

Instrumentation and Control Technology Assessments

*(1) Issues and Impacts Surrounding Circumferential Waterwall Cracking and
(2) Prognostics and Health Management*

1012275



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Technical Update, December, 2006

EPRI Project Manager

A. Hussey

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ABSTRACT

The purpose of this report is to provide a perspective on two areas of focus: Circumferential Waterwall Cracking and Prognostics and Health Management. CWWC was first observed in the early 1980's and the contributing factors were not all documented until the middle 1990's. Even today there is divergence as to the role of each of the contributing issues. Increasing demand for electricity capacity, decreasing availability of skilled labor, and increased competition for cost-effective generation are some of the forces behind the need for a Prognostics and Health Management (PHM) approach to maintenance of equipment.

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1

INTRODUCTION

This report gives an overview of two technology areas:

1. Circumferential Waterwall Cracking, Section 2 and Appendix A
2. Prognostics and Health Management, Section 3

Circumferential Waterwall Cracking

The purpose of Section 2 of this report is to provide a perspective on circumferential waterwall cracking (CWWC) including the causes and approaches to prevention and care. CWWC was first observed in the early 1980's and the contributing factors were not all documented until the middle 1990's. Even today there is divergence as to the role of each of the contributing issues. Thermal fatigue stresses are the overall driving mechanism behind this phenomenon. As implied by the name, thermal fatigue is effected by high tube surface temperatures (thermal) and large temperature changes and having these temperatures cycle over a fairly large number of cycles (fatigue). Thermal fatigue in waterwall boiler tubes result in a series of parallel circumferential cracks on the OD surface of the tube or in the overlay if applied. The problem is a complex one involving both fireside and water side conditions. These conditions must be together in the right combination for CWWC to begin. CWWC generally takes place in the highest heat flux areas of the furnace in supercritical boilers (although it has also been found in non-supercritical units to a much smaller degree). Supercritical design is a factor because of generally high heat flux coupled with thick-walled tubes necessitated by the high water-side pressures. In general, a heavy oxide layer is found on the tube interior. High heat flux, supercritical design, and an insulating oxide layer are factors in the formation of CWWC but are not sufficient to produce CWWC alone. The additional factor is cycling temperature conditions. Another contributing factor is the coal ash chemistry. The latter mechanism seems to use the crack locations to deposit corrosive material.

Minimizing CWWC must be approached from both the fireside and water side of the tube. Keeping the heat transfer high on the water side is a necessity in reducing tube metal temperatures. From an operations perspective, reducing the number and intensity of thermal cycles can be accomplished through intelligent sootblowing and understanding heat flux through direct measurement via heat flux sensors, chordal thermocouples, or model-based estimates.

Prognostics and Health Management (PHM)

Increasing demand for electricity capacity, decreasing availability of skilled labor, and increased competition for cost-effective generation are some of the forces behind the need for an improvement in the way power plants are operated and maintained. Power plants are filled with equipment, processes, and day-to-day activities in support of maintaining capacity factors

through ensuring proper equipment and process health. The complex relationship between operations and maintenance is complicated further by the effect of aging equipment on unpredicted failures. Unpredicted failures are costly due to loss in capacity, replacement power costs, and repair costs, to name a few. Resources for proactive detection and subsequent mitigation of equipment failures are scarce, necessitating a better approach to analysis of process and equipment data sources. Section 3 of this report focuses on the strategy of equipment management through a highly proactive maintenance strategy adapted by the Department of Defense (DoD), known as Prognostics and Health Management (PHM).

2

CIRCUMFERENTIAL WATERWALL CRACKING

Introduction and Historical Perspective

The objective of this paper is to provide a perspective on circumferential waterwall cracking (CWWC) including the causes and approaches to prevention and care. CWWC was first observed in the early 1980's and the contributing factors were not all documented until the mid 1990's. Even today there is divergence as to the role of each of the contributing issues. Thermal fatigue stresses are the overall driving mechanism behind this phenomenon. As implied by the name, thermal fatigue is effected by high tube surface temperatures (thermal) and large temperature changes and having these temperatures cycle over a fairly large number of cycles (fatigue). Thermal fatigue in waterwall boiler tubes result in a series of parallel circumferential cracks on the OD surface of the tube or in the overlay if applied. The problem is a complex one involving both fireside and water-side conditions. These conditions must be together in the right combination for CWWC to begin.

CWWC generally takes place in the highest heat flux areas of the furnace in supercritical boilers (although it has also been found in non-supercritical units to a much smaller degree). Supercritical design is a factor because of generally high heat flux coupled with thick-walled tubes necessitated by the high water-side pressures. In general, a heavy oxide layer is found on the tube interior. High heat flux, supercritical design, and an insulating oxide layer are factors in the formation of CWWC but are not sufficient to produce CWWC alone. The additional factor is cycling temperature conditions. Another contributing factor is the coal ash chemistry. The latter mechanism seems to use the crack locations to deposit corrosive material.

Circumferential waterwall cracking is not a new phenomenon. In fact, CWWC first came to our attention in the mid 1980's. In response EPRI published CS-4969, Circumferential Cracking of Supercritical Boiler Water-Wall Tubes in 1986. The objective of this effort was to develop a database on circumferential cracking in a larger number of supercritical boilers. Investigators obtained information on circumferential cracking from a survey of boiler operators and manufacturers and from a review of the technical literature. The study took particular note of locations of cracking; variations in design, operations, and materials; maintenance procedures; and coal composition. After assembling the database, they searched for common causative factors among the data from boilers that exhibited cracking. The 19 surveyed utilities represented 56 coal-fired supercritical boilers, about one-third of the units in the United States, and the major boiler manufacturers.

