On-Line Monitoring for Equipment Condition Assessment

Application at Progress Energy

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Technical Update, December 2004

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PRODUCT DESCRIPTION

This technical update discusses the emerging technology of equipment condition assessment based on on-line monitoring technologies. A preliminary review of the evolution of equipment condition assessment techniques is presented, leading to the current state of the art. Current equipment condition assessment technology has the capability to provide early warning before failure, allowing maintenance staff to proactively schedule maintenance accordingly, during more ideal conditions than reacting to a failure. The foundation of this technology is on-line monitoring, which has been the subject of EPRI studies for the past decade. Both on-line monitoring and equipment condition assessment are reviewed herein. A recent implementation plan for Progress Energy is described; however, no evaluations or results were available at the time of this writing. In addition, an overall view of EPRI's experience and vision are presented.

Challenges & Objectives

Equipment condition assessment technology presents an attractive alternative to post-failure reactive maintenance. By proactively scheduling and performing maintenance on components forewarned to fail, the repairs can be completed efficiently and at the most optimal time given the current state of the plant. Additional benefits can be acquired through enhanced safety, reliability, and the knowledge gained through continuous assessment of critical plant components. Equipment condition assessment technology has successfully been implemented in other industries, in recent years, with exceptional results. Power plant systems are expected to see similar results, though due to the more complex nature and individual characteristics of different plants, successful implementations will require significant initial oversight. As experience is gained, this initial investment will be reduced. While the capabilities are scalable from individual component monitoring to whole-plant monitoring, the greatest benefits would be for fleet-wide based applications, whereby the benefits of the technology could be exploited on a fleet level and the majority of the detailed analyses required could be conducted at a centralized location by trained personnel.

Applications, Values & Use

Equipment condition assessment software solutions are currently available. Their application to specific plant sites will require significant oversight and operations experience to produce accurate and reliable diagnostic/prognostic tools. It is in these areas where significant guidance and expertise are currently required. As the technology achieves more widespread use, the availability of model templates will simplify the implementation process. As many utilities look forward to centralized monitoring and diagnostic centers, the integration of equipment condition assessment tools with existing monitoring and maintenance technologies will lead to an intelligent top-down approach to plant maintenance and scheduling. Beyond this will be the integration of these technologies into risk-based and cost-based assessments, allowing maintenance to be completed to achieve the optimal balance between plant safety, reliability, and financial returns.

EPRI Perspective

EPRI has supported the development of on-line monitoring in the nuclear industry since the 1980s. In 1994, EPRI formed the EPRI/Utility On-Line Monitoring Working Group with the goal of obtaining Nuclear Regulatory Commission approval of on-line monitoring as a calibration reduction tool for safety-related instruments. Building on this experience EPRI began working on the Fleet-wide Advanced Plant Asset Monitoring project, utilizing equipment condition assessment technology. In this latest project EPRI uniquely brings together vendors and utilities while incorporating operational expertise to enable a seamless integration of equipment condition assessment systems into electrical generation facilities.

In addition to the calibration reductions and equipment condition assessments of on-line monitoring technologies, the overall vision is to create a fleet-wide monitoring system that enables both of these capabilities as well as merges other existing maintenance technologies. EPRI experience and expertise dictates a prominent role of guidance, oversight, and recommendations to achieve this level of integration.

Approach

This technical update presents a brief introduction to equipment condition monitoring or equipment condition assessment, and further describes the early plans and projected scope of a collaborative effort between Progress Energy, Smart Signal Corporation, and EPRI. The purpose of this report is to accomplish the following:

- Provide an overview of equipment condition assessment and its development history
- Discuss the potential benefits of applying on-line monitoring technology to equipment condition monitoring
- Discuss specific issues relevant to the implementation of equipment condition assessment systems.
- Describe related efforts in being co-sponsored by EPRI in on-line monitoring based equipment condition assessment.
- Describe the initial implementation and project plans for the implementation of an equipment condition assessment at a Progress Energy fossil site.

Keywords

On-Line Monitoring
Equipment Condition Assessment
Equipment Condition Monitoring

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OVERVIEW OF EQUIPMENT CONDITION ASSESSMENT

Most fossil power plants contain an abundance of on-line operating data that is archived to provide detailed information concerning the operation of many plant components. The data for these components includes operating temperatures, pressures, flows, and vibration levels. As sensor technology advances, hardware will improve in quality and become lower in cost and add to the quantity of on-line operating information.

Although there is an abundance of data, much of it remains unused. The process by which data is converted to information requires a great deal of attention from knowledgeable plant personnel. For example, a common technique for gathering information from data is for plant personnel to view trend plots or time series of the data on a periodic basis (e.g. daily or weekly). When changes occur, more data analysis can be performed to determine probable causes. There are problems with this approach. Data analysis is a time intensive task and requires sustained attention by trained people. Most power companies are not structured to allocate the required personnel to this task. Unless the appropriate people are assigned exclusively to this task, more urgent plant activities will always receive priority over routine data analysis. Another problem with this approach is that often, when changes in trends plots are apparent, the equipment has degraded significantly and excessive equipment damage has already occurred.

A technology that can enhance plant personnel's ability to detect equipment condition problems has been developed for the nuclear industry and has recently become more widely commercially available. Empirical based modeling techniques have been shown to detect changes in equipment operation long before they are apparent in trend plots. An additional advantage is that it can be highly automated to analyze large sets of data with no human interaction and provide alarm reports to highlight components or sensors that have changed.

EPRI has initiated a project to evaluate this technology for components in a fossil plant. EPRI is working with Progress Energy to evaluate this technology. The objective of this project is to evaluate this technology with respect to several factors that include: the level of automation it provides, the accuracy for detecting events and preventing false alarms, and understanding patterns that can be used to diagnose specific condition problems.

In this chapter, a brief summary of the early approaches to equipment condition assessment are provided leading up to the methodology of equipment condition assessment based on on-line monitoring technology, the subject of this report. Issues related to the implementation of such systems are also discussed, along with the proposed benefits.

