Effect of Operational Transients on Boiler Damage

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PRODUCT DESCRIPTION

It is increasingly the case that utility systems demand more flexibility in a unit's ability to respond to dispatch requirements, which can create a conflict between maximizing efficient operation and limiting damage accumulation. A boiler can be operated in various cycling modes and can be subjected to planned and unplanned transients associated with load following, minimum load operation, forced cooling, variable pressure operation, increased ramp rates, increased attemperation, over-temperature operation, and so on. Compared to steady-state or base load duty, cycling or transient operation can increase equipment damage, increase maintenance, and reduce availability.

Results and Findings

During cyclic operation, temperature and pressure transients cause fluctuating stresses, which give rise to damage accumulation. The stresses are a function of a number of factors such as the magnitude of temperature change, the rate of temperature change, and the physical geometry of the component (for example, thickness, stress-concentrating shapes, and attachment design). Stress is also affected by the pressure and mechanical forces experienced in operation. The number of stress-reversal cycles that a component undergoes while experiencing such stresses and the combined magnitude of these stresses contribute to fatigue damage in the component. None of the older design codes for fossil plants contained specific requirements for considering fatigue. Complicating the issue is that, in reality, the damage accumulated is often a synergy between fatigue and other damage mechanisms, leading to creep-fatigue (in high-temperature components), corrosion or oxidation fatigue, or thermal fatigue.

Challenges and Objectives

The objectives of this report are to provide fossil plant personnel with (1) an understanding of the impact of cycling and operational transients on boiler damage and (2) a review of past industry initiatives and approaches and the associated advantages and limitations of those approaches.

Application, Value, and Use

The information in this report can be used by fossil plant personnel to assist in establishing an effective strategy for assessing, monitoring, and maintaining boiler components.

EPRI Perspective

For many years, the Electric Power Research Institute (EPRI) has initiated and conducted studies on the impact of operational transients on fossil boilers, approaches to evaluate damage accumulation, and methods to effectively manage the issue. This document provides an updated information resource to assist plants in establishing an effective boiler component assessment, monitoring, and maintenance strategy.

Approach

Numerous reports, papers, and information published by EPRI and others in the industry describe methods and techniques for evaluating the impact of cyclic and other operational transients. This report provides background information on component design philosophy, analysis, and methods. It also provides examples of operational transients and the associated component issues and damage potential, as well as a relevant case study.

Keywords
Boiler damage
Corrosion fatigue
Cyclic duty
Operational transients
Stress
Thermal fatigue

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1
INTRODUCTION

Compared to steady state or base load duty, cycling or transient operation subjects power plant equipment to conditions that could increase equipment damage, increase maintenance and reduce availability. During cyclic operation, temperature and pressure transients cause fluctuating stresses giving rise to damage accumulation. The stresses experienced are a function of a number of factors such as the magnitude of change in temperature, the rate of change of temperature and the physical geometry of the component (e.g. thickness, stress concentrating shapes and attachment design). Stress is also affected by the pressure and mechanical forces experienced in operation. The number of stress-reversal cycles a component undergoes while experiencing such temperature, pressure and mechanically-induced stresses and the combined magnitude of these stresses contribute to fatigue damage in the component. Because such conditions occur more frequently on a unit that is cycled, fatigue is a principal concern. An important point is that none of the older design codes for fossil plant had any specific requirements for considering fatigue. Complicating the issue is that in reality the damage accumulated in often a synergy between fatigue and other damage mechanisms leading to e.g. creep fatigue (in high temperature components), corrosion/oxidation fatigue and thermal fatigue.

Also important is the impact of corrosion arising from deviations of water chemistry from the standards. Units are especially vulnerable to out of specification water chemistry during shut-down/start-up cycles. Fireside corrosion can also be worse under cycling conditions.

It is increasingly the case that utilities "system" demands more flexibility in a units ability to respond to dispatch requirements which can create a conflict between maximizing efficient operation and limiting damage accumulation. The aim is to limit the damage/cycle so components will last the desired lifetime. From a general engineering standpoint more rapid transients are deleterious but this general opinion is not easy to quantify with current tools. Manufacturers have recognized that there is a need to recommend limitations to start up and shut down procedures and are issuing further guidance to owners. However, the basis for the greater restrictions included in these recommendations is normally not open to evaluation. Thus, there is a need to understand the influence of boiler transients and based on this understanding improve programs of further monitoring, inspection, maintenance etc.

Examples of other potential deleterious effects of cycling include:

- The need for more rapid loading and the resulting rapid temperature changes during start-up prevent all components from expanding to their normal operating positions at the same rate. This time lag can cause failures in joints and connections due wear and fatigue due to physical movement (e.g. wear of sliding surfaces).
- The firing equipment must be placed into and taken out of service. This is a critical period of operation; the frequency of exposure to danger from implosion and explosion is greatly increased.
- Operator equipment manipulation requirements are more frequent and the opportunity for operator error is increased, which could lead to inadvertent equipment damage.

- The potential for boiler oxide exfoliation and subsequent solid particle erosion in the turbine steam path increases.
- Vacuum is broken during shutdown increasing the potential for oxidation.
- Many component surfaces become alternatively wet and dry during cycling, which increases the potential for corrosive damage and deposits.

There are design features, operational procedures, equipment modifications, maintenance practices and monitoring activities that can be utilized to control damage accumulation rates and allow for life management of the equipment. Examples include; turbine by-pass systems and sliding pressure operation to allow for less damaging starts, increased drain capacity, on-line monitoring systems to trend damage accumulation/performance and predictive maintenance techniques.

There have been numerous reports, papers and information published by EPRI and the industry which discuss and suggest methods and techniques for evaluating the impact of cyclic and other operational transients. This document provides a summary of the current understanding of the issue and a review of past industry initiatives, approaches and the associated advantages and limitations. Background information is provided on component design philosophy, analysis issues and methods. Examples of operational cycles/transients and the associated component issues and damage potential are highlighted with a relevant case study provided. Existing methodologies developed for assessing the impact of cycling operation are summarized. Appendix B provides brief content reviews of two relevant cycling documents.

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BACKGROUND

ASME Boiler and Pressure Vessel Design Considerations

In the United States, boiler pressure vessels, tubing and piping are designed in accordance with Section I, “Power Boilers” of the ASME Boiler and Pressure Vessel (B&PV) Code. The ASME B&PV Code was established to address the major safety concerns after many boiler explosions in the early 1900s. The concept that the pressure vessel is designed against major catastrophic rupture due to pressure loading has been reflected in the code

As mentioned none of the older design codes for power plants placed any specific requirements on considering fatigue as a failure mechanism. The design codes assumed that the effects of fatigue were contained within the conservatism of the design process. This could be an adequate assumption for base load plants, but it is now recognized that fatigue, especially in conjunction with creep-degraded material, is a significant concern under cycling operation. On the other hand, the Piping Code (ANSI B31.1) does provide some consideration in fatigue, that is, allowable stresses are varied with the number of cold start cycles, and stresses induced by thermal expansion of the piping system are also considered.

The design philosophy of the present Section I, “Power Boilers” and Division 1 of Section VIII, “Pressure Vessels” of the ASME Boiler Code may be inferred from a footnote, which appears in Division 1 of Section VIII on Page 9 of the 1968 edition. This footnote refers to a sentence, Par. UG-23 (c), which states, in effect, that the wall thickness of a vessel shall be such that the maximum hoop stress does not exceed the allowable stress. The footnote says:

It is recognized that high localized and secondary bending stresses may exist in vessels designed and fabricated in accordance with these rules. Insofar as practical, design rules for details have been written to hold such stresses at a safe level consistent with experience.

As such Section I and Division 1 of Section VIII do not call for a detailed stress analysis but merely set the wall thickness necessary to keep the basic hoop stress below the tabulated maximum allowable stress. They do not require a detailed evaluation of the higher, more localized stresses, which are known to exist, but instead allow for these by the safety factor and a set of design rules. Thermal stresses are given even less consideration. The only reference to them is Par. UG-22 where “the effect of temperature gradients” is listed among the loading to be considered. There is no indication of how this consideration is to be given. As such it is important to realize that the code does not formally define the actual design life of pressure components.

The ASME code provides material allowable stress at a given temperature and the formula for pressure vessel thickness determination. The average temperature through the wall thickness is used in code calculations. The assumption is that the differential temperature between the outer and inner surface is minimal because the tube is relatively thin. This assumption may be good enough for tubing design. However, for thick-wall headers, thermal gradients can induce substantial stresses during cycling operation. Some boiler manufacturers superimpose the material oxidation limits on tube outside diameter temperature. This non-uniform temperature distribution can induce secondary bending stresses. It is a very complex stress and strain problem if the creep and fatigue interaction, local stresses, stress redistribution, relaxation, and strain hardening are considered prior to the failure.

Considerable effort was directed toward the development of a creep-fatigue analysis method for incorporation in to the ASME code. In Section III, the rules for high temperature design have been under development over a number of years leading up to rules codified under Code Case N-47. However in its current form N-47 is conservative and reflects the numerous uncertainties in creep-life prediction. It is also purely empirical, but is the best that is currently available. The use of N-47 for the remaining life assessment of components represents an extremely conservative approach that may lead to premature and unwarranted retirements

The ASME Code provides rules for a safe and economically consistent design throughout the industry. However, any design has certain underlying assumptions, limitations, and constraints. It is important to understand the rationale behind these considerations and develop proper Downstream processes, such as fabrication, installation, monitoring, diagnostic, operation, and maintenance practices to protect them. Additional requirements or margins may need to be placed in the design if other operation conditions exist beyond the code considerations. The ASME B&PV Code Section I does not explicitly consider the effects of thermal stresses, local stresses, and fluctuations in load. To understand the reasons for this, it is necessary to understand some of the philosophy behind code development. The codes are design tools. Their purpose is the enforcement of design rules that ensure a low probability of failure by specifying the minimum allowable thicknesses of components made of approved materials and fabricated in a stated manner. The philosophy of the code is based on such concepts as:

- Allowed materials are ductile and, therefore, in many cases, forgiving.
- Life, operational effects, material variability, thermal and local stresses, and other similar effects are not directly considered but are expected to be accounted for by the conservatism applied in setting the allowable material properties.
- Design rules are developed by consensus within groups of acknowledged specialists and are subjected to multiple levels of review. Being developed in this way, there may be no precise physical justification for some of the rules.

Unfortunately, the simplifications that make for a good design tool inhibits the usefulness of the codes as devices for predicting with any precision the life of a component. The life of a component is very much related to the actual conditions including local stresses, thermal stresses and material properties.

Methods of Assessment

Analysis Methodologies

Numerous methods have been applied to evaluate the impact that various operating transients will have on boiler pressure vessels and piping. A phased approach (e.g. Level I, II, III) to condition assessment is commonly followed world wide and was developed originally for high temperature header life assessments based on practice from the former CEGB. Increasing levels of intricacy and detail can be applied which provide higher confidence in the output but also increases costs.

- Design method
- Operating History method
- Operating Conditions (pressure and temperature measurements) method
- Metallurgical Material Sampling method
- On-line Monitoring/Analysis method

Design Method

Original equipment manufacturers (OEM's) design pressure vessels and boilers to customer requirements of pressure and temperature. Each OEM has its own design procedures relying in part on experience and using the Code used as a design tool to ensure that its requirements are met. The stresses for the design conditions, calculated in the way that the Code requires, are confirmed to be no greater than the Code-allowable stresses for the specified material at the design temperature. This ensures that the sections will always be at least as thick as the Code requires and often much thicker. Frequently the standard practice is to make the thickness of a cylindrical component equal to the next commercially available size above the exact dimension required by the Code.

With knowledge of the design criteria for a component and its minimum allowable thickness based on closed form solutions, it is possible to perform a first level assessment of component life. In many cases the results predict that the majority of high-temperature vessels are close to, or have passed, their useful life and that the low-temperature ones are satisfactory-this despite the fact that there may be physical evidence of damage. Typically this method provides a preliminary assessment and is useful as a means of screening components for further more in-depth scrutiny.

Operating History Method

This method utilizes the design method with refinement by incorporating plant records. Improvements in computing capability at lower costs allows the benefit of using analytical modeling, although at this level, linear ramp rates are assumed as input data. As well minimum material properties and nominal dimensions are used.

Sophisticated finite element analysis techniques are used for heat transfer and stress-analysis computations which includes the effects of creep and plasticity. The limitations of the design method are surmounted by considering the effects of start-ups and shutdowns. However, it is important to be aware that because these transients are assumed to be linear, this level does not account for the actual non-linear behavior and can therefore be non-conservative.

Operating Conditions Method

Actual transient temperature, pressure and flow measurements, taken during operation, are used for the analyses noted above. These data are obtained from thermocouples and pressure transmitters installed on targeted components and running the unit in the manner required to gather specific data. For the short term it can be cost effective install a data-acquisition system so information and measurements can be done on-line during normal operation and avoid the expense of defining and scheduling unique tests and conditions.

In this stage actual measured thickness of components are used and any other results of a NDE program. As actual material data are not available, minimum material properties have to be used to provide a lower bound for remaining life.

Actual operating data allows the forecast of how various operating practices may affect damage accumulation and can identify possibly unknown sources of issues, e.g., slug feeding, condensate-flow events.

Metallurgical Material Sampling Method

The effort at this level is relatively involved and is aimed at determining actual material properties from material samples along with the detailed analytical techniques for more precise life assessment. This is particularly applicable to creep rupture or creep fatigue properties in high temperature components. This more detailed and expensive assessment may be justified on a cost basis, for example, when the alternative is replacement or significant repair.

Care must be taken in conducting and interpreting creep rupture tests. In order to obtain results in reasonable test times, accelerated conditions must be used with temperature acceleration being preferred for low alloy steels. A series of constant load tests are conducted at the same initial applied stress (iso-stress) equal to the actual or design service stress. Data from the tests at various temperatures are extrapolated to the service temperature on a linear temperature-logarithmic curve to give an estimate of remaining rupture life. An important issue with material testing is that the process of obtaining material samples should not create a repair problem e.g. generally the material sample has to be taken from an area removed from section changes and other discontinuities. Regrettably, often, the crucial locations are exactly those locations not appropriate for sampling. In some cases it is possible to take advantage of miniature sampling techniques and there has been considerable work done in developing standardized miniature specimens for creep and creep fatigue testing.

On-Line Monitoring and Analysis

Various OEM’s and a number of utilities have developed systems that monitors temperature, pressure, and flow, and uses these data together with material and geometry information to assess damage accumulation on a on-line i.e. real-time basis.

As noted in Section 5 due to the complexity of software development and associated hardware compatibility, often these systems have proven to be problematic. Both the high cost of software development and the necessary on-going technical support combined with the unwillingness of utilities to invest significantly resources in a competitive market have discouraged the widespread use and further development of these systems. The case for on-line damage monitoring is not clear and needs to be considered on an individual basis. However an option to the use of such systems is to evaluate "what-if" capabilities such that the effects of changing operating practices can be evaluated.

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TYPES OF CYCLES

A unit can be operated in various cycling modes as well as be subjected to other planned and unplanned transients. In the base load mode of operation, the unit is operated at or near the rated design capacity for the most part on a continuous basis.

Cycling can involve modes of operation such as:

- Load cycling: A typical load cycle is composed of load reduction, low-load operation, and re-loading. Load cycling can include the following cases:
  - Load following operation: The load cycles between minimum load and full load.
  - Low-load cycling: In lieu of shutdown at night, the unit load is reduced to a minimum capacity while continuing to operate on coal with or without supplementary oil or natural gas firing for flame stability.
- On/off cycling: A typical on/off cycle has four phases: load reduction, idle, restart, and re-load. The on/off cycling is further divided into the following categories:
  - Two-shift operation: The unit is cycled and shut down every night and restarted in the morning. This is typically referred to as hot start.
  - Weekend shutdown: The unit is shut down for the weekend and restarted on Monday. This is typically referred to as warm start.
  - Extended shutdown: The system is shut down for standby or outage. This is typically referred to as cold start. It might require a type of lay-up/protection for the boiler system depending on the duration of the shutdown.

On/off cycling induces more damage to boiler components than load cycling due to the range of temperature variations. Among the on/off cycling operations, the cold start can produce more damage than the warm and hot start per event basis due to the condition of complete cool down. However specific conditions and circumstances may lead to different outcomes.

Economics is the main reason for performing cycling operation. To maximize the cycling benefits, the units can be required e.g. to operate with the load as low as possible and ramp up as fast as the plant system allows. The following can affect the damage levels of boiler components in cycling operation:

- Number of startups and shutdowns in each category
- Operating temperatures and pressures
- Ramp rates (Heating and cooling)
- Force Cooling Practices

- Minimum loads, load ranges
- Variable Pressure Operation VPO
- Attemperator Operation
- Component configuration, geometries and material properties

Coal-fired units can be more limited than oil- or gas-fired units in their capability to perform cycling operation, due mainly to the larger heat capacities of the boilers and delays in the responses of pulverizer systems.

Ramp Rates

Cycling operation can require fast load ramping to minimize the fuel cost and to meet system dispatch requirements. A sluggish or slow ramp rate unit, which cannot keep up with the demands, is often subjected to peer pressure, because another power plant must make up the difference. Improving the fast ramping capability is a challenge; it might require a control upgrade, and sometimes the cure is within the existing system's equipment, which requires only proper maintenance and tuning.

The effects of cycling operation are caused by the rate and range of change in transient temperatures and pressures. A major problem with cycling operation involves the excessive life expenditure of critical components due to frequent startup and shutdown. Cycling increases the number of stress cycles experienced by boiler and turbine components as a result of temperature changes. Therefore, the rise rate of steam temperature is determined by allowable fatigue life consumption of either turbine or boiler components. In all modes of cycling operation, control actions are arranged so that prescribed ramp rates of SH and RH outlet temperatures are followed during load changes, and thermal stresses are thereby minimized. Sliding of variable pressure operation (VPO) can improve the situation and such capability can be an important element of a cycling program because it enables lower steam-to-metal temperature differences in addition to other benefits.

Variable Pressure Operation (VPO)

VPO provides benefits to units that frequently operate in cycling modes or at partial loads. The most common operating mode for U.S. utilities is constant steam pressure operation (CPO). Under CPO, main steam is provided to the HP turbine at constant pressure over the entire load range. Under VPO, turbine control valves are held at or near their full open position. Control of unit output is accomplished mainly by varying throttle steam pressure. In pure VPO, turbine control valves are held fixed at or near the full open position with little modulation. [12] Sliding pressure operation of a unit is beneficial from a fatigue view point for both the turbine and the boiler. In the case of the turbine, it reduces the chilling effect on the HP rotor so that the strain range experienced by the component is reduced. For boiler components such as headers and drums, the strain range amplitude is controlled by the pressure stress plus the thermal stress. Thus reducing pressure during shutdown reduces the overall strain range on these components.

Both for turbines and for boilers, the shutdown can be the most damaging part of the cycle since this produces tensile stresses at critical locations. Sliding pressure operation reduces the maximum tensile stresses and thereby increases the fatigue life of components.

During changing pressure the saturation temperature changes and this produces a temperature differential across the vessel wall. Stresses are built up as a result this temperature differential and repeated application of this thermal stress can lead to fatigue cracking, with the number of cycles to initiation being dependent, as mentioned on the strain range. Temperatures differences between the top and bottom of the main steam drum can produce hogging or sagging of the drum

Overheating can occur as a direct result of the lowered boiler pressure and its consequent effects on latent and specific heats. As the pressure drops, the amount of heat required to produce a given degree of superheat per unit of mass steam drops. However, the latent heat to produce that mass of steam increases. Boilers are generally designed for a set heat absorption ratio between steam generation and superheater and the increase firing at the lower pressure to compensate for the increased latent heat of the water will therefore results in excessive heat absorption in the superheater. This excessive heat can manifest itself as higher tube metal temperatures and higher steam temperatures.

Hydraulic Events - Water and Steam Hammer

All units are susceptible to hydraulic events such as water hammer or steam hammer. Since such events are most often initiated by normal valve and pump operation, it can occur as a matter or routine operation. However, units which perform cycling duty may have an increased level of risk since bringing pumps on and off occurs at a greater frequency. Additionally, there is more time spent operating with transient parameters (flow, pressure, temperature) which can increase vulnerability to flow upsets. With regard to cycling units, those designed for steady state or base load may exhibit a greater tendency for issues as the valve and pump design and control logic may not be compatible with the requirements of cycling duty

The term *water hammer* has different connotations depending on whether the fluid in the pipe is water or a two-phase mixture of steam and water. In water piping, water hammer generally refers to the formation of a pressure wave resulting from the rapid closure of a valve, similar to steam hammer. However, for MS and HRH piping, the terminology relates to a transient event that is associated with a two-phase fluid and that can manifest in two forms: slug flow and steam-condensation-induced water hammer.

Steam piping systems can be subjected to both steam and water hammer. Steam hammer results from rapid valve closure that interrupts the high-velocity flow of steam within the pipe. This in turn results in the formation of a pressure wave that moves back and forth through the system until the energy is dissipated either by reopening of the valve or through elastic displacement of the system.

Slug flow can result when water that has accumulated in a low spot, typically during shutdown, is picked up by the high-velocity steam flow. Varying levels of force are imparted to the piping when the slug reaches the next elbow or other obstruction.

A more violent form of water hammer, known as steam-condensation-induced water hammer, can also occur in MS and HRH piping. This form of water hammer is most violent when the water is highly sub-cooled. The sub-cooled water results in violent condensation of the steam, which in turn can result in substantial turbulence at the steam–water interface. If the turbulence is sufficient, a water slug can be generated, which entraps an isolated steam pocket. Continued rapid condensation of the steam pocket accelerates the water slug into the resulting void, causing a water hammer from the void collapse. Depending on the void fraction and the amount of sub-cooling, the resulting pressure wave can be considerable.

Both forms of water hammer (slug flow and steam-condensation-induced) are most likely to occur during unit startup. Standing water can collect in several possible locations in the MS and HRH piping during shutdown. The standing water is most likely to pool in natural low points. The MS and HRH outlet headers and piping systems are equipped with low point drains; however, standing water is likely if these drains are improperly designed, if the drains do not function correctly as a result of poor maintenance, or if sags have formed in the piping from thermal quenching or support deficiencies.

Condensate Flow/Pooling Events

Start-Ups

During boiler startup, possible problems exist when the flow through the boiler might not have been established or might be at low rates. In these situations, particular care is needed in order to avoid localized overheating [13]. Some common concerns are identified:

SH platens can accumulate condensation in the bottom loops (of pendant) if temperatures are allowed to fall below the ambient saturation temperature during shutdown periods. The temperatures naturally drop while the unit is off load but are further cooled when, at the beginning of the startup cycle, the induced draft fans are put into service. This water logging restricts the flow through the elements until such time as it is boiled out. There are periods when only some of the platens have established a flow while others are still stagnated and might experience localized overheating.

The RH flow is not normally established until after steam admission to the turbine. If this flow is delayed, then there is a significant risk of overheating the RH elements. The volumetric flows are much reduced in low-load operation, especially under constant pressure operation. In extreme circumstances, the flows through the boiler cease to be stable, and local stagnation can occur. Variable pressure control at reduced load reduces this threat by increasing the volumetric flow for a given load.

In the waterwall sections, especially with natural circulation drum boilers, residual heat in the upper sections bias the circulation so that some tubes have a stagnated flow. If these tubes are close to the burners, the high heat flux can result in localized overheating.

Force Cooling

When a boiler is shut down, air flow can be continuously forced through the furnace and convection gas passages in order to rapidly cool down the superheater tube metal temperature. In some cases, it is desirable to cool down the tubing as fast as possible to allow human entry into the boiler for urgent repairs. However, the main steam line temperature remains just below 540'C since the pipe is thermally insulated and there is little or no steam flow through it to transfer heat from the metal. Thermal quenching of the main steam pipe has been experienced under certain circumstances when a rapid cool down was in progress. These special conditions have been found to occur when the superheater tube metal temperature drops below the steam saturation temperature and steam condensation initiates.

