCAs. These calculations are outlined in detail in ASME PTC 12.1 [16]. The detailed design information required from the manufacturer is as follows:

- Heat transfer surface areas for each heater zone
- Steam- and water-side fouling resistances
- Steam- and water-side film resistances
- Expected heat transfer rate for each zone
- Expected inlet and exit pressures, temperatures, and flows for the extraction steam, feedwater flow, and drain flow

Representative measured data are the following:

- Inlet steam temperature and pressure
- Feedwater inlet and exit temperatures and pressure
- Drain flow temperature and flow rate
- Shell side pressure

PTC 12.1 outlines a calculation procedure to compute expected TTDs, DCAs, and pressure drops for the feedwater heater for comparison with the actual measurements.

3.1.5 Pumps

The three most important pumps in the turbine cycle are the boiler feedpump, the condensate pump, and the condenser circulating water pump. Both the boiler feedpump and condensate pump have a direct role in the thermodynamic efficiency of the turbine cycle because they increase the enthalpy of the feedwater. However, the enthalpy rise is very small relative to other components. Therefore, inefficiencies in these pumps play a very minor role in affecting the turbine cycle heat rate. Reliability is generally of greater concern than efficiency for these pumps. Reliability assessment typically requires mechanical performance data, such as bearing vibration and temperature data.

Determining a pump efficiency requires that the inlet and outlet energy of the pump be measured. The energy delivered by a pump per unit mass of fluid can be determined from the inlet and exit head for the fluid as shown in Equation 3-13:

$$H = (z_2 - z_1) + (p_2 v_2 - p_1 v_1) + (\frac{1}{2} g)\,(V_2^2 - V_1^2) \qquad \textbf{Eq. 3-13}$$

In many cases the last term in Equation 3-13 is zero because the inlet and outlet velocities are equal.

The power output of the pump can be computed from Equation 3-14. If the power input is measured, the pump efficiency can be computed with Equation 3-15.

$$P_{out} = KHQ \qquad \textbf{Eq. 3-14}$$

$$\eta_p = \frac{P_{out}}{P_{in}} \qquad \textbf{Eq. 3-15}$$

Measuring the power input to motor-driven pumps requires that the electrical power to the motor be measured. For turbine-driven boiler feed pumps, the inlet and exit enthalpies must be determined in addition to the steam flow rate. In most cases the steam is saturated, which requires obtaining a steam wetness measurement. Because of the complexity involved in performing this measurement, the boiler feedpump turbine efficiency is rarely measured.

3.2 Transforming Information to Business Intelligence

The previous section provided a general overview of transforming measured process data to specific information about equipment performance. This achieves a primary goal for performance monitoring, which is the transformation of data into actionable information. For example, trending a turbine’s efficiency established from enthalpy drop tests could show decreased performance that would lead a company to a decision to refurbish the turbine to improve its efficiency.

Although displays of trend plots, schematics of equipment showing the equipment performance, and automated alarms provide value, they do not efficiently summarize how a company is performing with respect to specific business objectives. Calculation procedures must exist that accurately quantify performance in terms of easily understood business parameters (for example, revenue and energy). These can provide information at the system, plant, and individual unit level. Metrics summarizing thermal performance can be created that meet these objectives.

The idea of a performance metric is not new. Most power companies use metrics to provide measures of how the company is progressing to meet specific objectives, for example, the forced outage rate of a unit. However, thermal performance metrics do not usually carry the priority of other metrics. The following section describes the overall features of performance metrics and how they could be implemented to summarize performance information.

3.2.1 General Features of Performance Metrics

Performance metrics for improved thermal performance must contain the following features to be effective:

- Clear line of sight between actions and results
- Capacity to promote the correct actions
- Ability to be viewed at any appropriate level of detail
- Accuracy and simplicity

The first objective of a performance metric is that it provides a clear line of sight between actions and their effects on the business objectives. A performance metric tracking extra fuel costs produced by poor condenser performance is one example. As the condenser becomes fouled, the fuel costs increase for a given load. When the condenser is cleaned, the extra fuel costs are significantly reduced. Evaluating this metric over any given time period would provide a clear indication of whether timely actions were being performed to keep condensers clean and operating efficiently.

The second objective of a performance metric is that it promotes the correct actions. When creating performance metrics, it is essential to periodically reevaluate them to ensure that they promote the correct actions. One example is the use of main steam throttle temperature as a controllable loss indicator. It is clear that maintaining the main steam temperature at its design value will minimize the controllable losses. However, the indicator must also include penalties for excursions above the design value. Although these excursions improve thermal efficiency, they can have highly adverse impacts on boiler reliability. In addition, an effective indicator ensures that the overall performance of the unit is accounted for, which includes contributions from the boiler and effect on emissions.

Incomplete process data can lead to ineffective performance metrics. For example, one anecdote about performance metrics involved a plant tracking unit heat rate with the input-output method. The mass of the fuel was continually measured by coal scales, but the fuel moisture was not accurately measured. Plant personnel manually entered an estimate of the fuel moisture content. As the moisture content of the fuel increased, the apparent amount of fuel burned was reduced because the thermal content was reported on a unit mass basis. The net effect was that the apparent heat rate of the unit could appear to be significantly improved by simply adjusting the moisture content.

A third feature of performance metrics is that they mirror the business hierarchy. For a power company tracking turbine cycle heat rate, this implies being able to view them at the highest level and to quickly drill down to find the most significant heat rate deviations. Figure 3-1 presents an example of a power company's hierarchy.

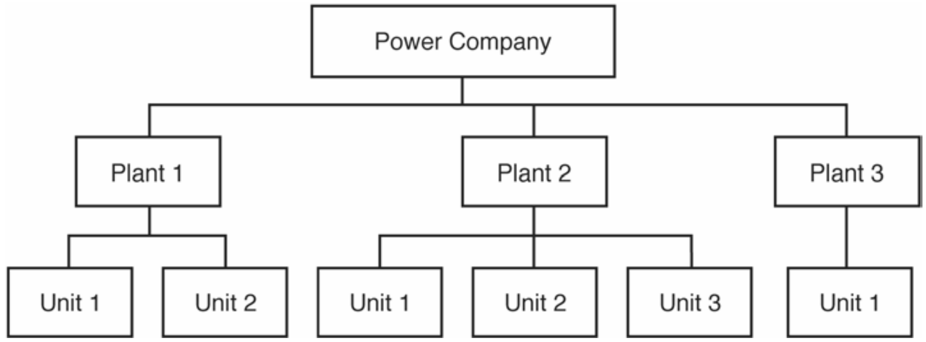

Figure 3-1
Top Three Levels of an Example Performance Metric Hierarchy

Figure 3-2 shows how this structure could extend to lower levels, with increasing levels of detail occurring as one drills down to lower levels.

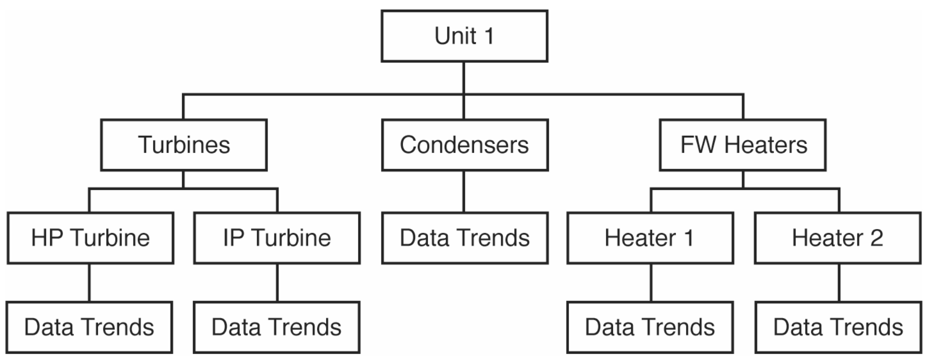

Figure 3-2
Additional Levels of a Performance Metric Hierarchy

Figures 3-1 and 3-2 illustrate a generic structure for a system of performance metrics. All boxes represent scalar information except the last level, which contains trends. With data structured in this form, a performance engineer can quickly drill down to items requiring the most attention. For example, a performance metric of interest could track the extra fuel costs that result from thermal inefficiencies of the turbine cycle. The system loss would be the first information that would be viewed. If it exceeds a given value, the performance engineer would drill down and examine the metric on a plant basis. If any plant exceeds a given value, the engineer would evaluate the losses on a unit basis. The engineer could then view the data on a component basis. The component producing the highest loss would then be examined in detail by observing trend plots and other appropriate presentations of the data. By examining information in this structure, a performance engineer's time is optimized. Most attention is given to the components producing the highest revenue losses.

Other desired features of performance metrics are that they be easy to understand and accurate. Obvious parameters for consideration in thermal performance metrics are revenue or energy. It is also essential that the metrics are accurate with respect to a utility's financial objectives. For example, if a company's business objective is to reduce the fuel cost for a 500-MW unit by $500,000 per year, the unit heat rate measurement must be precise to within 1%.

4
COMMERCIALLY AVAILABLE SOFTWARE FOR ON-LINE TURBINE CYCLE PERFORMANCE MONITORING

On-line heat rate monitoring has been a commercially available technology in the fossil power industry for nearly 20 years. Although some of its early products were limited to text-based output that ran on high-end computers, the products available today have sophisticated graphical user interfaces and run on standard PCs.

There are several commercially available software packages specifically designed for on-line monitoring of Rankine-cycle power plants. This section presents a general overview of what some of the more common packages provide. A more detailed description of these commercially available products follows.

4.1 Common Features

On-line monitoring systems provide the following basic functions:

- Retrieving data from historians
- Computing equipment performance
- Presenting the data on schematics and in graphical format

4.1.1 Data Acquisition

Most plants have a great deal of continuous process data. Units with DCSs commonly contain a computer that archives all measurements. Many utilities have also installed commercially available historians that integrate data from many sources. Standard drivers, for example, object linking and embedding for process control (OPC), enable most on-line monitoring systems to readily access the data. Most companies will also develop custom interfaces if a plant archives data in a custom historian or file format.

On-line monitoring systems provide tools for connecting with the data sources to identify the specific points that are to be continually read when the system is operating. A measurement point used in a monitoring system is accessed with a unique alpha-numeric string that is generally referred to as a *tag.* A significant amount of labor can be required to identify and link the tags in the historian to data inputs to a monitoring system. Most packages provide tools for streamlining this task, which are further detailed in the system descriptions.

4.1.2 Computing Equipment Performance

The previous chapter provided a background of the calculations that are required for computing equipment performance. Because there are many commonalities among coal-fired units, the calculations from unit to unit are similar, and many of them follow the procedures recommended by ASME performance test codes. The commercially available systems contain libraries of calculations for computing the component performances. In addition, some units might have features that require calculations not specifically covered in existing calculation libraries. Therefore, almost all commercially available systems provide means for a user to create custom calculations.

All commercially available packages provide a steam and water properties library that is required to compute the thermodynamic performance of components. These properties are usually based on either the 1969 or 1997 versions of the ASME Steam Tables.

4.1.3 Displays, Reports, and Alarms

A third feature common in a commercially available system is a highly configurable user interface. The graphical user interface might be different for any given unit, plant, or power company. This requires that the commercially available system provides a toolkit of objects for creating a customized user interface rather than predetermined, standard graphic screens. This toolkit generally consists of the following objects:

- Graphics of fossil plant components (turbines and condensers)
- Trend and x-y plots
- Text boxes for displaying user-defined labels
- Data boxes for displaying real-time data values
- User configurable links (buttons and hypertext) for controlling the navigation through each of the views

In general, commercially available systems also provide tools to create automated reports and tools to provide automated alarms.

4.1.4 Process for Researching Commercial Offerings

Information regarding specific monitoring packages was obtained through several means. In some cases interviews were conducted with a representative of the vendor, and in other cases interviews were conducted with customers of a particular vendor. Some of those interviewed chose to submit additional supporting documentation. Another source of information was obtained from vendor web sites and previous surveys.

Some vendors supplied more information than others, which has resulted in variations in the length of the descriptions. However, the level of detail in the descriptions is not intended to reflect on the quality of the systems. The primary purpose of this section is to give readers a general overview of capabilities in current commercially available systems. Interested readers are strongly encouraged to further discuss the details of systems with the vendors.

Five different commercially available systems are presented. The descriptions are in alphabetical order, based on the name of the product.

4.2 EtaPRO – General Physics

4.2.1 Data Acquisition

The EtaPRO System is configured for data acquisition using client tools and does not require source code programming. The EtaPRO Server acquires real-time data directly from an OSI Soft PI System or OPC data source and performs real-time calculations. The system can use the customer's existing PI System, or General Physics can provide a custom solution that embeds OSI soft technology in the EtaPRO Server. The EtaPRO System can acquire process data from external OPC-compliant data sources and can also serve as an OPC data source itself.

EtaPRO provides tools to streamline managing data tags with PI. Some of the features in PI are integrated directly into the EtaPRO System. For example, EtaPRO provides an interface to the PI Software Development Kit (PI-SDK) for managing PI tags. EtaPRO also supports exporting pre-configured tags to Excel for bulk creation of PI tags when systems are being developed.

The EtaPRO System supports data validation by comparing selected points to an expected value and substitutes this value when the difference between the data and reference value exceeds a threshold value. In the event of a substitution, the value is highlighted by screen color and formatting changes in the data display. Further, calculations that depend on the faulty data points also change appearance. Whenever a point contains a default value or a calculated value contains a default point, an alarm is logged to the historical database to flag these events.

4.2.2 Calculations

EtaPRO provides the capability for a power company to configure custom calculations or use calculations from an extensive library. The library includes over 500 performance calculations, such as steam and gas turbines, fossil fuel boilers, heat recovery steam generators (fired and unfired), air heaters, open and closed feedwater heaters, single- and multi-pressure condensers, cooling towers, and pumps (centrifugal and axial). Calculations are linked to the appropriate data points with menus and data entry forms. The detailed setup information is stored in a Structured Query Language (SQL) relational database.

EtaPRO can be configured to run in parallel with VirtualPlant, a thermodynamic model of the system, for Rankine-cycle units. VirtualPlant applies first principle models of major components, such as steam turbines, condensers, and feedwater heaters, to predict plant performance over a wide range of ambient and operating conditions. A primary use for these calculations is to evaluate alternate operating scenarios and to compute benchmark values for changes in cycle configuration and ambient operating conditions.

VirtualPlant Models and EtaPRO can share data, thereby providing the ability to use real-time data with VirtualPlant or to use modeled data with EtaPRO. For example, a model running on a user's desktop computer can connect directly to the EtaPRO System to initialize selected inputs, calculate values, and archive results. Alternatively, EtaPRO can acquire values from a VirtualPlant model running on a server.

The EtaPRO System provides the framework to calculate actual, corrected, expected, and design values for selected key performance indicators (KPIs). The actual value is the current process value; the corrected value is the parameter adjusted to applicable reference conditions; and the expected (best achievable) is the value the equipment should be capable of achieving given current ambient, operating, and equipment conditions. The design is the manufacturer's estimated value at current operating conditions of the unit, based on the steam or fuel flow as reference (these will be assignable by the user).