1.1 Evolution of Equipment Monitoring

Whenever a company has owned an asset that produced a good, from which they made money, the company has benefited by ensuring that the asset operates reliably for as long as possible. This prompted the development of the first equipment condition monitoring system which consisted of humans walking from machine to machine and listening, seeing, smelling, and perhaps feeling to monitor how well the machine or equipment was operating. Analyzing the data obtained from this system was very straightforward. If a problem was detected and deemed significant, immediate action could be taken by the operator involved.

A problem with walk around systems is that intensive personnel resources are required to obtain small amounts of data. The next improvement on the walk around system was the strip chart recorders. One operator in a control room then had the ability to simultaneously view several key process parameters. However, a problem with this system was that viewing and analyzing archival data was extremely time intensive and was probably rarely performed.

In the last few decades the computer and instrumentation revolution spurred by low cost microprocessors has led to a huge increase in the quantity and quality of on-line and archival data. Most fossil plants now have thousands of on-line data points. As the amount of on-line and archival data has increased, the techniques by which these data are analyzed and incorporated into a company's decision matrix has become a fundamental issue to the company's competitiveness. Of course data alone does not provide a benefit to a company. Rather, the actions a company takes based on accurate information it receives from the data is where the benefit occurs. The key step in this process is converting the data to information upon which actions can be based.

There are many techniques for converting data into information. The techniques gain value as the level of automation increases and as the information about the action to take based on an analysis becomes more specific. Understanding which are the most appropriate techniques to use is not straightforward. A brief survey of the data mining industry reveals that there are many companies, many of which offer unique sets of tools. The number of techniques will surely increase because of growing data resources and the huge profits to be gained from timely decisions based on accurate information. It is also likely that there will be no single technique that provides the one key for converting data into the key information a company needs. The type of data is simply too diverse.

In the power industry, the most common technique by which data is converted into information is for knowledgeable plant personnel to view trend plots of the data. The efficiency of this approach improves as computer hardware and software evolve, but a fundamental limit is the human operator's time, knowledge, and attention span. The next evolution of this technique is to apply filters and compare the data values to upper and/or lower limits. Whenever the data exceeds a limit an alarm is automatically triggered, prompting an operator's attention.

Moving beyond techniques of simple trending leads to approaches based on empirical, data-driven modeling, which has the capability of automatically analyzing trends between multiple variables and indicating when the current trends deviate from the normal trends, based on historical operational data. Further, empirical model based approaches to equipment condition assessment link trend deviations to specific instrument channel, component, or system degradation mechanisms.

The first step in empirical based modeling is to obtain data that define how a given component operates in a normal state. For the purposes of the present discussion, a set of data consists of a series of vectors, with each vector consisting of values for a set of instrument channel measurements related to the component or equipment being assessed. This data set is used to develop a model that determines the relative value of each given point as compared to all points in the data set. Once a model is developed or *trained*, subsequent data sets can be evaluated by the model which will detect whenever the relative value of a point has changed indicating a change in either the sensor or the point being monitored. Changes detected with this approach are commonly referred to as anomalies. *Training* refers to the process of embedding the information defining the normal state of a component into an empirical model of that component.

Empirical based modeling represents a fundamentally different approach to analyzing data than viewing trends of the data. With data trending, the primary knowledge source is trained plant personnel. Because of their experience, they can view trends and understand when data has changed based on their experience of the system. With empirical based modeling, the primary knowledge source is a trained numerical model. In many cases the numerical models can detect much smaller changes in the data than is possible with data trending and it is amenable to higher levels of automation.

An empirical model of a system or component can be used in different ways that include evaluating changes in how a unit is operated, evaluating sensor drift, or for equipment condition assessment. The terminology for these various applications can be confusing; therefore, a few definitions are appropriate. Considering the identification in how a unit or component is operating refers to the ability of an empirical model to identify process changes. These process changes are defined as changes in the relationships between monitored parameters that were unexpected based on the relationships present in the historical operational data used to develop the model. Applying empirical modeling to evaluate sensor drift was one of the first applications of this type of technology in the power industry, and is more commonly referred to as on-line monitoring. EPRI has been actively involved in the implementation of on-line monitoring technology for nuclear power plants for the past decade, and a wealth of documentation surrounding those efforts is available elsewhere [*On-Line Monitoring of Instrument Channel Performance, Volumes 1-3,* EPRI, 2004]. Equipment condition assessment is a direct extension of on-line monitoring and refers to the process by which empirical modeling is used for predictive maintenance of plant components. The ultimate objective is to not only detect anomalies but also to determine the root cause of the problem based on the pattern of anomalies.

A description of equipment condition assessment techniques based on empirical models follows in the next section, preceded by an introduction to on-line monitoring technology which was the foundation from which the current equipment condition assessment systems evolved. A more detailed description of equipment condition assessment is available in *Equipment Condition Assessment Volume 1* [EPRI, 2004].

1.2 On-Line Monitoring: The Foundation of Equipment Condition Assessment

On-line monitoring is an automated method of monitoring instrument performance and assessing instrument calibration while the plant is operating, without disturbing the monitored channels. On-line monitoring of instrument channels is possible and practical owing to the ease with which data acquisition and analysis of instrument channel data can be performed. In essence, on-line monitoring provides a proactive and beneficial approach to performing periodic instrument surveillances. It accomplishes the surveillance or monitoring aspect of calibration by comparing redundant or correlated instrument channel measurements with independent estimates of these parameters. It does not replace the practice of instrument adjustments; instead, it provides a performance-based approach for determining when instrument adjustment is necessary, as compared to a traditional time-directed calibration approach.

On-line monitoring differs from channel calibration in that the channel is not adjusted by the process of on-line monitoring. Instead, on-line monitoring compares channel measurements to empirical model estimations to determine if a channel calibration is necessary. The abilities of on-line monitoring techniques to indicate calibration status have been well demonstrated. Indications are based on the assumption that the empirical model's estimations are accurate and by comparing these estimates to the measured values output by the instrument channels, their calibration status can be monitored. When the residual difference between the measured and estimated values becomes *significant*, the channel is suspected to be out of calibration. Over a fairly short span of time, this suspicion can be verified by the consistent reporting that the channel is out-of-calibration. The significance of residuals can be determined by a variety of different methods, and the appropriate method to use is often case specific. Simple thresholding is sometimes applied, as well as more sophisticated statistical techniques. Figure 1-1 is provided to illustrate the monitoring capabilities. From the beginning of the plot the channel status is being reported as out-of-calibration. As indicated in the figure, the channel was re-calibrated and the residual difference subsequently reduced. Following the calibration, the channel status reverted back from out-of-calibration to normal.