The results made clear that circumferential cracking was not limited to the boilers of a single manufacturer. It had affected 45% of the units surveyed. The study identified several factors as being related to the problem--the composition and slagging characteristics of the coal burned; the frequency of sootblowing; the furnace pressure cycles; the feedwater flow; the rate of load change; and the excess oxygen levels. However, the data established no root cause. Some

utilities reported temporary success in reducing the cracking propensity in severely cracked units by means of coatings, coal cleaning, and operations changes. ^[1]

In addition, it was recognized that sootblowing played a significant roll in temperature cycling waterwalls. This was documented through the development of slag sensors in the early 1980's. Note in Figure 1-1 from data taken in 1984 from a supercritical unit with both a heat flux (slag) sensor and chordal thermocouple in the same area during a sootblowing event. The tube surface temperature goes from about 850-1040°F. ^[2]

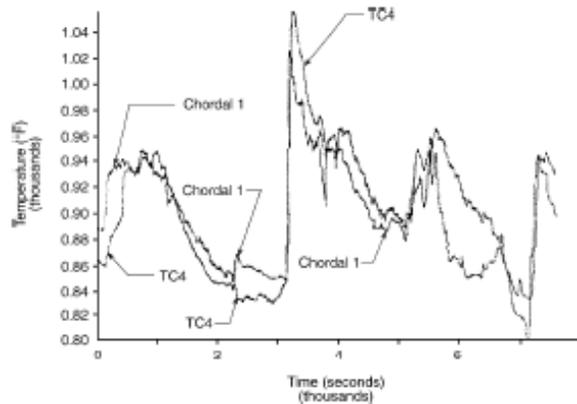


Figure 2-1
Typical Response of Chordal Thermocouple Compared with Heat Flux Sensor during Sootblowing Event ^[2]

While it was found that CWWC was fairly common on supercritical units, it has also been on newer and generally higher heat flux design subcritical units. One popular solution to CWWC in the 1980's and 1990's was to apply a weld overlay to damaged tubes with a material that possessed better high temperature properties. This approach has had limited success. Even though the new material had better high temperature properties, the added layer on metal added proportional increase in thermal resistance causing the tube surface temperature to increase, thus taking away a portion of the very advantage of the new material.

Water quality allowing deposits in the water side of the tubes was improved through the use of oxygenated water treatment. In the United States, the typical practice was to deoxygenate the feedwater for once-through or drum units either mechanically or chemically through the addition of an oxygen scavenger such as hydrazine. These treatments result in the generation and transport of feedwater corrosion products, which are directly responsible for a number of problems in the cycle including water-side deposits which contributed directly to CWWC. This contrasts with international practice where oxygen is added to the feedwater to produce a more oxidizing environment, thus eliminating the problems associated with feedwater corrosion products. EPRI recommend oxygenated water treatment and issued a proposed course of action in Cycle Chemistry Guidelines for Fossil Plants: Oxygenated Treatment, EPRI Technical Report TR-102285 in 1994. ^[3]

Further investigations in EPRI TR-104442 in 1995 reported the cause of CWWC to be the ability of the fireside surface to attain temperatures at which creep can occur. The elevated temperatures are caused by two complementary processes: the deposition of deposits on the water side and slagging-deslagging of the fireside surface. The internal deposits are formed from corrosion products entering the boiler from the feedwater and are most often in a "rippled" formation. In some cases, the onset of failure was accompanied by increasing boiler pressure drop due to growing internal (ripple) tube deposits.

Descriptions of circumferential cracking include:

- Cracks are most often observed in the highest heat flux zone,
- the cracking is deepest at the fireside crown of the tube but also occurs in the membrane between tubes,
- the extent of cracking can differ greatly between adjacent tubes,
- cracks appear to be uniformly-spaced
- adjacent cracks can be of quite different lengths
- cracks are sharp and dagger-shaped
- cracks are filled with oxide and usually have a central core of sulfide, and
- the oxide fillings in the cracks often have a crack running from the inner tip through the external scale.

The investigators concluded the cracking mechanism is one of corrosion-enhanced thermal fatigue.^[4]

Other factors have modified the CWWC issue. These include widely varying coal quality and the increasing use of Powder River Basin (PRB) sub-bituminous coal and increasing use of water as the sootblowing medium associated with PRB. Volatility of fuel costs will keep this issue ever changing for the foreseeable future. In addition, use of low-NO_x burners and over-fire air coupled with deep staging provide a fireside reducing atmosphere, possibly contributing to the propagation of cracks once established.

Since about 2000, intelligent sootblowing systems have become popular as a way to control all sootblowing media, steam, water, and air. The objectives of many of these projects were to control slag formation and reduce operation and maintenance costs. In addition to the initial objectives, one documented effect has been to reduce both waterwall tube leaks and the growth of thermal fatigue cracks in waterwalls.^[5, 6]

Problem Description

It has been established in the historical discussion that a number of conditions contribute to CWWC. This section will attempt to define each of these conditions and put them into some perspective. The following are issues that through engineering consensus are thought to be the important contributors to CWWC:

Internal deposits reduce the heat transfer rate from the tube material to the water. This in turn raises the overall tube metal temperature. Higher operating tube metal temperatures reduce both the yield strength and the fatigue strength of the material.

Sootblowing frequency and intensity exposes the tube material to high heat flux as bare tubes are exposed to the fireball as well as high temperature changes and large numbers of cycles.

Ash chemistry influences the properties of the slag layer on the tube surface. This affects the heat flux and temperature at the tube surface, can interact with the protective oxide layer, and may allow corrosive species into any available cracks.