The difference in specific volume of steam and liquid water varies with its pressure, but it is substantial even at l000 psia (22 to 1). The change in specific volume of condensing steam reduces the pressure within the superheater tube circuit and allows the generation of more steam in the boiler drum. This new steam will flow into the superheater tube circuit where it will condense again back to water. Since the pressure within the tube circuit is lower than the drum pressure, the steam saturation temperature will also be lower. This subsequently results in a lower temperature of the condensate. The steam condensation can occur quickly so that the superheater tube circuits can rapidly fill with water. The condensate will subsequently flow over into the outlet header and the main steam piping.

In a pendent-type superheater circuit, the tubes hang vertically down from the headers and can fill with water in such a manner that further steam flow and condensation will not occur. In a drainable-type superheater circuit, the tubes connect *horizontally* to the headers which allow water to flow from the tubes and continuous condensation can occur.

The condensation can occur at such a rapid rate that the superheater outlet header drain lines cannot remove it, and the cool condensate flows into the main steam pipes. Thermal quenching occurs since the pipe metal temperature is greater than 800°F (427°C) while the condensate temperature is approximately 300°F (149°C). The condensate touching the bottom arc segment of the steam pipe results in local quenching, and large thermal gradients are generated across the thick pipe wall and between the top and the bottom portions of the pipe. The temperature gradients being experienced during thermal quenching incidents clearly exceed typical recommended limits for thick walled pressure vessels. These thermal gradients produce tremendous stresses and strains that result in pipe distortions/yielding, steam line bowing or hogging, hanger/support breakage and potentially creep-fatigue cracking. If the pipe has developed residual bending strain during quenching, there is a strong potential for creep damage associated with girth welds.

Condensate Pooling, e.g., Cold Reheat Piping (1009863 – Guidelines Cold Reheat)

The presence of pooled water has been a common theme in a variety of cold reheat piping damage resulting from water hammer, corrosion pitting and corrosion fatigue. Steam can condense in the system during shut down, start –up, load transition or low load operation. This can lead to;

- Water pooling in horizontal or sagging piping with inadequate slope or drainage
- Water hammer may result if pooled water is entrained by steam on start-up
- Water hammer or quenching may cause overstress deformation or initiate or propagate fatigue cracks
- Pooled water can lead to corrosion pitting and corrosion fatigue cracking

Operation at Temperatures Above Design for Extended Time Periods

It is not unusual to find temperature imbalances from side to side in boilers. The temperature imbalance can be caused by uneven flue gas distribution across the boiler, unequal operation of desuperheater spray stations, and steam-side flow differences. The unit operator has no information at hand to indicate the temperature imbalance. Without this information, it is impossible to identify the presence or location of long-term overheating and other damaging events. Changes in fuel, upsets in operation, insufficient thermocouple (TC) coverage, and inaccurate TC measurements all contribute to the potential for unknown damage. Cycling operation causes deslagging, which can increase tube temperature, and overfiring in variable pressure operation can also cause the tube overheating problems].

Drum Top-Ups - Economizer Thermal Shocking

The slug feed's purpose is to maintain the drum level. The operation can cause significant damage to economizer inlet headers that absorb heat from the flue gas stream. During unit startup, feedwater flow is initiated to establish the correct water level in the drum and is then stopped until the water level becomes low. When this happens, the warm economizer inlet header is shocked by the relatively cold feedwater. This cycle can occur many times during a routine startup, happening every time feedwater flow is reestablished. The slug feedings impact the economizer inlet header through-wall temperature gradients. These gradients generate from a thermal quench and the difference between internal fluid temperature and outside metal temperature contribute to the formation of fatigue cracks through low-cycle thermal fatigue.

Furnace Sub-Cooling

Many boilers have suffered tube cracking in the lower furnace area after a period of on/off cycling operation.. The longitudinal cracks form on the casing-side internal tube surface and propagate through the wall, resulting in leaks. The failure mechanism is corrosion fatigue. The cause of the problem is a combination of thermal cycling and water chemistry at high-stressed areas. When the boiler is shut down and bottled up for the off-line period, the entire furnace is at, or near, saturation temperature. During the idle period, the boiler water cools off with subcooled water collecting in the lower section of the furnace tubes. There is then a temperature gradient from the lower to upper furnace. When flow in the furnace is initiated after the shutdown period, the hot water displaces the cold water—resulting in a thermal cycle. The greater the temperature difference, the greater the shock.

Testing for furnace subcooling consists of installing thermocouples at proper locations. Temperatures from these TCs, along with drum pressure and operating events, are monitored. Data are recorded to provide a continuous record and results used to evaluate the magnitude of the temperature differential between the upper and lower furnace during shutdown. The magnitude of the temperature differentials is used to evaluate the risk of failure.

4
CRITICAL COMPONENTS

As mentioned above, the majority of utility boilers in the United States were not originally designed to address non-baseload operation. Many vulnerable locations in the critical boiler pressure components are subjected to damage due to cycling operation. Due to many added constraints under cycling operation, it is a major challenge to operate these boilers to preserve boiler reliability and safety.

The life expectancy of the heavy-walled pressure vessels is affected by the complex effects of thermally induced fatigue and in some cases the interaction with creep. Terminal tubes can suffer from fatigue due to the effects of thermal expansion that result from changes in steam temperatures over the operating regime. As noted both steam touch and water touched tubing will be subjected to more arduous conditions associated with transient operations.

It is not feasible or necessary to evaluate in detail every component in a boiler. It is, however, important to determine the critical components. The initial step in the determination of criticality is an assessment of the consequences of a failure. If the consequences of the loss of a component are significant considering, for example, safety and or reliability, then that component meets the first test of criticality.

Experience indicates that several components should be considered candidates for critical items.

The following components have experienced difficulties under cycling operation and include:

- Waterwall Tubing
- Steam Drums
- Boiler Circulation Pumps/Piping/Valves
- Economizer Tubing and Inlet Header
- Superheat and Reheat Outlet Headers
- Superheat and Reheat Attemperators/Piping
- SH and RH tubing
- Main Steam and Hot Reheat Piping
- Cold Reheat Piping

Table 1 at end of this section summarizes problems and issues that have been observed as a result of cycling and low load operation of fossil power plant.

Waterwall Tubing

Operational Aspects.

Increased frequency of reduced load, load following and start/stop operation will aggravate temperature and stress problems. Corrosion fatigue occurs by the combined actions of cyclic loading and a corrosive environment. The predominant locations are near tube attachment locations where large stresses develop during transient operating conditions as thermal expansion has been constrained by the attachment.

Adequate cooling flow must be assured at low loads if turbine steam demand is less than minimum water-wall cooling-flow requirements, means of handling the difference in flows must be accommodated

Water chemistry is more easily upset during cycling operation. More of the pre-boiler cycle is under vacuum at low loads, increasing the potential for air in-leakage. Off line, whether condenser vacuum is being held or broken, air will be introduced into the cycle. Because cycle conditions change more frequently during cycling duty, proper water chemistry control is more difficult. An increased potential, therefore, exists for cycle corrosion and deposition of minerals and corrosion products in the boiler.

Potential Problems

- Corrosion fatigue failures
- Tube failures due to overheating can occur from inadequate cooling
- flow or from internal tube deposits which promote overheating.
- Tubes may not have adequate flexibility where attached to headers. This can cause excessive stress during temperature ramps and be subject to mechanical fatigue failure due to the increased number of heating/cooling cycles.

Steam Drum

Operational Aspects

Because the saturation temperature of steam is 700°F (371°C) or less, creep damage in carbon steel drum is negligible. Drums are, however, subjected to large temperature and pressure transients that can lead to the imposition of excessive stresses. The temperature differences occur: 1) through the drum wall thickness, and 2) between the top and bottom of the steam drum. As a result, manufacturers change is influenced by the heat transfer coefficients of steam and water. The upper saturated steam-touched portion of the drum heats up more rapidly than the lower, water-touched portion, leading to possible bowing of the drum during the startup. Allowable temperature differentials are based on tensile strength, drum diameters, wall thickness and pressure. As a result, each steam drum has its own recommended allowable temperature differentials for cooling and for heating.

Recent investigations appear to contradict the premise that in many cases drum ID cracking is mainly the result of thermal fatigue. The maximum stress intensities at the vulnerable locations include the contributions of internal pressure and thermal transient stresses to the total stress state. Analyses are required to determine the location and time at which the maximum stress occurs in the drum and depending on the particular operating scenario; the pressure and thermal stresses may in or out phase with each other. So although thermal stresses may not be dominant in many cases the impact is not negligible and needs to be evaluated.

In many cases, pressure stress and environmental influence of corrosion fatigue appear to play the dominant role in drum cracking and that as mentioned thermal stress is secondary. Exceptions to this include:

- downcomer circumferential ligaments on natural circulation units with numerous small downcomers (e.g. up to170) where the influence of thermal stress is significant.
- "Stick Through" nozzles where the portions of the nozzle extending beyond the ID surface respond faster to temperature excursions than the drum wall, a condition likely to cause toe cracking where the weld joins the drum ID.

Potential Problems

- Damage will be caused by a combination of cyclic loading (thermal and pressure) and a corrosive environment which will promote fatigue damage and could reduce drum life.
- Cracks have been commonly observed associated with steam drum penetrations and downcomers, as well as in the drum shell in the vicinity of these areas.
- Hole edges and the inside of holes in the drum are also susceptible to cracking.
- Cracking has also been found at drum shell girth welds, longitudinal welds and the heat affected zones of such welds in both mud and steam drums.
- Defects have also been found on fillet welds associated with end liner plates, liner wall plates, liner plate support brackets, manhole door hinge supports, and small bore penetrations.
- Defects in liner plate butt welds typically do not pose a threat to drum shell integrity in the short-to-medium term although any loosening of the baffle plate sections could result in local areas of the drum shell being subjected to increased thermal transients.
- Moisture removal may not be adequate at low loads, due to insufficient steam velocity through the separators.
- Oxygen attack due to regular startup with oxygen-contaminated water.

Boiler Circulation Pumps/Piping/Valves

Operational Aspects

Circulation pumps and associated piping and valves on a supercritical, once-through, or drum-type boilers are vulnerable to thermal shock. The introduction of hot boiler water to an idle (relatively cool) pump being started can result in thermal stress, due to a high differential in temperature across the thick walls of the pump casing.

Operational approaches can be taken to manage the thermal transient issue. One approach is to equalize the temperature of the idle pump prior to starting by keeping the pump discharge isolation valve bypass valves open and allowing natural-circulation flow through the idle pump. Another approach is to keep one pump in ·service while the unit is off line for short periods (such as overnight). Forced circulation through the active and idle pumps will eliminate the potential for thermal shock. In all cases, pump restart should be restricted if boiler water and pump casing temperatures differ by more than the manufacturer's recommendation. typically 100°F (56°C). Permanent thermocouples working in conjunction with electrical interlocks can be utilized.

Potential Problems

- Temperature mismatch may cause thermal shock and pump case damage.
- Thermal cycling may cause fatigue cracking.

Economizer Tubing and Inlet Header

Operational Aspects

Economizer cycling concerns include:

- Thermal fatigue.
- Gas-side/acid dew point corrosion
- Pitting corrosion
- Steaming.

All are essentially related to start/stop cycling. Thermal fatigue occurs when cold feedwater is introduced to a warm economizer following an overnight shutdown. In addition, condensate passing through the deaerator during startup will be aerated if pegging steam is not provided to the deaerator. Pitting is a form of damage that can occur in water touched tubing, especially economizers and is primarily a result of poor shutdown practices with oxygen saturated stagnant water. Undesirable steaming can occur in the economizer, if feedwater flow is very low while firing at startup. Gas-side corrosion can occur during low-load operation and off line, if operating temperatures fall below the acid (sulfuric) dew point temperature.

Potential Problems

- Thermal fatigue cracking of ligaments when cold feedwater is introduced to a warm economizer header.
- Increased frequency of tube stub failures due to thermal fatigue cracking.
- Boiler startups with boiler water containing excessive amounts of oxygen, may cause pitting corrosion of economizer tubing
- Acid dew point (Cold end) corrosion from SOx condensation.
- Steaming on startup resulting in water-hammer and drum-level control problems.

Superheater and Reheater Tubing

Operational Aspects

Operating changes (e.g. constant pressure to variable pressure operation), can effect change in steam and gas flow characteristics that can be important. Overheating can occur as a direct result of the lowered boiler pressure and its consequent effects on latent and specific heats. Different steam-specific volumes and temperatures will exist which will affect velocities and distribution. In some instances, flow stagnation may even occur. Gas flow distribution changes can occur at lower loads, which will create uneven heating. Start/stop cycling may promote increased exfoliation and may cause water and exfoliated products to collect in low points that are not drainable. Such impediments to flow can result in overheating of dead legs until boil-out occurs.

Thermal shock after boil-out can occur when cool steam and water meet hot tubes. Exfoliation can cause turbine damage.

Tubes to header connections are a thermal stress and mechanical fatigue concern, aggravated by an increased frequency of low-load or start/stop cycling.

Potential Problems

- Tube materials may not be adequate for new operating conditions (pressures, temperatures, rates of change, etc.).
- Overheating can occur during startup due to insufficient cooling flow, resulting in increased fire-side corrosion with a correspondingly greater risk of tube rupture.
- Pitting in horizontal tubing due to possible condensate pooling
- Rapid temperature ramps may cause excessive stress due to unequal heating and expansion; can lead e.g. to cracking at spacer/lug attachments, header connections
- Water and deposits may accumulate in the bottom of superheater loops.
- Exfoliation could cause tube p1uggage and turbine solid particle erosion damage.

Superheater and Reheater Headers

Operational Aspects

Regardless of how header pressures are controlled during cycling service (constant pressure or variable pressure), adhering to allowable temperature ramp rates is important. Poor temperature distribution in superheater or reheater tubes will result in header thermal stresses between areas with such differences. Ligament and stub cracking are likely consequences, if temperature differences are sufficiently great and occur with sufficient frequency. Ligament cracking can occur due to the quenching effect from stagnated condensate that is generated in shutdowns and start-ups, unrecognized local transients and/or “tight” ligament design. Some studies have found no correlation between incidence of cracking and operating hours or number of cycles implying that the dominant fatigue cycles are not the planned and controlled start-up/shut down events upon which design and traditional life assessment are based. Rather major contributors to ligament damage are emergency shut downs, spraying operation during cold starts, temperature excursions during hot starts and small but rapid temperature changes accompanying load changes.

Header bowing can also occur if side-to-side header temperature differential is excessive.

Potential Problems

- Ligament cracking
- Thermal/mechanical fatigue cracking at stub tube to header connections
- Header bowing due to unequal temperatures.

Attemperators (Desuperheaters) - Superheat and Reheat

Operational Aspects

Water spray attemperation is the most widely used method ocontrolling superheated steam temperatures. In a number of CRH piping failures, failure occurred downstream from or in close proximity upstream to a spray attemperator. In most cases, quenching of the inner surface of the piping by cyclic operation of the attemperator was the primary mechanism driving fatigue crack propagation. The spray attemperation system's adequacy for cycling duty is important. In variable-pressure operation, more spray flow may be required under certain operating conditions.

- Control and shutoff capability of the existing system should .be eva1uated.
- Accurate flow control over a wider range of operation is required. Turbine water induction prevention recommendations for the spray system should be followed.

Potential Problems

- Thermal cycling may damage adjacent reheat and superheat piping
- Thermal cycling may damage nozzles.
- Thermal cycling may damage sleeves.
- Cycling may increase wear on spray control valves.
- Rapid load change may exceed control stability range.
- Control range of water valves may be inadequate for new operating range.
- Water induction potential may be increased.

Main Steam and Hot Reheat Steam Piping and Supports

Operational Aspects

Main steam and hot reheat steam piping will be exposed to an increased potential for thermal transients during cycling duty. Rapid temperature changes are associated with rapid load changes at lower loads and during startup, and with the introduction of steam to; and warming of, main steam and hot reheat steam leads following an overnight or weekend shutdown. Fortunately, heat transfer is poor at the low flow rates experienced during the initial introduction of steam. Accelerated expenditure of the remaining material life may be manifested in fatigue or fatigue/creep cracking. Dynamic loads resulting from steam or water hammer or other flow transients during rapid load swings could induce high stresses not anticipated in the original design.

Potential Problems

- Start-Up, shutdown and load cycling - will increase the number of thermal transients and the potential for pooling of water accumulated from condensation during shutdown
- Fatigue and fatigue/creep cracking, resulting from increased therma1 transients.
- High stresses induced by flow transients, steam or water hammer
- Inadequate or incorrect supports - can shift stress and produce very local high stresses that will lead to damage

Cold Reheat Piping and Supports

Operational Aspects

Operating practices vary widely, even among plants of the same basic design within the same company. Plants in baseload service tend to have fewer fatigue issues because of the long durations between shutdown with nearly constant CRH piping flow, temperature, and pressure. Plants with one or more shutdown/startup cycles per day, or even per week, impart significant thermally induced stresses on thick-walled piping components and increase the risk of water hammer and other rapid pressure excursions. Temperature and pressure may also change frequently due to load following, either by high-pressure-turbine throttling or through sliding pressure operation. In general, greater operational change produces more stress and a greater likelihood of fatigue cracking in CRH piping. Frequent attemperator operation has proven to be a risk factor for CRH piping damage

Potential Problems

- Start-Up, shutdown and load cycling - will increase the number of thermal transients and the potential for pooling of water accumulated from condensation during shutdown
- Horizontal piping with inadequate slope – water may pool leading to potential water hammer, quenching and corrosion/fatigue
- Sagging pipes – may be caused by poor hanger design, overload due to external (e.g. impact, support failure) or internal (water hammer, differential quenching) forces; potential damage as above with inadequate slope
- Cyclic and intermittent use of attemperators – will introduce high thermal stresses in attemperators, shields and downstream CRH piping Excessive attemperator flow during normal operation – over attemperation may lead to quenching
- Inadequate operation of drains or drain valves due to design, maintenance or operating problems e.g. plugging, undersized, operator inattention – potential for pooling, quenching, thermal fatigue, water hammer
- Inadequate or incorrect supports - can shift stress and produce very local high stresses that will lead to damage
- Steam and Water Chemistry – Corrosion and corrosion fatigue is more likely with cycle chemistry problems and pooled water

Table 4-1
Issues Arising From Transient Operation of Fossil Power Plants (adapted from EPRI 1001507)

Plant Component/System	Transient/Cycling Associated Issues	Engineering Approaches/Solutions
Economizer		
Headers	Ligament cracking as a result of injection of cold feedwater during boiler startup Ligament cracking as a result of boiler top up with cold feedwater during shutdown Stub-to-header cracking as a result of temperature differentials between economizer tubes during low flow and boiler shutdown Internal erosion/corrosion of outlet stubs Fatigue cracking as a result of water hammer during startup on steaming economizers Quench cracking of inlet tees as a result of injection of cold feedwater on startup Thermally induced bending as a result of stratification of water flow during low-load operation or off-load boiler top up (top to bottom temperature differential)	Internal camera inspection for ligament cracking and internal corrosion/erosion. Perform external nondestructive testing of stubs Perform selective visual, MPI, and ultrasonic inspection at outages Replace headers or damaged sections with increased ligament efficiency Modify stub design to reduce local stresses Modify boiler feed to trickle feed system to reduce thermal shock Install economizer recirculation to maintain uniform temperatures during boiler shutdown
Tubing	Thermomechanical cycling of tube attachments	Perform opportunity inspections and repairs Perform selective visual/MPI inspection at outages Consider replacement of attachments with more flexible designs

Plant Component/System	Transient/Cycling Associated Issues	Engineering Approaches/Solutions
Evaporative Section		
Waterwall headers	Stub-to-header cracking as a result of temperature differentials between waterwall tubes during low-flow and boiler shutdown Thermally induced bending as a result of stratification of water flow during low-load operation or off-load boiler top up (top to bottom temperature differential)	Perform selective visual/MPI inspection of stubs at outages and repair or replace as required Consider a design change to increase flexibility between tubes Visually inspect header for evidence of bending; review observations and consider design changes to more flexible arrangement Consider off-load recirculation to even out or reduce temperature distribution
Waterwall tubes	Thermomechanical cycling of tube attachments Corrosion fatigue arising from water quality (especially O2 content) External corrosion during cold periods Fireside oxide spalling as a result of temperature cycling Localized overheating of tubes, especially on natural circulation drum boilers during low-flow conditions on startup as a result of slugs of warm water at the top of the boiler, inhibiting flow Overheating of tubes as a result of high heat flux or low flow on startup (that is, DNB)	Perform selective visual/MPI inspection at outages Modify tube-to-structure attachment to more flexible design Improve water quality control Consider off-load recirculation to even out or reduce temperature distribution Use of “rifled” boiler tube to reduce DNB

Plant Component/System	Transient/Cycling Associated Issues	Engineering Approaches/Solutions
Boiler structure	Thermomechanical fatigue of the boiler structure Increased air-in leakage as a result of failure of boiler casing Failure of windbox and ductwork attachments Failure of ductwork expansion joints Load migration in boiler sling rod supports and potential for failure	Perform opportunist visual/MPI inspection of attachments and expansion joints at outages and repair or replace as required Review design of components such as attachments and expansion joints; modify to improve flexibility Regularly inspect supports at outages for evidence of broken or slack supports Consider once-off check weigh of boiler supports to confirm support integrity; check weighing of hot and cold supports prior to adjustments
	Thermal cycling of pump bodies on startup Alignment problems as a result of distortion of pump casings and impellers during rapid temperature changes on startup Interference and clearance problems on pump seals as a result of rapid heating of impellers relative to casings	Perform selective visual/MPI inspection of pump bodies at outages Consider off-load recirculation to even out or reduce temperature distribution
Drum		
Drum Shell	Thermal cycling of the drum shell and localized cracking at stress concentrations and welds	Perform selective visual/MPI inspection of stubs, attachments, and body welds Assess defects for profiling or local repair Monitor large or repeat defects and perform engineering assessment of drum integrity

Plant Component/System	Transient/Cycling Associated Issues	Engineering Approaches/Solutions
Internals	Thermal fatigue cracking of attachments and seal welds	Perform selective visual/MPI inspection of drum furniture
Primary Superheater		
Headers	Quench cracking of bottom headers (especially horizontal sections) as a result of condensation in higher elements during startup Water logging of sagging bottom headers and possible circulation restriction during startup	Perform internal camera inspection for internal defects if quench cracking is a possibility Review drainage effectiveness and modify (additional drains), if necessary
Tubing	Potential for corrosion during off-load conditions, especially on horizontal	Monitor drainage of elements and inspect for internal corrosion Install tube-drying facilities or consider retubing with improved drainage, if possible Improve method for off-load storage, and consider nitrogen capping
Desuperheaters		
Attemperator sprays	Erratic control spray valves as a result of temperature variations during startup	Modify control systems with anticipatory control logic
Secondary Superheater		
Headers	Cracking of body welds and ligament cracking of thick-walled headers as a result of thermal fatigue Cracking of header stubs Thermal fatigue of dissimilar welds (ferritic and austenitic)	Identify headers at risk Perform internal CCTV inspection and external NDE of all headers, followed by periodic inspections Fit thermocouples and monitor temperatures and ramp rates Review operating procedures to control temperature ramp rates Assess thermal stresses and consider finite element analysis of high-risk headers

Plant Component/System	Transient/Cycling Associated Issues	Engineering Approaches/Solutions
		Repair headers as required by performing local repairs, replacing sections of headers, or installing new headers Consider replacement of worst-affected headers using thin-walled high-alloy ferritic steels; consider P91
Tubing	Local overheating as a result of high heat flux during low flow startup Local overheating caused by flow stagnation as a result of collection of condensate in U-tubes prior to boil out Potential for steam-side exfoliation of oxide layers as a result of thermal shock High stress levels in tube-to-tube attachments and tube-to-tube structure as a result of high temperature differences Thermal fatigue failures of fireside tube-to-tube attachments, resulting in tube misalignment	Perform selective visual/MPI inspection and thickness checks of tubes; check for evidence of overheating and monitor Ensure adequate drainage and venting to promote flow throughout elements and headers Monitor integrity of steam-side oxide layers Monitor and review tube attachments and alignment; consider design options Consider redesign of tubes to introduce more flexibility; consider expansion loops
Structure	Thermomechanical fatigue of attachments and supports as a result of temperature differentials during startup and shutdown Potential for load migration and subsequent failure of boiler supports Cracking at welded roof and wall seals	Review design to ensure adequate flexibility to accommodate relative expansion Redesign seals with tube sleeves