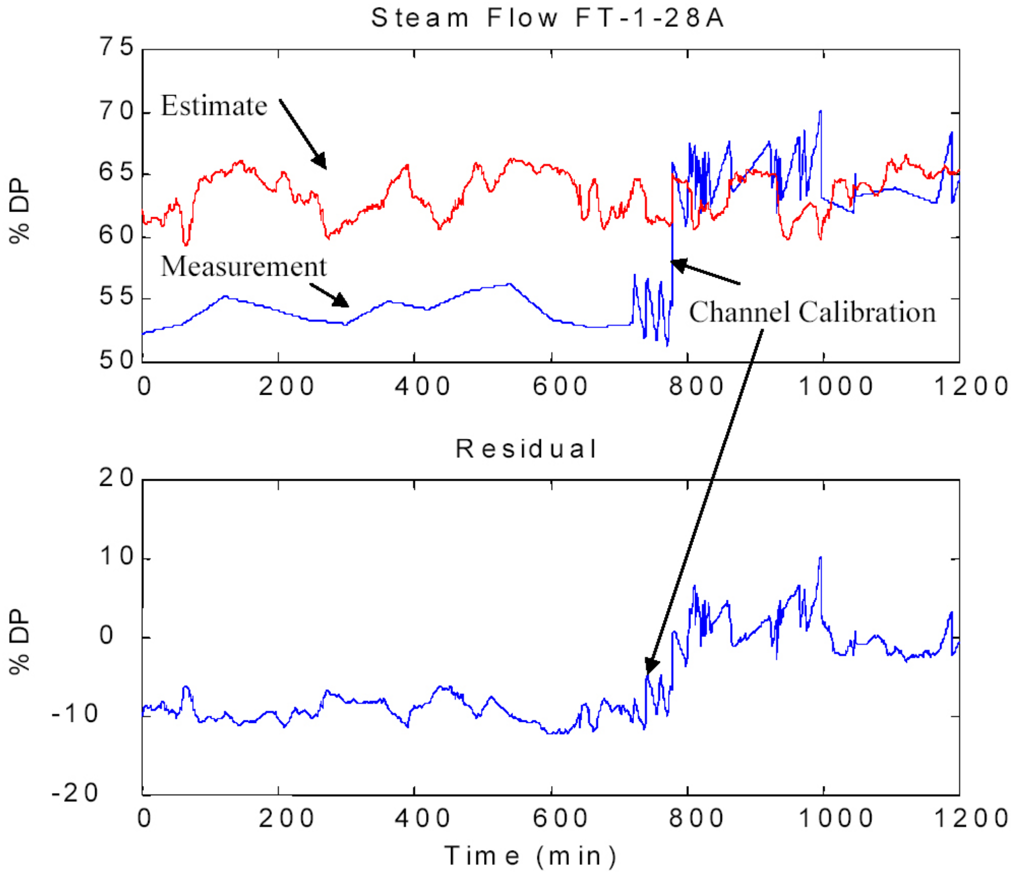

Figure 1-1Sensor validation example showing an out-of-calibration condition which was remedied following a recalibration.

Thus, on-line monitoring presents an alternate approach to time-directed periodic calibration, which will provide calibration maintenance capabilities that are equivalent to the traditional periodic calibration schedules. On-line monitoring allows for the use of condition-based calibration schedules, since the calibration status of the monitored channels is continuously verified to be within tolerable limits. Condition based calibration schedules present several advantages, including: reduced labor costs, reduced personnel radiation exposure, and increased instrument availability. Condition based calibration activities may also increase the usable life of an instrument through reducing the risks of instrument damage incurred during adjustments.

While calibration reduction is one possible benefit from sensor validation technology, other benefits are performance monitoring and information filtering. Performance monitoring is achieved through the continuous evaluation of the process, whereas information filtering results from the characteristic of an empirical sensor validation model to highlight specific areas of the process that may need attention. Thus, an operator can focus their attention on process variables exhibiting suspect behavior rather than the entire suite of process variables. Further benefits may be realized if a sensor validation system is linked to an anomaly interpreter. When a sensor validation system identifies changes in a monitored parameter's residual, it is referred to as an anomaly. Given a specific component outfitted with the standard sensors, it may be the case that a series of noted anomalies for these sensors indicate a particular component degradation mechanism. When more than one anomaly is being reported simultaneously, interpretations of the sensor validation system outputs will aid in understanding the current state of the monitored component or system and constructing a concise, usable prognosis. This concept is generally referred to as Equipment Condition Assessment. In essence, equipment condition assessment technologies can be built on the foundation of a sensor validation model simply through the appending of an anomaly interpreter. The substantial benefit through this approach is due to the sensitivity of sensor validation models to changes in the monitored process. Often, slight discrepancies or changes in the data are identified, which would otherwise go unnoticed until later in the operating life when the change becomes less subtle. Equipment degradations will generally provide mild indications well in advance of a failure. If these mild indications can be identified, and linked through an interpreter so that simultaneous anomalies can be translated into an accurate prognosis, equipment failures can be avoided. This final benefit of identifying component failure through early warning is the focus of equipment condition assessment.

1.3 Equipment Condition Assessment System Highlights

The utility of an equipment condition assessment model in providing early warning of impending equipment condition failure or degradation is based on combining the detected anomalies from an on-line monitoring system with a method to interpret these anomalies.

The key benefit of ECM technology is that of *early warning*. The premise is that prior to a component failure there will be precursory indications in the associated instrument channels. Through the identification of these indications a warning of pending component failure can be provided that will allow for:

- Maintenance plans to be arranged at the most convenient time, considering the current operating environment within which the notice was provided.
- Increased plant safety by eliminating a hazardous component failure while operating.
- Reduced down-time and cost due to the timely efficient repair enabled by the early warning.