EtaPRO supports both English and SI units or a combination thereof. All library calculations can accept inputs and produce outputs in the desired engineering units, and the conversions are automatically performed.

4.2.3 Displays, Reports, and Alarms

A set of heat balance diagrams is included in the EtaPRO installation along with graphical displays of boilers that can be used to create representative images for many common configurations. A screen builder (EPClient) is supplied with EtaPRO that provides a graphical user interface to build new or modify existing screens. Tabular values on screens are linked to graphical displays. Therefore, a user can easily switch from a graphical to tabular display by clicking on the appropriate area of the screen. Figures 4-1 and 4-2 are two examples of screens used with EtaPRO. VirtualPlant also provides a graphical interface for creating and editing models. Figure 4-3 presents an example of a model created with VirtualPlant.

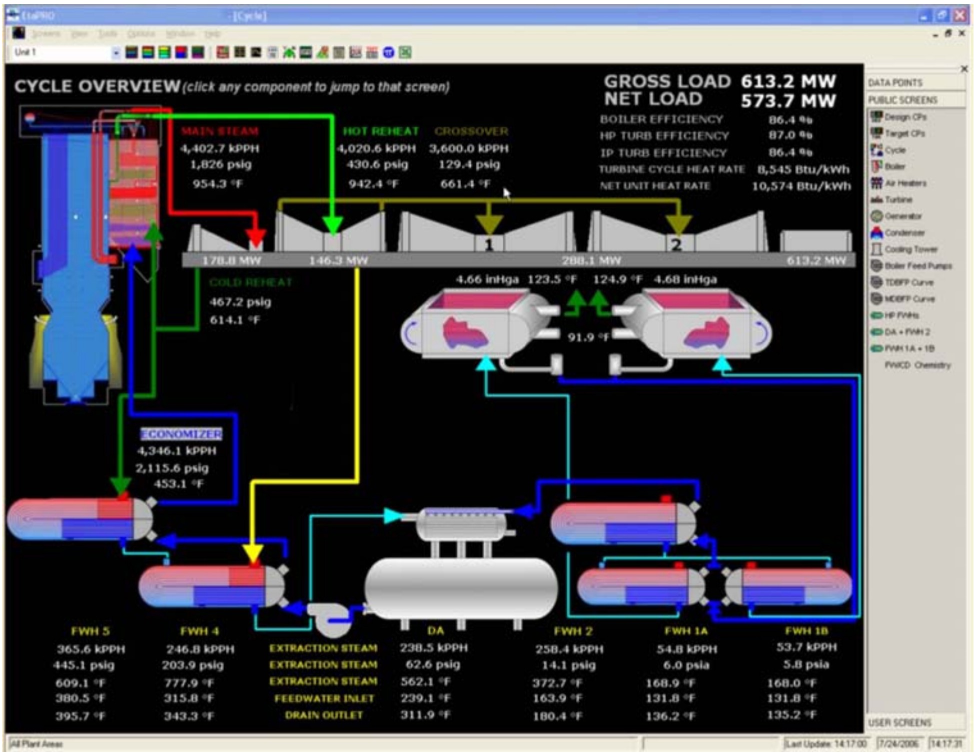

Figure 4-1
Example Turbine Cycle Overview Screen in EtaPRO
Courtesy of General Physics

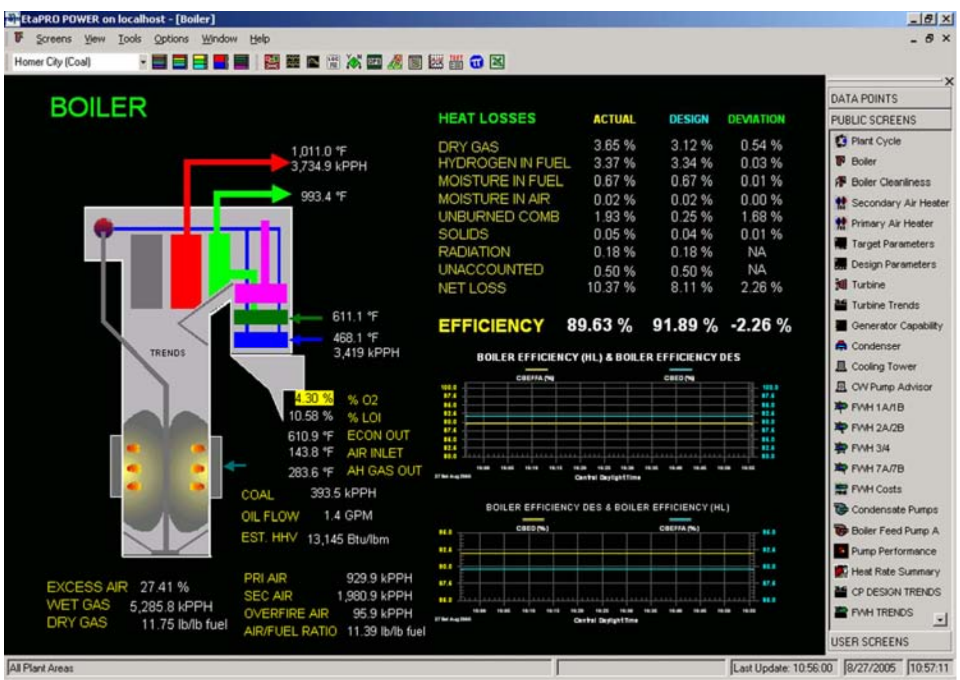

Figure 4-2
Example of a Boiler Performance Screen in EtaPRO
Courtesy of General Physics

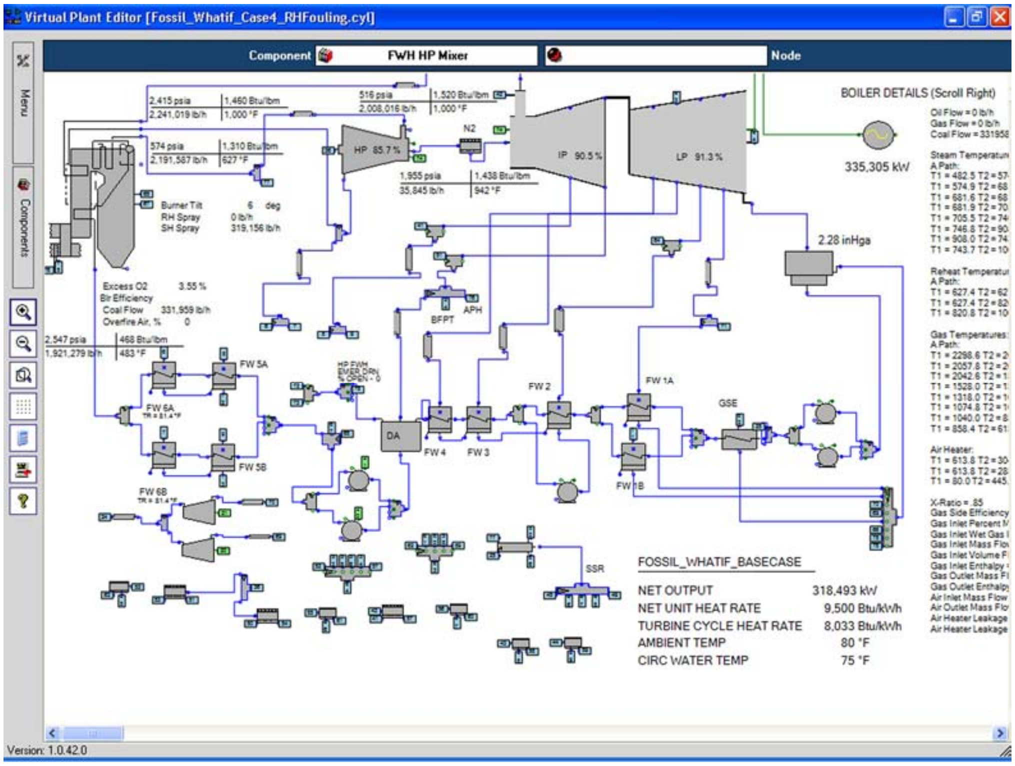

Figure 4-3
Example of a VirtualPlant Screen
Courtesy of General Physics

The controllable parameters screen is one of the most important screens. The EtaPRO System provides a tabular listing display of the operator controllable parameters with horizontal bars indicating graphically the heat rate deviation of each. These turbine cycle parameters typically consist of steam temperatures and pressures, final feedwater temperature, and condenser pressure. Two different benchmark values that include the operating and design targets are displayed for each controllable parameter. The operating target represents the condition for the unit with equipment in the current condition and current ambient conditions, and the parameter is set to the desired value. The design target also corrects for current ambient conditions but assumes the equipment is operating at design performance.

The EtaPRO System comes equipped with an Excel-based report writer (EPReporter) that has direct access to the PI System. The report writer provides access to historical and current process data snapshots, averages, maximums, minimums, and quality indicators for the user's defined dates and times. The report generator can create reports on demand or on a scheduled basis as specified by the user. EPReporter can be configured to automatically print reports on any printer, written to file, or e-mailed as an Excel attachment. Once created, these reports are stand-alone and do not require a connection to the EtaPRO System.

The EtaPRO System client software provides three electronic logs: an event log, a data log, and an availability log. The event log allows the user to record text entries describing an occurrence in the plant. Users can then query these entries by data and time and cross-reference these entries when viewing a trend plot. The data log provides a means for entering manual data into the EtaPRO System. The availability log provides a mechanism to record load-curtailing events, including a text description, North Electric Reliability Council (NERC) cause code, and an event type and derating. This information is stored in the PI System, from which an Excel report can be created for reporting unit availability statistics.

Diagnostic flowcharts are available to assist operators and engineers in diagnosing and resolving performance anomalies. Each diagnostic is customized to match the particular plant's process and equipment design as applicable. The following default set of flowcharts is included with EtaPRO:

- Low throttle pressure
- Low throttle steam temperature
- Low hot reheat steam temperature
- High condenser pressure
- High air heater exit gas temperature
- High superheater spray flow
- High reheat spray flow
- Hotwell sub cooling

All diagnostic flowcharts can be edited and customized by the user.

4.2.4 Additional Information

Additional information can be obtained on the EtaPRO web site [22].

4.3 Etracker – Encotech, Inc.

4.3.1 Data Collection

Etracker is a performance monitoring system, and the data historian used is PI in most applications.

4.3.2 Calculations

On-line calculations are made every five minutes using input data from a data historian. Most installations use between 75 and 100 inputs.

All quantities computed by Etracker are based on a first-principles basis. Components in the model, such as heaters, are described by their physical dimensions. Etracker does not use correction curves. The turbine is monitored on a stage-by-stage basis using a velocity diagram approach.

In addition to operating in an on-line mode, Etracker was designed and can run as a diagnostic tool. By manipulating program inputs, the user can perform what-if scenarios to evaluate unit operation under various conditions. Models typically take about one week to build, and they are entirely constructed by the vendor.

4.3.3 Displays and Reports

The standard output from the Etracker program is presented as a variation from the expected value. The baseline performance is based on user-provided data. The model that is presented to the customer is that of a new and clean unit.

Figures 4-4 and 4-5 demonstrate how Etracker can be used to troubleshoot a problem. The turbine cycle heat rate deviation, shown in blue, is relatively constant and then drops shortly after the time of 12/26 12:00. The generator output deviation is relatively steady and then displays a step increase that occurs when the turbine cycle heat rate deviation drops. The step changes in both the turbine cycle heat rate deviation and generator output deviation are anomalies that can be examined closer with an operating degradation profile. This profile appears on a single page as a bar graph and shows all parameters that have changed significantly (usually limited to parameters that change more than 0.5%). Figure 4-5 presents the operating degradation profile for this case. The six blue columns on the left, the larger parameter changes for this case, are all changes in inlet and extraction pressures associated with the LP turbine. The incident does not appear to involve anything associated with the HP or the IP turbine. The change was ultimately traced to a flow control valve for hot water, extracted from the boiler feed pump inlet to a glycol heater. It had been stuck in the fully opened position, bypassing significant quantities of hot water to the condenser. When it was finally closed, the heat rate improved, as illustrated on the Encotech web site [23].

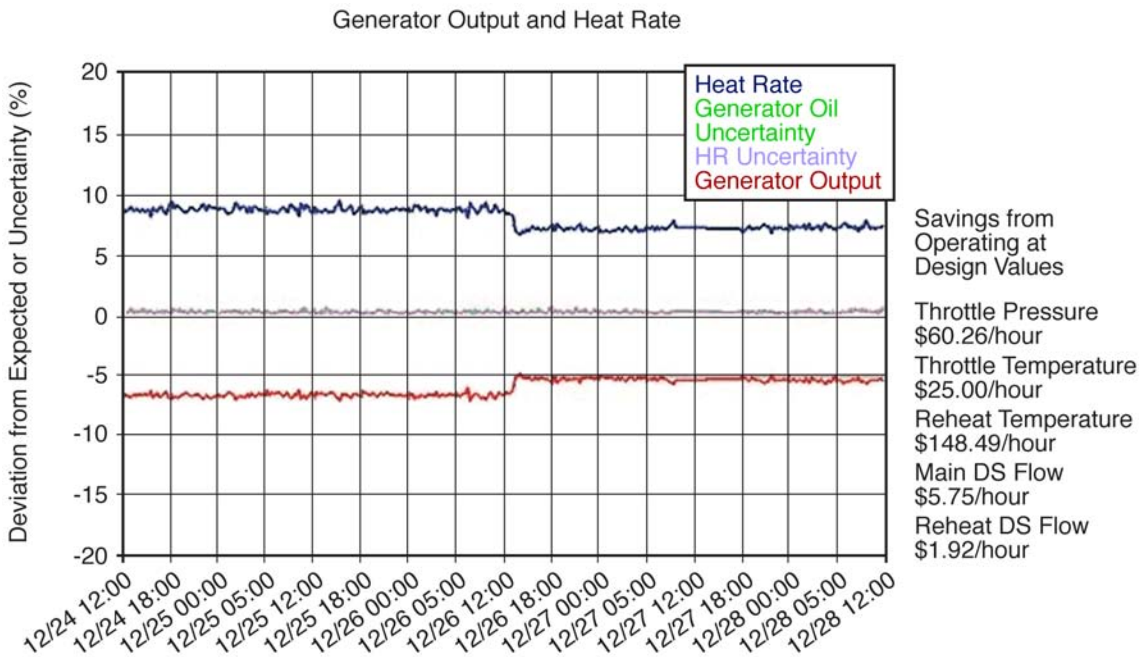

Figure 4-4
Example of an Etracker Diagnostic Screen
Courtesy of Encotech

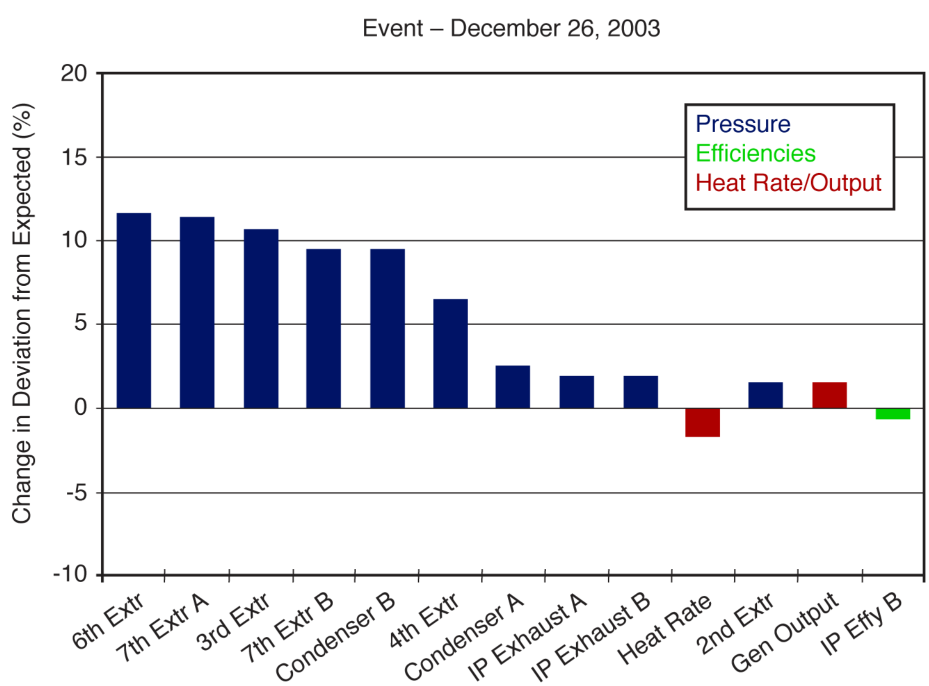

Figure 4-5
Example of an Operating Degradation Profile from Etracker
Courtesy of Encotech

4.3.4 Additional Information

Additional information can be obtained on the encotech web site [23].