Plant Component/System	Transient/Cycling Associated Issues	Engineering Approaches/Solutions
Reheater		
Headers	Little evidence of thermal fatigue in thinner walled headers Cracking at drain openings	Perform occasional visual inspection with NDE as appropriate to confirm integrity of headers
Tubing	Local overheating as a result of high heat flux during low flow at startup Potential for steam-side exfoliation of oxide layers as a result of thermal shock Thermal fatigue failures of fireside tube-to-tube attachments, resulting in tube misalignment	Perform selective visual/MPI inspection and thickness checks of tubes; check for evidence of overheating and monitor Monitor integrity of steam-side oxide layers Monitor and review tube attachments and alignment; consider design options
Structure	Thermomechanical fatigue of attachments and supports as a result of temperature differentials during startup and shutdown Cracking at welded roof and wall seals	Review design to ensure adequate flexibility to accommodate relative expansion
Boiler Valves		
Stop valves	Thermal fatigue cracking of thickwalled valve bodies, especially at changes in section Cracking of valve seat and disk hardfacing Quench cracking at valve bypass and drain connections	Perform selective visual/MPI inspection of valve bodies and drainage ports at outages Perform local repairs or replacement with rolling spares Consider replacement of valves with modern design, possibly with P91 bodies
Safety valves	Potential for excessive use as a result of poor boiler temperature and pressure control during rapid startup, shutdown, and load changes	Perform selective visual/MPI inspection of valve bodies and drainage ports at outages Review boiler operability, control, and instrumentation
Drain valves	Increased wear and tear as a result of frequent operation	Review and monitor valve performance with a view to improved maintenance, modifications, or replacement

Plant Component/System	Transient/Cycling Associated Issues	Engineering Approaches/Solutions
		Consider live loading of gland packings
Vent valves	Increased wear and tear as a result of frequent operation	Review and monitor valve performance with a view to improved maintenance, modifications, or replacement
Vent silencers	Increased usage may require acoustic improvements to reduce noise levels and contain emissions Increased corrosion as a result of frequent operation	Review design with respect to acoustic performance and local noise constraints; modify or replace as required
Main Steam Pipework		
Pipework	Potential for local thermal quenching of main steam pipework during boiler shutdown Thermal quenching at drains as a result of suction from drain system Thermal stressing as a result of temperature mismatch during rapid admission of steam on startup	Monitor the steam pipework and drain temperatures and assess implications Maintain pipework (and boiler) above saturation temperature for as long as possible Reduce pressure in steam pipework to reduce saturation temperature (sliding pressure operation) Optimize startup procedures to match steam-to-metal temperatures
Welds	Thermal fatigue and creep-fatigue of welds	Monitor welds—especially terminal welds—with visual inspections and NDE as appropriate at outages Consider the need for metallographic replication where creep and type IV cracking are identified as threats
Supports	Tendency for pipework to migrate to limit of travel on constant load supports Increased cyclic stresses from restrained or defective pipe support system, leading to overstressing at welds Overstressing and cyclic stressing of terminal welds at turbine, steam chest, and manifolds	Examine pipe supports and movements; compare with design intent to confirm correct functioning of pipework supports Consider the need for detailed pipe stressing assessment under cycling conditions Consider the need for additional pipe movement restraints

5
METHODOLOGIES – ANALYTICAL APPROACHES TO CRITICAL COMPONENTS

The basic question of how will cycling or transient operation affects unit performance is one that has been agonized over for a numbers of years in the utility industry. One of the acknowledged impacts of cycling is that it will lead to more operating problems and a greater rate of failure of key items. The forced outage rate will therefore obviously increase, but the difficulty lies in determining by how much and when. Some experience indicates that although increased starts will result in more failures, they will not necessarily occur until a significant period of additional service has accumulated. For example there is evidence that there is a relationship between forced outages and the number of annual starts but the statistical correlation is poor. In reality the extent of forced outages is dependant on numerous factors, not the least of which include, the quality of maintenance, the age and design of plant.

In the industry approaches utilized to assess the effects of cycling or transient operation on unit performance and cost have typically fallen into two main categories, either *"Top Down"* or *"Bottom-Up"* methods.

Statistical or ***Top Down***: starts with a statistical analysis of unit- and plant-level data for a large number of generating units industry wide (the “top”); the results of that analysis are then used to infer the impacts of cycling on the performance and costs “down” to a specific generating unit.

The top down approach quantifies cycling impacts on costs and performance of *a specific generating unit* by analyzing the data that represents the experiences of *a large number of generating units industry wide*. Data are generally on a unit- and plant-level basis and cover years(quarters, months, hours, etc.) of unit life for each sample member. The results of that analysis are then used to infer the impacts of cycling on the performance and costs of a specific generating unit.

Statistical analyses involve the development of statistical measures and models, using data for a large sample of generating units. In general, the starting point of the analysis is the specification of multivariate regression models that mathematically describe the causal relationship between unit costs or performance (‘‘dependent variables’’) and its principal drivers (‘‘independent variables’’)

The statistical approach differs from the bottom-up or engineering approach in four important respects.

- The statistical approach determines cycling impacts using *data for many generating units rather than only a few*. Because the sample comprises a large number of generating units, the collective industry experience encompasses a wide range of operating modes and cycling activity, including the experience of units that have switched modes of operation over their life.

- The statistical approach provides *quantitative measures of other units' actual experience with cycling load against which a specific generating unit can be compared*.
- The statistical approach looks at the question of "what is" to determine "what if." In the case of cycling, *the impacts of operating in various modes can be predicted for a specific unit*, even if a mode is not part of its actual historical experience.
- Statistical analyses use less detailed and disaggregate (i.e., component-specific) data but cover a wider breadth of experience and types of generating units. Statistical analyses are *less time-consuming and less expensive* than engineering analyses and can be used to determine whether a specific unit has likely incurred cycling damage and warrants a more in-depth engineering analysis. That is, *statistical analyses can quantify the extent of cycling damage at a specific unit, based on models developed using industry wide experience.*

Engineering or ***Bottom Up***: The "Bottom Up" approach uses condition assessment, engineering analysis and possibly on-line monitoring of key components to drive operational and investment decisions. The starting point of the engineering analysis is usually an on-site condition assessment of the subject unit's equipment, components and materials. Using established engineering principles and hands-on experience, engineering analyses determine accumulated damage and expected remaining life of equipment, based on the condition assessment of equipment at the subject unit. The condition assessment results are combined with a review of the unit's equipment design to determine the expected remaining life for materials, components and equipment.

More recent bottom up analyses have expanded the traditional engineering approach to include analyses of the subject unit's actual historical data, in addition to the condition assessment. Specifically, using historical operating data for the subject unit over time, the rate at which damage accumulated by damage mechanism is determined using engineering damage models. Accumulated damage can then be determined over a specific time period, say, for each year of a unit's life, based on the accumulated number of load cycles and linked to corresponding historical detailed cost data and component failures for the subject unit.

Because engineering analyses conduct detailed, on-site condition assessments of critical components at the subject unit, they provide in-depth, precise information for developing actionable component-specific strategies.

Traditional engineering analyses relied primarily on the results of the condition assessment and equipment design to set up targets and standards, many of which are achievable only under a specified (sometimes idealized) set of conditions, not necessarily what has actually been, or might be, achieved by the subject unit. More recent engineering studies have sought to remedy this by tailoring the analysis to the subject unit's history. That is, the subject unit's historical data, e.g., detailed costs, failure rates by component, operating history and cycling activity, are explicitly incorporated into the analysis. Depending upon data availability, the rate and level of accumulated damage by mechanism for key components by, say, year of unit life are linked directly to the outcomes, namely, to failure rates of components and then to the dollars expended to repair/replace components. Table xx provides a listing of typical information required for bottom-up assessment of critical boiler components

Previously EPRI proposed a three Level approach for addressing this issue. Level I and Level III are primarily the "Top Down" and "Bottom Up" approaches respectively. Level II extends Level I analysis to incorporate unit-specific differences from the peer group, including variables not contained in available databases. Level II accounts for the need to consider plant or unit specific differences in equipment and operations while minimizing analysis costs. The proposed Level III approach is a combination of "bottom-up" analysis performed by the utility for key components and Level II for everything else.

The advantages and disadvantages of the three Levels are briefly listed below.

	Advantages	Disadvantages
Level 1	• Easiest to execute *(with developed model available)* • Least resource intensive	• Lowest expected accuracy • Peer unit averages may not be appropriate
Level 2	• Higher accuracy than Level 1 without much additional effort • Takes into account key differences in unit(s) analyzed and available in – house information	• Estimates and adjustments applied to individual units to reflect the detailed condition of key components • Default adjustments may not fully reflect all unit specific differences
Level 3	• Best estimate of actual costs • Better knowledge of component condition and maintenance requirements • Better understanding how operating decisions affects remaining life	• Highest cost of the three levels • Analysis must be updated to maintain current knowledge of component condition and damage rates

Boiler Condition Monitoring

A bottom-up approach involves some level of inspection or condition assessment of components and represents a snapshot of off-line conditions at a specific point in time (see Table 2). Some aspects of this have been discussed previously in Section 2.

Off-line boiler monitoring is normally referred to as a condition or remaining life assessment of boiler pressure components and it is typically performed during plant outages as a part of the maintenance effort. In this case, boiler reliability monitoring can be defined as a series of surveys and planned activities to obtain comprehensive information on reliability conditions over time. Condition assessment is one of the primary techniques for monitoring and managing the useful life of boiler pressure components, and it relies on the following three pieces of information:

- The degree of damage currently in the component
- The rate of damage accumulation
- The degree of damage required to cause failure

Periodic boiler inspections, metallurgical evaluations, and remaining life calculations are essential parts of the condition assessment effort. EPRI research provides extensive information in these categories. Inspection and condition assessment is performed at a scheduled plant outage and represents a snapshot of static off-line conditions at a specific point in time. Boiler inspection and condition assessment can provide the following information:

- It provides important data for determining the degree of damage.
- Successive outage assessment data can be used to estimate the rate of damage.
- The actual conditions and material properties can be used to predict the remaining useful life for run/repair/replace decisions during the plant outages.
- If data are intelligently analyzed and extrapolated, they can provide valuable information to better understand the aging and damaging process and provide opportunity for root cause analyses.

On-line monitoring represents a greater commitment (costs & resources) to quantify the rate of damage and to understand and determine underlying causes of damage with real-time information. However because of the technology limitations, off-line inspection are often still be required for verification purposes. However, the inspection scope can be substantially reduced with on-line information.

Since the 1980s, several vendors have provided boiler stress and condition monitoring systems for monitoring the life consumption of heavy-wall boiler pressure components due to plant cycling operation. The boiler life monitoring systems include the following:

- Startup/Cycling Advisor by EPRI
- Boiler Life Evaluation and Simulation System - BLESS by EPRI
- Boiler Stress Condition Analyzer by ABB C-E (now Alstom Power, Inc.)
- Boiler Stress Analyzer by B&W
- Creep-FatiguePro by Structural Integrity, Inc.
- Plant Life Usage Surveillance System – PLUS by ERA
- Life Extension and Optimization - LEO by Powergen
- Life Monitoring System – by Mitsui-Babcock
- Systems based on German Code TRD 301

Generally the various systems take real-time plant process data and component data from additional instrumentation, that is, temperatures, pressures, and flow rates, and calculate damage to predict the remaining life of the boiler thick-walled components. Software programs have been developed to calculate thermal and stress distribution, and component damage depending on three fundamental inputs: loads, geometry and material properties.

Due to the complexity of software development and associated hardware compatibility, often these systems have proven to be problematic. Both the high cost of software development and the necessary on-going technical support combined with the unwillingness of utilities to invest significant resources in a competitive market have discouraged the widespread use and further development of these systems. The case for on-line damage monitoring is not clear and needs to be considered on an individual basis.

Table 5-1
Components, Damage Types/Locations, and Assessment Information for the "Bottom-Up" Analyses

Critical Component	Damage Mechanism	Damage Location	Information Needed for Assessment
Boiler Tubes	Corrosion fatigue Flash erosion Hydrogen damage Internal corrosion Fireside corrosion Short-term over heating Sootblower erosion Falling slag damage	Waterwalls	Current wall thickness Original wall thickness Wall thickness at a previous (known) time Original outside diameter Minimum strength at a temperature just below the creep regime Internal pressure Interval between measurements Temperature
	Thermal fatigue Erosion corrosion	Economizer inlet	Temperature history
	Long-term over heating (creep) Fireside corrosion Short-term over heating Sootblower erosion Rubbing/fretting	SH and RH tubing	Wall thickness Scale thickness Material of construction Service hours and temperature Post-service rupture tests
	Dissimilar metal welds		Metal temperature; detailed inspection results; metallographic samples
High-Temperature Headers Secondary SH Outlet Reheat SH Outlet	Creep cavitation Thermal softening (microstructural degradation) Thermal fatigue	Stub tube welds Header end-cap welds Saddle welds Girth welds Longitudinal seam welds Ligaments between tube holes	UT, MT and PT welds Metallurgical structures from samples at critical locations Scale thickness Post-service rupture tests Detailed stress analysis Temperature
Low-Temperature Headers Economizer inlet Steam drum Lower drum	Corrosion fatigue	Stub tube welds Ligaments between tube holes	Temperatures of inner and outer surfaces Feedwater temperature Number of thermal cycles Detailed stress analysis Actual crack sizes and locations

Critical Component	Damage Mechanism	Damage Location	Information Needed for Assessment
Main Steam and Hot Reheat Piping	Creep Creep-fatigue Microstructural degradation Corrosion fatigue	Welds, especially seam welds	UT scans at high intensity Size and location of all indications Dimensional measurements Stress analysis Material samples Creep rupture tests Temperature

6 CONCLUDING REMARKS

Fossil boiler components and piping systems can be subject to numerous “non traditional” operating transients which may have significant deleterious effects on pressure boundary integrity. Cycling and transient operation of conventional fossil power plants can produce reliability problems. Certain types of problems can occur within a short period while other types of problems take longer to become apparent and affect failure rates and reliability.

Major factors affecting a components vulnerability to cyclic damage accumulation include;

- Number of cycles
- Heating and cooling rates
- Component thickness, diameter and material
- Operating Temperature Level

The North American design codes (e.g. ASME Section 1, Section VIII & B31.1) governing pressure part design and fabrication do not require fatigue analyses and no specific requirements to consider the effects of thermal stresses, local stresses, and fluctuations in load. As such, older units “designed” for base load operation are susceptible to accelerated damage accumulation when subjected to increased cyclic service and operational transients, including both low and high temperatures components.

There are numerous approaches to evaluate the impact of cycling & operational transients ranging from simple, conservative screening type approaches to the use of sophisticated, monitoring and analysis tools. As the complexity of the analysis increases, confidence in the results increases, but as does the cost. In some cases however, there is a need to enhance the understanding and analysis modeling of damage mechanisms, particularly creep fatigue. Current approaches e.g. ASME Code Case N47 are considered to be very conservative.

The nature of power plant operation inherently produces a multiplicity of thermal and pressure transients in the steam and water circuits that contribute to some degree to damage accumulation. Not infrequently, there is a divergence between operational practices recommended by OEMs and actual utility practices which are an additional contributor to some of the observed damage in boilers. Additional difficulty is posed in establishing the relative ranking of damaging operational events by the sparseness of the instrumentation, mainly thermocouples, associated with strategic locations which could facilitate thermal and structural modeling.

Approaches to improve reliability of boiler components subject to cycling operation is not straight forward due to often conflicting considerations such as rigidity versus flexibility, local versus global stresses, and interactive mechanisms (for example, creep-fatigue interaction, corrosion-enhanced thermal fatigue, and chemistry-enhanced fatigue). Activities to evaluate and develop solutions to manage boiler component damage due to cycling include:

- Monitoring of the damaging conditions, detection of undesired transient condition, and taking necessary countermeasures to eliminate or reduce damages
- Cycling tests and operation procedure changes to minimize the cycling damage
- System and design modifications and material upgrades to minimize damaging conditions and increase the inherent baseline reliability under cycling operation, respectively

Operation procedure changes are normally attempted first because of their low cost. Not all cycling-related problems can be resolved by an operation procedure change for originally base loaded designs. Many variables encountered in cycling operation can require cross considerations of all possible approaches to achieve the most cost-effective resolutions. Increasing outage inspection and maintenance requirements are anticipated under cycling operation. On-line condition and damage monitoring provide critical information and locations for effective outage inspection, assessment, and maintenance activities. On-line monitoring results should be used first to develop operation strategies and procedure changes to prevent or minimize the damage due to cycling.

7
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A
APPENDIX

Glossary of Terms

2-Shifting	Operational sequence whereby a generating unit is started and shutdown within a 24 hor period, typically an overnight shutdown. Also used as a general term describing more than one shutdown within a 24 hour period (3-shifting or 4-shifting)
Attemperation	A method of steam temperature control involving the introduction of water, generally in an atomized form, to steam. The water removed heat from the steam, as it transforms to steam thus reducing the bulk steam temperature. Also known as Desuperheating.
Bottom-up	A Bottom-Up or Engineering approach uses condition assessment, engineering analysis and possibly on-line monitoring of key components to drive operational and investment decisions. (see Top Down)
Balance Draft	Condition inside a boiler characterized by a slightly negative pressure. Name comes from a balance in flows between a forced draft fan and an induced draft fan creating the negative pressure inside the furnace. The Alternative is pressurized draft with positive furnace pressure created by a forced draft fan
Cold start	The start type often defined by turbine temperatures below 150°C (300°F) at the time of boiler light-off (see *Hot Start)*
Constant Pressure Operation (CPO)	Controlling steam flow to the turbine, and thus generator output, by altering the position of the turbine governor valves while maintaining constant pressure in the boiler.
Cycling	2-Shifting or load following operation following cyclic nature of daily electrical demand
Departure from Nucleate Boiling (DNB)	Condition in waterwall/evaporator tubes where the normal boiling process of discrete bubble nucleating independently on the tube wall changes to grouped or film boiling. The point of changes is referred to as DNB as is used to define the critical heat flux. Under DNB the tube wall temperature rises rapidly and can result in a tube burst.
Drum Top-up	An operating procedure for drum boilers involving feeding water to the boiler to maintain a desired water level in the steam drum during off-line periods. Top-up is periodically necessary as the water volume decreases as the boiler cools.

Hot start	The start type often defined by turbine temperature, either at the HP inner cylinder or reheater inner bowl, greater than 350°C (660°F) at the time of establishing first fires in the boiler (light-oft)
Load Following	Process of adjusting unit electrical output with demand. Assumed to be load change of magnitude greater than 50% MCR.
Load Rejection	An event where the generator is suddenly disconnected from the grid. The exciter field is removed and thus the turbine is suddenly unloaded.
Off-Line	The period where the generating unit is not connected to the grid, also not producing electricity.
Peaking	Term used to describe a mode of operation where the unit is used to meet the highest point, the peak, in demand and then is shutdown
Progressive Draining	An operating procedure for draining condensed water (condensate) from a boiler. The procedure involves progressively opening drains through the boiler steam circuit starting with the primary superheat and ending at the turbine stop valves
Ramp Rate	The rate of change of specific parameters. Generally applied to boiler pressure or temperature, turbine speed or temperatures, or generator output.
Shutdown	The process of removing a generating unit from service
Slug Feeding	Batch feeding of feedwater to a boiler.
Start-Up time	The time interval required for the unit to reach defined milestones during a start. Generally considered to be from the point first fires are established (light-oft) to synchronization with the grid.
Sub/Supercritical	Critical pressure for steam is 22.11 MPa (3208 psia). Above critical pressure (supercritical) water converts directly to steam without boiling and thus there is no latent heat of boiling.
Top-Down	A Top Down or statistical approach with a statistical analysis of unit- and plant-level data for a large number of generating units industry wide (the "top"); the results of that analysis are then used to infer the impacts of cycling on the performance and costs "down" to a specific generating unit. (See Bottom-Up)
Trickle Feed	Continuous low feedwater flow rate used as an alternative to slug feeding of feedwater to a boiler, to prevent high thermal stresses from developing
Turndown	The control range for a piece of equipment. A large span of control reflects high turndown.

Variable pressure	Controlling steam flow to the turbine, and thus generator output by reducing boiler pressure and leaving the turbine governor valves in a fixed position
Warm start	The start type often defined by turbine temperatures between 150 and 350°C (300 and 660°F), at the time of boiler light-off (see *Hot Start).*
Water Hammer	Hydraulic effect of a significant change in water or steam flow in a contained system, e.g. piping, causing a mechanical reaction force. Often an audible event resulting from sudden closure of a valve, a change in section, or a sharp bend.

Figure A-1
Log of Events

"Log of Events"
Cold Start

- Unit off line July 1, 1982 at 21:49
- July 3, 1982 at 18:30, fans in service to cool boiler for economizer hopper inspection

July 4, 1982

21:45 Extraction pump and polisher in service

22:00 Igniters in service

22:40 "F" mill in service; "B" BCP in service (A&D BCPs had been operating)

23:20 Drum Pressure 2.18 MPa

23:32 Drawing vacuum

23:56 Turbine roll

July 5, 1982

00:29 Synchronize and load slowly to 35 MW and hold for soak

01:50 Step loading to 50 MW and holding

02:51 "E" mill in service

03:30 Hold at 114 MW

03:35 "A" BFP in service

04:06 "D" mill in service

04:17 "C" mill in service

05:55 "A" and "B" mills in service, "E" mill out of service

07:21 Hold at 400 MW (SCC request)

Force Cool Shutdown and Subsequent Start

July 5, 1982

20:50 Unloading from 500 MW

21:10 "B" BCP out of service at 400 MW
Feedwater temperatures HP7A = 182°C HP7B = 210°C

21:25 Reducing main steam temperature from 550°C at approximately 200 MW

21:42 "A" BFP tripped at 120 MW

21:44 Unit off line

Note: Unit force cooled by opening drains and blowing steam. Fans on at 80% capacity.

July 6, 1982

04:00 Force cool terminated; zero pressure

04:20 Polishers in service; condensate extraction pump in service; "A" and "D" BCPs are running

04:25 Fans on

04:34 Igniters in service

05:40 "C" BCP in service

06:08 "B" mill in service

07:10 Drawing vacuum

08:06 Attempt to synchronize failed due to vacuum trip

08:26 Synchronized

09:15 "A" mill in service

10:05 "C" mill in service

10:50 "D" mill in service, "C" mill out of service

11:30 "E" mill in service

12:00 Holding at 340 MW - "B" BCP in service

14:40 500 MW

Warm Start

- Unit off line July 9, 1982 at 22:00

- "A" and "D" boiler circulation pumps in service

July 11, 1982

22:30 "C" BCP in service; fans on

23:03 Igniters in service

23:30 "E" mill in service

July 12, 1982

00:37 Rolling on steam

00:45 "A" BFP in service

01:22 Synchronized; hold at 20 MW to get crossover temperature

02:00 "B" BCP in service

02:50 Raising load

04:00 "E" mill in service

05:00 "B" mill in service

05:10 "A" mill in service; "F" mill out of service
(R/H temperature increase)

10:00 Polishers out of service

Normal Shutdown and Hot Start

July 13, 1982

21:00 Shedding load

21:07 "F" mill out of service

21:19 "B" BCP out of service

21:27 "D" mill out of service

21:32 "E" mill out of service

21:43 "C" mill out of service

21:49 "C" BFP in service; "A" BFP out of service

21:54 "B" mill out of service

21:57 "A" mill out of service

21:59 Unit off line; reheater drains open

22:06 Fans tripped

22:07 "C" BCP out of service

- one topup during the night at about 01:15

- "A" and "D" BCPs on

July 14, 1982

02:51 Fans on

02:55 Electric BFPs on

02:58 Feedwater flow started; economizer differential 30°C

03:00 Boiler trip

03:07 "A," "B," and "C" Igniters in service; "C" BCP in service

03:12 "B" mill in service

03:14 Condensate polisher in service (flow is 68%)

03:16 Main steam leads open; reheater drains closed

03:23 Drawing vacuum

03:34 Condensate from deaerator - 92.9°C

03:39 Rolling "A" BFP

04:10 Rolling on steam

04:31 On line

04:33 Condensate from deaerator* - 60.7°C

04:45 "A" mill in service

04:51 Condensate from deaerator* - 81.7°C

05:07 Condensate from deaerator - 104°C; slow loading rate due to BFP temperature mismatch

05:24 "C" mill in service

05:25 Condensate from deaerator - 121.8°C

06:50 "D" mill in service

07:00 "F" mill in service ("E" mill out on permit)

Note: Since the overhaul, main steam has not been supplied to pressurize the deaerator. The most critical time is when there is feedwater flow and no steam flow to the feedwater heaters.