A successful equipment condition assessment program will provide a diagnostic system to detect equipment failures early enough to warn operators in advance of impending failures and to inform maintenance personnel about the nature of the failure. A successful ECM program must:

- Have a clear understanding of failure modes
- Have installed instrumentation capable of detecting each failure
- Instrument signatures must be definable for each failure mode

- Failure mode must progress slowly enough to allow early detection

- On-line monitoring model must provide indication of impending failure that is so unambiguous that it prompts early action

- Probability of false alarms must be negligible

A clear understanding of failure modes is required for setting up and optimizing equipment condition assessment models. A failure mode must be definable for its detection to be available, and differentiable from competing failure modes for its diagnosis to be available. The failure mode must be slow enough such that the onset of failure can be identified well in advance with enough confidence in the prediction to allow personnel to either shut equipment down for repair or recommend scheduled downtime. The assessments made by the system must be unambiguous to establish confident decisions and negligibly false to maintain personnel confidence in the system itself.

1.4 Equipment Condition Assessment Model Development

The development of an ECM model based on OLM technology requires the following general steps:

1. Select Component

2. Construct an Empirical Model

3. Define Failure Modes

4. Create Failure Signature Chart

5. Develop Anomaly Interpreter

While the first 2 steps are required for on-line monitoring in general or equipment condition assessment, the last 3 steps are specific to equipment condition assessment. To provide a useable diagnosis regarding the current condition of a given component, the possible failure modes must be defined. The equipment condition assessment model can be set up to accurately diagnose failures for which the degradation mechanisms are known. The detection of anomalous behavior may also indicate unknown failure mechanisms but the model can only alert to this unknown failure and will not have the ability to specify the failure.

The development of a failure signature chart for a given system or component can be based on simulations and/or historical data. A failure signature chart is a unique pattern of anomalies that relates to a specific component degradation mechanism.

Interpretation of the observed anomalies requires the setting of probabilities associated with each possibly anomaly to each possible failure mode, or alternatively the design of a logic rule-base for the same purposes. Figure 1-2 illustrates the required components of an equipment condition assessment system along with indications of the current availability of each of these components.

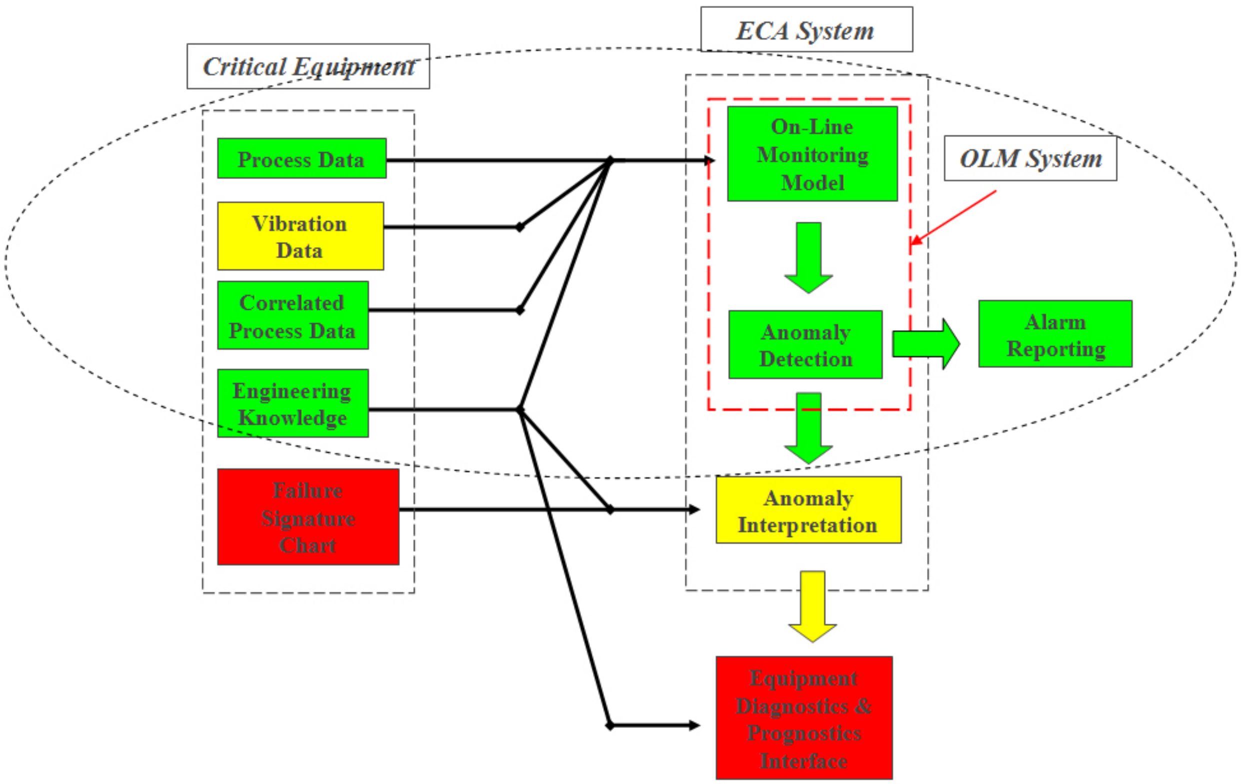

Figure 1-2 Equipment Condition Assessment and Diagnostics Flow Diagram

There are 3 main subcomponents in Figure 1-2: the critical equipment, the ECA (equipment condition assessment) system, and the equipment diagnostics and prognostics interface. The colors indicate readiness of each specific subcomponent in the figure. Green indicates that the technology or subcomponent is currently available. Yellow indicates that the technology is available, though not necessarily proven to the point that it can be reported readily available. Red indicates a subcomponent that has not been developed. The components included in the dashed oval are presently available and well developed. Development considerations surround all other components in the figure.

A specific piece of equipment to be monitored has the following set of subcomponents: process data, vibration data, correlated process data, a base of engineering knowledge about the equipment, and a failure signature chart. The 2 subcomponents that are not readily available in many cases are the vibration data, which in many cases can be easily made available through the addition of vibration sensors and the proper connections, and the existence of a failure signature chart. Both of these issues are currently being addressed in EPRI projects. While some failure signature charts currently exist, they are the property of software vendors and are not in the public domain. The engineering knowledge is required every step of the way in the equipment condition assessment system development. Process and vibration data is required by the on-line monitoring system, and the failure signature charts are essential for the anomaly interpretation.