4.4 PerformanceOpt - Black and Veatch/NeuCo

4.4.1 Data Acquisition

PerformanceOpt contains ProcessLink, which was developed by NeuCo as its enterprise optimization platform. ProcessLink provides tools to connect to plant data. Many interfaces are supported, including industry standards such as OPC. The ProcessLink data engine also provides data filtering, validation, and visualization tools. The data validation system creates flags for each suspect data element and highlights potential instrumentation issues.

Calculations created by PerformanceOpt are stored in a ProcessLink database. Therefore, companies with a fixed number of tags available in their data historians will not have to purchase additional tags for PerformanceOpt. ProcessLink also supports calculation on demand, which enables users to recalculate all appropriate values when a key value changes. For example, in some tools, performance calculations are completed with estimated fuel properties. Actual fuel properties are not known until the laboratory performs and reports the fuel analysis, which can have a lag time of a few weeks. With ProcessLink, a user could update the estimated fuel analysis with the actual fuel analysis, and all archived calculations would be automatically updated.

4.4.2 Calculations

A first-principles model of the Rankine cycle is integrated within PerformanceOpt. The model is configured with several interconnected flowsheets that represent the plant equipment, their interconnecting streams, the source streams, and the products. This model is used for both real-time monitoring and predictive diagnostic simulations.

The model runs continuously at the same time the PerformanceOpt model is running in either a real-time monitoring mode or in a predictive mode. In monitoring mode, actual unit performance is calculated; in predictive mode, it calculates the achievable unit performance as well as the efficiency and capacity impacts associated with the deviations between actual and achievable unit performance.

Differences between actual process values (from the monitoring mode calculations) and achievable process values (from the predictive simulations) are continually computed. When the difference exceeds a preconfigured threshold value, PerformanceOpt triggers an event. To prevent triggering many false alarms, a series of rules can be programmed that govern when an alarm is triggered from an event. As an example of a rule set, the unit must be at full load, in steady-state operation, and the event has to occur multiple times before an alarm is triggered.

After an alarm is triggered, PerformanceOpt carries out an analysis in an attempt to resolve the performance deficiency. This analysis is done either automatically or manually, depending on the problem. If manual diagnostics are necessary, NeuCo's MaintenanceOpt can be used. MaintenanceOpt contains a knowledge base of diagnostic rules for determining the root cause of a problem. MaintenanceOpt provides guidance and relevant data to differentiate among possible causes of the problem. PeformanceOpt also provides the framework to differentiate between problems that can be immediately eliminated versus those that require a unit outage.

4.4.3 Displays, Reports, and Alarms

Examples of the PerformanceOpt controllable loss screen and boiler performance screen are presented in Figures 4-6 and 4-7, respectively. Figures 4-8 and 4-9 show two screens displaying the automated alarming and maintenance recommendations provided by PerformanceOpt. Figure 4-8 shows the first-level diagnostics for which all relevant data are displayed. Figure 4-9 shows the diagnostics that are generated for this problem by MaintenanceOpt.

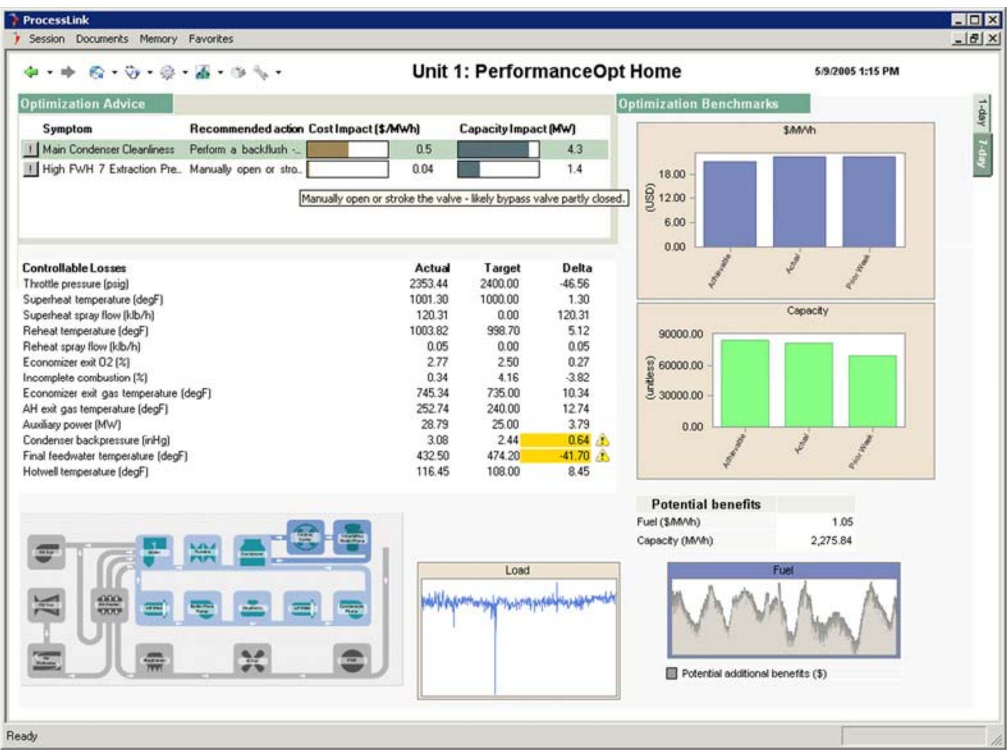

Figure 4-6
Example of a PerformanceOpt Controllable Loss Screen
Courtesy of Black and Veatch/NeuCo

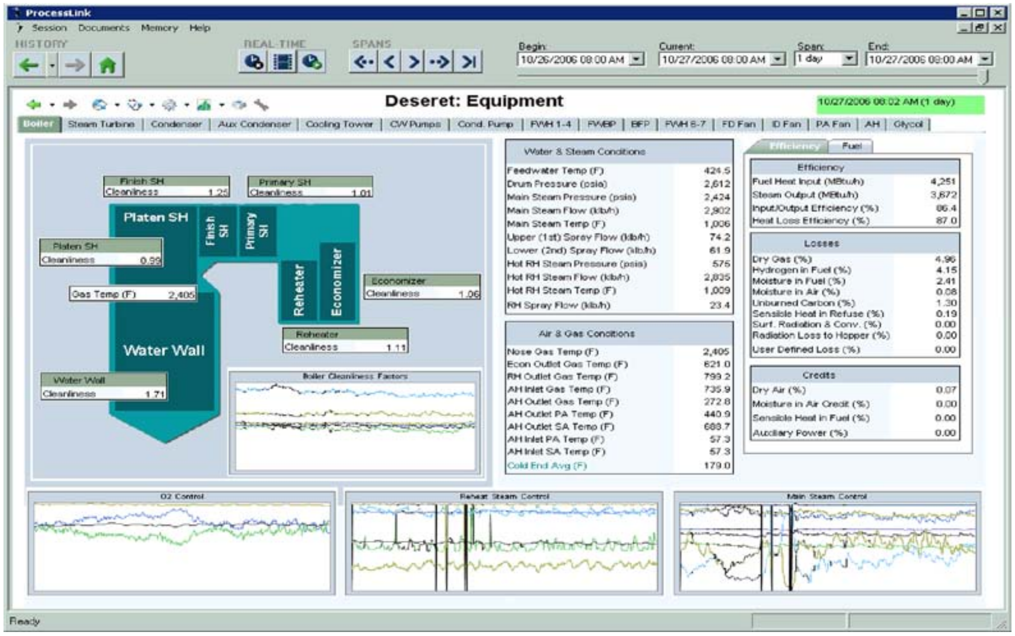

Figure 4-7
Example of a PerformanceOpt Boiler Performance Screen
Courtesy of Black and Veatch/NeuCo

4.4.5 Additional Information

Additional information can be obtained on the Black and Veatch web site [24].

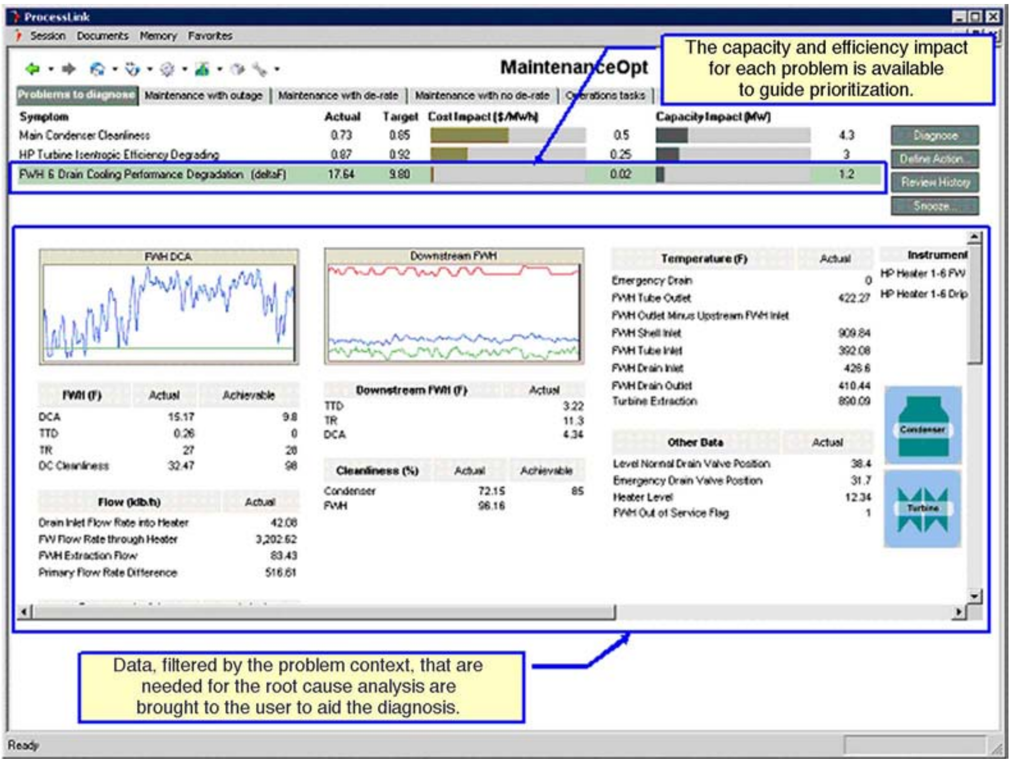

Figure 4-8
Example of Graphical Output from a PerformanceOpt and MaintenanceOpt Diagnostic Screen Showing Relevant Data
Courtesy of Black and Veatch/NeuCo

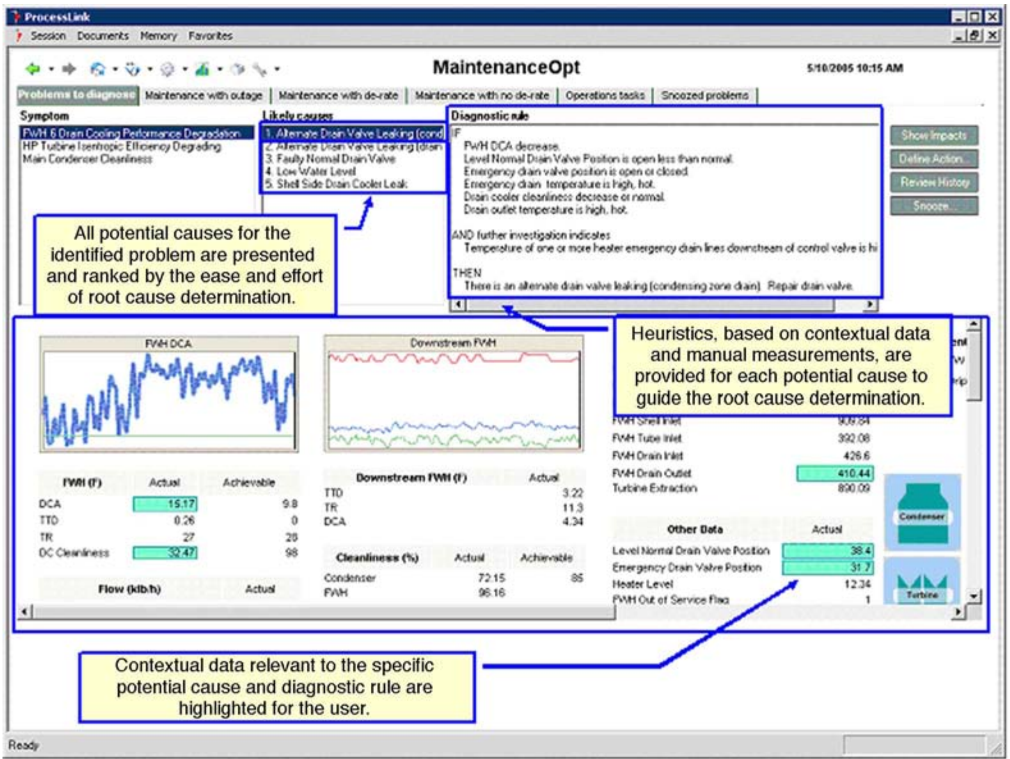

Figure 4-9
Example of a Graphical Output from PerformanceOpt/MaintenanceOpt Diagnostic Screen Showing Relevant Data, Potential Causes, and Heuristics for Problem Diagnosis
Courtesy of Black and Veatch/NeuCo

4.5 PMAX – Scientech

4.5.1 Data Acquisition

PMAX is not dependent on third-party databases and includes an internal 64,000-point database. This database receives incoming points, stores validated and time-smoothed results, and stores intermediate and final performance results.