B
APPENDIX – CASE STUDY

Introduction

Cracking has been found to occur on the inside of lower waterwall headers (LWWH) at the toe of the welds of the boiler circulation pump (BCP) discharge nozzle and crossover connection penetrations. In addition, cracks have been generated in the seats for the manway doors. The location and extent of this crackling has been well documented and is summarized in Figure A. More recently, similar cracks have been discovered in the steam drum at the welds of various nozzle connections. These inc1ude:

- Superheater connection tube nozzles (saturated steam to superheater).
- Riser tube nozzles (water from boiler).
- Economizer feed nozzles (feed water from economizer).

This cracking is common to all four boilers and other boilers in the system.

Corrosion fatigue is the most probable mechanism for this Cracking. Fatigue stresses are cyclic in nature and may result from pressure loading, stresses produced by thermal gradients and system stresses. System stresses result from loads produced by the overall structure, eg, due to support systems. In addition, the static or mean stress is also important. Static stress can be due to residual stress. The cycling is due to the shutdown/start-up operation of the boiler, and/or major load changes.

The corrosion factor is dependent on water chemistry, although little information is available on the effects of boiler water chemistry parameters on crack initiation and propagation. In an effort to gain an understanding of the factors controlling the crackling at the weldments in these components, a series of tests was planned to monitor various unit parameters during shutdown and start-up periods. The purpose of this investigation was to:

- Determine the levels and relevance of any thermal stresses.
- To gain an understanding of the changes in water chemistry which occur, particularly during unit start-ups. In addition, water samples were taken at different locations to determine water chemistry variability as a function of location within the boiler.

Test Program and Equipment

Test Program

Header/drum and nozzle temperatures, water quality and a number of unit operating parameters were monitored continuously during a series of tests (see Table 1). The data logging system was used with the parameters being scanned every 20 seconds during startups and shutdowns and every 2 to 5 minutes at all other times. Five tests were conducted under different unit startup conditions:

- Test 1 - normal shutdown and cold start
- Test 2 - normal shutdown and warm start
- Test 3 - 7-hour force cooled shutdown and subsequent start (cold boiler, hot turbine)
- Test 4 - normal shutdown and hot start
- Test 5 - force cooled weekend shutdown and subsequent start (cold boiler, warm turbine)

Temperature Monitoring

The objectives were to measure the through-wall temperature gradients on the front LWWH and the steam drum and also the temperature differences between the various nozzle penetrations and the header/drum surfaces.

On the front LWWH, temperatures were monitored at a BCP discharge nozzle (D3) and a crossover line (C1) (Figure B).

In the case of the steam drum, temperatures were measured at an economizer feed nozzle, a riser tube nozzle and a superheater connection tube nozzle (Figure C).

Thermocouple Installation

Outside Surfaces

Type K, fibreglass sheathed thermocouples with the conductors butt welded at the hot end were used. The hot junction of the thermocouple was inserted into an l/8-inch diameter hole, l/8-inch deep and lightly peened in place.

Through-wall

Thermocouples similar to those described in Section 2.3.1 were used. The hot junction of the thermo- couple was inserted into an 1/8-inch diameter hole which was drilled to within ¼-inch of the inside surface and 1ightly peened in place.

Inside Surface

Type K thermocouples with a 1/8-inch OD stainless steel sheath and grounded junction were used. A 1/8-inch diameter hole was drilled, l/8-inch deep at a 30º angle into which the thermocouple was inserted and 1ightly peened in place. The stainless steel sheath was anchored to the inside surface of the header by means of spot welded stainless steel shims. The thermocouple was led out of the header through a "Swagelock" compression fitting which was threaded into a plug that had been temporari1y welded to a 1-inch test nozzle on the header.

Water Chemistry Monitoring

Chemistry of the boi1er water was monitored by analyzers at two sample points. One was the regular boiler steam drum sample off the CBO line, the other was a temporary sample line from the middle of the LWWHs. Although either of the two lower headers could be sampled, the blend of both was monitored. The temporary LWWH sample was conditioned to ambient conditions by hardware normally used for the boiler drum steam sample.

Both boiler water samples were instrumented to continuously monitor pH, conductivity and dissolved oxygen (D02) All analyzers were by Beckman Instruments except for the conductivity of LWWH sample which was by Leeds and Northrup (L&N). The D02 analyzers used were Beckman (Model 735X). and the pH analyzer was a Beckman Model 941. For tests 3, 4 and 5, two Orbisphere Model 2713 D02 analyzers from other Ontario Hydro departments were employed as backups for Beckman analyzers. Data from the continuous analyzers were recorded on two L&N Speedomax 3 pen strip chart recorders and by the HP-S5 microcomputer.

Although the greatest emphasis was placed on continuous monitoring of pH, conductivity and dissolved oxygen, other chemical variables such as phosphate, silica, chlorides and sulphates were also periodically analyzed via grab samples. The station charts were also utilized to monitor various other locations such as the condensate extraction pump. HP heater outlet and boiler feed pump. The monitored parameters are presented in Table 1, a schematic drawing showing the parameters monitored at various locations is presented in Figure D.

Results

The results are presented in graphical form in Figures 1 to 13. A considerable volume of data was collected and numerous graphs plotted; for a more complete compilation of figures for all the tests, In the present case, complete data for temperatures are presented for the cold start and selected figures for the other tests are shown to illustrate specific points noted In the text.

Temperature Behaviour

The figures indicate the absolute temperatures and the throughwall temperature gradients (•T) on the header and the steam drum during each test. The maximum •Ts on startup generally occurred about one hour after fires-in, with the inside surface being hotter than the outside surface. These maximum values at various locations are presented in Table 2. This indicates that a cold start produced the largest •T at all locations whereas the smallest •Ts occurred during a hot start. The maximum •T of 39°C was recorded on the steam drum at the economizer feed nozzle during the cold start. This location consistently showed the highest •T In all tests, even though the drum wall was thicker at the other two monitored nozzles on the drum. Except for one instance, the •T values on the LWWH were smaller than on the steam drum.

The maximum •Ts occurred prior to turbine roll and equilibrium values were more or less achieved by the time of turbine loading.

Table 2 also shows that, during a force-cool shutdown, negative •Ts were generated, ie, inside surfaces became cooler than outside surfaces. The relevance of this is that the thermal fatigue stress is dependent on the total range of •T experienced by the component.

One anomaly in temperature behaviour occurred at the feeder riser tube during the first hour of the cold start and, to a lesser extent, during the first hour of the start after a force cool, which could be also classified as a boiler cold start.

Figures 3 and 7 indicate that the feeder riser nozzle remained relatively cool initially and then was subject to a virtually instantaneous temperature excursion of about 60ºC. It is surmised that the cause of this is no flow through this particular nozzle (and probably some others) during the low flow conditions at the initial period of the startup, followed by a surge of relatively hot water a few minutes later when the flow rate becomes large enough to fully establish flow through all riser nozzles. This phenomenon was not observed during the hot or warm starts, since metal and steam temperatures are high prior to loading.

The temperature behavior of the economizer feed nozzle differs from that of the other nozzles (Figures 5, 8, 10 and 12). During operation under stable conditions, the nozzle surface was always cooler than both the outside and inside surfaces of the drum wall. The reason for this is that the feed water from the economizer enters the drum through a thermal sleeve directly to a distribution header located at about the middle of the drum. The feed water does not come directly in contact with the inside surface of the drum. The feed water is colder than the saturated steam in the drum during normal operation and it is thus expected that the feed nozzle would run colder than the drum. There was a constant •T of about 25ºC between nozzle and header surfaces during stable conditions and a maximum of about 40ºC was measured between the nozzle and the inside drum surface during the transient startup conditions. During the startup, the nozzle surface and drum outside surface were about the same temperature.

One other item of interest to be derived from these tests was the temperature difference between the top and bottom surface of the boiler circulation pump discharge line. During the July series of tests, the bottom thermocouple malfunctioned and the top thermocouple was unstable (eg, see Figure 9). The test indicated that there was no measurable difference between the top and bottom of the boiler circulation pump discharge line at any time during the test.

In order to determine the degree of error introduced by measuring the inside surface metal temperatures of thick components by installing through-wall thermocouples about 6 mm away from the ID surface, probe thermocouples were installed on the inside surface of the LWWH and monitored at the same time as the other thermocouples. The two sets of thermocouples gave virtually identical results (Figure 1). Since very rapid changes in metal temperature were not observed, this result was not unexpected.

Water Chemistry

The initial test commenced two weeks after an HCl boiler clean. Although the boiler water chemistry was stable at that point. the crud levels in the samples were excessive. In fact, the in-line filters could not be used because they plugged up within a few minutes. Crud concentration did not affect the sensors of pH and conductivity analyzers, but it prevented meaningful measurements with the Beckman D02 analyzers in all the July tests. The pH and conductivity data are presented in Figures 1 to 12. (Due to a malfunction with the analyzer, the conductivity could not be obtained in the lower waterwall header for Tests 1 and 2.)

Orbisphere D02 analyzers were found to be less sensitive to boiler crud concentration and thus were used during the November supplementary test. Unfortunately, for the lack of special adaptors, nether Orbisphere analyzer could be connected to a recorder and all data were therefore, periodically transcribed manually.

Reliable D02 readings were obtained in Test 5, which involved a force-cool of the boiler prior to startup (Figure 13). It can be seen that the D02 level declined from saturation levels at the beginning of the test to 72 ppb at turbine roll (Table 4). Typical on-load levels should be less than 10 ppb.

Table 5 shows further results obtained during various types of shutdown/startup cycles. In these supplementary tests temperature monitoring was not performed. For hot and warm starts D02 levels were always well below 10 ppb and high levels were only monitored after the boiler had been force-cooled.

An example of the dissolved solids levels monitored in samples from the CBD and the LWWH is presented in Table 3 for a warm start (Test 3). Silica levels showed an increase upon loading the unit whereas phosphate levels increased during the initial load period and then declined.

Discussion

Corrosion-Fatigue

Corrosion-fatigue cracks have been found at a large number of pipe penetrations into the main steam drum and lower waterwall headers. These mainly grow Into the drum or header shell at the toe of the filler weld on the inside surface and are mostly 360º around the pipe penetration (Figure A). At the time of the first grind out, maximum crack depths of 5 mm were removed from the header (1979) and 12 mm from the drum. There was no obvious corre1ation between the location of the deepest crack and the circumferentia1 orientation at the penetration.

Corrosion-fatigue invo1ves the initiation of a crack, usually at a stress concentrating feature, and its subsequent propagation.

Corrosion-fatigue is a fai1ure mechanism dependent on the interaction between a cyc1ic stress, a corrodent, and the materia1. Several sources of cyclic stress may exist:

- Internal pressure.
- Thermal stresses.
- External stresses, which may consist of direct loads and bending moment loads.

In addition, residua1 stresses may exist at welded joints, although such stresses were experimentally determined to be neg1igib1e in a lower waterwal1 header at Lakeview(6).

Since virtua11y all penetrations in the main steam drums and the lower waterwa11 headers have exhibited cracking, it is un1ike1y that external stresses are important. This is because the external stresses would be expected to vary with location.

Crack Initiation

By considering the cyc1ic pressure and thermal stresses, calculations have been made to determine the number of cycles to cause fatigue crack initiation at various locations. In Appendix B, the calculations for the worst conditions are presented. This invo1ves crack initiation at an economizer feed nozzle on the main steam drum and is based on cold start conditions, which generated the largest through-wall temperature gradient at this 1ocation. However, the potentia1 for high thermal stresses at this 1ocation had been reduced by the uti1ization of a thermal sleeve. The ca1cu1ations predict 2500 cycles for crack initiation at the above 1ocation. The total stress ranges associated with warm and hot starts for the crossover pipes on the headers were considerably smaller which would give significant increases in the number of cycles (8 500) to crack initiation.

In the case of cold starts, this unit had accumulated only about 50 such starts. Even considering the total number of starts of all kinds of about 650, it is obvious that fatigue crack initiation occurs far more readily than predicted.

Several factors have to be considered in assessing the ease of crack initiation:

- The assumptions in the analysis.
- The role of other factors.

The analysis is concerned solely with the initiation of cracks and the lifetimes are calculated from the ASME fatigue life curve. This curve is based on laboratory tests of smoothly polished specimens in a nonaggressive environment, i.e., data are not obtained in boiler water conditions. Considering the real situation, earlier initiation than that predicted by the fatigue curve would thus be expected.

With respect to the role of other factors, initiation may be easy because of:

- A very large stress concentration factor at the toe of the fillet weld.
- Poor surface finish at the weld toe.
- The presence of corrosion pits.
- The microstructure of the weld metal and heat affected zone (HAZ) at the initiation sites.

Factors (1) and (2) can be considered together since the weld bead to parent metal interface is the critical location for initiation. At this site, there was no evidence of post-weld blending to improve the surface finish and reduce the stress concentration factor. Leaving the surface finish in the as-welded condition, is certainly not desirable from a fatigue aspect.

Fatigue cracks may be initiated at corrosion pits, the latter resulting from Interaction between the metal and the water. The range of microstructures in weldments gives rise to variations in electrical potentials so that corrosion mechanisms are encouraged at such locations. The pits act as stress concentrators which enable easy fatigue crack initiation. In low alloy steels, pits as small as 70 mm deep have been shown to cause a significant reduction in fatigue strength and a lowering of the stress intensity range for crack propagation under fully reversed loading conditions.

In welded steel structures initiation generally occurs at the toe of the weld with subsequent propagation through the HAZ and sometimes followed by further propagation through the parent material. It has been suggested that small sharp inclusions tend to segregate to the weld toe during welding and these may act as stress initiators. The crack path after initiation will depend on the local stress field and the microstructures of the weld metal, HAZ and parent material. Typica11y. the presence of large grains in the HAZ encourages propagation through this zone.

The conclusion that may be drawn from the above, is that crack initiation is very easy at the toe of the fi11et welds and that, by itself, reducing the thermal stress levels wi11 not be effective in preventing such behavior. In fact the potentia1 for reducing the thermal stress levels is small since the nomina1 thermal stresses (ie, remote from the weldment) are relative1y low in any case.

In order to alleviate the problem, it should be considered as a two-stage process: crack initiation followed by crack propagation. In order to increase the time for crack initiation. the most effective method is to grind the weld toes with the objectives of:

- Improving the surface finish.
- Reducing stress concentrations.
- Removing stress initiators such as inclusions in the metal and existing corrosion pits.

In the case of waterwall headers, this was started several years ago and has, in general, been successful in controlling the problem. Some crack reinitiation has been observed but it is not clear if these were new cracks or the reappearance of old cracks which had not been fully removed. However, the role of water chemistry In initiating cracks has not been determined, except that minimizing dissolved oxygen levels is advantageous. The present tests showed that the highest dissolved oxygen levels occurred during a cold start which was also the worst thermal stress condition. Corrosion-fatigue studies at Research division uti1izing rea1istlc boiler water chemistry conditions, should pinpoint the important factors and help to devise a long-term solution.

In considering a reduction of the stress range, the existing levels of stress need to be examined. The stress range Is the sum of the mechanical stress, due to the internal pressure, and the thermal stress. Thermal stresses are compressive during the start-up and these control the minimum stress in the cycle (see Appendix B). In contrast, the maximum stress occurs under full pressure conditions. However, the nominal levels of pressure and thermal stresses are relatively low and, also, the maximum thermal stress does not coincide with the maximum pressure stress. The worst case with respect to thermal stresses is associated with a cold start when the inside surface of the component heats up more rapidly than the outside surface. Figure 5 shows that a constant through-wall temperature gradient is in existence for 30-40 minutes during firing prior to turbine roll which indicates quasi-steady state heat transfer conditions were achieved. The latter gives rise to the maximum thermal stress. The through-wall gradient could presumably be reduced by reducing the firing rate but, realistically, any such reduction is likely to be small. Overall, considering all types of start-up, reductions in nominal stress levels are likely to be difficult to achieve and not of great benefit in increasing the time to crack initiation.

Crack Propagation

The next factor to consider is the rate of crack propagation, subsequent to initiation. Crack propagation in plain carbon steels has been extensively studied In pressurized water reactor (PWR) environments at temperatures up to 288ºC but nothing is available at the higher temperature and different water chemistry conditions applicable to fossil-fueled units. However, it is known that crack propagation rates are very dependent on the environment. Thus, crack growth rates increase with increasing dissolved oxygen levels above 10 ppb, The rate of crack propagation will not necessarily increase as the crack gets deeper. When cracks are Initiated from notches, crack growth rates can decrease initially (and may even stop under certain conditions) because:

- As the crack grows it leaves the high stress field associated with the notch and enters the lower general stress field In the component.
- Any thermal stress will decline as a function of distance from the notch surface.

However, if the crack continues to grow, its rate of propagation will eventually accelerate, this point being dependent on the instantaneous crack depth and the general stress level. A quantitative assessment of this decelerating and accelerating crack growth rate behavior would require extensive stress and fracture mechanics analyses.

Control of Corrosion-Fatigue

The conclusion that can be drawn from the above discussion is that crack initiation is very easy while little is known in a quantitative manner about the subsequent propagation of such cracks. On this basis, the best approach to control the problem seems to be to increase the crack initiation time. This is best achieved by grinding the toes of the weld to suitable contours and ensuring a smooth finish. This procedure has already been used in many areas on the drums and headers. If care is taken to produce a good finish, *the* stress concentration factor will be reduced considerably. In the case of the feeder riser tubes on the steam drum, the nozzle protrusions on the inside of the drum have been machined-off. While this is an effective method of removing the stress concentrating feature, It will *have* little effect in reducing the through-wall temperature gradient of the drum, as has been suggested.

In addition, crack initiation can be made more difficult by inducing compressive stresses at the ground-out areas. This can be achieved on a local scale by employing a technique such as shot peening. On a larger scale, overloading of the structure in tension wil1 cause yielding at notches and subsequent compressive residual stresses at these locations when the load is removed. This, in effect, happens when the component is hydrostatically tested at, say, 1.5 times the design pressure.

The unknown factor in the initiation stage is the role of the water. As discussed, further information Is needed to determine if corrosion pits can be initiated (ie, without the assistance of cyclic stress) and act as sites for crack growth by fatigue.

Water Chemistry

The data recorded in this series of tests are considered typical for boiler water chemical conditions during a start-up.

In general, the oxygen concentration in the cycle is directly proportional to the duration of unit shutdown while the latter affects the deaerator efficiency on the subsequent startup.

D02 levels in boiler water are affected by an ingress of oxygen into the unit on shutdown and by the efficiency of its removal in the condenser and the deaerator. The following two conclusions can be made on the basis of this test program:

- (1) Following natural cooling of the boiler during shutdown, D02 concentrations remain below 5 ppb for the period before and during hot and warm starts.
- (2) In the case of a cold boiler, resulting from natural or forced cooling, the oxygen concentration in the boiler water may rise up to the saturation point (-8000 ppb) for the corresponding temperature. If the unit water cycle is not properly blanketed with steam *or* nitrogen, ingress of oxygen commences following a reduction of steam pressure below the atmospheric level in either or both the deaerator and the boiler. This would be in addition to the saturated condensate in the condenser hot-well shortly after vacuum in the condenser is broken and to the saturated boiler water make-up added for boiler water level control.

Boiler pressure raising rapidly reduces D02 concentration in boiler water below 100 ppb, however, near zero oxygen levels are not reached until some time after unit synchronization.

Other chemical operating parameters, monitored continuously or analyzed periodically included pH, conductivity, chlorides, silica, phosphate and sulphates. The collected results are presented here to provide a general information on "typical" levels of other dissolved solids in boiler water on start-up besides D02 it should be realized that the chemical parameters are affected by several operating variables such as boiler blowdown, solids concentration or dilution effect due to a variable steam/water volume ratio, boiler chemical additions, etc. Therefore, only qualitative statements in regards to their variation on start-up can be made at this time.

During unit shutdown and on startup prior to synchronization, there was no significant difference between the water chemistry in the steam drum (CDS) and lower waterwall header. With an increase in unit load, however, CSO values were progressively higher than LWWH values ind1cating the concentration effect of vapour1zatlon in the riser tubes and the diluting effect of feed water in the downcomers.

The generally observed reduction in boiler water pH from around 9.5 when on-load to approximately 8.0 on shutdown is a reflection of a slight phosphate hide-out present in this unit.

Conclusions

- Corrosion-fatigue cracks are readi1y initiated at the weld toes of pipe penetrations into the main steam drum and lower waterwall headers because of high stress concentrations at these locations.
- Through-wall temperature gradients were largest during a cold start.
- However, the nominal levels of thermal stresses generated by these •Ts were not very high.
- Disso1ved oxygen levels increased with increasing shutdown time. Thus, excursions in D02 levels were relatively minor during shutdown and hot or warm start cycles. Startup of a cold boiler, resulting from ether natural cooling or force-cooling led to the water becoming saturated with oxygen.
- At times of the highest stress during a cold start, the water temperature was 220 to 250ºC whi1e D02 levels were high and pH was low (7.5-8.0).
- The time to crack initiation can be increased by contouring the weld/base metal interface to reduce the stress concentration and remove crack initiators. Generating compressive surface stresses at these locations would give additional benefits.
- A quantitative understanding of the effects of water chemistry on crack initiation and propagation needs to be evaluated.

Table B-1
Investigation into Lower Waterwall Header and Steam Drum Cracking

Table 1

Investigation into Lower Waterwall Header and Steam Drum Cracking

List of Parameters Monitored

1.0 TEMPORARY THERMOCOUPLES

1.1 Lower Waterwall Header (Front)

1.1.1 At BCP Line (D3)

(1) Header Surface (Outside)

(2) Header Through-wall

(3) Inside Header Surface

(4) BCP Outside Nozzle Surface (Top of Nozzle)

(5) BCP Outside Nozzle Surface (Bottom of Nozzle)

(6) Nozzle Surface Inside Header

1.1.2 At Crossover (C1)

(1) Header Surface

(2) Header Through-wall

(3) Crossover Surface, Top (12 o'clock)

(4) Crossover Surface, Bottom (6 o'clock)

1.2 Steam Drum

1.2.1 At Economizer Feed Nozzle

(1) Steam Drum Surface

(2) Steam Drum Through-wall

(3) Economizer Feed Line Surface

1.2.2 At Feeder Riser Tube

(1) Steam Drum Surface

(2) Steam Drum Through-wall

(3) Feeder Riser Tube Surface

1.2.3 At Superheater Connecting Riser

(1) Steam Drum Surface

(2) Steam Drum Through-wall

(3) Superheater Connecting Riser Surface

2.0 PERMANENT THERMOCOUPLES

2.1 At the Steam Drum*

Thermocouples 1-8

2.2 At the Boiler Circulation Pump Suction Header*

Thermocouples 52-59

3.0 WATER CHEMISTRY

(1) pH - lower WW header, steam drum, condensate extraction pump (CEP), HP heater outlet.