How do these items impact CWWC? First, we can address the oxide layer (generally magnetite) on the interior of the tube. This deposit may affect the temperature in two ways. The layer reduces the efficiency of heat transfer to effectively increase the tube wall temperature. In addition, the increase drag on the fluid caused by the rippled surface of the magnetite will increase the pressure drop along the tube and can reduce the flow in the tube and cause fluid imbalances in the boiler circuit.^[4]

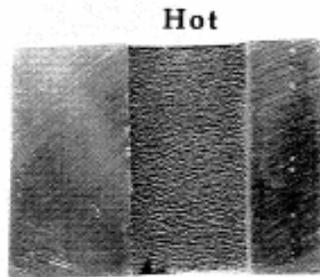


Figure 2-2
Ripple Magnetite on Hot Side of Internal Tube Surface^[4]

Next, let us take a simplified look at the heat transfer mechanism in a waterwall boiler tube. The energy, q , from the fireball is driven primarily through radiation heat transfer:

$$q = eF_v s A(T_f^4 - T_1^4)$$

where:

T_f = flame temperature

T_1 = ash layer surface temperature

e = emissivity

F_v = geometric view factor

s = Stefan-Boltzmann constant

A = surface area (unity for our simple model)

For our example, T_f is a constant as are e , F_v , and s . T_1 (Figure 2-1) is also constant as long as the slag layer remains intact. The slag layer is a complex heat transfer mechanism involving elements of convection, conduction, and radiation, depending on the local conditions of the slag (molten, porous, solid, or a combination). We will consider it solid to greatly simplify matters

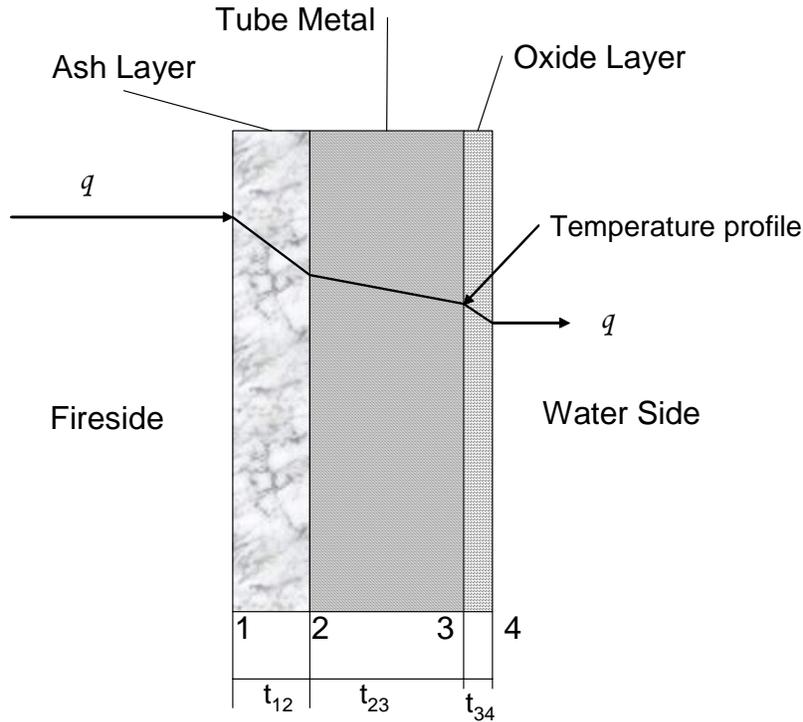


Figure 2-3
Simplified On-Dimensional Model of Heat Transfer Across a Boiler Tube

The one dimensional boiler tube heat transfer model becomes:

Where: k_a , k_m , and k_o are the convection heat transfer coefficients for ash, tube metal, and oxide

$$q = -k_a A \frac{T_2 - T_1}{t_{12}} = -k_m A \frac{T_3 - T_2}{t_{23}} = -k_o A \frac{T_4 - T_3}{t_{34}}$$

layer respectively. And t_{xy} are the respective materials thickness. Again, A is the unit area and set to unity here. Solving these equations simultaneously, the heat flow becomes:

$$q = \frac{T_4 - T_1}{t_{12} / k_a + t_{23} / k_m + t_{34} / k_o}$$

The total resistance to heat transfer is found at the terms in the denominator. ^[7] Paying particular attention to the terms in the denominator, the slag and oxide layers resistances to heat transfer are $1/k_a$, and $1/k_o$. The conductivities, k , for ash and oxide are not well documented in the literature. However what information there is indicates they are significantly lower than typical boiler tube material. ^[8] This provides two very important clues to CWWC. First, if the oxide layer conductivity coefficient is low relative to the metal, then T3 and therefore T2 must be higher to achieve the same heat flux. These higher metal temperatures mean lowered yield and fatigue strengths. Second, with heat transfer limited by the resistance provided by the slag layer (slag conductivity low relative to tube metal), when this resistance is removed (sootblowing event), T2 effectively becomes equal to T1, yet another temperature increase again reducing further the yield and fatigue strength.

When the tube surface undergoes this temperature transient, the surface of the tube tries to expand proportionally. Because this is a transient, the underlying material constrains the surface and drives it into compressive stress given by the simplified one-dimensional relationship:

$$s(t) = a E(T(t) - T_{max})$$

Where:

s = stress

a = coefficient of thermal expansion, $6.5 / ^\circ\text{F}$

E = elastic modulus, $30 \cdot 10^6 \text{ lb/in}^2$

This simplified case yields that a temperature spike of 200°F causes a calculated stress increase of $39,000 \text{ lb/in}^2$. This calculated stress may be overestimated as it assumes a fixed end model and a more rigorous model may be needed. ^[9]

Given this is possibly over estimated, it still provides two interesting insights. First, a stress increase of even $20,000 \text{ lb/in}^2$ seen several times per day can be a significant fatigue factor. Second, data indicate there are occasional temperature spikes of 400°F providing the potential to exceed the yield stress of common tubing material T-11 and T-22, $30,000 \text{ lb/in}^2$.

This underscores the need to carefully control sootblowing and activate blowers only when and where needed. This will control the temperature spike amplitude and reduce the number of fatigue cycles. One additional note; with the increasing use of PRB, water is the medium of choice in removing furnace deposits. If one applies water to an area without the protective slag coating, this will create a quenching effect driving the tube temperature down before the immediate upward spike when the tube is again exposed to the fireball.



Figure 2-4
Metallographic Cross-Section of Circumferential Cracks Showing Typical Sharp-Pointed Characteristic and Oxide (Dark) and Sulfide (Light) Deposits. (4)

Ash chemistry also contributes to the problem in several possible ways. First, if the boiler is operating in a reducing atmosphere, the H_2S and HCl in the ash will remove the protective oxide layer on the fireside of the tube, effectively raising the tube surface temperature when the bare metal is exposed to the fireball. The second mechanism is that these species attack the metal at the grain boundaries. This can initiate surface cracks and be possible sites for the cracks to grow driven by thermal cycles. The third mechanism is for these same corrosive compounds to deposit in the root of the cracks further removing base metal although there are some mixed data on this last mechanism (Figure 2-3).