The second main subcomponent: the ECA system is readily available through outside software vendors. Both on-line monitoring models and anomaly detection are well studied and understood. The theoretical basis for anomaly interpretation is readily available, though the status of this subcomponent is still regarded as incomplete (yellow) because this subcomponent is application specific. Over time and with experience a base of knowledge in developing equipment condition assessment systems and repeated applications on similar types of equipment will enable a more streamlined and efficient approach to defining anomaly interpretation modules.

The final main subcomponent, the diagnostics and prognostics interface, has not been developed specifically for equipment condition assessment applications. It is this component that ties all of the technology and information together and formulates a usable diagnosis, prognosis, or recommendation. This is the most essential module related to the success of an equipment condition assessment system in assigning accurate, concise, and unambiguous diagnoses and succinctly relaying this information to plant personnel.

1.5 Equipment Condition Assessment Implementation Issues

While commercial equipment condition assessment software systems are available, there are several issues that must be addressed before their full potential can be realized for power plant applications:

- Adequacy of existing instrumentation for detecting equipment failure modes.
- Identifying additional sensor types and emerging technologies that can provide enhanced capabilities.
- Incorporating qualitative information as well as numerical data collected at random intervals.
- Integrating the diagnostic outputs from equipment condition assessment systems into existing plant information systems to make efficient use of the technology while limiting additional unnecessary maintenance.
- Defining critical equipment and the financial impact of degradation or failure to develop supporting business case.

1.6 Benefits of Equipment Condition Assessment

There are a multitude of benefits that can be obtained from the implementation of an equipment condition assessment system. The most apparent benefits are listed below:

- Provide system engineers and maintenance staff with necessary information to make informed, cost-effective operations and maintenance decisions based on the actual condition of the system/equipment

- Provide more options to the operations staff to handle the fault and its consequences
- Allow earlier mitigation or corrective actions
- Reduce the likelihood of unplanned plant trips or power reductions
- Reduce challenges to safety systems
- Reduce equipment damage
- Reduce likelihood of repetitive failures
- Facilitate the implementation of condition-based predictive maintenance practices
- Significant cost-benefits in excess of $1M/year (estimated

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IMPLEMENTATION PLAN FOR PROGRESS ENERGY FOSSIL

In October 2004, work began to implement an equipment condition assessment system at Progress Energy’s Mayo fossil plant. The Mayo Fossil Plant is located near Roxboro, NC. Mayo and is a 745 MW unit with a split furnace. This work is a collaborative effort between Progress Energy, Smart Signal Corporation, and EPRI. The initial implementation has included 2 boiler feed pumps, 2 ID fans, and 2 FD fans. Two models were created for each component, a thermal performance and a mechanical model. The thermal performance model contains points the include temperatures pressures and flows that affect the thermal efficiency of each component. The mechanical components include temperatures and vibration readings that are affected by the condition of machine elements (e.g. bearings). The implementation plan is to expand this effort to include the most critical components across the entire plant. Smart Signal has prepared the initial models for the site demonstration and the EPRI I&C Center will be involved with model performance evaluations and improvements. Currently, a link between Progress Energy's plant server where the equipment condition assessment models are running and the EPRI I&C Center staff computers is being established.

While applying equipment condition assessment systems to plant components has been widely reported, EPRI plans under this project to investigate their applicability to control systems. Control system monitoring could alert operators of abnormal behaviors in control system loops. This novel approach to control system optimization will be evaluated during this collaborative project, though results are not yet available.

This current objective in the fossil industry draws on a prior EPRI effort in evaluating the use of equipment condition assessment systems for pulverizer monitoring [*On-Line Predictive Condition Monitoring System for Coal Pulverizers: Application of Wireless Technology*. EPRI, Palo Alto, CA. Smart Signal Corp, Lisle, IL. & Dynegy Midwest Generation, Decatur, IL: 2003:1004902].

A related effort at Progress Energy has been focused on the implementation of equipment condition assessment systems for their fleet of combustion turbines using the SmartSignal eCM equipment condition assessment software package. This project plans to evaluate the use and performance of an equipment condition assessment system plant-wide for the Mayo fossil plant.

During the course of this project, the EPRI I&C Center staff will assist in a further deployment of equipment condition assessment models across the Mayo plant. In addition, the system will be monitored and evaluated with the intention of finding areas for improving or enhancing the initial models. The application of the technology to control system loops will also be investigated. A future EPRI technical update will provide further results on the project.

Proper control system performance is an important component of overall plant performance and reliability. Poor control system performance leads to off-design operation and excessive variability in key plant parameters such as excess oxygen and steam temperatures. Excessive oscillations in plant response can also mask other process problems from detection by operator and plant engineers.

Historically control system performance has been monitored in an ad hoc fashion by the plant operators in the normal course of running the plant. This works well for detecting equipment failures but is less effective at detecting poor performance. Studies in other industries have shown that a large percentage of the control loops in a plant do not perform well primarily because of tuning or actuator problems.

Several vendors have commercial products today for monitoring control system performance using a variety of proprietary techniques. EPRI even developed a system several years ago that used control loop error analysis to assess control system performance. One problem with these techniques is the control system response in a power plant depends greatly on the operating conditions on the plant. For example, when a plant is operating a steady state full load, the control system is not being challenged and as a result the control system performance might appear to be very good. However if the plant suddenly has to reduce load, the control system will now be tested and the performance may not be optimum. In other words, the variability of the controlled parameters in the plant will depend on whether the plant is at a steady load or is changing load. Some plants are base-loaded and change load very little, while others are load following and change load all the time. Parameters such as steam temperatures will vary much more on the load following plant than on the base loaded plant even if the control system performance is identical on both.

Empirical modeling techniques have the potential to learn the characteristics of the control system response in both steady load and load changing conditions. As a result, they should be more sensitive to changes (anomalies) in control system performance than other types of analysis techniques.