(2) Conductivity - lower WW header, steam drum, CEP.

(3) Dissolved Oxygen - lower WW header, steam drum, CEP, boiler feed pump.

(4) Main steam cation conductivity.

(5) Main steam sodium concentration.

(6) CBD silica concentration.

4.0 UNIT OPERATING PARAMETERS

(1) Unit Load

(2) Turbine Speed

(3) Steam Drum Level

(4) Feedwater Flow

(5) Steam Drum Pressure

(6) Feedwater Pressure

(7) Superheater Outlet Pressure

(8) Hot Reheat Temperature Before Intercept Valve A

(9) Feedwater Temperatures from Heaters A and B

(10) Feedwater Temperatures from Economizers A and B

(11) Flue Gas Temperatures to Economizer

(12) Flue Gas Temperatures to Secondary Air Heaters A and B

Table B-2
Maximum Header Through-Wall Temperature Difference
(Inside Surface – Outside Surface)

	Test 1	Test 2	Test 3	Test 4	Test 2
	Cold Start	Start After Force Cool Shutdown	Warm Start	Hot Start	Force Cool Shutdown
Lower Waterwall Header at Boiler Circulation Pump Discharge	23	12	12	10	-2
Lower Waterwall Header at Cross-over	24	14	17	9	-13
Steam Drum at Feeder Riser	28	18	19	7	-20
Steam Drum at Superheater Connecting Nozzle	36	21	22	13	-19
Steam Drum at Economizer Feed	39	21	24	15	-18

Table B-3
Lambton Unit 4 – Boiler Water Quality Data
Test 3

Date	Time	CBD Dissolved Solids (ppm) SiO_2	CBD Cl^-	CBD PO_4^{3-}	CBD SO_4^{2-}	LWWH Dissolved Solids (ppm) SiO_2	LWWH Cl^-	LWWH PO_4^{3-}	LWWH SO_4^{2-}	Unit Load MW
Jul 11	21:45	0.07	0.10	8.0	-	0.07	0.06	7.0	-	0
	24:00	0.09	0.22	14.4	-	0.04	0.02	-	-	0
Jul 12	02:00	0.11	0.17	17.0	-	0.13	0.17	13.2	-	28
	03:00	0.16	0.22	17.7	-	0.16	0.19	15.2	-	41
	04.00	0.18	0.21	12.7	.38	0.17	0.21	10.2	0.37	151
	05:00	0.21	0.17	7.8	-	0.18	0.14	5.4	-	317
	06:00	0.26	0.17	7.6	0.64	0.20	0.12	5.8	0.50	384
	07:00	0.26	0.19	7.1	-	0.20	0.14	2.4	-	505
	09:00	0.23	0.17	8.0	0.45	0.19	0.10	2.7	0.34	515

Table B-4
Dissolved Oxygen in Boiler Water Samples – Test 5

Date	Time	Analyzers DO_2 (ppb) CBO Beckman	LWWH Orbisphere	HPHO Beckman	Unit Status	Turbine Temp °C	Notes
Nov 26	19:51				Off Line		Force Cooling Boiler
Nov 27	23:32				Fires In		BCP Temperature 50°C
Nov 28	00:30		6 140	–			
	01:00	–	485	6 250			
	01:15	–	385	5 600			
	01:30	–	303	5 000			
	01:45	–	278	5 000			
	02:05	125	100	5 000			
	02:15	–	96	5 000			
	02:30	120	100	5 000			
	02:45	65	85	4 250			
	03:00	40	72	3 500	Rolling Turbine		
	03:15	25	67	2 500			
	03:23				Synchronized		
Nov 28	03:30	–	59	1 750			
	03:45	42	55	150			
	04:15	19	58	100			
	04:30	12	40	100			
	04:45	10	–	110			

Table B-5
Dissolved Oxygen in Boiler Water Samples – Supplementary Start-Up Data Tests

Date	Time	Analyzers DO_2 (ppb)			Unit Status	Turbine Temp °C	Notes
		CBD Beckman	LWWH Orbisphere	HPHO Beckman			
Oct 1	13:00		2.0		500 MW		
	21:30		2.5		Off Load		
	22:00		2.5		Off Line		
Oct 2	05:30	–	2.5		Fires In	380	Hot Start
	07:00	–	2.8		Synchronized		
	10:00	-	3.0				
	12:00		3.0				
	16:00		3.0		Off Line		
	22:00		4.0				
Oct 3	00:00		5.0				
	12:00		5.5				
	24:00		5.8				
Oct 4	01:30		6.0		Fires In	245	Warm Start
	03:30		6.0		Synchronized		

Table 5 (cont)

Date	Time	Analyzers DO_2 (ppb) CBD Beckman	LWWH Orbisphere	HPHO Beckman	Unit Status	Turbine Temp °C	Notes
Oct 4	10:00		5.0				
Oct 29	18:00	5.0	3.0		510 MW		
	20:47	10	3.0		Off Line		Force Cooling Boiler
	22:30	50	5.0				
Oct 30	01:00	35	35				
Oct 31	23:41				Fires In	220	Cool Boiler
Nov 1	01:30	200	90				
	02:00	200	80				
	02:30				Turbine Rolling		
	03:00	200	70		Synchronized		
	04:00	100	60				
	04:50	50	10		50 MW		
	06:00	–	5				
	07:00	40	10				

Date	Time	Analyzers DO_2 (ppb) CBD Beckman	LWWH Orbisphere	HPHO Beckman	Unit Status	Turbine Temp °C	Notes
Nov 15	03:35		2 000		Turbine Rolling		
	04:01		2 000		Synchronized		
	06:00		10				
	09:00	10	5				

Figure B-1
General Location of Cracks in Lower Waterwall Header

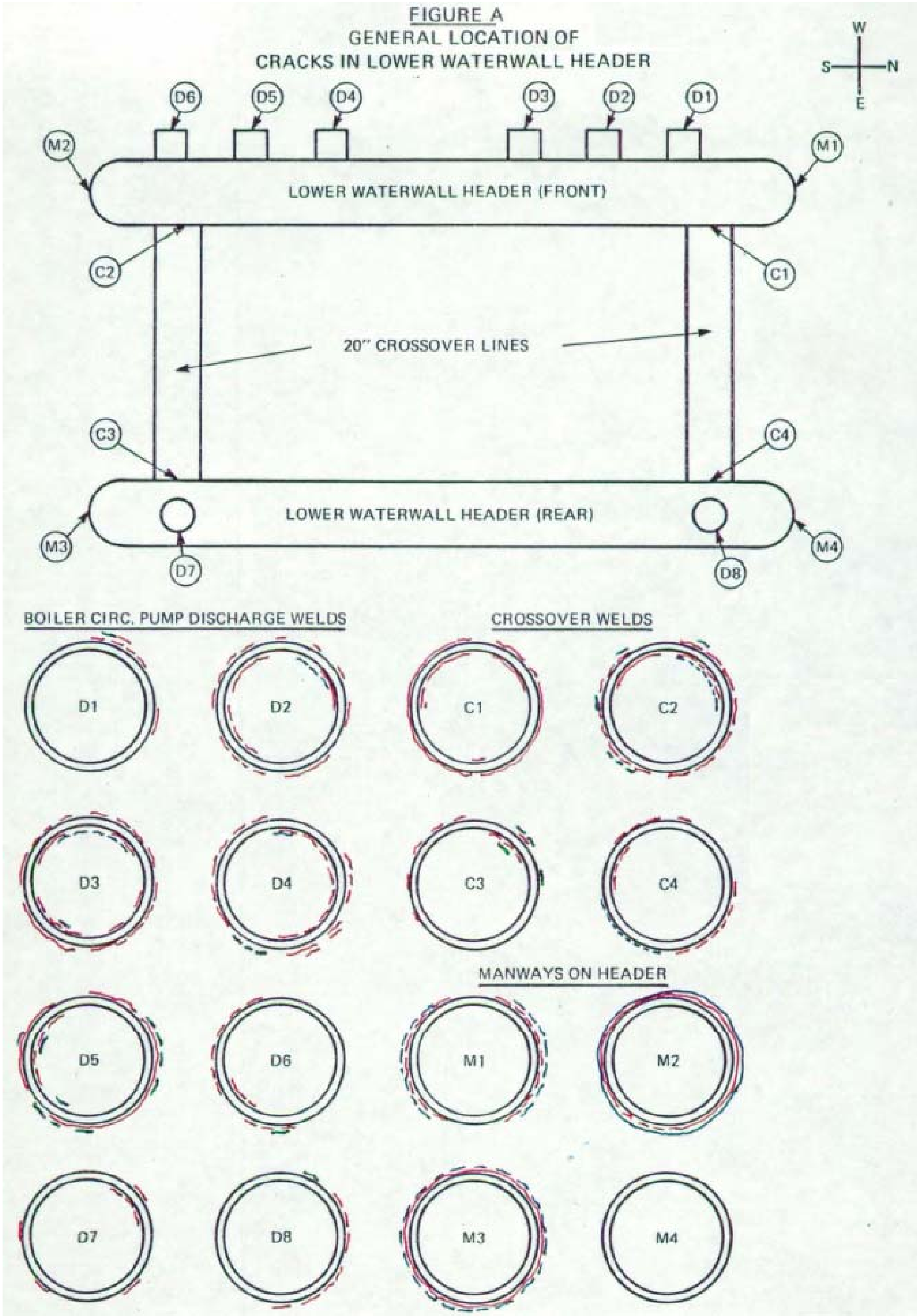


Figure B-2
Location of Test Thermocouples on Front Lower Waterwall Header

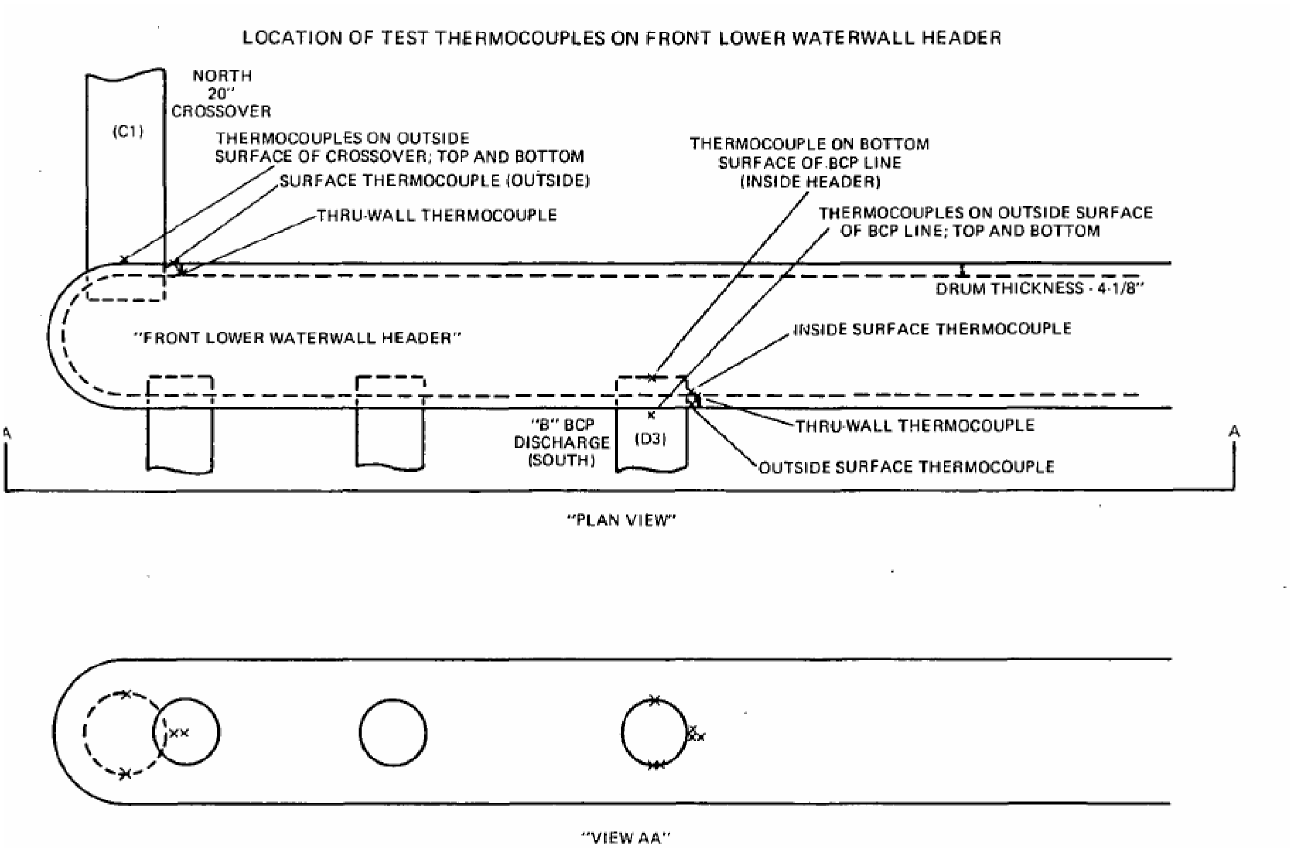


Figure B-3
Location of Test Thermocouples on Steam Drum

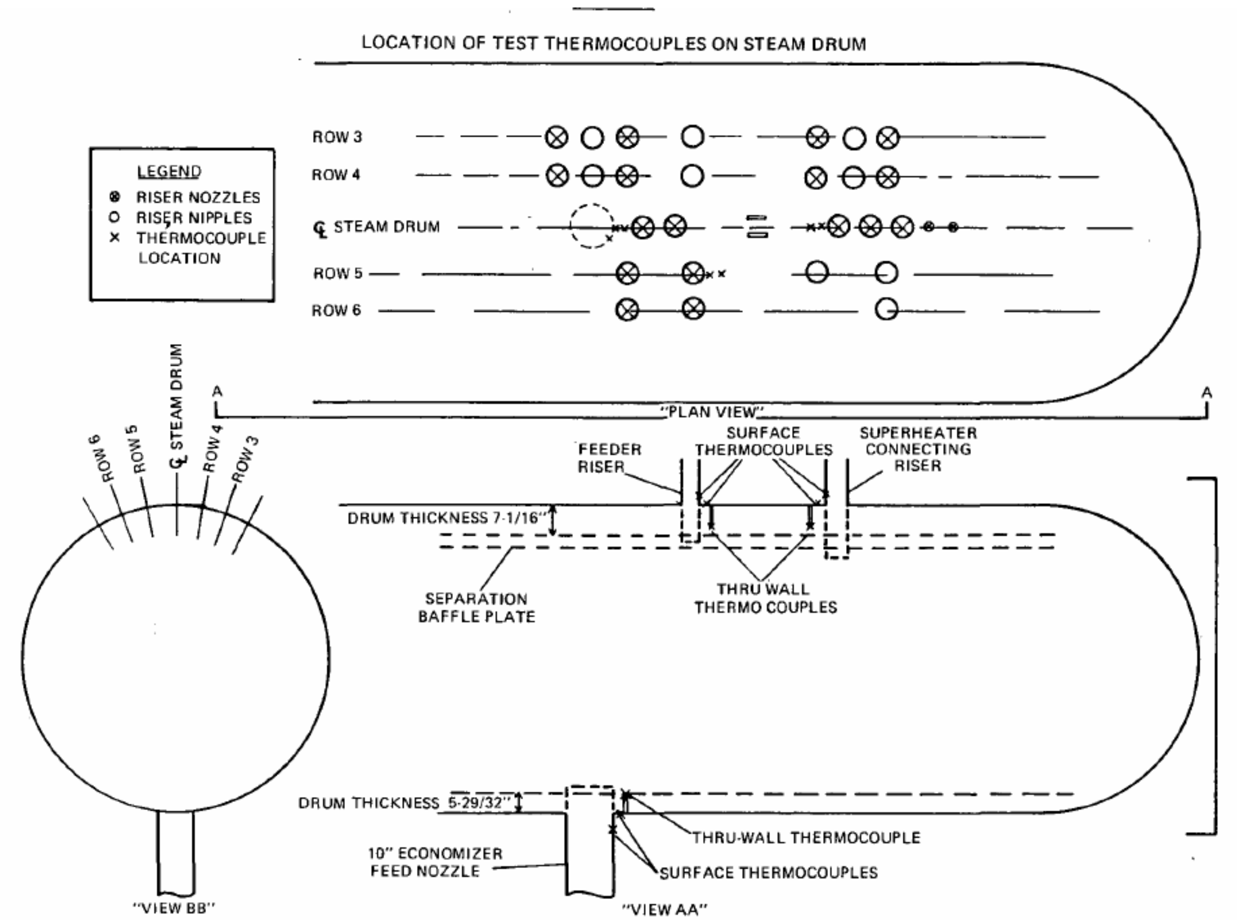


Figure B-4
Cracking in Lower Waterwall Headers and Steam Drum

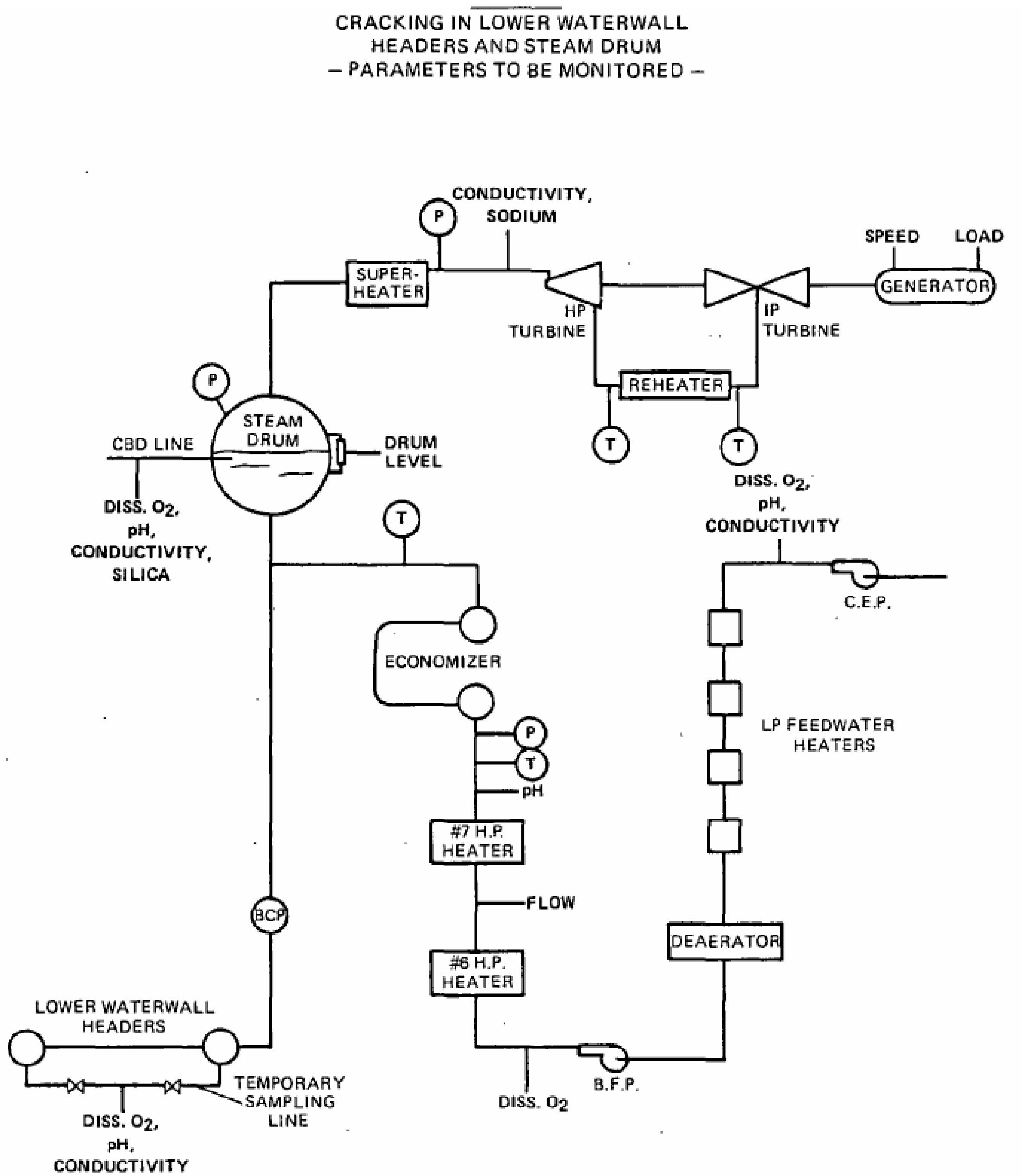


Figure B-5
Test 1 – Cold Start (Lower Waterwall Header at Boiler Circulation Pump Discharge)

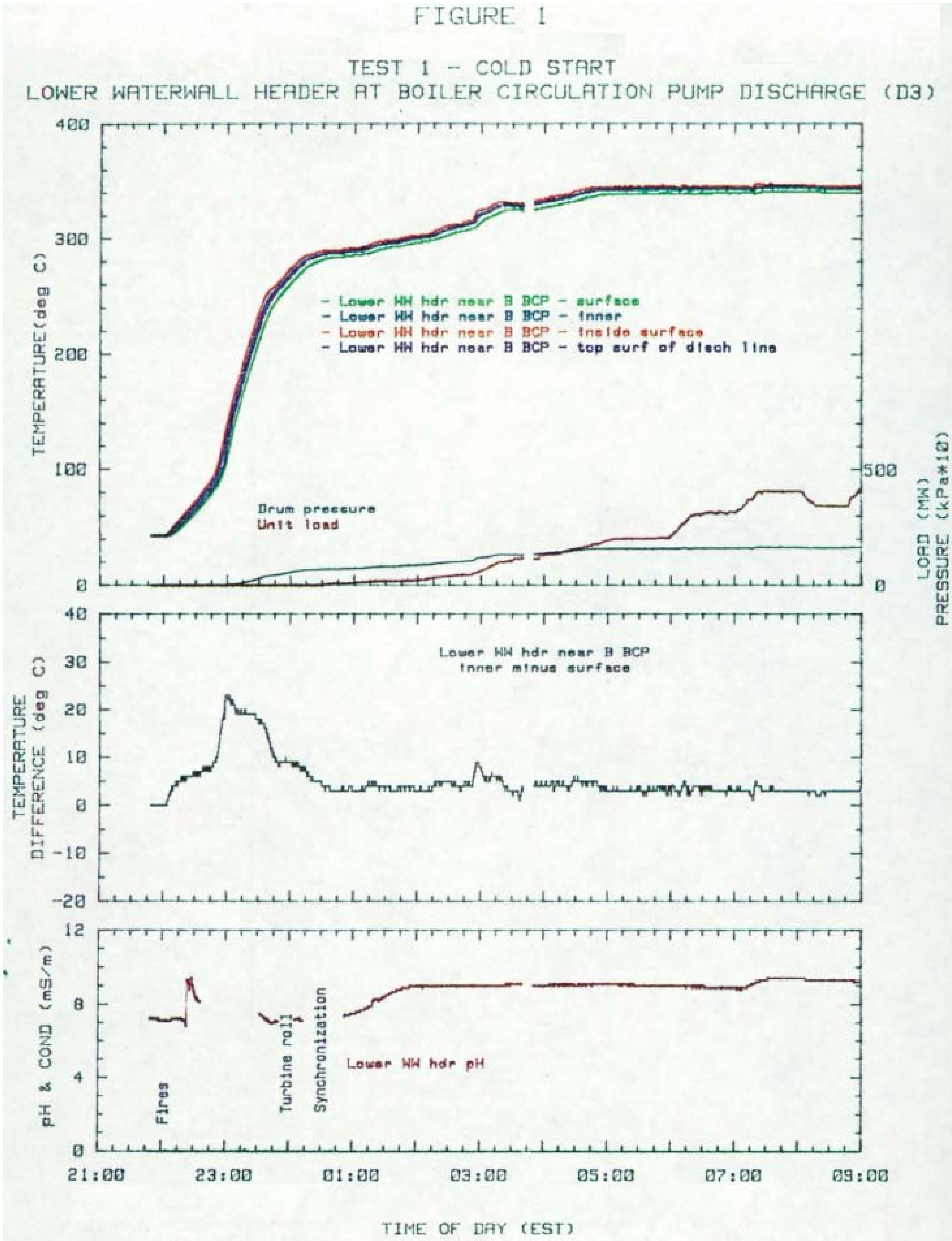


Figure B-6
Test 1 – Cold Start (Lower Waterwall Header at Crossover Nozzle)