The ash chemistry aspects are of particular interest because of the recent drive to add scrubbers to existing plants. Why should this be an issue? The answer is simple. Units without scrubbers burn low sulfur coal. Units that have burned low sulfur for some time and add scrubbers will now burn less costly higher sulfur coal. The coal can have significantly higher levels of H_2S and HCl in the flue gas and molten slag which will in turn generally aggravate the above ash chemistry issues.

This is not an exhaustive list as other conditions may certainly have an impact on CWWC. As mentioned previously, supercritical design is a contributing factor. It is however not one easily changed. Start-up conditions may add a contribution from both to water chemistry and internal deposits as well as high tube temperatures. The latter are a result from local flow conditions and the fireside dynamics during startup.

Action Plan

What can a plant staff do to minimize CWWC? Of the three contributors to CWWC, the first two can be directly affected by plant operations. Internal deposits can be minimized through diligent oxygenated water treatment, chemical cleaning, and attention to operating conditions. [10] This will improve the unit furnace effectiveness and help prevent overheating as well as reducing the potential for CWWC.

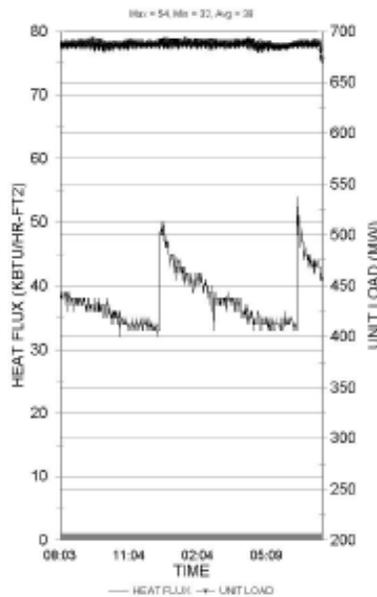


Figure 2-5
Typical Heat Flux Sensor Response to Sootblowing Event [5]

Better control of sootblowing is perhaps the most obvious way of reducing the damage of thermal fatigue. By not operating the sootblowers until the tubes are protected by sufficient external deposit, the tubing material is not subjected to unnecessary thermal cycles (Figure 3-1). The most effective way to control sootblowing is by current intelligent sootblowing (ISB) systems offered in several forms. These can use direct measurement heat flux sensors embedded in the tubes, chordal thermocouples, or “soft sense” modeling which use boiler conditions to determine through empirical models and first principals the most effective sootblowers to operate. Data indicate sootblowing frequency reductions of 40 percent or more are possible by implementing effective ISB systems. Other benefits include reduced sootblower erosion, improved steam and gas temperature control, and reduced maintenance costs. [5, 6]

There is limited control of ash chemistry outside of coal preparation. And with the aforementioned likelihood of worsening coal quality, plant operators will likely face more ash chemistry challenges. However, keeping the furnace out of a reducing atmosphere will decrease some of the effects. This consists of good fuel and air distribution in the combustion zone and may be improved by increased oxygen sensors and the addition of CO sensors in the flue gas stream. New sensor technologies such as tunable diode lasers may provide good tools to monitor the combustion process in locations never before practical.

Because of the impact of CWWC, EPRI has combined parts of several programs to study this phenomenon in depth. A description of the plan under Program 171 is found in Appendix A.

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3

PROGNOSTICS AND HEALTH MANAGEMENT (PHM)

Introduction

This chapter focuses on the strategy of equipment management through a highly proactive maintenance strategy adapted by the Department of Defense (DoD), known as Prognostics and Health Management (PHM). An overview of the major elements of a PHM program is given in this chapter. Prognostic and Health Management applications include sensor placement, data acquisition and processing, online monitoring, anomaly detection, diagnostic, and prognostic algorithms to identify probable causes of failure and the associated timing to enable proper maintenance planning, or Health Management [1,2].

Electric Utilities Need

Increasing demand for electricity capacity, decreasing availability of skilled labor, and increased competition for cost-effective generation are some of the forces behind the need for an improvement in the way power plants are operated and maintained. Power plants are filled with equipment, processes, and day-to-day activities in support of maintaining capacity factors through ensuring proper equipment and process health. The complex relationship between operations and maintenance is complicated further by the effect of aging equipment on unpredicted failures. Unpredicted failures are costly due to loss in capacity, replacement power costs, and repair costs, to name a few. Resources for proactive detection and subsequent mitigation of equipment failures are scarce, necessitating a better approach to analysis of process and equipment data sources.

Department of Defense Need

“Emerging system development programs and future weapon system development programs have become highly reliant on the success of efforts to develop and integrate automated Diagnostic and Prognostic technology into Prognostics and Health Management (PHM) Systems. These technologies are driving the implementation of new maintenance approaches and are central to achieving the reductions in manning and operating costs on these new systems as well as legacy systems. This has resulted in new technical challenges and a renewed R&D focus on Prognostics and Health Management (PHM) technology....Automated diagnostics and prognostics effectively combined into a Prognostics and Health Management (PHM) System will reduce or eliminate this maintenance shortfall.” –*Sandia National Laboratories PHM Center of Excellence*

Sensor Placement

Sensor placement for any process is decided primarily during the design phase. Two major types of design for end use exist:

1. Process effectiveness design
2. Equipment reliability design

Process Effectiveness Design

Process Design is focused on controllability. Designing a process requires knowledge of the required functions, operational limitations, equipment maintenance practices, and desired controllability. A process design begins with a high-level look at process inputs and outputs. It is important to design the process such that the desired outputs are constantly achieved. This is done by adjusting the process based on the input measurements. An adequately instrumented process will enable controllability and will produce the desired output. Process variations can ultimately be controlled through adjusting the process. However, when equipment health degrades, the process health degrades, and the process cannot be adjusted to maintain the desired output without restoring equipment to its designed health.