The PMAX archive system provides a set of tools and utilities for users to design and implement their own custom data historian system. Duration, frequency, event-driven characteristics, and file type are all configurable by the user.

The PMAX software includes a module called the Input Validation Module (IVM). The IVM continuously computes the differences between incoming data and their expected values. If a difference exceeds a threshold value, IVM can be configured to label the data as questionable and to substitute a default value. The substituted value is then used in all dependent calculations. All validation events are stored in a security-protected file that contains real-time and historical information.

PMAX includes a set of circular buffers that store data for various periods, including weekly, monthly, every 180 days, and so on. These buffers enable rapid data retrieval and minimize processing time when trends are displayed.

4.5.2 Calculations

PMAX provides several standard functions for computing the performance of any component in the turbine cycle, such as steam turbines, condensers, feedwater heaters, boiler feedpumps, and controllable losses. A user configures calculations by specifying the required points for the calculation. The points can either be entered as constant values or be obtained from the real-time data set that includes both measured and computed values.

PMAX provides the framework to compute heat rate deviations when data and calculations deviate from target values. The deviations are typically presented in terms of heat rate, load penalty, and the associated costs.

The PMAX system is designed with a modular approach to model construction and allows access to the performance calculations for desired modifications. The model is constructed and maintained through a graphical user interface.

4.5.3 Displays and Reports

PMAX has a display builder that enables a user to configure the text, data, graphic elements, and equipment schematics on a display screen as shown in Figure 4-10. All displays can be modified while the system is running. A large library of predefined icons and generic displays are provided to enable companies to easily create custom displays.

Graphic displays that appear as a standard part of a screen can be trend plots, x-y plots, or bar charts as shown in Figures 4-11 and 4-12. On any given plot, up to six sets of data can be plotted. Each variable is presented in a unique color for easy identification. Custom trend plots for diagnostics can also be created with the trending tool. Both on-line and archival values can be viewed with the custom graphs. Archival data can be viewed on any trend plot by clicking a Show History button.

PMAX provides tools to retrieve archival data, which can be filtered, trended, and exported. The filtered data can subsequently be replayed with PMAX, and any set of criteria used to obtain archival data can be stored for subsequent use at a later date.

A reporting tool is provided with PMAX that enables a user to configure custom reports that are then automatically generated. The reports are automatically stored in files, displayed, printed, or sent by e-mail to the appropriate personnel. A logging system is also provided that enables construction of log reports for operations and engineering staffs for any desired time interval. Figure 4-13 presents one of the features of the reporting tool, a drop-down menu from which desired data can be selected.

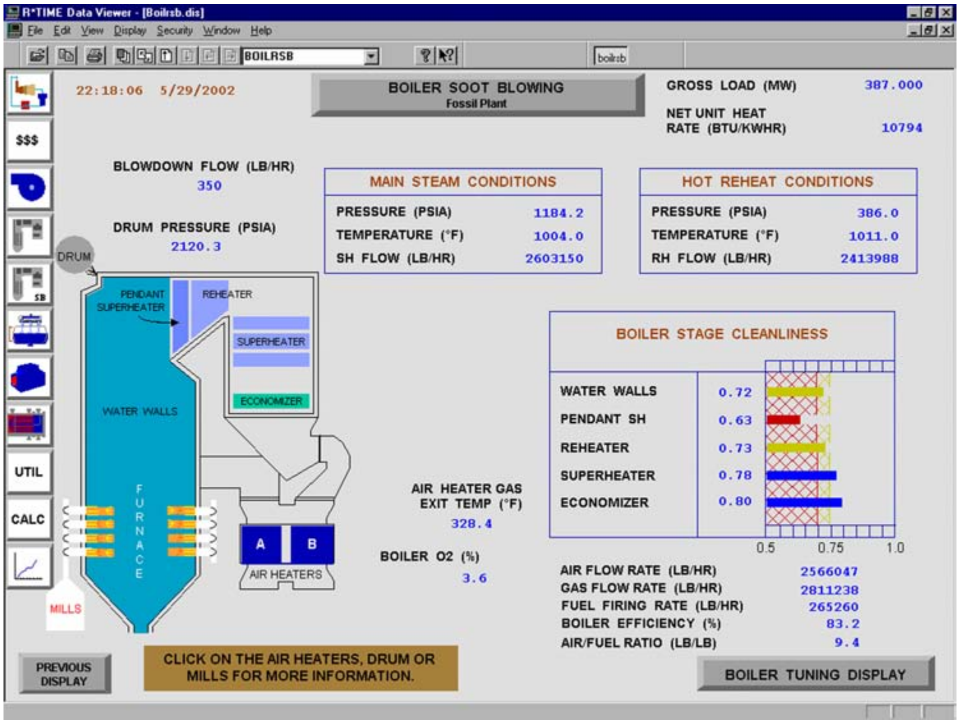

Figure 4-10
PMAX Boiler Performance Screen
Courtesy of Scientech

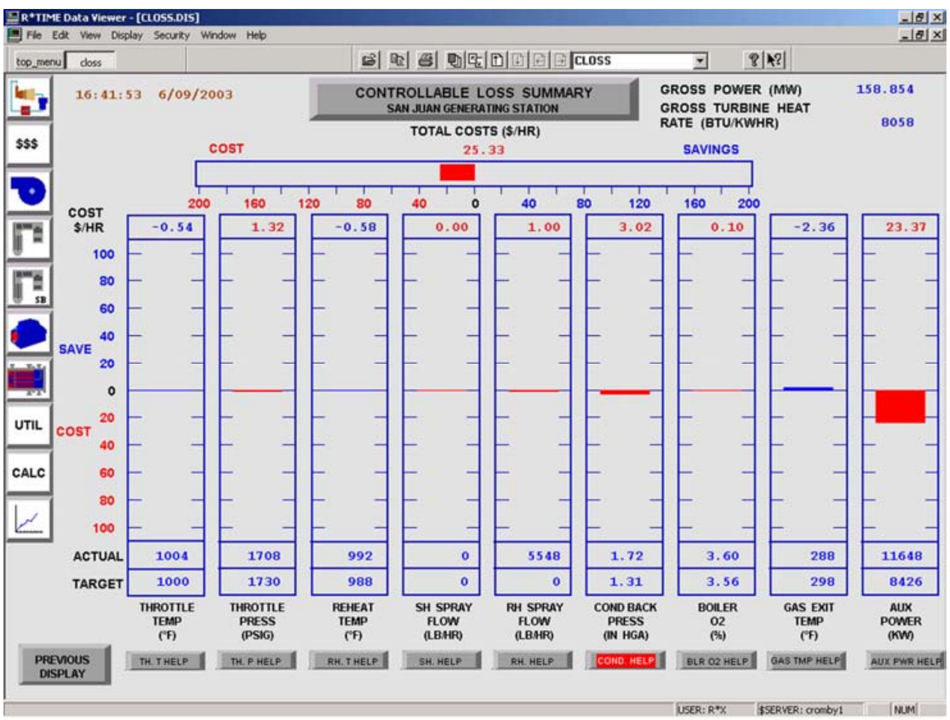

Figure 4-11
PMAX Controllable Loss Summary Screen
Courtesy of Scientech

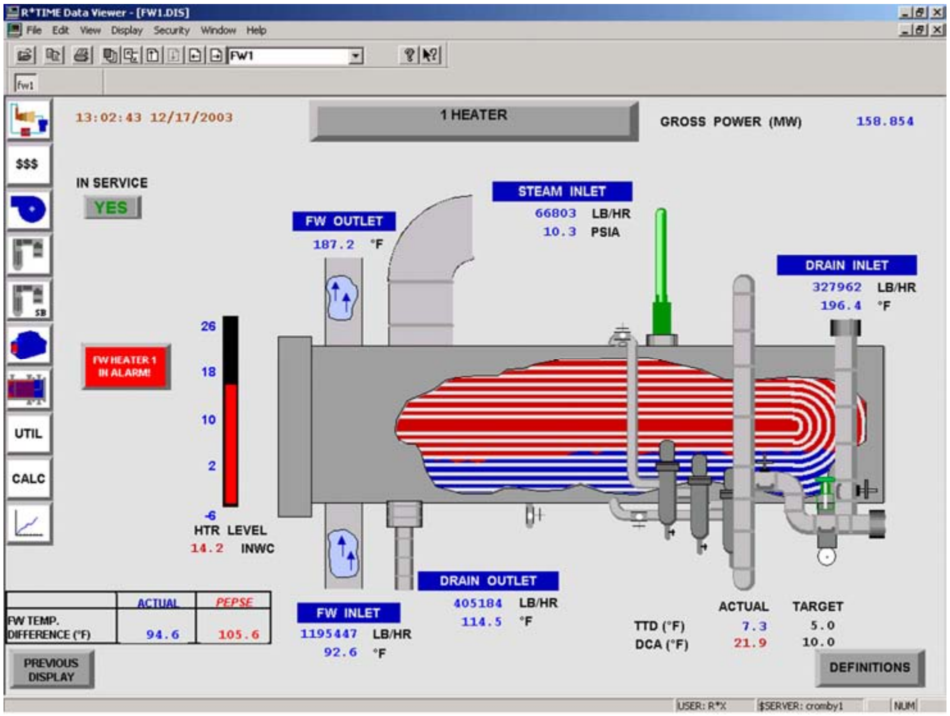

Figure 4-12
PMAX Feedwater Heater Screen
Courtesy of Scientech

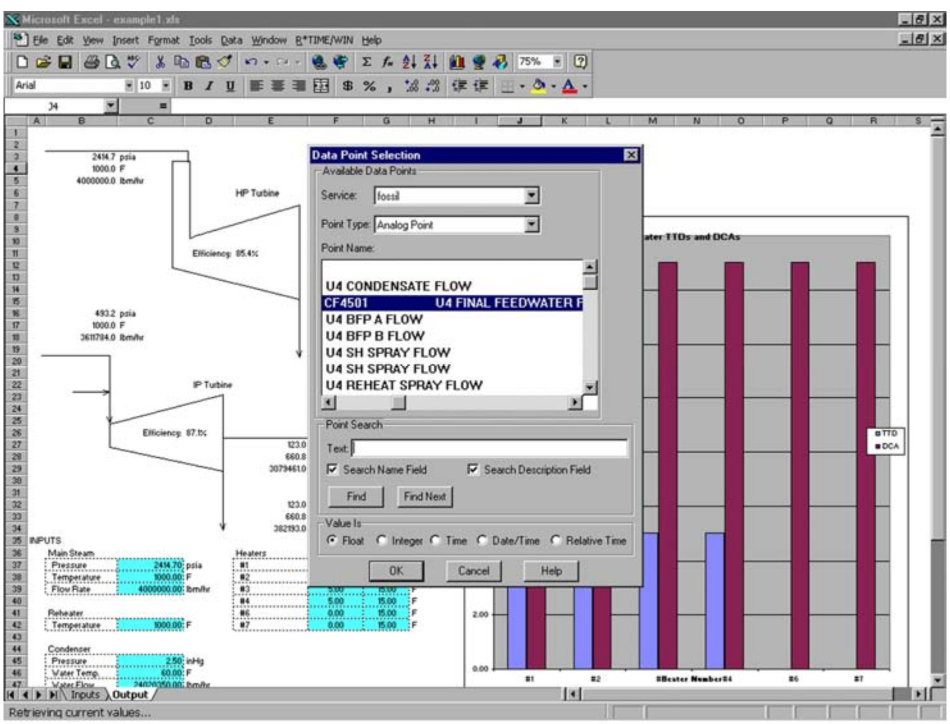

Figure 4-13
Example of a Report Generation Screen
Courtesy of Scientech

4.5.4 Additional Information

Additional information can be obtained on the Scientech web site [25].

4.6 SmartProcess Global Performance Advisor – Emerson Process Management

4.6.1 Data Collection

SmartProcess Global Performance Advisor (GPA) is OPC compliant. Typical data sources include PI and DCS historians.

To enable easy access to OPC data, the GPA includes an OPC tag browser, a module for retrieving and customizing tags. Tags in many historians are often difficult to interpret, and this module enables a user to assign tags that are meaningful to performance engineers.

4.6.2 Calculations

GPA contains a comprehensive set of calculations for all turbine cycle components and supports three different modes, on-line mode, replay mode, and test mode. The on-line mode is based on real-time data, the replay mode is based on archival data, and the test mode is used to investigate what-if scenarios. The replay data feature is useful for adjusting calculations that are based on estimated coal properties. For example, coal properties are generally based on estimated values because of the lag time between sampling the coal and performing the laboratory analysis.

GPA includes tools to streamline the creation of incremental heat rate curves. According to an Emerson representative, some utilities have not updated their curves since the 1970s, when their unit(s) was installed.

4.6.3 Displays and Reports

GPA provides tools to create custom displays similar to other commercially available systems as described previously. The design tool to create displays contains a drag-and-drop interface. GPA also provides reporting and event-logging tools.

4.6.4 Additional Information

Additional information can be obtained on the Emerson Process Management web site [26].

5
CASE HISTORIES

Interviews with several plant performance engineers were conducted in order to obtain an overview of how successful power producers have been in improving thermal performance. In conducting the interviews, care was taken not to disclose business-sensitive information. For example, specific information that enables the plant to be easily identified is not included, and detailed business and operating data are not presented.

The interviews followed a general outline:

1. How companies structure their thermal performance programs
2. Tools used for thermal performance monitoring
3. How companies integrate thermal performance information into actions and overall performance objectives for employees
4. An overview of management's commitment to thermal performance in various companies
5. A historical background to obtain an understanding of how the power industry's position on thermal performance is shifting

Although these discussions provided clear indications that some companies have more extensive heat rate programs than others, the intent of this research was not to cast judgment on how a given company should manage thermal performance. Rather, the intent was to gain an understanding of the role of on-line monitoring systems and how they should be evaluated within the context of current heat rate programs.

The interviews do not focus strictly on turbine cycle heat rate. It was determined that programs were more effectively evaluated in the context of their approaches to overall plant heat rate monitoring.

5.1 Interview A

Power Company A operates many units at several sites. The power company maintains a centralized test and/or analysis group and also maintains some capabilities at each plant for thermal performance testing and analysis. Rate increases are governed by a corporate-level board.

5.1.1 Technology

This company currently uses a data historian that was developed in house on a systemwide basis. The historian can be configured with custom calculations and custom graphics for displaying information. The central staff and plants also use DataFuser (software sold by General Electric) for displaying operator controllable parameters on a systemwide basis. The results are configured to enable roll-up and drill-down capabilities. For example, if losses on a plant basis are displayed, the user can readily change the display to present the losses on a unit basis. Currently the program is configured to provide only monthly reports. The company also has a web-based program in which various activities that affect heat rate (both positive and negative) can be entered. The program evaluates the activities in conjunction with current data to predict heat rate impacts on a unit, plant, and system basis. The system was envisioned as a business-planning tool to assist plants with setting goals and evaluating the benefits achieved with various projects, but it currently is not used for that purpose.