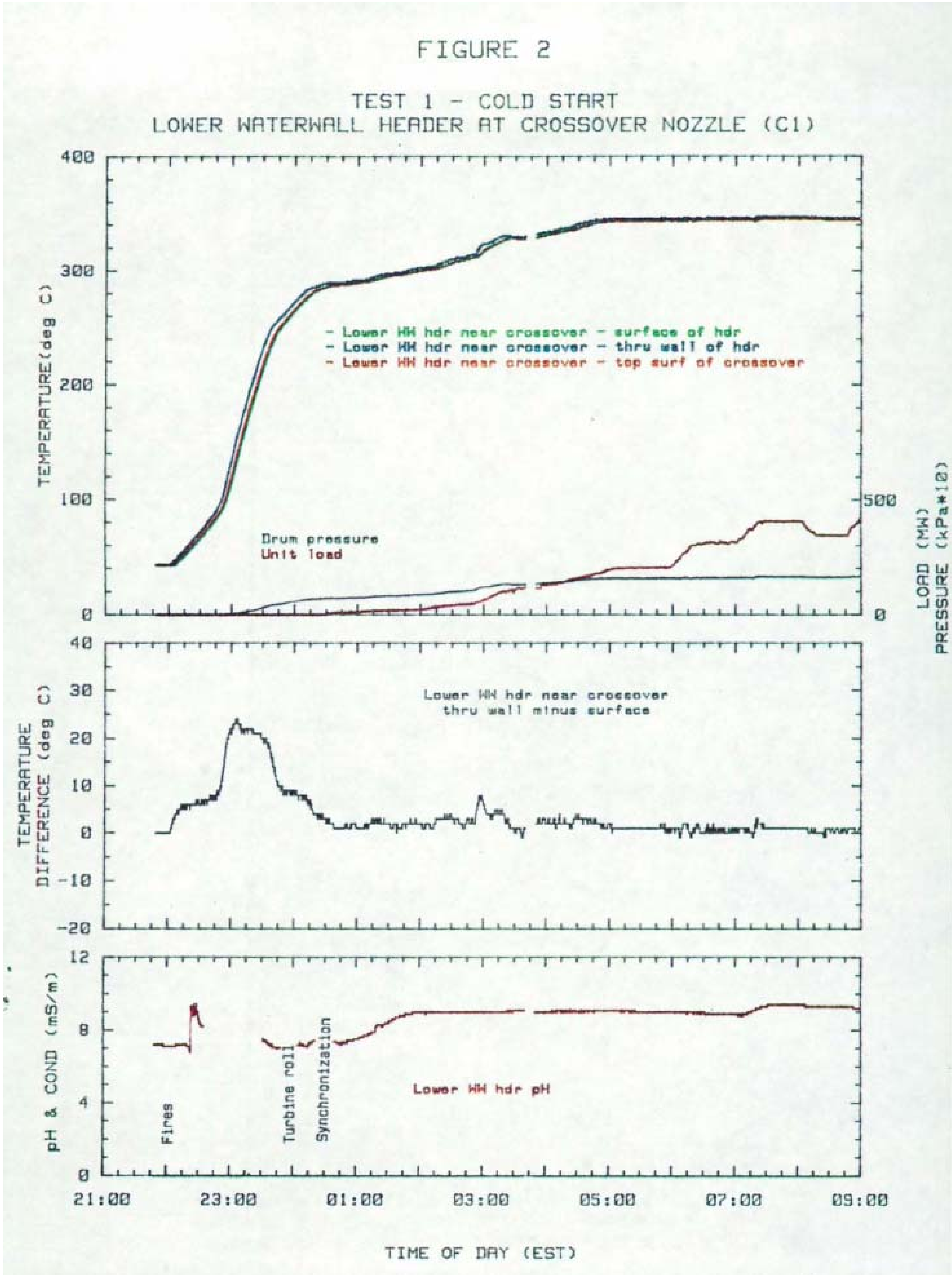


Figure B-7
Test 1 – Cold Start (Steam Drum at Feeder Riser Nozzle)

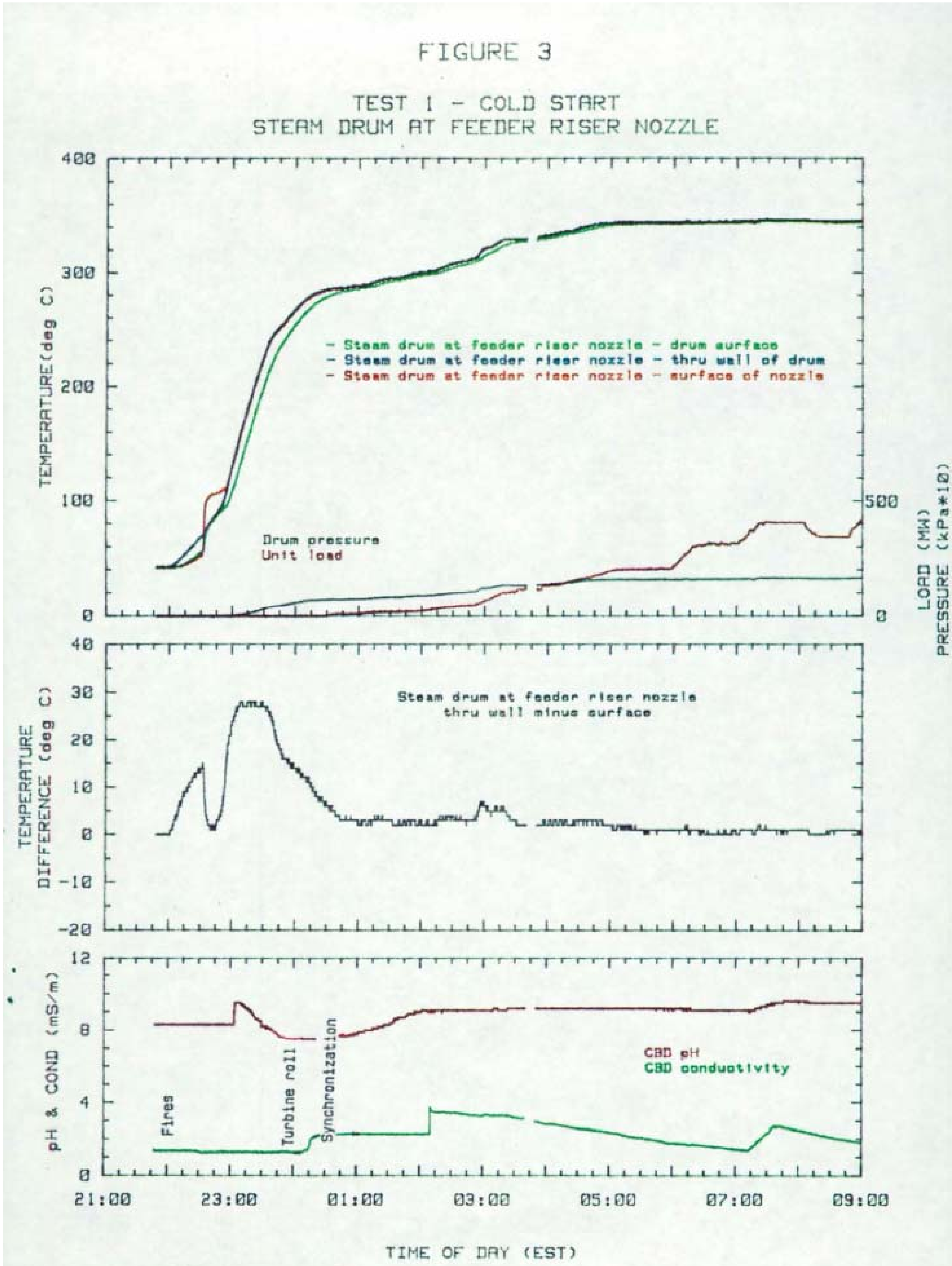


Figure B-8
Test 1 – Cold Start (Steam Drum at Superheater Connecting Nozzle)

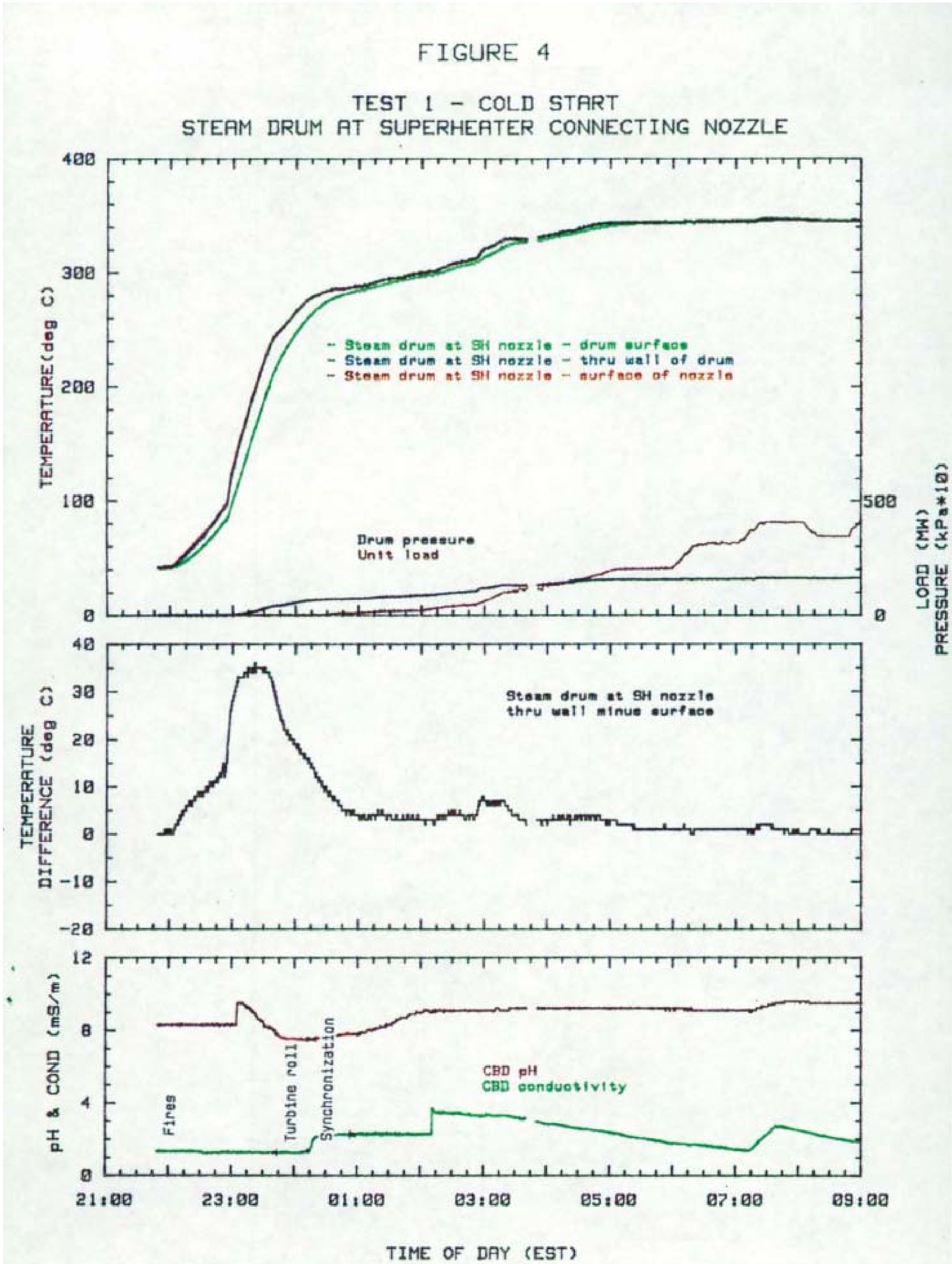


Figure B-9
Test 1 – Cold Start (Steam Drum at Economizer Feed Nozzle

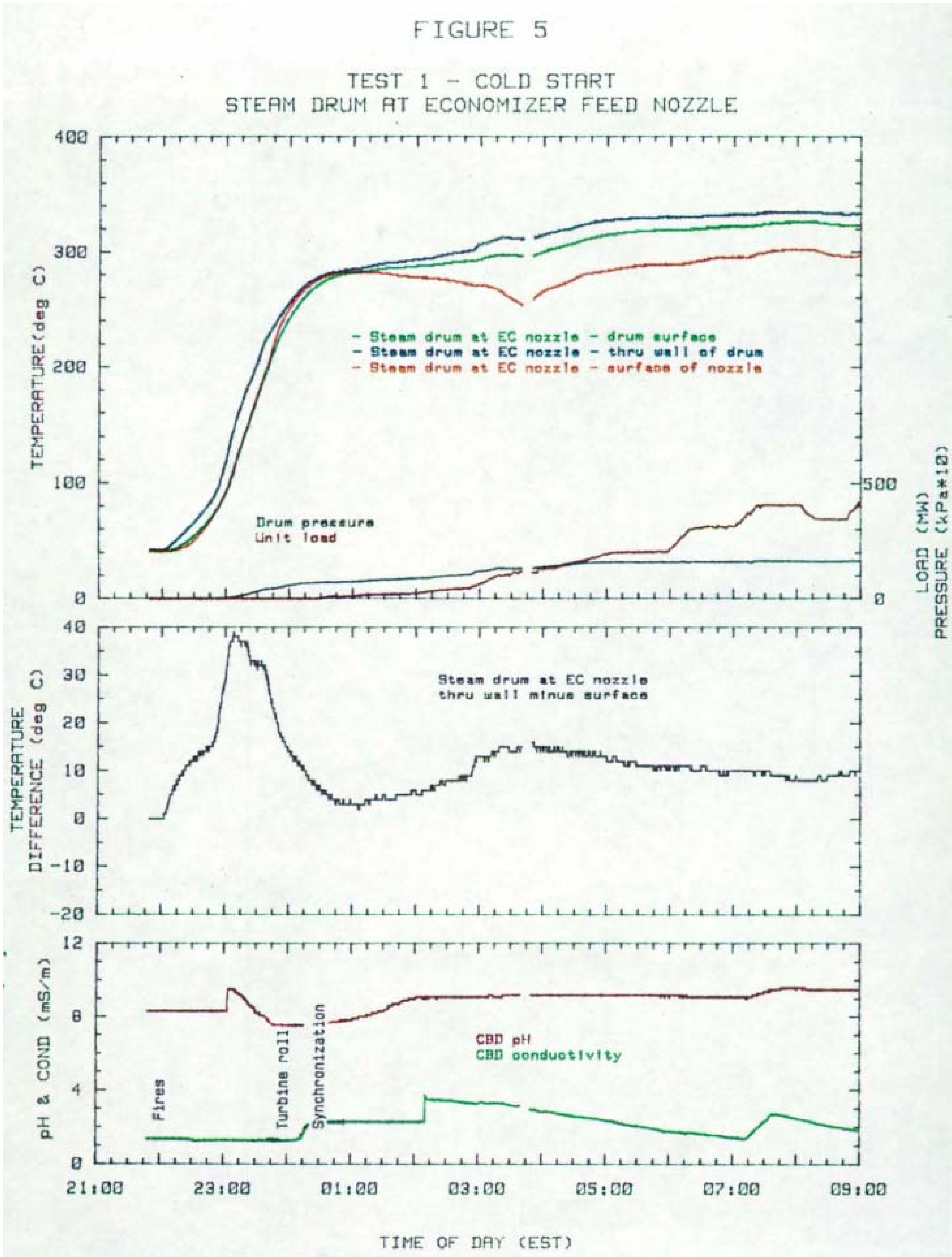


Figure B-10
Test 2 – Force Cooled Shutdown & Subsequent Start (Lower Waterwall Header at Crossover Nozzle)

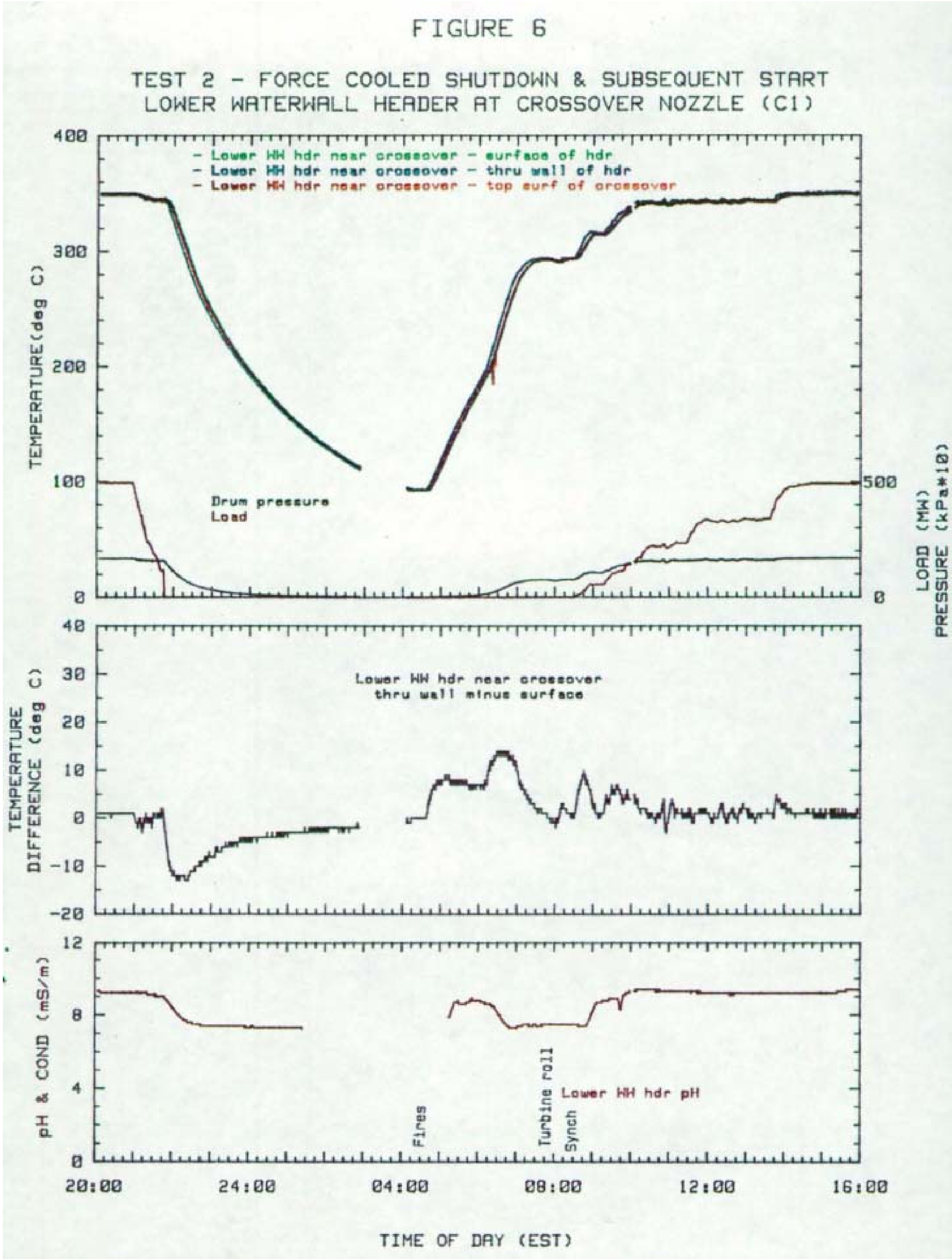


Figure B-11
Test 2 – Force Cooled Shutdown & Subsequent Start (Steam Drum at Feeder Riser Nozzle)

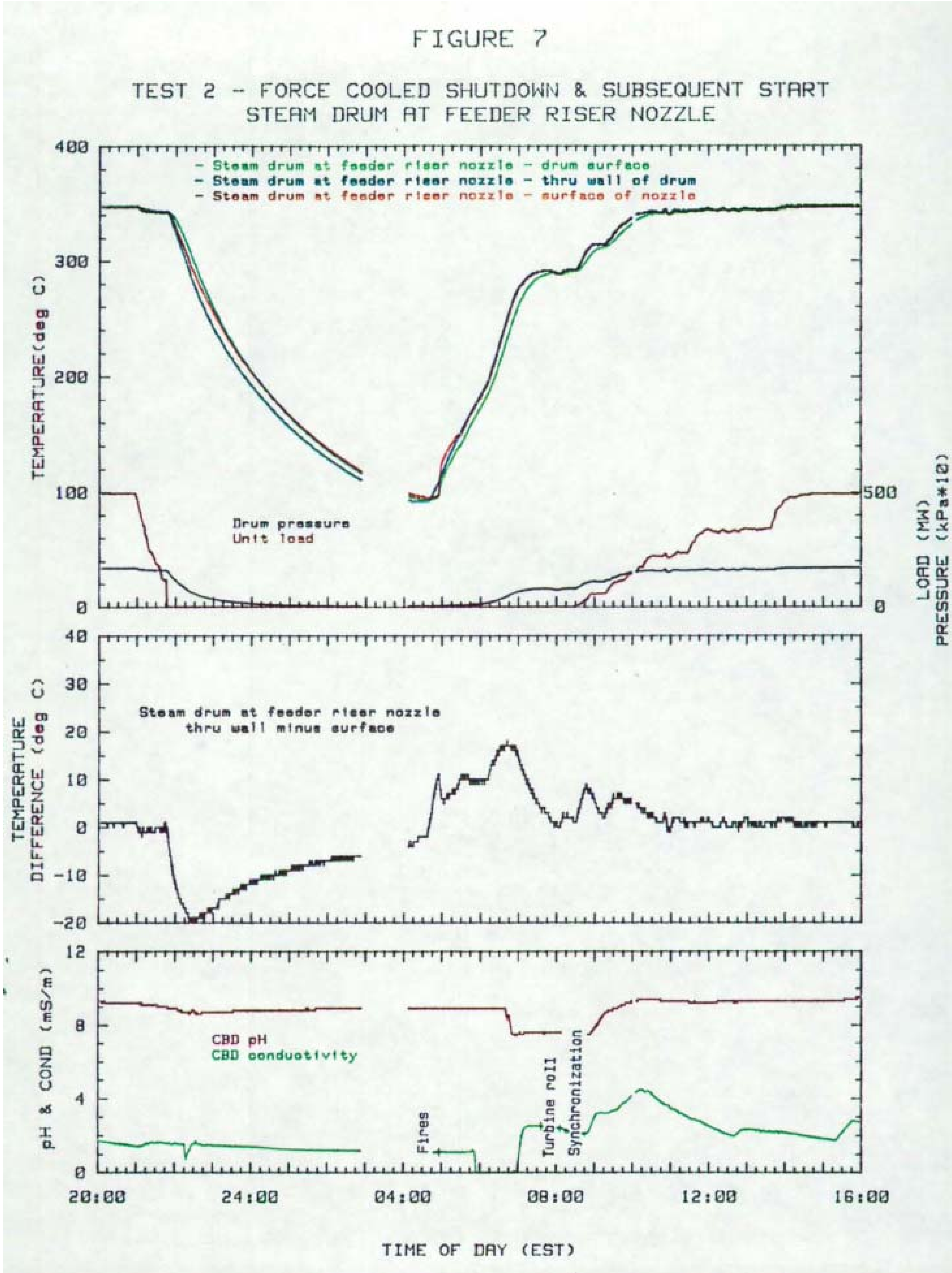


Figure B-12
Test 2 - Force Cooled Shutdown & Subsequent Start (Steam Drum at Economizer Feed Nozzle)