Equipment Reliability Design

Designing an individual piece of equipment requires engineering knowledge to achieve the desired performance. Performing a Failure Modes Effects and Criticality Analysis (FMECA) on a piece of equipment determines optimal sensor placement to detect and mitigate potential failures before losing equipment functionality during operation. FMECA performed during the design phase results in 1) optimal sensor placement and 2) design iterations to remove or reduce consequences of failure modes and/or effects.

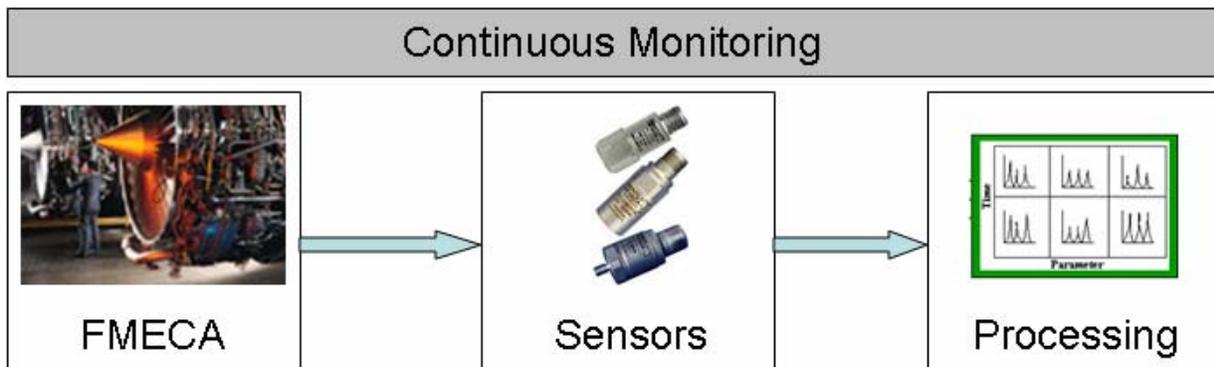


Figure 3-1
Equipment Reliability Design for Optimal Sensor Placement

Data Acquisition and Processing

Equipment degradation indicators exist in sensors, predictive maintenance measurements, operator rounds, and other sources. Each type of information source has its own data acquisition method. The importance of using all types of information in a PHM program cannot be underestimated. Regardless of the data acquisition specifics, all data sources related to equipment condition should be mined for information extraction. The data need not align side by side in its raw form if the information content is aligned. It is the information from the underlying data that is used for diagnostics and prognostics.

Online Monitoring

A properly designed piece of equipment will operate effectively throughout its designed life-cycle, given proper operating conditions and preventive maintenance. A failure mode begins at the degradation source, propagates until a subcomponent is not performing its proper function, which affects the performance of the equipment and, therefore, the process. The placement of instrumentation directly affects the sensitivity of early warning of equipment failure, and therefore, process degradation. This placement directly affects the required strategy for diagnostics, prognostics, and health management of equipment.

Monitoring During Designed Equipment Life

The two givens, operating conditions and preventive maintenance, warrant some attention. For a process effectiveness design, instrumentation exists primarily for controllability of the process. Off-design operating conditions will wear equipment in an unknown fashion, given the initial instrumentation design. Process related instrumentation will help identify degrading conditions only after initial equipment degradation has progressed significantly. To identify earlier signs of equipment degradation, further measurements are required. Predictive Maintenance (PdM) technologies such as vibration analysis, thermography, and oil analysis can help identify early signs of equipment degradation. Operator Rounds also provide meaningful early warning signs, since human perception includes sound, smell, and sight. Measurements from PdM technology and Operator Rounds are obtained periodically, since labor is involved in obtaining, transferring, and analyzing the underlying data.

Monitoring During End of Equipment Life

Once the designed life-cycle is reached, unforeseen failures can be expected to increase. Maintaining high levels of equipment reliability requires proper maintenance. If the equipment is adequately instrumented, the failures can be counteracted through the proper maintenance planning. However, this often requires periodic measurements through PdM technologies and Operator Rounds.

Anomaly Detection

Anomaly detection is associated with finding a condition outside of the normal expected conditions, through data collection sources including automatic data acquisition and periodic manual data acquisition systems. The accuracy and completeness of available anomaly detection systems are dependent on instrumentation, data acquisition and storage, and proper application of data mining algorithms.

Diagnostics

Diagnostics are typically performed once a failure mode has progressed to a certain level, affecting equipment performance. As an insight to failure mode degradation progression and the resulting diagnostic strategy, consider the following automotive example:

1. The battery is 4 years old, designed to last 3 to 5 years.
2. At time $t=0$, the battery is discharged after sitting for one week. The car is jumpstarted and the battery maintains charge while driven daily.
3. The battery is suspected to be near its end-of-life.
4. At time $t=1$, the ignition key is turned and nothing happens
5. After turning the key again, the car starts.
6. This behavior continues for two weeks.
7. At time $t=2$, the car starts and the starter remains engaged with the flywheel. The starter solenoid has failed.
8. The starter and battery are replaced.

The following table represents the above events, with the diagnostic decision made by the information available.

Time	0	1	1	2	3	4
Information	Battery is 4 years old	Battery dead after two weeks	Battery acid/water level okay	Battery retains charge upon daily driving	Ignition requires two key turns	Starter fails
Diagnosis	None	Battery at end-of-life	Battery at end-of-life	Battery at end-of-life	Battery at end-of-life	Starter bad
Confidence Level	N/A	Medium	High	High	High	High
Action Required	None	None	<i>Check retention of charge during daily driving</i>	<i>Plan on replacing battery</i>	<i>Plan on replacing battery soon</i>	<i>Replace starter</i>

Table 3-1
Automotive Diagnostic Example

The two key turns required at time $t=3$ showed that something other than a worn battery was degrading. However, because of the battery's condition in respect to its design life, the additional information at time $t=3$ was assumed to support the previous diagnosis of a worn battery. If, at time $t=3$, the new information were combined with the prior belief, at least two probable causes would be possible – battery and starter. An electrical *inspection* of the solenoid would have helped the diagnosis.