5.1.2 Thermal Performance Practices

The company has significantly reduced the resources committed to thermal performance monitoring over the past several years. One example of this is that the company no longer accurately measures heat rate on a unit basis. Previously the amount of coal burned by a unit was measured by batch coal scales and in a few cases with volumetric or gravimetric scales. However, because the power company had trouble maintaining the scales, it implemented a program to measure only the coal flow rate feeding the bunkers, thereby simplifying the maintenance to only a few scales per plant. In principle, the power company could still measure the coal flow to each unit if the integrator readings were recorded each time the tripper changed the coal flow to a different unit. However, in practice this is not done. The bunker changes are not consistently tracked, which eliminates the possibility of determining unit coal burned on a unit basis and therefore heat rate measurement on a unit basis.

The power company does not have a consistent, systemwide approach to heat rate monitoring and improvement. The central staff provides support to the plants when in need of specialized analysis or testing, but each plant largely determines how it manages its thermal performance. For example, benchmarks for unit heat rates are not set on a systemwide basis. Each plant also has significant autonomy in determining the performance data it measures and reports, thereby resulting in a wide variability in the quality of available performance information.

5.1.3 Management Support

The performance engineer interviewed was concerned that management did not have a deep enough understanding of heat rate in fossil plants. For example, one senior manager was concerned that the benchmark heat rate was not constant from month to month but varied with ambient conditions and that the system benchmark varied with the generation mix of the units. Another example was that heat rate accounting was modified to be consistent with the nuclear plants, which was inappropriate for fossil units. Management had also implemented several performance goals for employees with no clear line of sight between employee’s actions and their effect on the performance indicators.

5.1.4 History

The performance engineer provided a fairly detailed historical perspective of this power company's approach to heat rate monitoring. Thermal performance monitoring received significant emphasis until the 1990s. Each fossil plant contained a group of people dedicated to periodic performance testing, including tests for enthalpy drop turbine efficiency, condenser performance, coal fineness, air heater performance, feedwater heater performance, and station service surveys. The heat rate for each individual unit within the system was tracked with the input-output method. The fuel input was measured with coal scales, and the coal supplies to the bunkers were continuously sampled to determine the heating value of the fuel. The coal scales were calibrated on a periodic basis. Data from unit heat rate monitoring, periodic performance tests, and specialized performance tests were analyzed on a mainframe program that ranked the heat rate deviations for the entire system. Each plant wrote a monthly report on its thermal performance that included a discussion of current problems and actions being taken to correct them. These reports were reviewed by upper management.

Heat rate curves for the individual units were also updated every six months with current unit heat rate data. The unit heat rate curves were based on data from acceptance tests (boiler and turbine cycle) on the given unit or based on acceptance tests for a sister unit. Data from multiple bunker periods (four per month) were examined, and when they met certain conditions (for example, the unit ran the entire period at or near full load), those data were used to create correction factors for the unit heat rate curves.

In the late 1980s and early 1990s, the power company created and installed an on-line heat rate monitoring program that continuously measured turbine cycle heat rate and provided information about the performance of many components, including steam turbine and condenser performance. The system was installed on about half of the units within the power company. Support for the system was terminated after about five years of operation. Other systems were also implemented after the on-line system was discontinued. These included a walkaround system in which critical data were entered into handheld data loggers for subsequent downloading to a computer for calculations and trending and a commercially available centralized system that provided control charts for many processes. The power company has had the widest success with a historian that was developed in house and is now used at all fossil sites within the system. It has also recently implemented DataFuser, which was described previously.

In the late 1980s and early 1990s, the power company implemented a significant downsizing in which a large portion of the work force was eliminated and implemented a significant change in management. At about the same time the company reduced its work force, it placed a much greater emphasis on reducing the equivalent forced outage rate (EFOR). For example, the main steam temperature and pressure set points were reduced at some units. It also adopted a much more aggressive maintenance program for examining and replacing boiler tubes during outages and eliminating the root causes of tube failures. Technicians who had been performing thermal-performance-related tasks were reassigned to reliability-related tasks. The thermal performance tasks that were supplanted were running tests, conducting boiler and condenser air in-leakage surveys, and conducting IR scans of boiler casings. The reliability-centered tasks that were initiated were boiler water chemistry testing, lube oil sampling and analysis, and IR scans of electrical equipment. With the greater management attention to EFOR, the following heat rate improvement activities were discontinued:

- Preparing monthly reports on thermal performance
- Modifying the unit to enhance thermal performance
- Placing emphasis on the heat rate effects of daily operations

The engineer interviewed expressed significant concern that heat rate had significantly degraded over the past several years. He pointed out that although the company tracks individual unit heat rates, most knowledgeable people realize that these rates are not accurate. Because the fuel budget and operations and maintenance budgets are separate, plant managers are directly responsible for controlling maintenance costs but are not responsible for their fuel budget. A common scenario with this budget structure is that maintenance activities to improve thermal performance (for example, condenser cleaning or valve maintenance) are neglected because, from the plant's perspective, they are strictly budget expenses with no returns.

5.2 Interview B

Power Company B is an investor-owned utility in a deregulated power market with many coal-fired units at several sites. It performs systemwide performance monitoring from a central site, and there is only one plant with an on-site performance engineer.

5.2.1 Technology

The company has standardized on using PI as its historian and the thermal performance monitoring system. It translated the calculations in EPRI's Performance Monitoring Work Station (PMW) to work in the PI-ACE System. Because PI runs on a central server, the data and calculations are available systemwide. Currently, the information generated by the monitoring system is used primarily by the central office staff.

5.2.2 Thermal Performance Practices

The performance engineer provided a detailed overview of many aspects of the company's approach to thermal performance monitoring. A description of several components follows.

Controllable losses. This power company does not stress controllable losses. Most units are supercritical, and there are always tradeoffs involved with controllable losses. For example, on one unit, increasing the main steam temperature causes the reheat temperature to be too high because the burner tilts are currently ineffective at controlling reheat temperature. Therefore, the reheat attemperation spray flow would also have to be increased, which has an adverse impact on heat rate. Computing the benefits from tighter control on operator-controllable parameters is also complicated because most units have been modified significantly, and the corrections from the manufacturer's turbine thermal kit no longer apply.

Condenser performance. This company computes condenser performance based on the same approach used by the EPRI PMW software. Condenser duty is determined from a heat balance around the turbine cycle. The method also requires inlet and exit CCW temperature measurements. It measures the exit CCW temperature with four RTDs in each exit pipe.

An example was provided by the interviewee describing how the condenser performance information was recently used for evaluating a program to perform chemical cleaning of the condensers. Because macrofouling is a problem at many units, it had difficulty cleaning the condensers using rockets, which are commercially available from GE-Betz. As a result, there was interest in chemical cleaning. However, the chemicals (chlorine and bromine) produced a manganese precipitate that formed a coating on the inside of the condenser tubes that was extremely difficult to clean. Once the coating formed, scrapers were required to remove it. The company also observed tube pitting with chemical cleaning. A novel approach it tried with condenser cleaning was to inject both horse food and dog food in the CCW. The horse and dog food remain solid as it flows through the condenser tubes and cleans the microfouling as it passes through. After passing through the tubes, it dissolves and is completely biodegradable, thereby producing almost no environmental impact. It measured a 4–5% improvement with this method. The company tried to implement macrofouling monitors. This required a differential pressure measurement from the inlet waterbox to the exit waterbox and a second differential pressure measurement from the exit waterbox to the outlet water pipe. However, it ceased measuring macrofouling because the requirement to keep the sensing lines bled was too problematic because of vortices in the CCW flow.

Turbine performance. This company measures turbine performance across any sections where there is sufficient instrumentation. Many of the turbines do not have thermocouples or pressure measurements between the IP and LP turbines, but for those that do, IP isentropic efficiency is computed.

Feedwater heaters. The primary parameters it monitors with feedwater heaters are TTD, DCA, temperature rise, and drain temperatures. With feedwater heater monitoring, this company discovered cracked partition plates and a drain cooler section that was not working. It had also diagnosed valves that were not working properly when it wanted to bypass a parallel string of heaters.

Boiler feedpumps. This company has recently begun more detailed boiler feedpump performance monitoring. It found that the manufacturer curves are frequently incorrect; therefore, it used on-line data to determine the performance curves. This approach is more difficult for variable speed boiler feepumps.

Cycle isolation. This company is very aggressive about ensuring that the cycle isolation is working properly. One strategy used was to evaluate cycle isolation with thermal imaging during unit startups. This ensures that leaking valves are identified immediately and prevents long-term losses. It also worked with two different companies, Leak Detection Services (LDS) and Valve Technologies. These companies employ acoustic techniques for measuring valve leakage, which has the advantage that the magnitude of the leak can be estimated, whereas thermocouples simply provide a leaking or not-leaking indication. However, because this company replaced all leaking valves immediately, there was little advantage in using acoustic techniques.

Incremental heat rate curves. This company does not currently have a routine process for updating the unit dispatch curves. Because of the characteristics of its power system, it requires only a single curve to characterize all of the fossil units. The dispatch order for the fossil units is fixed based on factors other than incremental heat rate. For example, one unit services a large industrial client, and its dispatch is dictated by this customer's needs. Other factors that influence dispatch are the individual plant's mining and fuel delivery costs.

Unit heat rate. The company uses the input-output method as the standard way for determining unit heat rate. However, the company is moving toward using the output loss method more because of the difficulty in keeping the coal scales calibrated. Currently this company does not set specific heat rate goals for each unit in the system.

5.2.3 Management Support

Although this engineer was keenly interested in thermal performance, he indicated that the key to getting upper management interested in heat rate was the selling of the higher capacity associated with more efficient units. Capacity was a concern for this company because the power grid had limited power available from nuclear, hydro, and coal-fired plants. Therefore, higher capacity from the coal plants reduced the power production by the gas-fired units. An example he provided for management's emphasis on capacity was that a $6 million transformer replacement was easily justified based on a capacity increase of 10 MW.

This performance engineer has experienced the power company's transition from operating in a regulated to a deregulated marketplace. Under deregulation, change is occurring, and more attention is being placed on heat rate. The primary incentive for keeping management focused on heat rate is the value of higher unit capacity.

5.3 Interview C

Power Company C is an independent power producer and participates in a deregulated power market. It has many coal- and gas-fired units located in several plants. The company employs engineering managers in central staff and also employs a performance engineer at each individual plant. The central staff supports both coal-fired and gas-fired units. Because the power company participates in a deregulated market, fuel costs are not passed to consumers.

5.3.1 Technology

The monitoring tools it uses are PI, EtaPRO, and custom tools developed in house. PI is used throughout its system as both its historian and as its primary tool for on-line heat rate monitoring. Two units have EtaPRO; however, the calculations configured in PI and EtaPRO do not always agree. Because of this, it primarily uses PI as its on-line monitoring tool because it is consistent across the entire system. This company has also developed a custom controllable loss screen, which it uses throughout its coal-fired system. The components it monitors with its on-line systems are HP and IP turbine efficiencies, condensers, feedwater heaters, boilers, and other critical components. The company has developed heat balance models with performance evaluation of power system efficiencies (PEPSE) on approximately three quarters of its units, which are used to conduct what-if analyses.

5.3.2 Thermal Performance Practices

Turbine cycle heat rate is determined on-line and during tests using feedwater flow elements that have not recently been calibrated to meet ASME specifications. It has also employed portable ultrasonic flowmeters in most of its units (either from Panasonic or Controllotron) to accurately measure final feedwater and spray flows. These test values are compared with process indications and used to correct or justify maintenance to ensure reliable process indications for these critical flow rates. Boiler efficiency is determined with the ASME energy balance method. The amount of fuel burned at each plant is measured in multiple ways that include belt scales, stock feeder scales, and coal pile surveys. The frequency and method by which coal samples are acquired and analyzed are plant specific. The boiler unit heat rate results are reconciled with the various measurements of the amount of fuel burned.

The power company performs a significant amount of on-site testing. These tests include scheduled boiler efficiency tests, turbine cycle heat rate tests, and turbine enthalpy drop efficiency tests. Testing is also performed on an as-needed basis whenever significant heat rate deviations are detected and questions remain after the data are reconciled. The company performs cycle isolation verification on a semiannual basis. In addition to monitoring and trending performance, heat rate test results are fed into the calculation for incremental heat rate to determine dispatch order.

The company invests a significant amount of time establishing heat rate goals for each plant, which are first established by the performance engineers on the central staff. The goals are established largely on past performance but also take into account modifications that are or will be done to the units. Once the preliminary goals are established, they are published and discussed with plant and management personnel. These discussions are taken very seriously because achieving heat rate is an important part of the performance targets for the plant manager, the production engineer, and the central staff.

This company's approach to monitoring and reporting heat rate is not a rigid framework that is applied throughout the company but rather is based on current problems and on the specific needs of each plant. For example, central staff produces monthly heat rate reports, but if significant problems occur, those are addressed immediately. During the discussion, the performance engineer mentioned that one of the problems the company was closely monitoring was a condenser that was operating with a significant increase in back pressure. The performance monitors indicated that it was caused by fouling, but it was concerned that because the condenser was at the end of its life cycle, cleaning it might cause the tubes to rupture, thereby causing an outage during peak summer production. The engineer was working with others to explore options for reducing the back pressure but not risking a lengthy forced outage.

Heat rate monitoring and reporting are also done at the plant level, and each plant tailors the reporting and monitoring to its needs. The reporting frequency ranges from daily to monthly. In addition, each plant has a heat rate improvement team that meets on a monthly or quarterly basis.

The company uses a hybrid approach of centralized and on-site monitoring. At one point the company chose to eliminate performance engineers from plants. That capability was completely centralized, which was not as effective. The first problem with this approach was that engineers spent a large portion of their time driving from one plant to another. A second and larger problem was that they found it essential to have a liaison at the plant who had daily experience working with the various plant personnel, coordinating activities, and taking responsibility for getting things done.

5.3.3 Management Support

Based on the discussion with this engineer, it is clear that he and his company take heat rate seriously and dedicate significant resources to managing it. At the most basic level, managing heat rate is a straightforward business decision because fuel costs represent about 75% of a plant's budget. The three most important factors that enable this company to have a sustained commitment to heat rate improvement are, as quoted by the engineer, "management support, management support, and management support." The engineer also displayed significant respect for his manager, who fully supports improving plant performance.

5.4 Interview D

Power Company D operates multiple units at a few plants. The company employs a performance engineer at a central site and does not employ performance engineers at individual plants. The company is operating in a partially deregulated market.

5.4.1 Technology

This company has recently installed EtaPRO on two units at one of its plants and has a program under way to install it at its other plants. The EtaPRO installation contains a fairly complete set of modules, which include controllable loss, boiler efficiency, turbine, generator, feedwater heater, boiler feedpump, cooling tower, condenser, and air heater. It has also installed SmartSignal to perform equipment condition monitoring. Performance Consulting Services (PCS) is now assisting the company in the initial stages of using the SmartSignal system. The SmartSignal system provides early anomaly detection, which allows performance problems to be identified earlier compared with using simple trending.

5.4.2 Thermal Performance Practices

This company is in the beginning stages of establishing a fleetwide on-line monitoring program. The key business drivers for this company are equipment reliability and plant emission control. A benefit of thermal performance is that improved efficiency reduces emissions. The engineer is performing the heat rate monitoring on a part-time basis because the program is not established enough to merit dedicated staff. The engineer is currently conducting weekly meetings to update management on findings from the on-line monitoring system. As the program gets under way, he plans to conduct weekly meetings to inform each plant of the monitoring system results.