In this project, empirical models will be developed for a few key control loops. The inputs to the models will be the inputs and outputs of the control loop and possibly a few internal points in the loop as well. In particular, the command signal to the actuator and the position feedback from the actuator will be included in the model since the actuator is where a large number of problems occur. These models will also be capable of detecting when loops are operated in manual mode and when tuning changes are made to the loops. Obviously these kinds of changes can be detected in other ways, but this type of technique provides a significant data reduction function which makes it much more likely the anomaly will actually be detected.

One weakness of this technique is that only relative changes in the performance can be detected, not absolute performance. If the loop is performing badly in the model training data set, then it will not be detected when the model is running online. Some of the other vendor's products assess the absolute performance of the loop, which can be important in some situations.

3

REVIEW OF EPRI EXPERIENCE WITH EQUIPMENT CONDITION ASSESSMENT, PAST AND FUTURE

EPRI has supported the development of on-line monitoring in the nuclear industry since the 1980s. In 1994, EPRI formed the EPRI/Utility On-Line Monitoring Working Group with the goal of obtaining Nuclear Regulatory Commission approval of on-line monitoring as a calibration reduction tool for safety-related instruments. Building on this experience EPRI began working on the Fleet-wide Advanced Plant Asset Monitoring project, utilizing equipment condition assessment technology. In this latest project EPRI uniquely brings together vendors and utilities while incorporating operational expertise to enable a seamless integration of equipment condition assessment systems into electrical generation facilities.

In addition to the calibration reductions and equipment condition assessments of on-line monitoring technologies, the overall vision is to create a plant-wide monitoring system that enables both of these capabilities as well as merges other existing maintenance technologies. EPRI experience and expertise dictates a prominent role of guidance, oversight, and recommendations to achieve this level of integration.

The first implementation experience gained by EPRI was in collaboration with Dynegy Midwest and SmartSignal Corporation. That project involved the implementation of an equipment condition assessment system for a coal pulverizer [*On-Line Predictive Condition Monitoring System for Coal Pulverizers: Application of Wireless Technology*, EPRI 2003]. Rather than a basic equipment condition assessment implementation, the project included the integration of vibration data through the installation of a wireless vibration sensor system, with the intent of enhancing the diagnostic capabilities of the condition assessment system. The results indicated that the percentage of known failures that could be predicted with early warning increased from 11%, using the original suite of instrumentation, to 46%, with the addition of the vibration sensors (Figure 3-1). Along these lines, the traditional vibration based maintenance practices are envisioned to eventually merge into an overall monitoring system where traditional methods are available along with enhanced diagnoses made available by the degradation and future predictive capabilities of an integrated equipment condition assessment system.

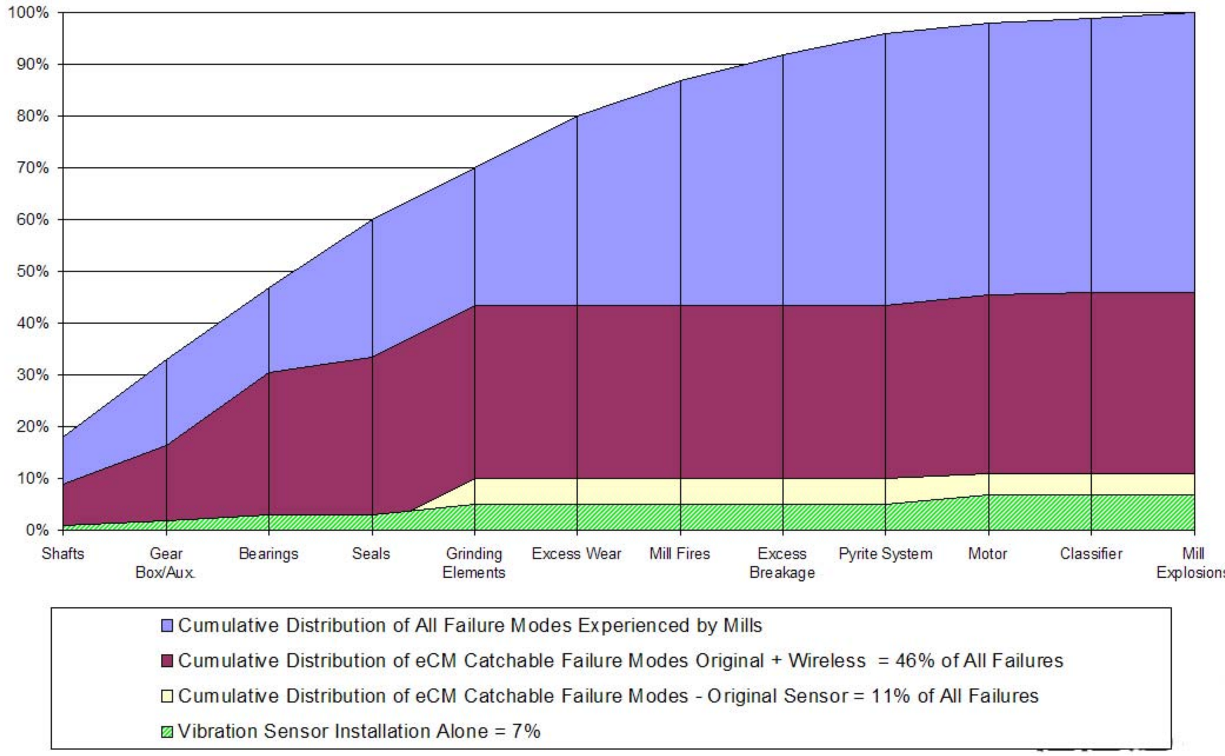

Figure 3-1 Cumulative failure mode Pareto chart of predictable failures

Additional efforts were initiated in the nuclear sector in 2003 with Exelon, Tennessee Valley Authority, and beginning in 2005, Texas Utilities.

In 2003 a vendor evaluation was completed to assess equipment condition assessment software package capabilities, and an implementation undertaken to include data integration. During 2004, work was completed for the development of equipment condition assessment models for Tennessee Valley Authority's nuclear plants. In 2004, 2 technical reports were published documenting the results and experiences gained to date through the nuclear sector implementation [*Equipment Condition Assessment, Volumes 1-2*, EPRI, 2004].