The above example suggests that two diagnostic strategies were possible:

1. Use prior information, suggesting the most probable cause as the diagnosis
2. Use all information to suggest multiple probable causes and *inspect* for diagnosis

Current Automotive Diagnostics Strategy

The automotive industry implemented a required emissions diagnostic system in all vehicles 1996 and newer. The on-board diagnostic system, OBDII, receives signals from a variety of emission and engine control sensors and processes the information in the engine control computer. When a signal from a sensor is non-normal, a diagnostic code is assigned according to the OBDII specification. The check engine light then alerts the vehicle operator that there is a problem. The diagnostician then has to plug in a diagnostic code reader to the engine computer. The diagnostic code reader displays the code according to the OBDII specification, and an associated problem area is displayed or cross referenced. The vehicle owner then makes a decision about repair strategies using the information. The diagnostic code is associated with a sensor or measurement. It is left to the diagnostician to determine if there is a problem with the sensor itself or with an actual component. Often this requires inspection to isolate the root cause.

The health of this diagnostic system and sensors associated is checked annually through emissions control inspections. In the future, wireless transponders will transmit emissions code diagnostics when there is a problem at certain checkpoints along the highway system, eliminating the need for annual emission system inspections.

Diagnostic Algorithms

Since effective diagnostics depend on information from multiple sources, different types of diagnostic algorithms exist. The most common approaches to diagnostics include statistical processing, artificial intelligence (AI), and model-based [6].

Prognostics

Diagnostics and prognostics are related, but the order is important. Diagnostics are necessary when a failure either has occurred or is near. Prognostics are necessary when an estimated time to failure is desired. This can be before or after equipment degradation exists. A failure prediction before degradation, or without an indication, is based primarily on prior knowledge of failure modes. In the latter case, when equipment degradation is in its early stages, prognostics utilize remaining useful life projections. The physics of degradation progression are essential to understand when projecting remaining useful life. The degradation timing is dependent on the failure mode, therefore, diagnostics of the failure mode is a prerequisite to prognostics for remaining useful life calculations.

**Table 3-2
Diagnostics and Prognostics Strategies and Information Sources Required**

End Goal	Strategy	Information Required
Identify failure for repair	Diagnostics	Prior knowledge Sensor information Inspection and testing
Predict time to failure based on history	Prognostics/Reliability Estimate	Prior failure history Operating conditions Reliability calculations
Predict time to failure upon actual degradation	Prognostics/Remaining Useful Life	Diagnostic information Reliability estimate Stressor information Failure models

Prognostic Algorithms

In the case of a failure mode degradation occurrence, it is desirable to produce a remaining useful life (RUL) estimate to determine when the optimal point of maintenance would be. This requires physics-based modeling of the failure degradation to project the timing. If failure mode degradation is not present, the prediction is based on past history of failure for similar components and subcomponents until an indication of degradation is obtained.

Improvements

Sensors and Data Processing

For effective equipment condition monitoring, many future improvements will involve new sensor technology to enable more advanced data gathering capabilities. As diagnostics are performed in a more automated fashion, uncertainty can be reduced through addition of sensors that address specific failure modes. Since wiring new sensors can be a significant cost, many new sensors will be wireless. On-board processing of sensor data will enable low-power, low-maintenance wireless sensors to be deployed at a low cost. Additionally, on-board processing will reduce the amount of data transferred to the plant network, reducing the typical data flood experienced when new sensors are added to the plant.

FMEA for Diagnostics

Failure modes and effects analysis (FMEA) is essential to support improved diagnostics. However, in addition to an FMEA, probabilities of failure and information source specification are necessary. Using the EPRI Preventive Maintenance Basis as an example, notice that the discovery/prevention opportunity requires vibration data and inspection for the diagnosis.