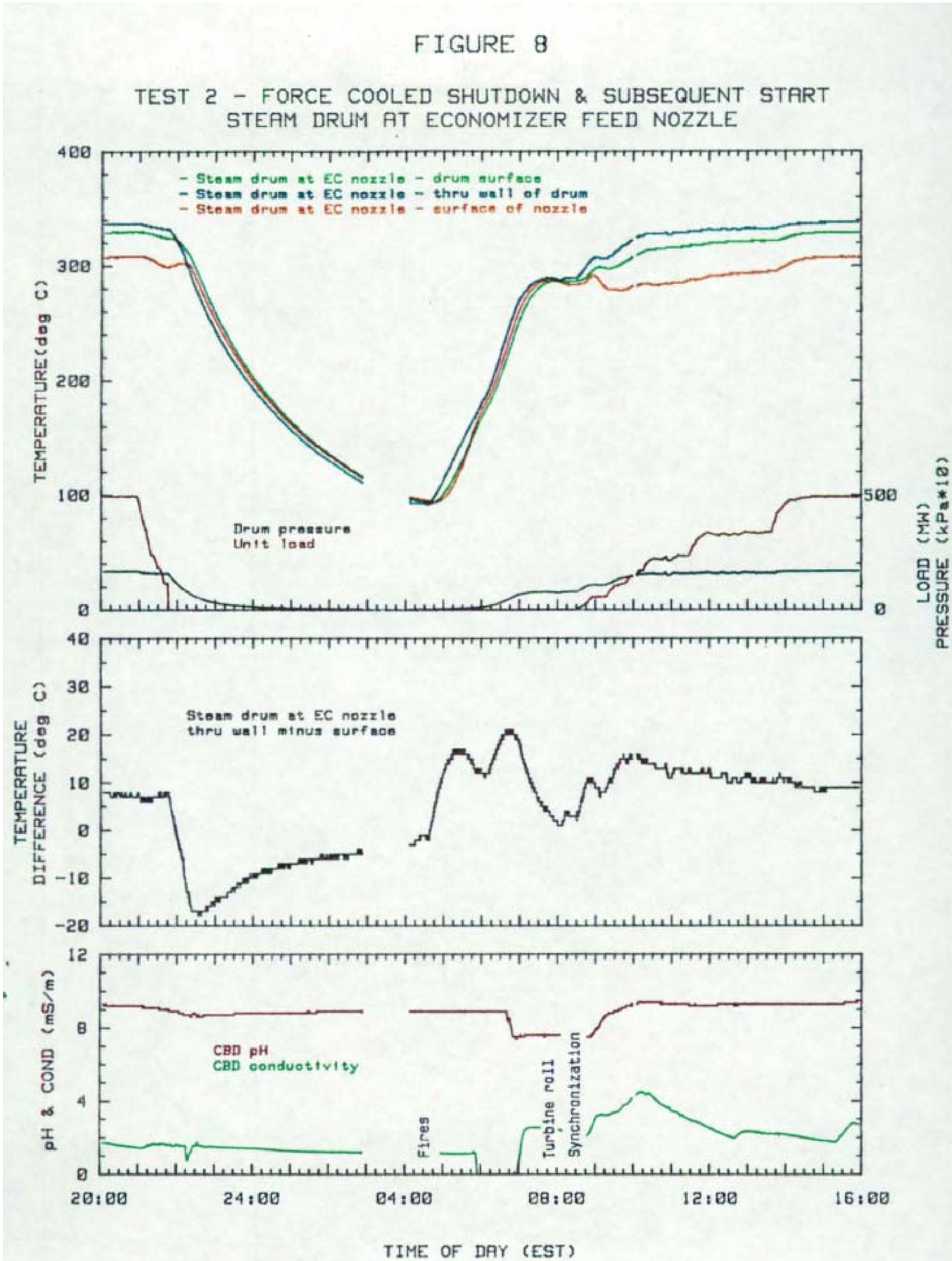


Figure B-13
Test 3 – Normal Shutdown & Warm Start (Lower Waterwall Header at Crossover Nozzle [C1])

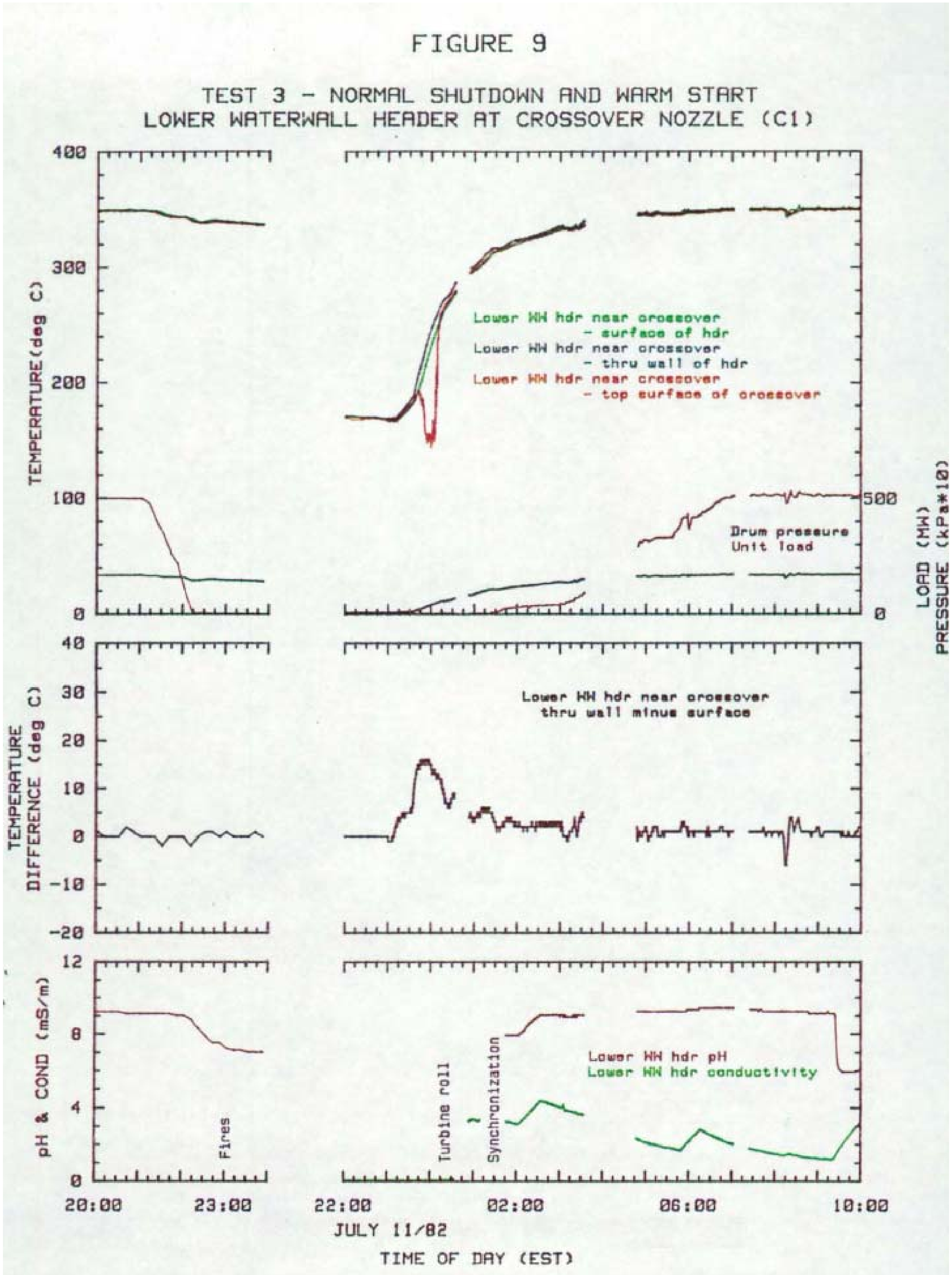


Figure B-14
Test 3 – Normal Shutdown & Warm Start (Steam Drum at Economized Feed Nozzle)

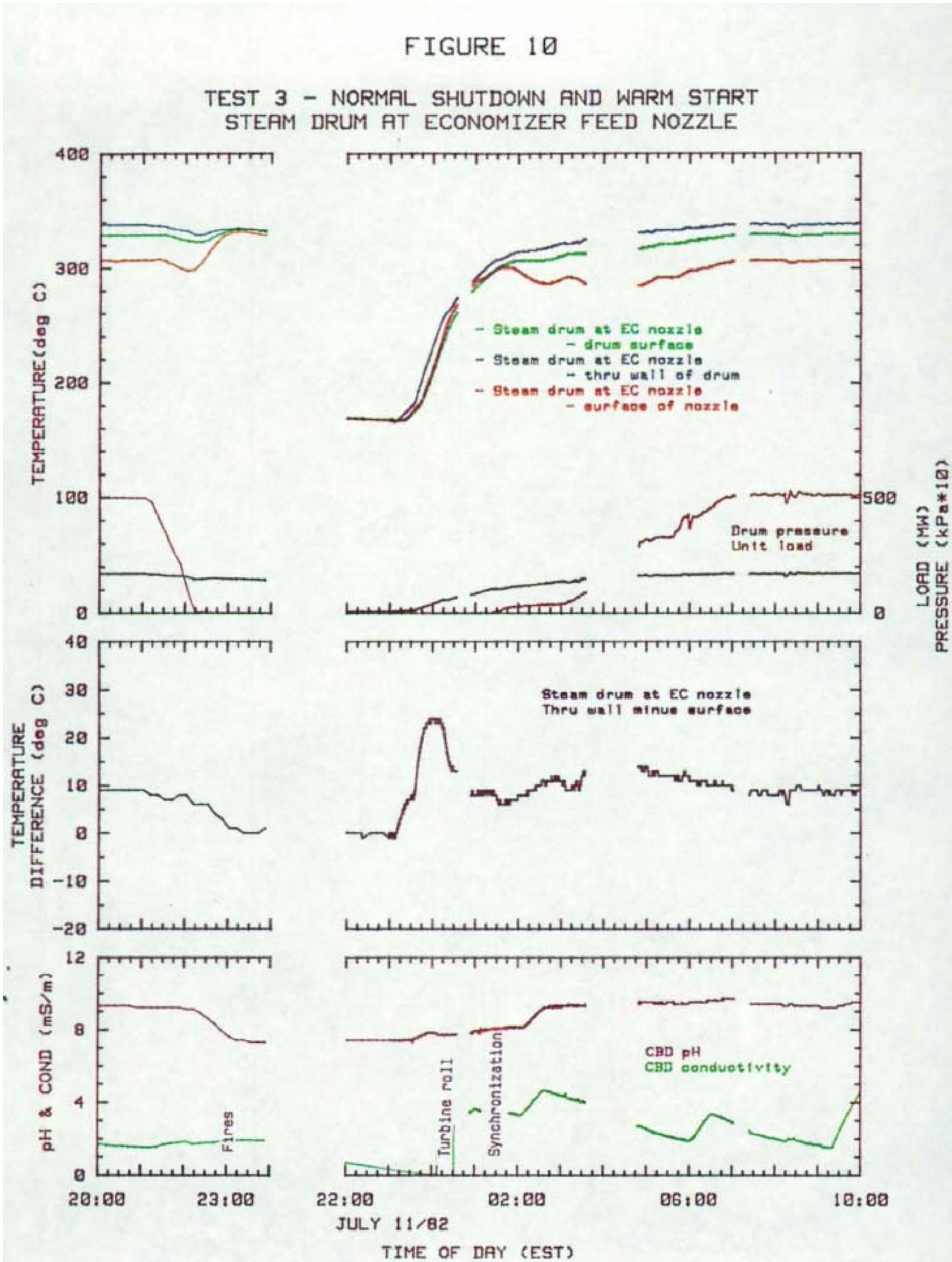


Figure B-15
Test 4 – Normal Shutdown and Hot Start (Lower Waterwall Header at Crossover Nozzle [C1])

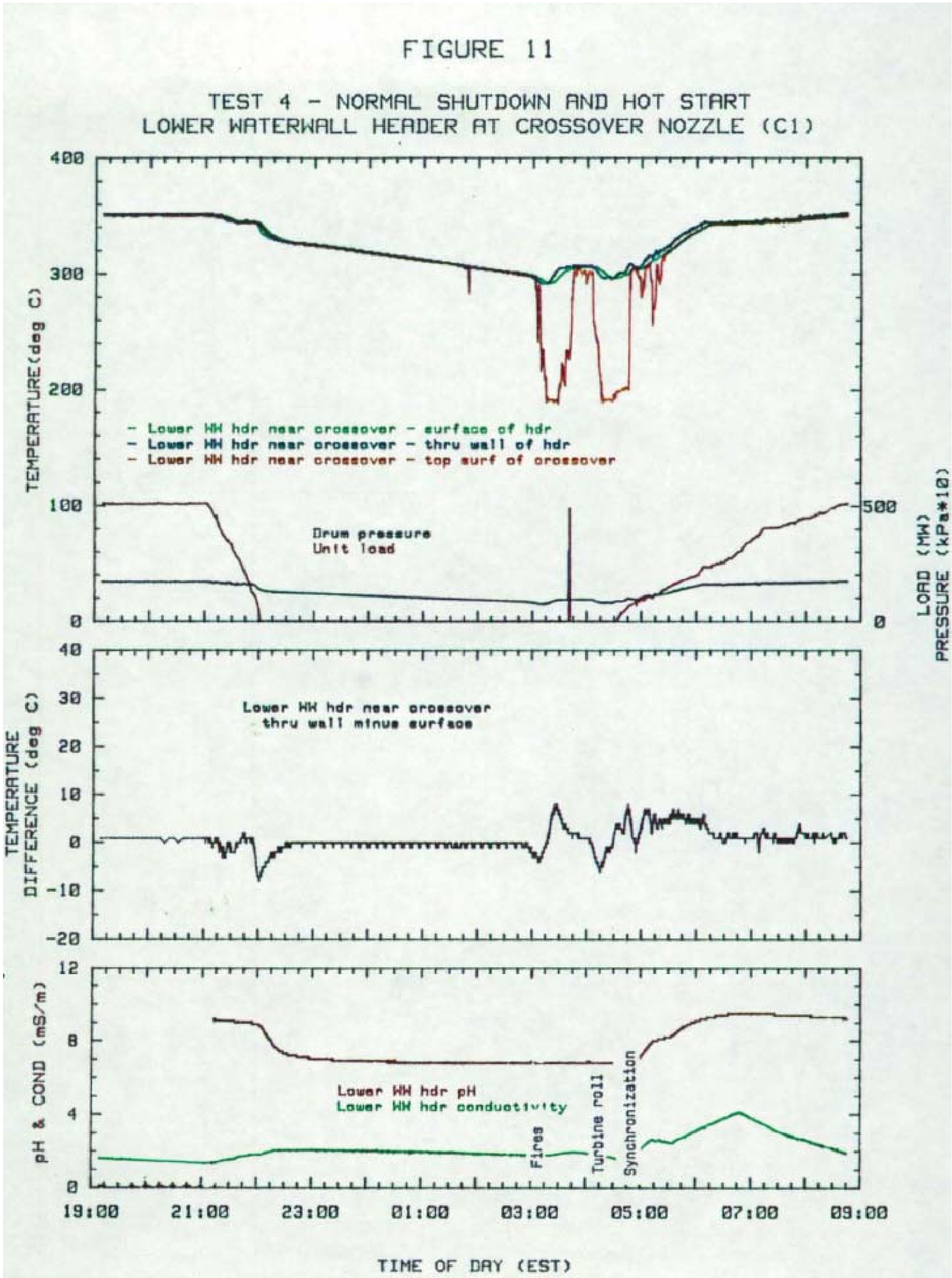


Figure B-16
Test 4 – Normal Shutdown and Hot Start (Steam Drum at Economizer Feed Nozzle

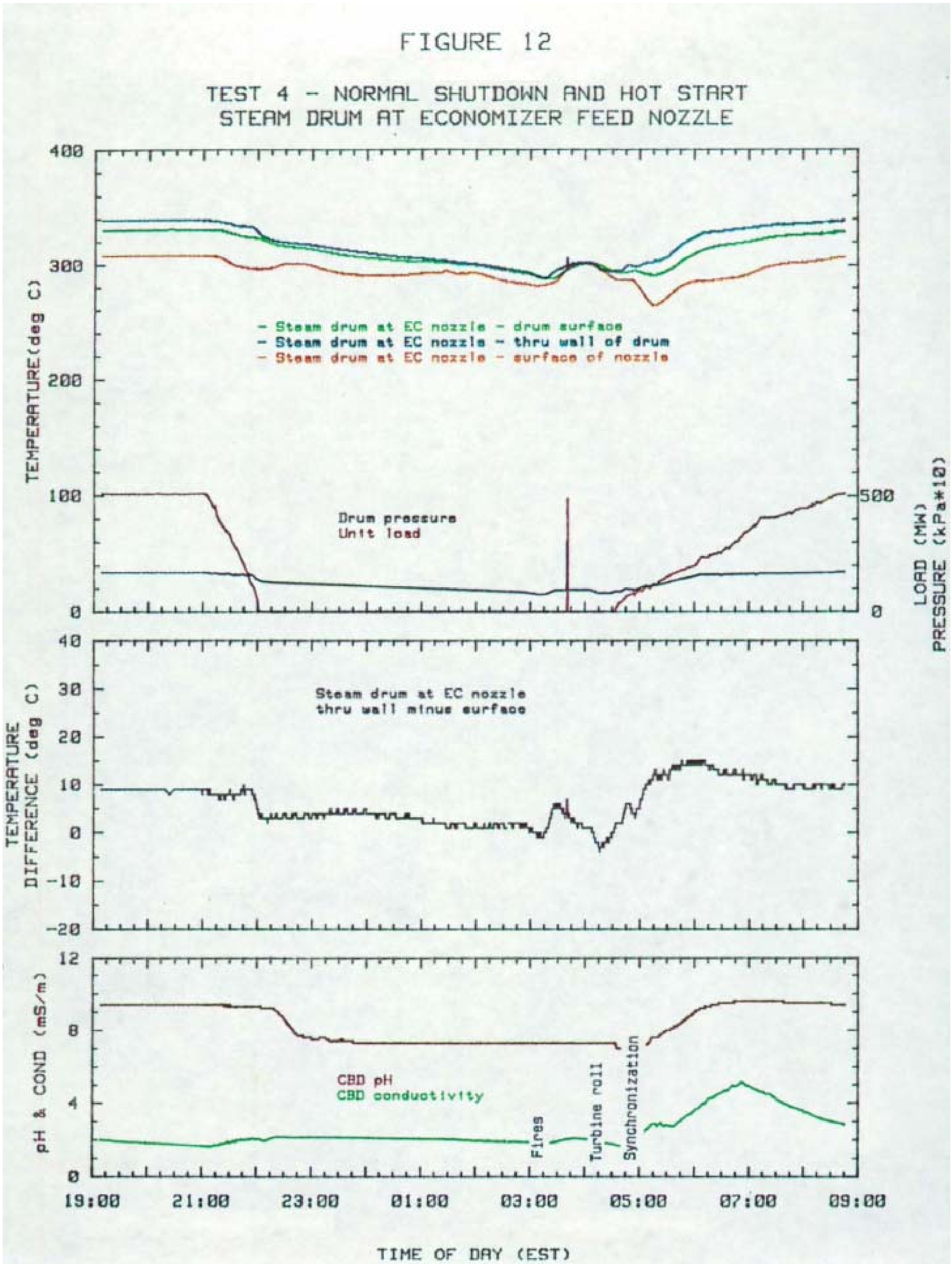


Figure B-17
Test 5 – Cold Start After Weekend Forced Cool

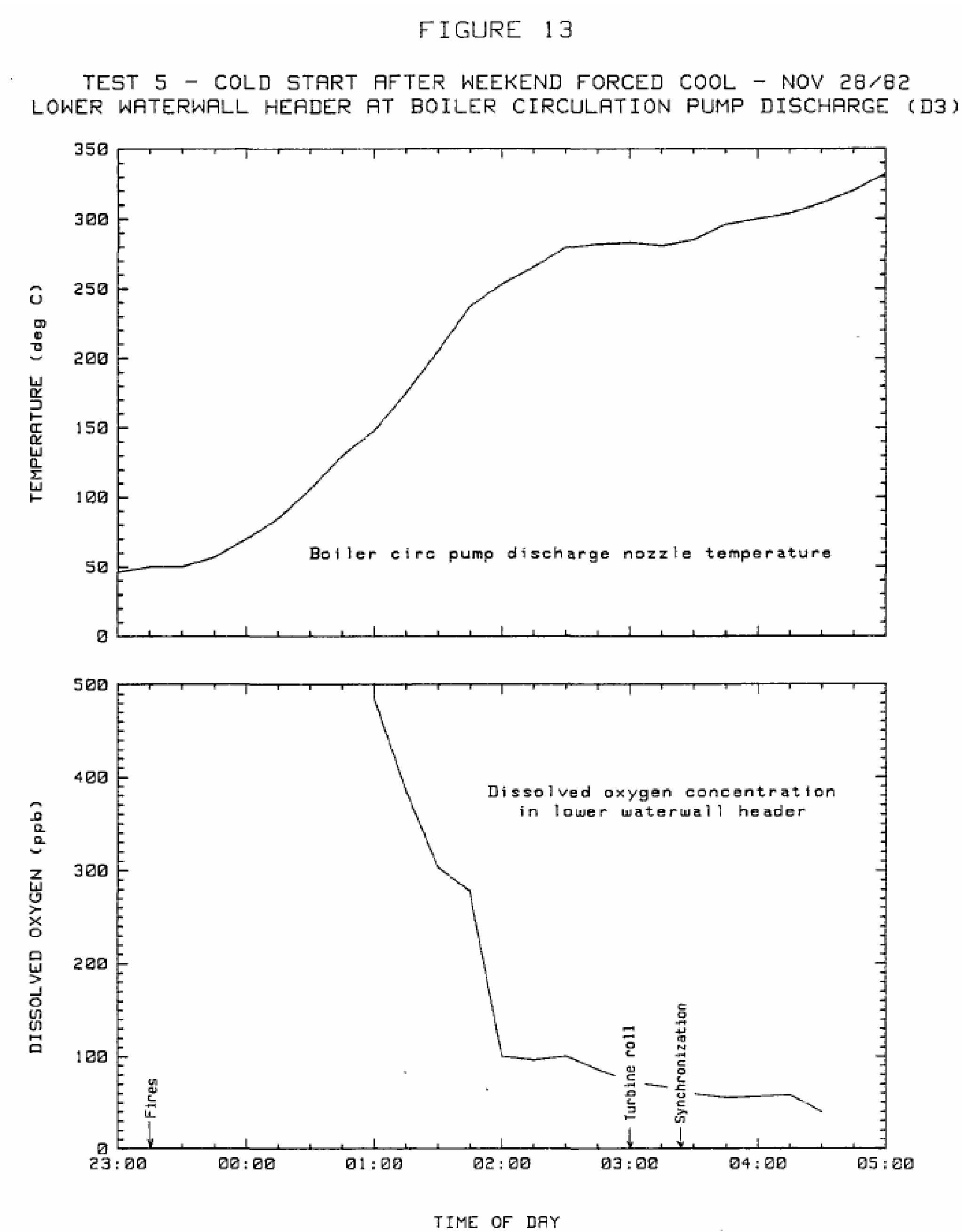


Figure B-18
Fatigue Crack Initiation Analysis

Fatigue Crack Initiation Analysis

Nomenclature

P	= Pressure (MPa)
σ_{MAX}	= Maximum stress (MPa)
σ_{MIN}	= Minimum stress (MPa)
σ_p	= Hoop stress due to pressure (MPa)
σ_{th}	= Thermal stress (MPa)
$\Delta\sigma$	= Stress range = $\sigma_{max} - \sigma_{min}$ (MPa)
E	= Young's modulus (GPa)
α	= Linear coefficient of thermal expansion (°C^{-1})
T*	= Governing temperature = $T_{min} + 0.75\ (T_{max} - T_{min})$ (°C)
T_{MAX}	= Maximum temperature of cycle (°C)
T_{MIN}	= Minimum temperature of cycle (°C)
ΔT	= Through-wall temperature gradient (OD-ID)
K_t	= Stress concentration factor (mechanical)
K_{th}	= Stress concentration factor (thermal)
D_m	= Mean diameter of drum (mm)
t	= Measured wall thickness (mm)
N_f	= Number of cycles to crack initiation

Location: Main steam drum economizer feed line.