The company currently tracks monthly heat rate on a plant basis with the input-output method. Belt scales are used to measure the amount of fuel consumed, and the heating value is determined from a sample that is acquired for each run of coal. These data, in conjunction with the net plant generation, are used in the monthly heat rate calculation.

5.4.3 History

Previously the company had a much more active program to measure unit heat rate. In the late 1970s, each plant had a testing crew to conduct component performance tests. One of the tests it routinely performed included measuring section efficiencies for the HP and IP turbines. Two primary factors led to the termination of the routine testing program. First, unit reliability was often so poor that it prevented the team from performing the routine efficiency test. A second problem was that the test results were rarely used to change operating or maintenance processes. As a result, in the early1980s the company eliminated the routine performance tests and began placing much more emphasis on reliability. The only components that are routinely tested now are the air compressors because maintaining sufficient service air has been problematic. Plant engineers focus on maintenance and reliability issues rather than testing. The company has also eliminated pre- and post-outage tests. For example, the L-0 and L-1 turbine blades were recently replaced, and no performance test was performed to evaluate the effect on efficiency.

5.5 Interview E

Power Company E is a medium-size, investor-owned utility with multiple units located at several plants. There are two full-time employees in addition to two part-time employees responsible for thermal performance monitoring at all of the company’s coal-fired plants. Individual plants do not have thermal performance engineers.

5.5.1 Technology

This company has implemented PI ProcessBook throughout its fossil system to monitor controllable losses at each plant. EtaPRO is also installed at one site with multiple units. Because this company has standardized an OSI PI ProcessBook, it serves primarily as an engine for thermal performance calculations. The EtaPRO results are written to the PI historian for subsequent display with ProcessBook.

5.5.2 Thermal Performance Practices

The controllable loss parameters that are routinely monitored are main steam temperature, main steam pressure, reheat temperature, reheat and main steam attemperation sprays, excess oxygen, condenser pressure, exit gas temperature, air heater temperature, and final feedwater temperature. The controllable parameter deviations are converted to both efficiency and capacity losses. The controllable loss screens implemented in PI ProcessBook enable each operator to view his individual performance. In addition, the central staff produces monthly reports that summarize the performance of each plant.

The power company performs a limited amount of plant testing. It has recently started performing quarterly VWO tests to determine HP and IP turbine efficiencies using the on-line monitoring system with station instrumentation. The company also performs semiannual boiler feedwater pump tests to ensure that unit load is not limited due to performance degradation of the feedwater pumps. Each plant also measures monthly unit heat rate based on the input-output method. Each plant is responsible for maintaining calibrated coal scales or flowmeters.

This company sets annual targets for unit heat rate that are based on historical data. Although plant managers have incentives for maintaining plant heat rate, meeting reliability and environmental requirements are given much greater emphasis. Plant managers are not required to implement recommendations provided by central staff for thermal performance improvement. Implementing heat rate improvement activities is viewed as a maintenance cost at the plant level because plant managers are responsible for the plant maintenance budget but are not directly responsible for the plant fuel budget. The performance engineer interviewed has predicted that the company will place more emphasis on heat rate because of escalating fuel costs and because the public service commission is placing more emphasis on thermal performance improvement and asking plants to develop efficiency improvement plans.

5.5.3 History

In the 1980s and early 1990s, the company had large test crews and performed a significant amount of scheduled testing. These tests included routine ASME turbine cycle heat rate performance tests. In the 1990s, the test crews were eliminated and the plant testing was significantly reduced. There has not been an ASME turbine cycle heat rate test performed since 2001, when a turbine rotor was replaced.

5.6 Interview F

This interview was conducted with two performance engineers at a remote power plant with two coal-fired baseload units. Although there are additional plants in this power system, the thermal performance program for this plant is conducted solely by plant personnel. The thermal performance monitoring group consists of one engineer with two technicians available when they are needed. An additional engineer manages the mechanical reliability program with the same two technicians available for additional support. This power plant is part of a public power utility that is regulated by a board.

5.6.1 Technology

This company monitors turbine cycle heat rate with two systems: the Total Plant Performance Monitor by Honeywell and PMAX. Prior to 2000, it used PMAX exclusively on a Microvax computer, but due to Y2K compliance concerns, it installed the Honeywell system. The company currently uses the Honeywell system as its primary monitoring system, but it was in the process of upgrading PMAX, operating on a PC platform, to serve as its primary system. PMAX will also be used at an additional plant in the system. Other important software systems it uses are the Honeywell PHD Historian and EPRI's PlantView. The primary use of PlantView is to compute and track avoided costs achieved by diagnosing either thermal performance or mechanical problems in advance of the next outage or in advance of equipment failure.

5.6.2 Thermal Performance Practices

The on-line monitors provide information about turbine cycle heat rate and individual component losses, which are condensers, controllable losses, feedwater heaters, and turbines. The company has taken significant effort to improve the accuracy of the on-line turbine cycle heat rate measurement. As part of this effort, it conducted an independent instrumentation audit to determine the most important unit instrumentation for turbine cycle performance monitoring according to ASME specifications. The instrumentation is an ASME flow element installed in the HP feedwater line.

The company performs quarterly VWO tests with on-line instrumentation to trend HP and IP turbine efficiencies and also performs routine cycle isolation checks by closing valves in a given sequence as turbine cycle heat rate is continuously monitored. If closing a given valve produces a change in turbine cycle heat rate, valves located downstream are examined closely. With this approach, the company streamlines the cycle isolation check for the entire system.

The engineer pointed out that a key to effective monitoring of thermal performance is that the thermal engineer have significant experience with the units and be familiar with causes of performance degradation. Because of his experience, he can better locate the root cause of heat rate deviations not directly measured with on-line instrumentation. For example, unaccounted heat rate deviations are not automatically assigned to LP turbine efficiency degradation because this unit has never experienced significant changes in LP turbine efficiency. When unaccounted performance losses are detected, cycle isolation is checked because this is what historically has caused the deviation.

Both units have ASME quality flowmeters installed in the HP feedwater lines that provide one source of continuous flow measurement. The cost for these flowmeters was justified based on the need to run performance tests to measure the efficiency improvements achieved by replacing the last two rows of the LP turbine blades. The engineer pointed out that although feedwater flow measurement is simplified by using an HP feedwater flow element, which is important because it is used in the company's control system, maintenance is problematic. The flow measurement is affected by deposits on the nozzle and gradually drifts. The flow elements are cleaned during the outages by using the access provided by the inspection ports. Because of the errors created by the fouling, first stage pressure is used as an alternate measurement to verify the feedwater flow measurement. The feedwater flow nozzle is always used for unit control.

Specific unit heat rate goals are established for each unit based on EPRI guidelines (*Heat Rate Improvement Guidelines for Existing Fossil Plants*, CS-4554). The approach taken by this plant differentiates between the heat rate that is obtainable with the unit in its current condition and the heat rate that could be achieved with modifications that could be performed during a unit outage. For example, the benchmark heat rate is currently 80 Btu/kWH (84.4 kJ/kWH) poorer because of the turbine conditions found during a steam path audit. As part of the planning process for each outage, the plant performs an economic evaluation of this efficiency loss to determine whether it is feasible to refurbish the turbines.

Boiler efficiency is measured with the following three techniques:

- ASME heat loss method
- ASME input-output method
- Output-loss method

The output-loss method is used only when significant discrepancies exist between the energy balance and input-output methods. The company is in the process of calibrating a recently installed on-line coal analyzer, which operates based on the principle of X-ray fluorescence and plans to use a bunker model in conjunction with the analyzer data to obtain on-line measurements of coal heating value. It currently obtains the heating value for the coal with a combination of vendor measurements and with the samples that the company acquires on a daily basis, with the analysis results returned approximately four weeks later.

As an indication that this company values equipment monitoring, of which thermal performance is a subset, it also has an effective predictive maintenance (PdM) program and an on-line Bently Nevada vibration monitoring system that is supplemented with walkaround vibration measurements. The walkaround measurements are performed on a monthly basis. If other activities prevent the employees from doing the walkaround routes during normal working hours, they are performed on overtime. The company has substantial confidence in its PdM program and base unit outages on the results from its PdM and thermal performance monitoring programs. An example of one significant problem recently diagnosed was a generator winding problem. The vibration measurement system detected a small change in generator vibration and a large change in phase angle, which was correctly diagnosed as a generator winding problem and led to a unit outage to rewind the generator.

PlantView is used to quantify and report the avoided costs associated with catching both thermal and mechanical performance problems. The performance engineer stressed the importance of basing the revenue gains on conservative assumptions to keep the numbers believable.

5.6.3 Management Support

Management is very supportive of the thermal performance program at this company. Two primary reasons are that the power plant operates in a system that is capacity limited, so achieving the highest possible thermal efficiency is important for maximizing unit power output to meet the system load requirements, and thermal efficiency is part of the corporate culture. The engineer highlighted the fact that the managers he works with have extensive experience with the operation of coal-fired power plants, and they value achieving high thermal efficiency as part of their role as corporate citizens.

5.6.4 History

The company has had an active heat rate program since 1992. Significant gains were achieved over an eight-year period until 2000. After 2000, management placed higher priority on other items, which ultimately caused the heat rate to fall and return to the 1992 level. Since 2002, the company has resumed an active heat rate improvement program.

5.7 Interview G

Interview G was conducted with a performance engineer who works for an investor-owned utility that contains coal-fired generating units at several plants. The engineer works in the central staff, which consists of approximately 10 engineers, 10 technicians, and 10 employees working in a laboratory that calibrates test instrumentation. A performance engineer is also located at each plant and serves as a liaison between the central staff and the plant activities.

5.7.1 Technology

This company has standardized on AspenTech to serve as its historian at all plant sites. AspenTech acquires the data from the DCS systems at the plants, which are not standardized throughout the system. The thermal performance calculations are integrated into the calculation module of AspenTech. Each unit also has its own thermal performance model.

5.7.2 Thermal Performance Practices

A primary objective for the on-line monitoring system in the heat rate improvement program for this company is managing avoidable losses (commonly referred to as *operator-controllable losses*). AspenTech is configured to display graphics showing the avoidable losses that can be viewed throughout its system in real time. Avoidable loss reports are automatically generated each shift and each day and then sent as an e-mail to the appropriate personnel. The shift and daily reports integrate the efficiency losses that occur because of differences between the actual and expected values for each avoidable loss component.

The company performs a significant amount of routine plant tests. These include VWO tests to measure HP and IP efficiencies and simplified ASME turbine cycle heat rate tests. In some cases the company still performs full ASME turbine cycle heat rate tests when significant modifications have been made to the unit. Many units have flow elements originally calibrated to ASME specifications that have flow elements in the condensate line and in the HP feedwater line. Other on-site tests include routine cycle isolation checks and component tests in which the type and frequency vary based on the characteristics of the individual units. The central staff also routinely performs heat rate reviews at plants and provides a report that prioritizes the potential heat rate improvement opportunities. Turbine performance losses caused by internal horizontal joint leakage are a common reason for the larger heat rate deviations that occur.

Economic dispatch curves are updated annually based on the performance tests. In general, the curves are shifted up or down, but the shape is not changed.

Each plant is responsible for measuring its own heat rate using the input-output method. Coal sampling strategies are different for each plant, but in general coal samples are obtained throughout the day to create a composite daily sample. These samples are used to measure the daily heating and moisture value.

5.7.3 Management Support

Plant managers have heat rate goals that are established each year by the central staff. Once the heat rate goals are determined, they are discussed with management and plant personnel to ensure that all parties involved agree that they are reasonable. Performance goals for each plant manager vary from plant to plant because each plant has a unique set of challenges. In general, however, being reliable and meeting environmental compliance have higher priority than meeting the heat rate objective, but heat rate still receives significant emphasis. For example, the interviewee stated that the vice president of generation has a great deal of experience in fossil plants and continuously emphasizes the importance of heat rate to company employees.

5.8 Interview H

Interview H was conducted with a performance engineer who works on the central staff for a company that is an investor-owned utility with many generating units at several plants located in multiple states. The states in which the plants operate are under different regulatory requirements. One state is moving aggressively toward a deregulated structure, and another state operates in a more traditional environment and is regulated by a public service commission. The thermal performance for all plants in this company is managed in a similar manner.

5.8.1 Technology

This company is investing significant resources in a fleetwide monitoring center. It has implemented EtaPRO and Smart Signal for all generating units in their company. The central staff is expanding with the goal of providing support on a 24-hour, 7-days-a-week basis. The staff will eventually contain 10–15 employees with a combination of monitoring specialists, engineers, and supervisors. The first line of communication for the fleetwide monitoring center will be to plant operators and plant engineers. At present, there are no formalized reporting activities or specific personnel at the plants whose primary role is to support the central staff to assist in monitoring and improving thermal performance.

5.8.2 Thermal Performance Practices

The company currently does not establish benchmark heat rates for any of its coal-fired units but does track the heat rate of each plant on an accounting basis. This approach involves using vendor measurements of coal heating value and weight in conjunction with measured power to compute plant heat rate. A limited amount of coal sampling is performed at the plants to validate the vendor guarantees.

5.8.3 History

The interviewee has worked as a performance engineer for over 20 years. His first experience with on-line heat rate monitoring systems was with one he developed in 1985. He has since worked with multiple commercially available monitoring systems. In the interview, the engineer said that he had experienced several initiatives by the company involving the purchase of monitoring software that promised significant benefits. These initiatives were never sustained by the company, and the software was left to "die on the vine" because the software did not provide the anticipated benefits.

5.9 Interview I

Interview I was conducted with a performance engineer who works on the central staff for a company that is a power cooperative. It operates a few power plants with several generating units. The central staff consists of two performance engineers; one focuses on monitoring, and the other focuses on long-term planning. When the engineers run tests at the plants, plant personnel are available to assist them. The central staff works closely with both plant supervisors and plant technicians to address thermal performance problems.

5.9.1 Technology

The central staff and plants use Scientech's PMAX and Emerson's GPA. The data from these systems are available both at the central staff location and at the individual plants. Performance engineers generally preferred PMAX, but operations personnel generally preferred working with GPA, which was installed as part of a control systems upgrade. The engineers also use Excel extensively to process data. A program that assists the Excel-based analyses is End Result [27], which is an add-in and provides a set of functions for combustion performance calculations. The central staff also uses the Advanced Condition Monitor (ACM) available from PCS software for signal validation and for equipment performance monitoring. ACM is no longer commercially available.

5.9.2 Thermal Performance Practices

The on-line monitors provide information for the following systems:

- Turbine cycle heat rate
- Fan and pump performance
- Air heater performance
- Boiler performance
- Condenser performance
- Controllable losses

The performance engineers calculate boiler efficiency with the ASME energy balance method, the ASME input-output method, and the output-loss method. Each plant acquires daily coal samples for which approximate analysis results are returned in five to seven days. For the input-output method, several different types of coal scales are used for which the calibration is checked every six months and recalibrated when required. The information from these systems is used to compute unit heat rate in multiple ways. In general, the central staff provides monthly heat rate reports that provide the overall status of the each unit, and the plant personnel examine component performance on a continual basis to ensure that all components are operating properly.