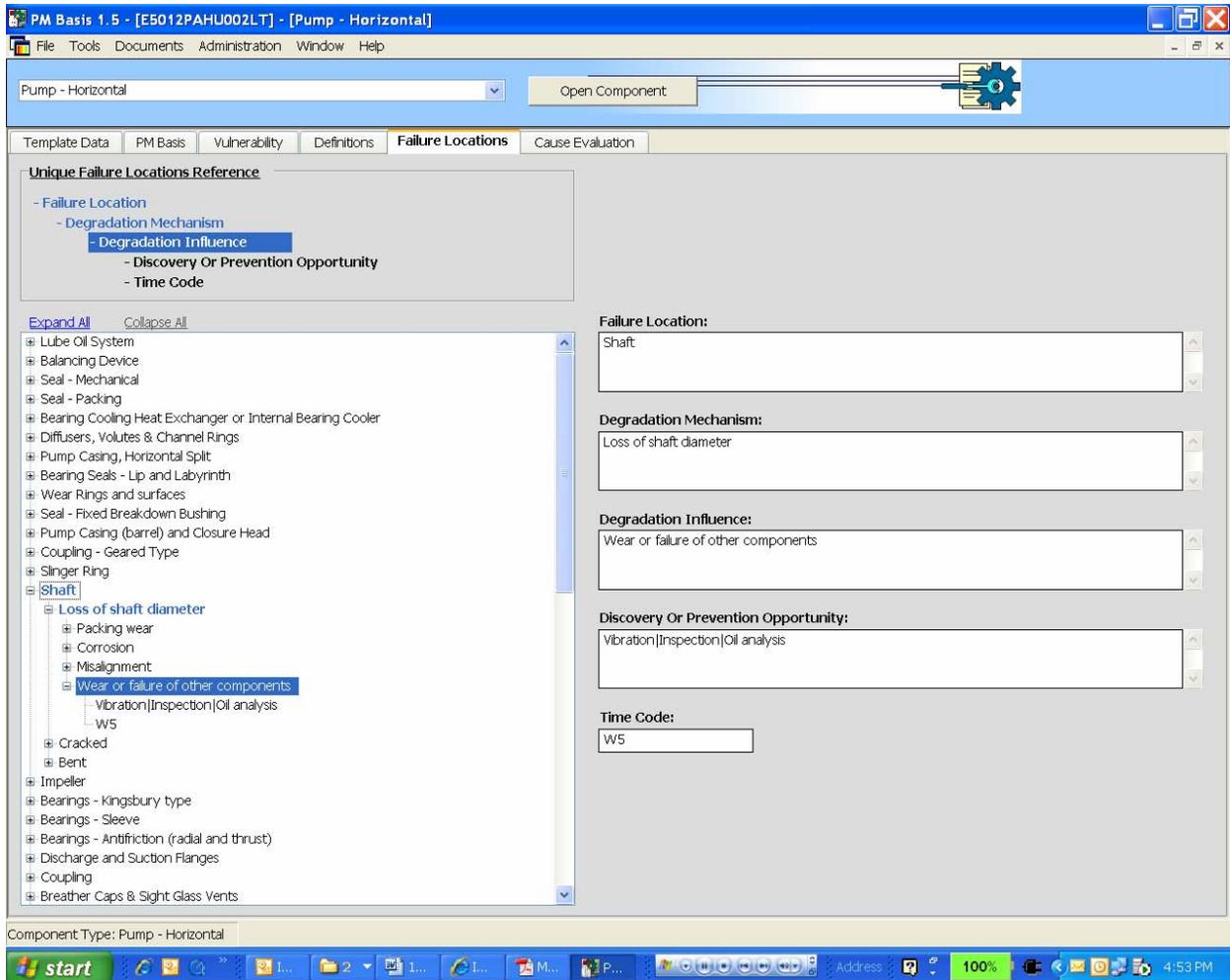


Figure 3-2
EPRI PM Basis Table for Pump-Horizontal

Definitions

- **Diagnostics:** The process of identifying an equipment failure. In the dictionary, a diagnostic is an adjective with meaning “Serving to identify a particular ... characteristic” [1].
- **Prognostics:** The prediction of equipment failure. In the dictionary, prognostic is a noun with meaning “a forecast or prediction” [2].
- **Health Management:** The practice of scheduling and performing equipment maintenance functions based on information collected from prognostic and diagnostic systems.
- **Failure Modes and Effects Analysis (FMEA) [3]:** A procedure and tools that help to identify every possible failure mode of a process or product, to determine its effect on other sub-items and on the required function of the product or process.
- **Failure Modes and Effects Criticality Analysis (FMECA) [4]:** The Failure Modes and Effect (Criticality) Analysis is termed as a bottoms up analysis. The FMEA is based on an qualitative approach, whilst the FMECA takes a Quantitative approach and is an extension of the FMEA, assign a criticality and probability of occurrence for each given failure mode.

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A

171.001 DEVELOPMENT OF SOLUTIONS FOR THERMAL FATIGUE

171.001 Development of Solutions for Thermal Fatigue

Benefits

This project will provide tools to inspect and size thermal fatigue cracks; new waterwall coatings to resist thermal fatigue; and a predictive capability for heat flux patterns as a function of combustion and fuel quality. An overall guideline on how to comprehensively address thermal fatigue will be one of the culminating deliverables. Another deliverable will provide the optimum waterwall for new supercritical units that will have thermal fatigue resistance designed and built-in.

Description

Thermal fatigue boiler tube failures (BTF) result in a series of parallel circumferential cracks on the OD surface of the tube or in the overlay if applied. The cracking is driven by two factors: a) an increasing tube surface temperature, and b) frequent thermal transients. In the case of tubes with overlay there is an instant increase in tube skin temperature once the overlay is applied. In most cases of thermal fatigue, a thick internal oxide has been observed, which resembles an oxide grown in steam circuits. This also results in elevated temperature. Other sources for increasing tube surface temperature are increased heat flux and flame impingement. There are a multitude of possible root causes for the frequent thermal transients. The supplemental EPRI project on thermal fatigue was designed to demonstrate how to determine the time in operating space when those thermal features occur. This is vital in determining the root cause.

Once the root cause is defined, it is necessary to accurately size and monitor the thermal fatigue cracks to assess tubing life. Reliable NDE techniques do not currently exist although initial work has been conducted in the Boiler Life and Availability Improvement Program (Program 63). This process is complicated for tubes with overlay. EPRI will develop the NDE tools and associated processes (workshops) to manage this damage mechanism to avoid in-service failures. EPRI will also develop generic NDE procedures to assist members and their vendors in implementing the technology. Concurrently, EPRI will prepare and provide on-site workshops on an as-requested basis.

EPRI will utilize advanced tools such as computational Fluid Dynamics (CFD) modeling to quantify the impacts of low NO_x combustion systems on waterwall temperatures, heat loads and thermal fatigue. In addition, the impacts of boiler heat release rates and other design characteristics that impact waterwall heat loads will be assessed.

EPRI has extensive chemical cleaning experience and guidelines for boiler waterwalls, which

were developed in the Boiler and Turbine Steam and Cycle Chemistry Program (Program 64). However those projects and guidelines have not been directed towards high temperature oxide growth on waterwalls, so EPRI will make a complete assessment of this new morphology and develop specific guidelines to assess and chemically clean the internal surfaces.

It is anticipated that the need to provide protection to the fireside surfaces of the tubes will continue to exist in boilers with heavily staged low NO_x burners. EPRI already has work in developing weld overlays in the Fossil Materials and Repair Program (Program 87) and has initiated work under EPRI's Technology Innovation Program to assess whether nanotechnology coatings may be applicable. In this project EPRI will undertake two activities. The first will involve optimization and application of the nanotechnology coatings. A demonstration using the optimum chemistry and application methods will be performed. The second will investigate newly developed application techniques, which include high velocity methods, use of bond coats, and various heating methods to develop a metallurgical bond between the coating and the substrate. Tests will involve bond strength, thermal expansion, fatigue, and corrosion resistance.