The majority of efforts to date have focused on establishing equipment condition assessment implementations and quickly deriving the benefits thereof. In doing so, the results and diagnoses from the equipment condition assessment system have become an additional consideration to be taken into account in addition to all other indications previously available. While the more advanced technology provided in the equipment condition assessment system should lead to a more accurate and timely diagnosis, there are generally no methods in place to relate this diagnosis to simultaneous indications available from related plant applications. The end result may be a variety of different indications from which plant personnel must infer the proper plan of action and maintenance plan. This is illustrated in Figure 3-2, where the green component blocks refer to well developed and available information or applications, the red blocks refer to components not yet available, and the yellow blocks indicate components which are under development.

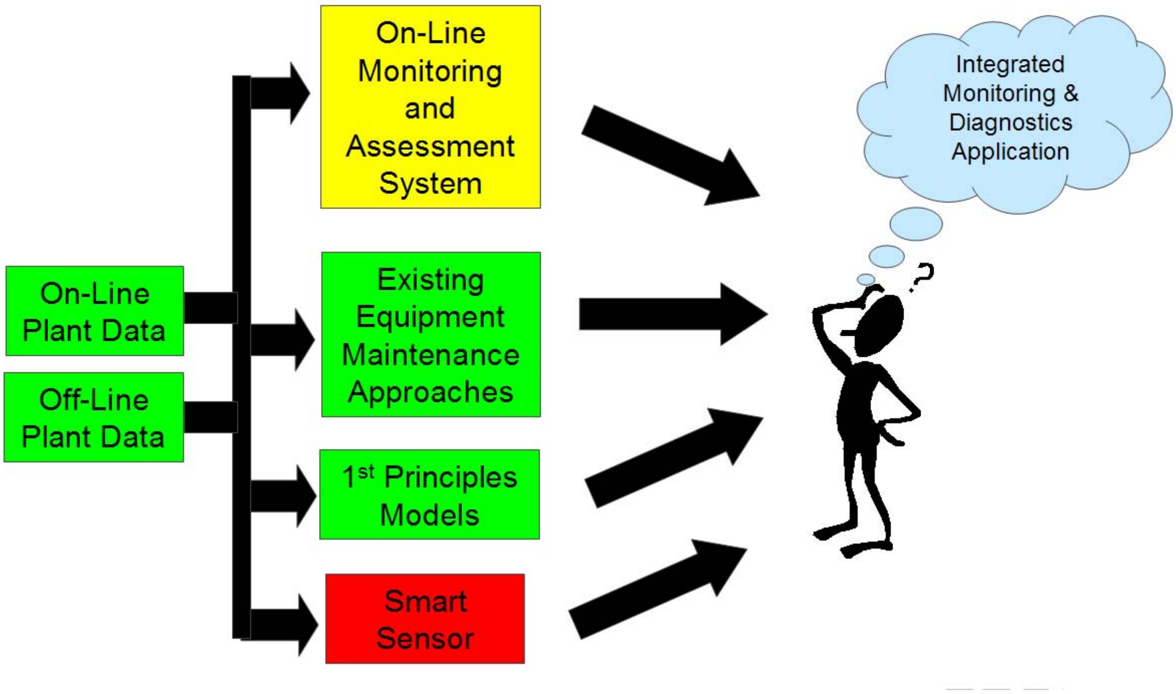

Figure 3-2 Current diagnostic system information flow

There are various applications that are currently available that utilize both on-line, and off-line data (e.g. operator rounds data) to monitor a plant's components. Existing maintenance approaches have performed well in many cases and are specific to each plant site. These approaches need to be augmented with the new information from equipment condition assessment systems rather than replaced. First principles models are also often available. Adding an on-line monitoring and condition assessment system adds another component to the overall monitoring system and produces additional component indications to consider. Finally, the Smart Sensor is a proposed method of implementation of an equipment condition assessment model at the site of the monitored component. This method plans to exploit new hardware capabilities and perform all computations at the component site, transmitting only component indications back to the plant computer. Again, this new proposed research method will provide another piece of information that must be integrated into an overall monitoring and diagnostics application. An illustration of the information flow required for this integrated application is provided in Figure 3-3.