The benchmark heat rate is based on the performance of the last three years. The company began a comprehensive heat rate program 17 years ago. During the first several years of the program, the heat rate target was established based on a 1–2% improvement over the then-current unit heat rate. Initially some plants achieved a 6–8% improvement in a single year. However, after approximately five years, the unit heat rates leveled off, and the engineers considered them to be at the best achievable level.

5.9.3 Management Support

The engineer interviewed expressed significant confidence in the company's heat rate program and stated that although its program might not be the best in the country, it is definitely one of the top performers. A key business factor identified is that as part of a cooperative power company, the owners are the customers. The owners recognize that lower heat rate translates to lower energy costs. In addition, the interviewee indicated significant management commitment to thermal performance. The heat rate program that is currently in place evolved over a 17-year period of sustained commitment. The key managers in the company have performance engineering backgrounds with significant experience in this area. The interviewee stressed the importance of education in achieving an effective heat rate program. An example he provided was operator training to enhance understanding of heat rate and to raise awareness. Participation in industry conferences on heat rate is also valued. This gives employees an overview of how effective their program is with respect to others and provides them with more information.

5.10 Interview J

Interview J was conducted with a performance engineer who works on the central staff of a company that has several coal-fired plants with many units in multiple states. Power rates are regulated by state-level public service commissions. The company currently has a very limited thermal performance program with one performance engineer on central staff and two technical specialists in a test group. There are no additional plant-level personnel whose primary responsibility is thermal performance. However, the company is undergoing significant management changes, and its approach to thermal performance monitoring may change during the next few years.

5.10.1 History

The engineer provided details concerning the past practices of this company, whose previous extensive heat rate program put it among the most efficient companies in the country. In the 1970s and 1980s, the central staff contained approximately 15–20 people, consisting of both performance engineers and technical specialists. Approximately half of them were dedicated to the plant results group, which performed heat rate analyses, created monthly reports, and updated the unit dispatch curves. The other half were dedicated to testing. In addition to the central staff, the plants contained personnel dedicated to thermal performance. The larger plants typically had one full-time performance engineer with two technicians, and the smaller plants typically had one performance engineer. Beginning in the 1990s, the thermal performance group became more centralized, and the number of plant personnel was reduced. The central performance group has subsequently experienced several stages of downsizing and currently consists of the staffing described in the previous paragraph.

The company installed PI shortly after it was first commercially available and created an on-line thermal performance monitoring system from the tools available in PI. The system measured both boiler efficiency and turbine cycle heat rate to compute the overall unit efficiency. The boiler efficiency calculation was based on the ASME heat loss method. The turbine cycle monitoring system computed overall turbine cycle heat rate, in addition to the performance of individual components, such as HP and IP turbine efficiencies, condenser performance, feedwater heater performance, boiler feedpump performance, and controllable losses. This on-line monitoring system remains in service.

The company also created monthly reports that measured unit heat rate based on the input-output method. This heat rate calculation was based on the analysis of daily composite coal samples and calibrated coal scales. The company continues to acquire daily composite samples for determining each plant's coal properties. It measures the quantity of coal to the plants with belt scales feeding the bunkers and then apportioned the total flow of coal to each unit based on batch scale readings. The belt scales were calibrated weekly by checking the scale reading while placing a calibration weight on the scale. In addition, each belt scale was checked annually by measuring the weight of a carload of coal on certified scales and checking this weight against the belt scale measurement. Loss on ignition (LOI) measurements were also performed on a weekly basis. The company had tried implementing on-line LOI measurements but was not satisfied with the results. It continues to acquire daily coal samples and calibrates the belt scales frequently. Some of the plants continue to measure LOI samples on a weekly basis.

The on-site test group performed quarterly VWO turbine tests. In the past, several significant heat rate deviations were found that included deposits on the turbine blades and broken control valves. Frequent cycle isolation checks were also performed. These tests have been almost completely eliminated because of the reduced staffing levels.

The company set a target heat rate for each unit in the system based on the five-year weighted average of the unit performance. By setting goals in this manner, the performance programs for different types of units could be compared; for example, a cycling unit could be compared with a baseloaded unit. In the past, the company promoted competitions among the plants and sponsored a celebration at the plant that produced the largest heat rate improvement. It also included thermal performance bonuses as part of the employees' compensation. These incentives are no longer in place.

5.11 Interview K

Interview K was conducted with a performance engineer who works on the central staff for a company that operates in a deregulated power market. The company owns several plants with many units in multiple states. Although the performance engineer interviewed had a great deal of experience with thermal performance monitoring, currently his primary role is reliability monitoring. He provides recommendations on thermal performance only when his services are requested by the plants.

5.11.1 Thermal Performance Practices

This company has obtained its plants through acquisition. As a result, the thermal performance programs at the plant level are based largely on past practices. However, in general, the company places minimal emphasis on thermal performance. The most comprehensive thermal performance program exists at a plant with large, baseloaded units that the company jointly owns with several others. Other plants within the system have eliminated personnel whose primary duty was monitoring thermal performance.

The company uses accounting heat rate as a primary method to evaluate plant production costs. Because it is participating in a deregulated power market, the value of each plant is evaluated primarily by the profit margin it provides. This is measured by the difference between the revenues from power sales and the production costs for each plant. Because of this philosophy, the company might emphasize thermal performance for the plants with the smallest margin to ensure that they are profitable. It is possible that less emphasis would be placed on units with higher margins for which improvements in heat rate produce a smaller relative increase in profit margin.

The company is currently evaluating its thermal performance program in an effort to standardize it across the system. It has installed SmartSignal throughout the system and is considering using empirical modeling for a significant component of the thermal performance program. A key advantage of this approach that was highlighted by the performance engineer is that it provides information even when a sensor fails. With a first-principles approach, each measurement point must have data to compute performance. Therefore, maintaining the instrumentation requires a large investment in personnel resources. For older and smaller units within the company, a large investment in personnel resources is not justifiable.

5.12 Interview L

Interview L was conducted with a performance engineer who works in a diagnostic center for a company that operates coal-fired plants with many units in multiple states. The fossil plants this performance engineer worked with operate in a regulated market. Of the fossil units, approximately 22% of the capacity is produced by coal-fired units.

5.12.1 Thermal Performance Practices

The company distributes responsibility for thermal performance throughout its organization in essentially a three-level system. The first level of information is acquired by thermal performance test groups located in field offices dispersed over the company's service region. There are approximately five field offices, and each field office has approximately one engineer or technician whose primary responsibility is thermal performance. The public service commission in one of the states in which it operates requires that power plants operating within its jurisdiction perform periodic unit heat rate tests, typically on an annual basis, with the primary goal of ensuring that the unit dispatch curves are accurate. Although only one state within its region requires this, the company performs similar tests on all regulated fossil units. The periodic performance tests are conducted with calibrated test instruments. The diagnostic center staff and a central performance engineer also perform quarterly performance tests similar to the annual tests, except that plant instrumentation is used rather than test instrumentation. These results are trended with the primary objective of detecting changes in unit performance. Both the annual and quarterly tests provide information that drives unit maintenance.

The second tier of responsibility is at the plant level. At this level the information is supplied by an operations information system that includes on-line heat rate and controllable losses information. The system was developed by the company with the tools contained in the PI data historian and supplemented by programming and the use of EtaPRO for the thermal performance calculations. All units that have DCSs are provided with the operations information system. This represents approximately half of the fossil units within the system. The other half that do not have DCSs are generally used for peak power production only and therefore produce a much smaller percentage of the annual MWh output. These on-line monitoring systems contain a complete set of turbine cycle performance calculations, which are overall turbine cycle heat rate, controllable losses, turbine performance, condenser performance, feedwater heater performance, and boiler feedpump performance. In addition, the on-line system contains boiler performance calculations. The information provided by the on-line monitoring system is available throughout the company, and one primary use for this information is to help unit operators minimize controllable losses.

The third tier of responsibility and information for thermal performance is provided by the diagnostics center. The primary function of the diagnostics center is for equipment condition and operations monitoring; however, it spends approximately 10% of its time on thermal performance monitoring and diagnostic activities. The primary source of thermal performance information is the central on-line monitoring system. The diagnostics center notifies plants whenever it discovers problems with thermal performance. For example, if the center observes that the excess oxygen is too high or that the oxygen analyzer is not working properly at a particular unit, it notifies the plant.

5.12.2 Management Support

The company promotes improved thermal performance by setting goals tied to heat rate for each unit and further emphasizes thermal performance by sponsoring peer group meetings that are attended by thermal performance personnel from each of the field offices, the operations information group, and the diagnostic center. Peer group meetings help each of the organizations compare procedures and help them improve their thermal performance efforts within their individual organizations.

Until the early 1990s, the company had a larger, semi-centralized staff whose primary role was monitoring and improving thermal performance. However, all departments throughout the company have since been downsized. The interviewee characterized the current thermal performance program as being much more cost effective than what was achieved with a larger staff. The company vice president responsible for the thermal performance program is an engineer with a significant plant background.

5.13 Interview M

Interview M was conducted with a staff engineer who works at the central location of a company that has many coal-fired plants with many units in multiple states. In general, the thermal performance program is not highly centralized; instead, each plant has a great deal of autonomy in directing its thermal performance program. Central Engineering works with thermal performance throughout the company, and the regional teams work in specific areas of the country. These teams appoint and work with a heat rate champion for each plant to coordinate thermal performance improvement activities.

5.13.1 Technology

To improve heat rate and increase awareness, the company has developed its own comprehensive on-line monitoring system with tools available in PI. The system contains the cycle heat rate modules commonly found in commercially available systems, such as controllable losses, turbine efficiency, condenser, feedwater heater, boiler efficiency, and boiler feedpump modules. The modules compare actual performance to design performance and compute on-line heat rate deviations. The heat rate deviations are integrated on a monthly basis and packaged in a heat rate report, which is available to each thermal performance team and to the individual plants.

5.13.2 Thermal Performance Practices

Overall unit heat rate is measured in various ways at the plants. Both the input-output and output-loss techniques are used. For the input-output technique, the coal is measured in various ways, including belt feeders and stock feeders. The coal sampling also varies from plant to plant and might be acquired by either automatic or manual sampling methods.

5.13.3 Management Support

The company has several initiatives for encouraging its plants to improve heat rate. It sets specific heat rate targets on a unit basis throughout the system for evaluating and managing the thermal performance program of each plant and plans to incorporate these goals into the company incentive program in 2007. Another initiative involved the creation of a separate budget reserved for innovative heat rate improvement activities. Allocating special funds for heat rate improvement ideas, in addition to the normal budget, provides a valuable tool because maintenance activities that improve reliability tend to rank higher in the budget process. The company also promotes heat rate awareness by participating in an international partnership whose primary objective is reducing greenhouse gases and publishes a quarterly newsletter to promote heat rate awareness. Through all of these initiatives, the company hopes to positively impact the heat rate culture to better prepare itself for potential environmental directives.

5.13.4 History

This company previously had a central staff dedicated to thermal performance, but that staff was downsized and then eliminated in the 1990s. When the company reduced its resources for thermal performance improvement, most plants also reduced their efforts in this area. However, one of the plants has maintained a strong emphasis on thermal performance and has also maintained the best reliability and consistently maintained good heat rate. This suggests a direct relationship between thermal performance and reliability.

5.14 Interview N

Interview N was conducted with a company that provides consulting services to power companies seeking thermal performance improvement. This company has worked with several power companies and has engineers on staff that focus almost exclusively on thermal performance of power plants. The two employees interviewed had decades of combined experience, specifically in the thermal performance of power plants.

Because the perspective of this company is more general than that of the individual power companies previously interviewed, the questions asked and the dialog were somewhat different. The interview first covered the subject of on-line monitoring tools that are currently in use in the power industry. Next, key factors important for implementing an effective heat rate improvement program were discussed. The final discussion topic covered current management philosophy, trends regarding efforts to improve thermal performance in the power industry, and a brief discussion of fleetwide monitoring.

5.14.1 Technology

This company has worked with utilities that have a variety of monitoring systems, such as commercially available systems and in-house developed systems. Its view regarding commercially available systems is that there is not a great deal of difference in the functionality provided by the monitoring tools. All are based on the same set of performance equations, and the technology is very mature. The approaches taken by companies seeking a capability in thermal performance monitoring vary a great deal. For example, some clients had installed extensive commercially available monitoring systems, and others had created their own spreadsheets to manage data and achieve improvements in thermal performance. Some companies simply had a list of targets to ensure that the operators paid attention to controllable losses.

The interviewees stressed important points that were essential to follow with any implementation of monitoring tools. Operators and performance engineers have fundamentally different needs in a monitoring system. Operators must be continually aware of a large amount of information; therefore, it is essential to minimize the amount of additional information from thermal performance monitoring systems. As a general rule, the information produced by performance monitors should be limited to a maximum of three additional screens. In addition, it is important to streamline how operators access the information, and the best approach is to fully integrate the information into the DCS screens. Placing the thermal performance information on separate computers or even requiring the operators to switch between programs almost always reduces the effectiveness of on-line monitoring systems.

Packaging the information into a useable format is essential. The calculation and display of lost generating revenue is effective, and the time period is an important part of the information. The time period should be large enough to ensure that heat rate increases produce a noticeable revenue change but not too large so that the measurements in the time period reflect the state of the equipment. For example, with heat rate increases produced by major components that require a unit outage to repair (turbine efficiency reductions), time periods of several months or even a year are appropriate. For operator-controllable parameters that might change on a shift-to-shift basis, a daily or shift time period is more appropriate. Generating revenue is also important as a metric for prioritizing heat rate improvement activities.

5.14.2 Thermal Performance Practice

Thermal performance improvement requires accurate measurements of unit heat rate to continually evaluate the performance status and effectiveness of the program. Accordingly, the interviewees recommended that power generators use at least two different methods for quantifying unit heat rate. Those suggested were the input-output method and an energy balance method. The results of these two methods should be continuously reconciled to enhance the accuracy of the heat rate calculation. When reporting heat rate information over a long term, it is important to keep the precision of the heat rate measurement in mind. For example, reporting quarterly or annual heat rate values to four digits (9912 Btu/kWH [10,460 kJ/kWH]) is misleading, but rounding to the nearest 50 or 100 Btu/kWH (52.8 or 105.5 kJ/kWH) is appropriate. However, on-line systems that provide a continuous heat rate measurement typically have very good repeatability. For example, if the heat rate reported today is 9912 Btu/kWH (10,460 kJ/kWH) and increases to 9922 Btu/kWH (10,468 kJ/kWH) tomorrow, a performance engineer can be fairly certain that it is not caused by a precision error and should attempt to find the cause of the heat rate increase.

This company stressed that selecting instrumentation providing high absolute accuracy is typically not necessary; however, instrumentation with very good precision is important. Some companies have reportedly spent a disproportionate amount of their resources on ensuring that instrumentation is absolutely accurate and have not received a commensurate level of benefit. The final feedwater flow measurement is an important example. In the view of the interviewees, installing a flowmeter calibrated to ASME specifications on an existing unit is generally not worth the investment. Plant final feedwater flow measurements are almost always adequate for heat rate improvement programs. However, when commissioning new plants, it is a good investment to install calibrated flowmeters for performing accurate acceptance tests on new units.