Once the work to demonstrate how to determine the root cause of thermal fatigue (which will be performed in a supplemental project) and the work within this Program is complete, EPRI will assemble an overall comprehensive guideline on how to address thermal fatigue in boiler waterwalls. As a subset to this, a complementary guideline will be developed on the optimum waterwall for supercritical boilers to resist thermal fatigue cracking. This will embellish the initial 2007 report to be developed in the P71.001 project, and will cover not only the optimum tube materials and coatings but also the construction details to reduce any thermal expansion restrictions.

Using multimedia software, EPRI will develop a computer based training (CBT) course that contains all information relevant to thermal fatigue cracking on supercritical waterwalls.

Delivery Approach

This project will be delivered through a series of technical reports.

Completion Criteria and Duration

The program participants will review this project. Its continuation and scope are contingent on the outcome of that review.

**Table A-1
2007 Deliverables**

Deliverable Title	Delivery Year	Deliverable Type
Assessment of Internal Oxides	03/31/2008	Technical Report
Assessment of New Weld Overlay Applications	03/31/2008	Technical Report
Thermal Fatigue Damage and Analysis (As-requested)	03/31/2008	Service
Optimum Approach to Assessing the Root Cause of Thermal Fatigue	03/31/2008	Technical Report
Modeled Results of Waterwall Heat Loads	03/31/2008	Technical Report

**Table A-2
Future Years Deliverables Table**

Deliverable Title	Delivery Year	Deliverable Type
Guideline for Chemical Cleaning of Internal Oxides	2008	Technical Report
Generic NDE Procedures	2008	Technical Update
Impacts of Boiler Design and Operation on Thermal Heat Loads and Transients	2008	Technical Report
Guidelines for NDE Procedures	2009	Technical Report
Optimum Supercritical Waterwalls	2009	Technical Report
CBT Course for Thermal Fatigue	2009	Software
NDE Workshop (As-requested)	2008/09	Workshop
Advanced NDE for Thermal Fatigue	2008/09	Hardware
Thermal Fatigue Damage and Analysis (As-requested)	2008/09	Service
Demonstration of Coating Technology	2008/09	Technical Report
Application of CFD Analysis to Thermal Fatigue	2008/09	Technical Report
Guideline for Thermal Fatigue	2008/09	Technical Report

B

CWWC PROJECT OPPORTUNITY

Evaluation of Supercritical Boiler Waterwall Cracking due to Thermal Fatigue

With a number of new supercritical boilers recently becoming operational, and with an increase in the number of existing supercritical boilers now operating in a staged, low NO_x mode, cracking of fireside surfaces remains a critical issue that needs to be understood and addressed. By considering both the fireside and waterside conditions, this effort will assess operational considerations resulting in circumferential cracking of fireside surfaces so that mitigation methods may be applied.



Figure B-1
Waterwall Cracking

Value

If left unresolved, tube cracking can lead to boiler tube failures, the number one cause of forced boiler outages. By an improved understanding, the operating conditions consequential to circumferential cracking (e.g., increased thermal loads due to combustion modifications, weld overlays, etc., and/or thermal transients consequential to slag falls, sootblower events, etc.), this cause of tube failures can be addressed and mitigated.

Drivers and Trends

One of several drivers pertains to the increased use of weld overlays, which have become a method of choice for combating fireside corrosion consequential to the reducing conditions needed for low NO_x boiler operation. Unfortunately, the addition of overlays has resulted in a significant increase in reports of tube cracking, especially in more corrosive environments due to higher sulfur and/or chlorine in the fuel. Even independent of overlays, operating in a deeply staged low NO_x mode often results in increased flame lengths, yielding higher tube surface heat loads with an increased potential for tube cracking due to thermal fatigue. It also needs to be emphasized that this problem can occur in boilers that do not have weld overlays and that are already on oxygenated treatment. Independent of low NO_x operation, an increase in the number of high heat release supercritical units has made tube cracking a critical issue in need of a solution. In general, all new owners/operators of supercritical units need to be cognizant of the boiler characteristics and operations that drive this mechanism.

Project Summary

The project's primary objective is to identify the root cause(s) of tube cracking in supercritical boilers. Specific tasks include:

- Identify and document existing tube cracks.
- Perform/document Non-Destructive Examination (NDE) at critical locations.
- Acquire operational data to yield insights into possible causes (e.g., flame impingement, ripple magnetite, etc.)
- Design/install monitoring equipment. At a minimum, this will include strain gauges, thermocouples and heat flux meters, along with a thermal/corrosion scanner monitoring system, which will measure and map tube temperature, heat flux, and possibly crack growth.
- Long term monitoring of both common and infrequent operating regimes for the purpose of identifying those regimes responsible for cracking.
- Data analysis, including correlations between acoustic emissions events and metallurgical damage characteristics; correlations between operating parameters (e.g., Megawatt load, fuel flow, heat absorption rates, etc.) and furnace wall heat absorption and temperature differentials; and model development.
- Diagnostic monitoring and troubleshooting with alternative operating conditions that offer the potential to minimize cracking.

Project Deliverables

A final report will be prepared summarizing the results and findings of the demonstration, including identification of alternative operating conditions that offer the potential to minimize cracking.

Cost

Total project cost is estimated to be approximately \$1.1 million. Co-funding is being sought at a level of \$100,000 per participating organization, which may be funded with Tailored Collaboration (e.g., \$50,000 + \$50,000). Funding may be provided over a two-year period.

Project Status and Schedule

PPL's Brunner Island Unit 3 has been selected as the host site. The monitoring equipment will be installed during the fall 2006 outage. Following the outage, the project should last for approximately one year to allow for data collection and report preparation.

Who Should join

Power generating organizations with coal-fired boilers experiencing circumferential cracking of bare tubes and /or weld overlays.

Contact Information

For more information, contact the EPRI Customer Assistance Center (EPRI CAC) at 800.313.3774 (askepri@epri.com).

Technical Contacts

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