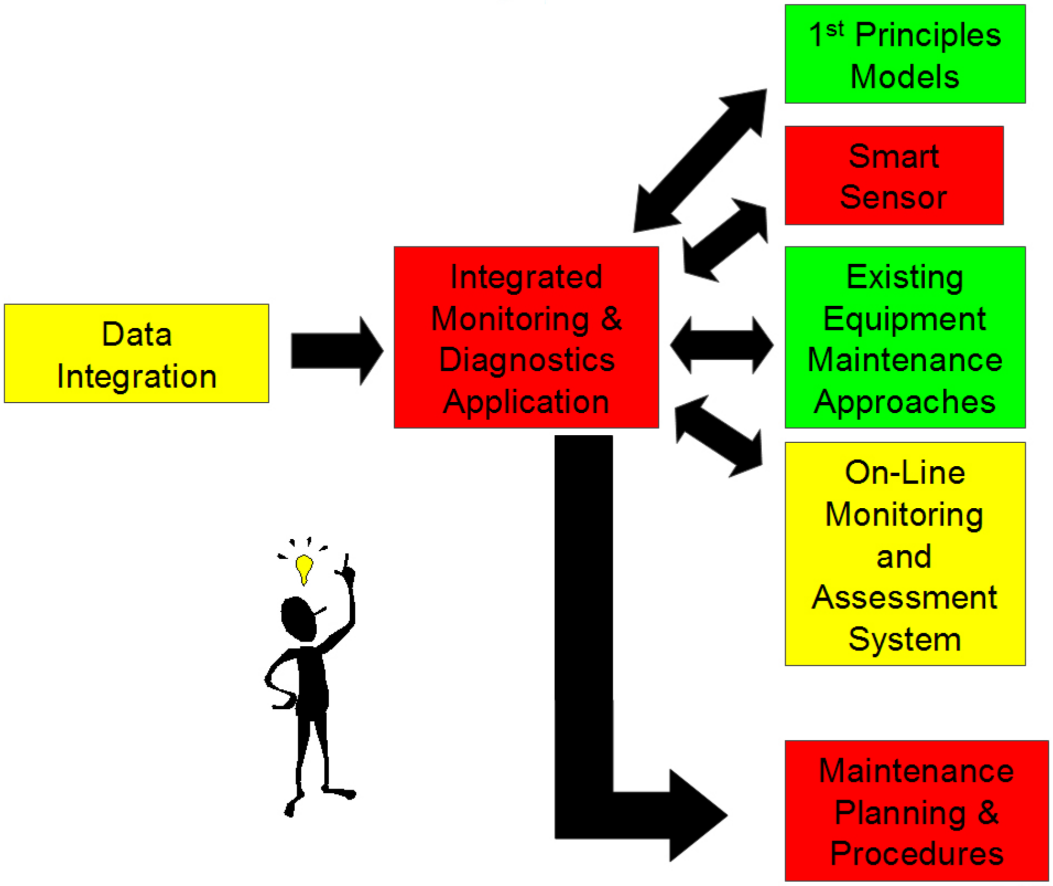

Figure 3-3 Integrated diagnostic system information flow

Figure 3-3 maintains all of the components of Figure 3-2, yet here the monitoring and diagnostics application resides between an integrated database and all of the plant's diagnostic and monitoring applications. The flow to and from the monitoring and diagnostics application is bi-directional such that results from one diagnostic system can be utilized by all other diagnostic systems. From the central hub, all information can be considered and condensed into a single most probable assessment which can be used to direct maintenance and planning procedures.

Extending these ideas of integration to the larger scope of fleet-wide rather than plant-wide monitoring results in the same generic architecture with the following modifications:

- The data integration includes the data from all plants in the fleet
- The maintenance and planning procedures are directed to the appropriate plant

Beginning in 2005, Texas Utilities (TXU) will collaborate with EPRI in the implementation of a fleet-wide equipment condition assessment system. The project being headed by TXU is to develop a centralized performance optimization center to monitor their fleet of electrical generating facilities. EPRI experience in many areas of optimization including: performance monitoring, equipment condition assessment, thermal performance, maintenance planning, and failure analysis provides a broad base of usable knowledge that can be exploited for the development of an integrated fleet-wide monitoring center. The proposal by TXU to set up a performance optimization center included in its scope, the following functions:

- Monitor thermal performance of nuclear, lignite, and gas fired generating units.
- Provide consistent plant process performance calculations.
- Monitor equipment performance through modeling and predictive maintenance technologies.
- Integrate data from each of the disciplines into a common assessment of equipment health.
- Provide analysis and diagnostic capabilities for process and equipment performance issues, both through advanced mathematical applications and through human interface.
- Provide early detection of equipment performance issues, and initiate proactive actions to mitigate loss of production efficiency or capacity.
- Provide analysis of equipment health for maintenance and budget planning.
- Establish consistency across the fleet regarding critical equipment maintenance and operations practices.
- Provide technical direction, operating recommendations, maintenance recommendations, root cause analysis, and field support as initiated by a plant, by management, or by the performance optimization center.
- Provide performance optimization center staff with subject matter experts from thermal performance, equipment performance, system and equipment design, physical analysis, mathematical analysis, and reliability centered maintenance.

The main areas in which guidance and assistance can be provided by EPRI in this TXU headed effort are:

- Remaining Useful Life software and integration
- Equipment Condition Assessment Model Development
- Development of Failure Signature Charts
- Thermal Performance Monitoring System Oversight
- Integration of Monitoring and Diagnostic Modules into an Overall Maintenance Planning and Early Warning Interface.

RUL software description and applicability

Remaining useful life of certain critical plant systems, such as those containing high temperature components, can be assessed with modeling tools. One example is high temperature turbine rotors, which accumulate significant damage when cycled. A valuable benefit of applying ECM is the potential to include automatic assessment of critical component life consumption based on actual operating profiles. This life consumption estimate, periodically compared to the remaining life based on the most recent rotor inspection, can be a measure of remaining useful life (RUL).

Equipment Condition Assessment Model Development

On-Line Monitoring and Equipment Condition Assessment projects have been underway at EPRI over the past several years. The experience gained in utilizing this technology will aid in the development of appropriate models for condition assessment as well as understanding the limitations of the technology.

Development of Failure Signature Charts

ECM systems require that component failure modes and degradation pathways are well defined. In addition failure signature charts need to be created to appropriately design ECM models. There is a wealth of knowledge acquired through past EPRI projects in understanding equipment failure mechanisms. This information can be condensed into a useable form specific for the needs of ECM models. Failure signature charts are also required to establish patterns that can be differentiated to perform accurate diagnoses for the monitored equipment.

Thermal Performance Monitoring System Oversight

EPRI experience in thermal performance monitoring, gained through their past projects can be mined to enhance or advise the project managers at the performance optimization center during the early stages of development.

Integration of Monitoring and Diagnostic Modules into an Overall Maintenance Planning and Early Warning Interface

In considering the various separate pieces of software and applications which will be required for a fleet-wide monitoring center, it is obvious that significant time and thought is needed to integrate the resultant information. The various modules will all need to report to a centralized application that sorts through the information and produces a useable diagnosis. The success of a monitoring center rests on this task. Diagnoses must be unambiguous and correct. A further step will be in setting up a protocol for transferring diagnoses to the appropriate plant personnel. A list of the various modules that may be incorporated into a fleet-wide monitoring system is provided below:

- ECM software module
- Calibration Monitoring Module
- Condition Assessment Module
- RUL estimation software
- Thermal Performance Module
- Spectral Analysis Module
- Preventative Maintenance Planning Module
- Replacement Parts Inventory & Ordering Module

- Operational Flexibility Optimization Module
- Information Transfer Module
- Failure Mode Analysis Database
- Plant-Specific Application Modules

While there are many components to the TXU performance optimization center's project plan which EPRI could provide guidance and assistance, the exact tasks to be performed by EPRI are not yet defined. Overall, EPRI will take on an advisory role and apply efforts where necessary, especially in the areas of equipment condition assessment model development and implementations.

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