The interview also covered the location where a company should install an ASME calibrated flowmeter. The company has experience with companies that had installed nozzles in the final feedwater line and in the condensate line. It suggested that it is important to have a flow measurement in the final feedwater line for unit control because it requires much less instrumentation than a condensate flow nozzle. Reduced instrumentation is required because a final feedwater flow measurement with a condensate flow nozzle requires that the extraction steam flows be measured. However, an ASME flowmeter in the condensate line can be easily maintained. The interviewees briefly discussed flowmeter fouling, and some recalled cases in which final feedwater flow elements had precisely tracked the condensate flow measurement for almost a decade. However, it was pointed out that the nuclear industry had experience with flowmeter fouling affecting accuracy.

5.14.3 Key Elements of Thermal Performance Programs

Although having the appropriate systems in place to monitor heat rate can be important, there was a wide range of variability observed by the interviewees in the effectiveness of heat rate improvement programs. In general, the company stated that there was little correlation between the effectiveness of the heat rate programs and the tools used for monitoring them. In fact, it had at one point performed a survey and found that only 25% of on-line monitoring systems were actually used. In some cases, companies employing the most basic tools had more effective heat rate programs than companies with the latest, most comprehensive systems. The discussion covered several factors that were important for maintaining heat rate improvement programs.

Management interest and support are viewed as primary essential elements for sustaining a heat rate improvement program. One of the most effective actions a manager can take is to show an interest in heat rate by making frequent visits to the control room to inquire about the current operator controllable losses. Three common reasons operators state for not being concerned about heat rate are the following:

- "Why should I care when nobody else does?"
- "Why should I care? I receive no benefits."
- "Why should I care when fuel comes out of the corporate budget?"

Each could be addressed with more active management involvement.

Another means by which management can influence heat rate is to eliminate organizational boundaries between performance engineers and plant personnel. For example, the interviewees thought that performance engineers should be closely aligned with operations and should spend significant time in the control room. Performance engineers with limited plant visibility have more difficulty implementing changes in operation. In almost all cases, qualified performance engineers are needed at fossil plants even when the company has implemented a centralized fleetwide performance monitoring system. Experience with fleetwide monitoring systems has shown that effectiveness is limited if there is not a staff member acting as a liaison at the plant to implement actions. The liaison at the plant does not necessarily have to be a trained engineer but someone who acquired the skills with extensive on-the-job training.

Education was viewed as the next most important factor in sustaining a successful heat rate program. As mentioned before, management support is viewed as the most critical factor, so it is essential that managers have a fundamental understanding of heat rate for coal-fired power plants. The interviewees felt that heat rate was not maintained as low as possible at some power companies because management did not have a clear technical understanding of heat rate and therefore did not track it because it was thought to be too difficult to measure.

5.14.4 Training

Training in heat rate is often provided by vendors of commercially available tools, and the education is thus centered on how to use specific commercial systems. A more important aspect not adequately addressed in this type of training is how to effectively use the information provided by the monitoring systems. In addition, some companies have multiple monitoring packages that include thermal performance, equipment condition, vibration, and lube oil monitoring. Integration of this information is an important factor in successful monitoring and diagnostics. Companies that supply commercially available monitoring systems often want to be viewed as the single "silver bullet" supplier who addresses all possible needs. In contrast, a more effective approach is to integrate and use information from all sources. The industry is currently seeking effective platforms and methods for effective data integration.

Another key barrier to effective heat rate implementation recognized by the interviewees is the number of qualified performance engineers available. The interviewees provided an example of three power companies that had been searching for performance engineers for 18 months. One factor contributing to this trend is that performance engineering is typically viewed as a temporary position serving as a path to other positions with higher status and higher pay. A more appropriate view is that understanding the technology of thermal performance improvement in a fossil plant requires a great deal of education and experience and could provide tremendous value to any power company. Most plants could easily expect to achieve a heat rate improvement of at least 1% with a qualified performance engineer.

5.14.5 Fleetwide Monitoring

This interview concluded with a discussion of the trend toward centralized, fleetwide monitoring systems and the effectiveness of this trend. Given the aging and shrinking pool of talented performance engineers, having a centralized performance monitoring center is an effective technique for leveraging the expert knowledge of an individual across a company. However, it is essential to have qualified people at the plants who have responsibility for implementing recommended actions and who will have less organizational resistance to overcome. There is a need for expert staff even when working with systems that implement artificial intelligence. There are too many variables interrelated in complex ways that might not be part of an automated measurement system to make an artificial intelligence system completely reliable.

5.14.6 Industry Trends

The interview concluded with a question of whether the power industry as a whole was becoming more focused on thermal performance given rising fuel costs and the effects of deregulation. The interviewees expressed the view that the industry is not moving consistently toward improved thermal performance. They cited examples in which some companies have displayed sustained commitments to thermal performance, and others have reduced their commitments.

5.15 Summary

This section documents 13 interviews describing thermal performance programs for 13 power companies and includes a consulting company's view of thermal performance programs in the electric power industry. The case histories are based on conversations with thermal performance engineers, many of whom had over 20 years' experience working as performance engineers. The case histories provide a broad overview of both the tools that are being used for on-line performance monitoring and the key factors for effective use of the on-line systems.

All companies interviewed have access to archival process data for all units in their systems. Most companies have purchased commercially available, stand-alone data historians, and a few others used the historians available with their DCS; one has developed a data historian in house. All companies are using the archival data at some level for monitoring the components in the turbine cycle. Most companies interviewed have comprehensive on-line turbine cycle analysis systems that monitor overall turbine cycle heat rate, controllable losses, turbine performance, condenser performance, feedwater heater performance, and boiler feedpump performance. Many of the plants had purchased commercially available systems, and several had used tools available with the data historians to develop monitoring systems within their companies.

There is wide disparity in how the information from these monitoring systems is being used in heat rate improvement programs. Heat rate improvement programs consist of the following four basic steps:

1. Identify the target performance.
2. Measure the actual performance.
3. Identify where the deviations occur.
4. Implement actions to eliminate the heat rate deviations.

Each one of these steps is important for using information from an on-line monitoring system effectively. The following summary describes each of the case histories with respect to this established framework.

When a company sets a target performance, it is important to note that, with turbine cycle heat rate monitoring systems, default target performances of the individual components are usually available in the form of constants, curves, lookup tables, or a heat balance code that runs in the background. However, these default targets embedded in software are not considered effective for completing the first step of a heat rate improvement program. Software targets provide guidance only on what should be fixed. Performance targets must be established at a corporate level to motivate employees to improve thermal performance.

Approximately one-half of the power companies (Interviews C, E, F, G, I, and L) stated that they have established performance targets that are integrated into their performance evaluation programs for each of their units. Company M will begin this in the next year. The two primary methods used by the companies to identify the target performance are basing the target on past performance and using design information and heat balance codes.

On-line monitoring systems can play a key role in measuring actual performance and helping personnel identify the source of heat rate changes. Nine companies (Interviews B, C, F, G, H, I, J, L, and M) have implemented turbine cycle heat rate monitors that measure overall turbine cycle and component performance throughout most of their systems. One company (Interview D) has installed on-line systems on two units and is in the process of expanding them throughout the company. One company (Interview A) has installed on-line monitors on many units within its system but is no longer supporting it on a corporate-wide basis. Another company (Interview E) has installed controllable loss monitors throughout its system and has comprehensive monitoring systems installed on a few units. The performance engineers interviewed did not point out faults with the on-line systems, indicating that this technology is perceived as effective and available from many sources. The technology currently in use is either commercially available or developed within companies using tools available in the data historians.

The final step of a heat rate improvement program is arguably the most important: implementing actions to reduce or restore heat rate. There were a wide variety of approaches for accomplishing this. Some companies (Interviews C, G, and I) dedicated performance personnel at a central site who worked closely with plant personnel to implement heat rate improvements. Interview F described a situation in which the plant staff evaluated heat rate changes and implemented heat rate improvement actions. Other companies (Interviews B, D, H, and J) have central support staffs but do not have dedicated staff resources at the plant sites. Company E has partial performance monitoring capabilities at a central site without dedicated resources at the plant sites. Company A has a central staff with significant experience in thermal performance, but there is no overall framework in place for it to work with individual plants for heat rate improvement. Company K has no central staff dedicated to thermal performance monitoring and places minimal emphasis on thermal performance. Companies L and M described an approach in which thermal performance responsibilities were distributed among plant personnel, field offices, and central staff.

Table 5-1 provides a summary of the thermal performance interviews. Readers are strongly encouraged to read the entire section to gain a more complete overview.

Table 5-1
Summary of Thermal Performance Interviews

Company	Thermal Performance Monitoring Tools	Comments
A	No systemwide turbine cycle heat rate monitor, DataFuser from General Electric, custom historian	Sharp decline in emphasis on thermal performance since 1990s.
B	PI, custom turbine cycle heat rate monitor based on EPRI's PMW, used systemwide	Fleetwide monitoring center; one plant with performance engineer; limited capacity promotes management interest in heat rate.
C	PI, EtaPRO, custom turbine cycle heat rate monitor used systemwide	Strong emphasis on thermal performance; comprehensive, systemwide approach to practice and technology.
D	EtaPRO, PI	Company in initial stages of implementing centralized thermal performance program.
E	PI, EtaPRO, custom turbine cycle heat rate monitoring tools	Primary emphasis is on operator-controllable losses.
F	PMAX, Total Plant Performance Monitor and PHD Historian from Honeywell, EPRI PlantView	Strong emphasis on thermal performance; comprehensive approach at a single plant to practice and technology.
G	AspenTech, custom turbine cycle heat rate monitor used systemwide	Strong emphasis on thermal performance; comprehensive, systemwide approach to practice and technology.
H	EtaPRO, PI	Company in initial stages of implementing fleetwide thermal performance monitoring center.
I	PMAX, Emerson GPA, PI	Strong emphasis on thermal performance; comprehensive, systemwide approach to practice and technology.
J	PI, custom turbine cycle heat rate monitor used systemwide	Sharp decline in emphasis on thermal performance since 1990s.
K	PI, no systemwide turbine cycle heat rate monitor	Minimal emphasis on thermal performance.
L	PI, EtaPRO, custom turbine cycle heat rate monitor	Distributed approach to thermal performance monitoring.
M	PI, custom turbine cycle heat rate monitor used systemwide	Distributed approach to thermal performance monitoring.

6
REPORT DISCUSSION

This report describes the details of on-line turbine cycle thermal performance monitors and the business culture in many companies that supports thermal performance improvement. Looking at both aspects provides a framework for understanding the needs of the electric power industry.

Since EPRI's demonstration project with on-line monitoring systems at Morgantown Unit 2 [1, 5, 6, 7], the technology supporting on-line monitoring has become very mature and is now widely commercially available. Several of these systems are described in detail in Section 4. In addition, many companies have developed their own customized systems using development tools commonly available with data historians. The calculations common to many on-line systems are described in Section 3. Because the technology is mature and widely available commercially, the packages provide much of the same functionality and effective tools for a power company's thermal performance monitoring program.

Although the technology of on-line turbine cycle heat rate monitoring has matured and is fairly uniform from one system to the next, the importance placed by management on heat rate improvement has changed significantly since the 1980s and now varies widely from company to company. In the 1980s many companies employed large central staffs whose primary role was thermal performance. For example, it was not uncommon for a central thermal performance staff to consist of 15 or more engineers and technicians with additional support heat rate engineers and technicians located in each plant. Today, some large companies have completely eliminated full-time thermal performance staffs or have reduced them to just a few employees.

Although improved technology can help companies implement effective thermal performance programs with reduced staffs, interviews with many performance engineers show that in practice this has generally not been the case. A heat rate improvement program requires the following four basic steps:

1. Identify the target performance.
2. Measure the actual performance.
3. Identify where the deviations occur.
4. Implement actions to eliminate the heat rate deviations.

Of the utilities interviewed, only 6 out of 13 clearly stated that they currently have a process that systematically performs each of these steps.

The discussions with thermal performance engineers highlighted many key points about heat rate improvement programs. The following is a summary of these points:

- The resources that a company commits to thermal performance are driven by management support and company culture. Companies with the more extensive heat rate programs were typically managed by personnel with performance engineering backgrounds and significant experience in coal-fired power plant performance.
- Success requires a long-term commitment by management to create an environment that sustains ongoing thermal performance improvement. Education is a key component of this commitment.
- The regulatory environment in which a company operates does not necessarily determine the characteristics of its thermal performance program. Companies that both do and do not commit resources to thermal performance can be found in both regulated and deregulated markets.
- Effective thermal performance programs require personnel engaged at the plant level. Fleetwide thermal performance monitoring is an effective strategy for leveraging limited personnel resources, but it requires plant level resources to effectively implement heat rate improvement recommendations.
- Measuring the efficiency of a coal-fired unit is difficult, requires significant resources, and might be a primary obstacle for implementing heat rate improvement programs. For example, many companies use the input-output method to quantify unit heat rate, which has an error of 3–6%, according to ASME [28]. Errors of this magnitude will obscure changes in performance caused by equipment and operational changes, thereby making it difficult to measure the improvement or degradation of heat rate over the short term.
- Reducing short-term financial obligations by eliminating personnel is easy to quantify and will provide a measurable and immediate decrease in a plant's production costs. However, sustaining a thermal performance program requires that long-term objectives are not sacrificed for short-term cost reductions.
- With the move to a deregulated power market, staffing levels for thermal performance have decreased dramatically since the early 1990s. This reduction in staff parallels a lowered emphasis on thermal performance. There does not appear to be any immediate and significant shift in the U.S. power industry to promoting the thermal efficiency of coal-fired plants.

7 CONCLUSIONS

The authors have reached the following conclusions:

- Turbine cycle heat rate monitoring is a very mature technology. Both commercially available and custom systems are in use throughout the U.S. electric power industry.
- Thermal performance programs vary widely among power companies. A few companies place a strong emphasis on thermal performance and have maintained a thermal performance staff, and others place minimal emphasis on thermal performance and have almost completely eliminated the thermal performance staff.
- Management support is the primary factor in maintaining a successful thermal performance program. Companies with stronger thermal performance programs are generally managed by personnel with significant fossil plant experience.
- Successful heat rate programs require a sustained, long-term commitment.
- Companies in both regulated and deregulated power markets were interviewed. The move toward deregulation has not motivated most companies to focus on thermal efficiency.
- On-line monitoring systems provide the key technology to enable fleetwide monitoring centers that can leverage the knowledge of a few performance engineers across a system. However, a successful heat rate program still requires knowledgeable personnel who work closely with the monitoring center in the plants.

The changes in the electric power industry have led to significant downsizing over the past two decades and a dramatic reduction in thermal performance staffing levels. The electric power industry is still changing rapidly, given the changing market structure, volatile fuel prices, and changing environmental regulations. Maintaining and improving a thermal performance program is an effective strategy for mitigating the effects of each of these factors.

Although on-line monitoring systems are a key technology for thermal performance programs, effective heat rate programs are built on process as the first ingredient and technology as the second. Creating and implementing the necessary management processes requires a long-term commitment. Companies that pursue this sooner rather than later will be better prepared to adapt to the changes that will occur.

8
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