$T^* = 40 + 0.75\ (350-40)$ (See Reference A1)

$T^* = 272.5°C$

$K_t = 4.6$ $K_{th} = 2.0$ (See Reference A2)

Component

Material: SA299 - Plain - carbon steel

$E_{RT} = 207$ GPa $E_{T*} = 187.5$ GPa

$\alpha = 14.85 \times 10^{-6}\ °C^{-1}$

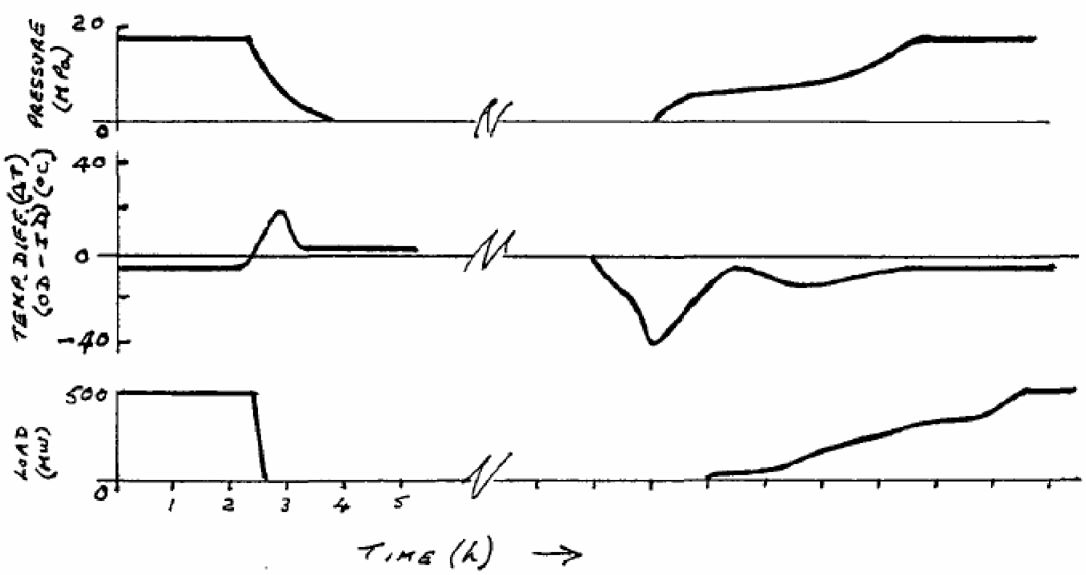
$D_m = 1830$ mm

$t = 152.4$ mm

$P = 18.0$ MPa at full load

Largest $\Delta T = -39°C$ during cold start.
For shutdown part of cycle, force-cool data will be used.

Cycle Schematic



Step 1

Calculate σ_{MAX}: σ_{MAX}: $= \sigma_p + \sigma_{th}$

(i) At maximum pressure: $P = 18$ MPa $\Delta T = -7°C$

$$\sigma_{p1} = K_t \frac{P\ D_m}{2t} \quad - - - - (1)$$

$$= \frac{4.6 \times 18 \times 1830}{2 \times 152.4}$$

$$= 497 \text{ MPa}$$

$$\upsilon_{th1} = \frac{K_{th} \alpha E \Delta T}{1-\upsilon} \quad - - - - (2)$$

$$= \frac{2.0 \times 14.85 \times 10^{-6} \times 187.5 \times 10^3 \times (-7)}{0.7}$$

$$= -56 \text{ MPa}$$

$$\sigma_{MAX1} = 497 - 56 = 441 \text{ MPa}$$

(ii) At maximum ΔT: $P = 8$ MPa $\Delta T = +20°C$

$$\sigma_{P2} \equiv \frac{8}{18} \times \sigma_{P1} = 221 \text{ MPa}$$

From 2 $\sigma_{th2} = +160$ MPa

$\sigma MAX2 = 221 + 160 = 381$ MPa

Therefore, maximum stress is given by σ_{MAX1}, therefore, $\sigma_{MAX} = 441$ MPa

Step 2

Calculate σ_{MIN}: $\sigma_{MIN} = \sigma_p + \sigma_{th}$

σ_{MIN} occurs when $\Delta T = -39°C$, $P = 0$ MPa

Therefore, $\sigma_{MIN} = \sigma_{th}$

Using equation (2), $\sigma_{th} = -310$ MPa

Step 3

Calculate stress amplitude $\Delta\sigma_a$ to evaluate N_f from ASME Section 8, Division 2 (1980) fatigue life curve.

$$\Delta\sigma = \sigma_{MAX} - \sigma_{MIN}$$

$$= 441 + 310$$

$\underline{\Delta\sigma = 751 \text{ MPa}}$

For ASME: $\Delta\sigma_a = \frac{\Delta\sigma}{2} \cdot \frac{E_{RT}}{E_{T*}}$

$$= \frac{751}{2} \times \frac{207 \times 10^3}{187.5 \times 10^{-3}}$$

$\underline{\Delta\sigma_a = 414 \text{ MPa}}$

Step 4

Enter fatigue life curve at $\Delta\sigma_a = 414$ MPa to find N_f.

$\underline{N_f = 2500 \text{ cycles}}$

References

A1 - German Boiler Code, Technical Rules for Steam Boilers, TRD 301, Appendix 1, Design, 1975.

A2 - Pich, R., VGB Kraftwerkstechnik, 1979, 59, 510.

C
APPENDIX (REVIEWS)

Cyclic Operation of Plant Technical Operation and Cost Issues Proceedings of the International Seminar held at the Institute of Materials, London 25, 26 June 2001 (Conventional Steam Plant), 27 June 2001 (CCGTs)

S1-1

Technical and operational issues involved in the two shifting of power plant -salient features of a recent study by ETD

Fred Starr
European Technology Development, Surrey, UK

Abstract

The paper summarizes some of the main problems in converting base load coal and oil fired generating plant to a two-shift scenario. It is based on an industry-sponsored study carried out by European Technology Development (ETD). Although many of the longer term problems in steam plant involve creep- fatigue of high temperature equipment, the report highlights a number of other issues such as thermal movement of boiler structures, waterside problems, fatigue cracking of steam turbines and alternators. The paper emphasizes that there is a need for plant management to take action to improve plant start up rates and reliability. These actions include staff training, checking out the susceptibility of equipment to cyclically induced failure mechanisms, and changes to the boiler and steam circuits.

Paper does not specifically address the evaluation methods.

S1-2

Cyclic operation experience at ENEL with conventional thermal power plant

S. Concari and G. Fedeli
ENEL PRODUZIONE Laboratory ofPiacenza, Italy

S.Jean
ENEL PRODUZIONE Energy Management

Abstract

ENEL experience in cyclic operation of power units j; described. An overview of the electric sector situation is presented enhancing a situation of strongly increasing interest in cyclic operation and related costs evaluation. An analysis of the historical company databases lead to evaluate technically and economically the effect of cyclic operation on the different conventional power units. The results obtained can be used as a basic tool for management on how to operate power plant in accordance with two shifting requirement of the electricity market.

Paper discusses “Top Down” analysis based on past experience. There analysis was based on a minimum of 10 years of historical data dating back to 1972. ENEL also used an historical archive of the most relevant failure analysis investigation documents. Detailed methods of assessing the costs of cycling are not provided.

SI-3

Operational experience of two-shifting large coal fired units

P Dukashe, T Nieuwoudt and J H Begg
Eskom South Africa

Introduction

Eskom is a large state owned utility based in South Africa with an installed capacity of 41237 MW. The plant mix is predominantly coal fired with 33165 MW of coal fired plant being in active service and a further 3800 MW in reserve storage. Due to an ambitious electrification programme which saw Eskom electrify over two million homes between 1994 and 2000 the load profile has changed to show a more accentuated evening peak, especially in winter. This lead to a greater requirement for peaking capacity.

In 1982 Eskom committed to building Majuba Power Station with a capacity of 6 * 660 MW and the first unit was due to be on load in 1988. However, due to a downturn in the demand for electricity in South Africa the project was postponed and the first unit actually came into service in 1996. Majuba was originally conceived asa mine mouth station, but problems encountered on the mine with large faults and inclusions of rock lead to its closure and a rail link was built to transport coal. As a result, Majuba became the most expensive of Eskom's Power Stations during a time of surplus capacity. This fact, together with the increased demand for peaking capacity, made the market niche of two shifting seem attractive to the station and a decision to further investigate this operating regime was made.

Initial Review

Initially there were concerns about the ability of units designed for base load operation to be two shifted at all. The station researched the experiences documented by stations and utilities on the subject of cycling and two shifting. The OEM's of the station were also requested to comment on the ability of the ir equipment to operate in these conditions. A number of overseas study tours were undertaken by station staff and other Eskom personnel to obtain first hand experience of how stations and utilities have done in practice to succeed in cycling and shifting their plant. A research project on the impact of cycling on materials was commissioned by the Research group of Eskom and is still ongoing.

However after many discussions and studies, it was realized that all designs are conceived with a balance between creep and fatigue in mind and changing this balance is not as important as the rate of consumption. The conclusion of these studies was that this mode of operation was possible in the case of Majuba provided that the process was well managed and controlled

A Risk Model was developed by the station to enable sound management of the process. The model records the plant area impacted, the risk involved such as possible material damage due to temperature cycles, the impact of the risk such as either premature or catastrophic failure of components as a result of the material damage, and actions to be taken to mitigate the risk through monitoring results and managing these results. In order to ensure compliance to the model external reviews have been done with positive results. The model covered the total plant and is still in use.

Specific Issues

Boiler Plant

As it was concluded during the preliminary studies that material damage due to temperature cycles would be the most likely problem, a Remnant Life Monitoring model was commissioned to be developed. PowerGen was tasked with this. The six most critical headers are modeled and give a representative status of the fatigue and creep fatigue damage due to temperature cycling. The model is currently functional and is used to identify potential life consuming operating actions and practices.

The importance of good chemistry control was also identified as criteria to ensure long term plant health management. A set of indicators has teen developed and is monitored on a daily basis to ensure compliance. In order to ensure temperature control during light up transients it is important to have the oil burners and the milling plant operational with a high reliability. High level focus was therefore put on this.

Conclusion

It can be concluded that the operating of large coal fired units in a cycling mode of operation has been successful and that no major long-term damage to the plant is evident. This can be attributed to the managed practices that were developed and are been applied. It is foreseen that if these practices are followed the risk of potential major damage will be minimal.

Comments

This paper indicates that an analytical model has been developed to help manage cyclic operation. This involved modeling of the six most critical headers to obtain representative information with respect to fatigue and creep-fatigue damage due to temperature cycling.

Details of the method are not provided.

S1-4 ESB Experience with two shifting of power plants and some cost Implications

Electricity Supply Board - Ireland

Analyses of the estimated cycling costs for a 120 MW unit were performed. The results showed a significant variation in estimated costs for starts between ESB estimates and Aptech estimates. See table below:

Table 7-1
Comparison of ESB and Aptech Estimated Cycle Costs (by Factors Relative to ESB Estimated Hot Start Cost)

	ESB Estimate	Aptech Best Estimate	Aptech High Estimate	Aptech Low Estimate
Hot Start	1	4.3	3.0	6.7
Warm Start	1.5	3.8	2.4	6.7
Cold Start	4	2.1	1.4	3.3

(Note – seems to be a typo or discrepancy re Aptech High Estimates and Aptech Low Estimates) – Low estimate should have a lower multiplier than high estimate

"One of the most important aspects of these findings is the possible impact on dispatch. If the Aptech results are accurate then a reduced level of starts would yield major savings in avoided O&M and reduced forced outage rate (FOR) costs in the medium to long term. However to accomplish this would require an immediate increase in the fuel cost (high fuel cost units would remain on load by reducing the load on higher merit (low fuel cost /high efficiency) units). Clearly a high level of confidence in the accuracy of the cycling costs would be needed before embarking on this course of action."

Concluding Remarks

The foregoing serves to highlight the complexity and indeed sometimes contradictory nature of some of the data arising from efforts to establish accurate costs of cycling It is evident that the costs are substantially higher than the basic fuel, chemicals andauxiliary power costs normally assumed. It is also apparent that there is as yet no verifiably method for confirming the accuracy of any estimates. Improved knowledge from the various studies currently ongoing e.g. EPRI projects, together with the industry wide improvement in the focus on cost tracking should eventually deliver improved cost forecasting models. Until then it must be recognised that any estimates will be prone to a large degree of uncertainty and hence financial risk.

Commentary

This report discusses cost of cycling and comparisons between ESB cost of cycling estimates and APTECH evaluations. In general, the Aptech estimates for Hot and Warm starts were significantly higher than the ESB estimates (4.3 to 1 and 3.8 to 1.5)

The investigations highlighted the need for better data on costs, operational information and on the condition (remanent life) of the major components. It was stated that ESB had recently installed a comprehensive information system to monitor efficiently and log component operating information on the main units of the system. However, methods of determining the remaining life of the major components were not detailed.

The report references the following:

1. W.F. Coe and T. Newton "Plant Non Recurring Costs and Major Expense Projections Analysis in SEI Report for ESB, May 1995.

2. Lefton S.A. " A Method to Measure the Impact of Cycling Operational and Power Derations on Plant Life and Reliability" EPRI Fossil Power Plant Conference,1992
3. Lefton et al "Managing Utility Power Plant Assets to Economically Optimize Power Plant Cycling Costs" EPRI Fossil Plant Cycling Conference Sept 1994
4. Lefton et al "Using Fossil Power Plants in Cycling Mode: Real Costs and
5. Management Responses" EPRI Managing Fossil Generating Assets in the
6. Emerging Competitive Marketplace" Washington D.C. October 1996

It also has forced outage rate data similar to EPRI Damage to Power Plants due to Cycling.

SI-7

Experience from extensive two-shift operation of 680MW coal / gasfired units at Castle Peak P.S., Hong Kong

Has some cost data for cycling

S3-1

Experience in cycling cost analyisis of thermal power plants in North America and Europe Steven A. Lefton, Phil Besuner, Paul Grimsrud, and Todd Kuntz

Aptech Engineering Services, Inc., USA.

This paper outlines a concerted effort to develop a methodology to address the influence of cycling that has been undertaken by Aptech Engineering Services, Inc. This paper outlines the methodology for evaluating the cost of cycling. In particular, damage models have been developed that include creep and fatigue and their interaction for each unit type. The models account for cyclic operation, base-loaded operation and operation above MCR damage for various key components such as boilers (including tubing), turbines and generators at conventional fossil units. Plant signature data (measured temperatures and pressures) for key unit components obtained during typical load transients are used to calibrate the damage models. The model validation process included the assessment of key components using finite element and creep / fatigue analysis methods to determine remaining useful component lives. The life analyses of key high cycling cost components were statistically calibrated to historical failure data for the components. Aptech states that “Traditional, un-calibrated engineering fatigue and creep analyses, however ambitious and expensive, are rarely useful and often misleading in predicting cycling costs”

The signature data is analyzed for critical components such as the steam drum, first pass water wall tubing, SH and RH tubing and headers, economizer inlet, as well as turbine/generator related components such as valves, cases, generator windings and steam chests. Maximum temperature ramp rates and overall temperature variations experienced by the components are key indicators used for the evaluation of cycling-related creep and fatigue damage. This data is used to quantify the severity of the each units load transients. The signature data can also be used to manage the cycling operations to minimize damage, maximize the asset’s life and reliability and reduce maintenance costs.

The damage modeling is combined with historical capital maintenance spending and unit loading over time to derive cost per unit-specific typical load cycle. Typically, at least 10 years of annual capital and maintenance spending information is evaluated. These costs are evaluated by screening out costs not related to unit operation to arrive an annual candidate costs.

Quote “Traditional un-calibrated engineering fatigue and creep analyses however ambitious and expensive are rarely useful and often misleading in predicting cycling costs.”

S3-3

A REVIEW OF SOME OF THE COST ISSUES INVOLVED IN TWO SHIFT OPERATION OF FOSSIL PLANT

Fred Starr
European Technology Development Ltd., Ashtead, Surrey, UK

Alan Bissell
Electricity Supply Board, Ireland

Abstract

To address an industry need for more information on the effects and costs associated with cycling of conventional fossil plant, European Technology Development Ltd. recently conducted a comprehensive survey. This paper presents some of the information obtained. The link between starts and a delayed increase in forced outage rate is confirmed but no common cause of this pattern was found. Some cost information is examined and the requirements for predictive analysis are considered. A simplistic ranking model is also proposed, which if developed would potentially allow a first order prediction of O&M costs under cycling.

Need to Review

Similar data is found in “Damage to Power Plants due to Cycling”

Review Ranking Criteria (Plant size, age of plant, quality of historical maintenance, way plant is operated - % of starts outside of OEM procedures).

S4-3

Monitoring of boiler life during cycling operation
Damien Charman1 and Andrew Croker2
1Pacific Power International~Newcastle, Australia
2Australian Nuclear Science and Technology Organisation, Sydney, Australia

Comments

On Line Damage Assessment is used.
Basis is R5.

Finite element stress analysis models are developed for the specific component geometry and, where possible, actual component elastic-plastic properties are used to determine the elastic and plastic stresses and strains.

Current modules that are installed in several power stations include; Creep life consumption of Tubing, Creep life consumption of Headers and Creep-Fatigue crack initiation in Headers.

Further modules that are planned include; assessment of damage to steam chests, HP Rotors, HP Casings and turbine fasteners

S6-1

Effects of two-shift operation on the remaining life of heat recovery steam generators
L B Lim and C Dometakis
ERA Technology Ltd, UK

Abstract

Most heat recovery stearn generators (HRSGs) have been designed for, and will operate at, base-load conditions. At present, many plant owners are considering the potential financial benefits to be gained by adopting a two-shifting or secondary response operation regime. However, experience has shown that some HRSG designs are particularly vulnerable to thermal fatigue induced failure, and must be classified as a critical CCGT plant item when subjected to cyclic operation. In this paper, typical HRSG design weaknesses are identified, with respect to cyclic operation capability. Specific examples illustrate the effect of cyclic- induced damage mechanisms on the remaining life of critical boiler components. Potential solutions involving a combination of operational and design changes are given, which could allow a plant designed for baseload service to operate safely in a cyclic regime.

Review this paper for basic approach to cycling evaluation even though application is a HRSG.

Damage to Power Plants Due to Cycling

Final Report, July 2001
EPRI 1001507
Prepared by: European Technology Development Ltd., UK

Introduction:

From Report Summary:

This report is a revision of a report originally prepared and published by European Techology Development limited (ETD) The report was intended to evaluate the effects and implications of cyclic operation on equipment in steam-based fossil-fueled power plants.

The objectives of the report were:

- To survey, compile, and report on the global utility industry status and needs in the area of cyclic plant operation
- To highlight the main factors than increase the operation and maintenance costs with a view to discussing the feasibility of technical and management palliatives required to minimize or control such costs
- To help generators increase plant availability and efficiency and better understand cycling costs

- To indentify problem areas requiring research and development (R&D)

A five-member multidisciplinary team was used to perform the study. The study utilized two questionnaires. One questionnaire addressed plant operations and costs and a second questionnaire addressed R&D requirements. Organizations based in the UK, Italy, Ireland, the United States, Canada, Hong Kong and Australia were involved.

This report is intended to provide individual station management and senior engineering staff with guidance on cost-effective cyclic operation on moving from base load operation to two-shifting or load cycling.

The report presents information on operating problems, mechanisms of component failure, preventative maintenance and repair, and costs. Major cost implications of two-shift operation were found not to occur until approximately three years after changing from baseload. After this time, the cyclic effects of two-shifting begin to cause significant damage to components.

The report shows that repair and replacement cost of items such as superheater headers and other critical plant components can be extremely high. The medium and long term cost implications of this are not always considered and vary from unit to unit.

It states that as a result of privatization and ensuing competition, advanced fossil fuel power plants will need to work in a situation which cycling of power plants is the norm. This cyclic tendency could be further exacerbated as a result of the increasing input of wind, sola and tidal power, which by their very nature are extremely variable.

It is stated that the severity of the cyclic operation affects boiler, turbine, electrical, and auxiliary components. The effect is largely design dependant with older plants which were originally designed for base load being less tolerant of cyclic operation. (These units were originally designed with heavy section headers and pipes, which have a poor response to thermal fatigue. In addition, a potential problem exists with stress corrosion and corrosion fatigue of turbine units.

The report points out that it is important to understand the issues involved in two-shifting, including the following:

- Better monitoring of plant operation and behavior of critical components
- Better plant management systems
- A strategy of component inspection and replacement
- Proper assessment and forecasting of costs involved

A study performed by APTECH Engineering Services Inc. of the United States showed that many utilities regard maintenance and capital spending as the only additional cost associated with cycling. In short, the basis for two-shift costs is often ill determined, which can create long-term problems.

A review of operating state and the level of cyclic operation of a large number of utilities around the world is provided. This review substantiates the need to address cyclic operation effects on power plants.

Failure mechanisms and implications for key components are outlined in the report.

It is stated while older base load fossil units were designed, almost by definition to operate predominantly under creep conditions, none of the older design codes placed any specific requirement on the designer to consider fatigue as a failure mechanism. It was assumed that he effects of fatigue were accounted for through the conservatism of the design codes. While this was an adequate assumption for base load plants, it is now recognized that fatigue in conjunction with creep-degraded material is a significant concern.

It is stated that the most common problem that is experienced as a result of cyclic (two-shifting operation) is thermal fatigue damage which leads to cracked components and the mechanical failure of structures. Component cracking is attributed to the severe thermal gradients and subsequent stresses that result from excessive steam-metal temperature differentials and through wall temperature differentials that result from rapid rates of steam temperature changes that occur during the startup, shutdown and load changes.

Creep and Fatigue mechanisms can act synergistically to cause premature component failure. The effects of this interaction are acknowledged. The ASME Code, for example, provides guidance on the interaction between creep and fatigue and the subsequent effect on the material life expectancy. The interaction between creep and fatigue based on ASME N-47 and the consequences of two-shift operation on a typical power plant steel (2.25Cr1Mo) are discussed. It is stated that where operational cycling is introduced on a formerly base loaded machine, the residual life can be greatly reduced to between 40% and 60 % of the original design life due to the combined effects of creep and fatigue.

A number of components are affected by Creep-Fatigue. These include the thick wall components such as boiler and turbine stop valves, governor vales, loop pipes and HP turbine inlet sections (belts). Thermal fatigue cracking of the ligaments between header stubs and penetrations is known to be one the main life-limiting mechanisms on Superheater and Reheater header components.

In headers, crack initiation and growth is driven by temperature transients which can be created as a result of the following processes:

- During a hot start, condensate which had formed during the previous shutdown is passed into hot headers and subsequently quenching the header.
- If during a start-up, hot steam is admitted to relatively cold headers resulting in a rapid metal surface temperature change.
- If attemperator sprays are used without sufficient control resulting in water quenching of the hot surfaces downstream of the attemperator sprays.
- During rapid un-loading and forced cooling of a unit in order to perform tub repairs, saturated steam can travel from the drum to superheater sections.
- Rapid load changes (block loading) can impose sudden changes in airflow through the boiler and changes in steam flow

Evaporator Header Stub-to-header or Stub-to-tube welds can also be susceptible to thermal fatigue due to differential expansion of the furnace wall tubes during a boiler light up as the center tubes are more exposed to the firing than the wing tubes.

Economizer headers can also experience significant thermal fatigue during startup as slugs of cold feedwater are injected into the boiler as flow is established.

Tube failures attributed to attachment weld failure is of the main areas leading to reduced availability when boilers are cycled. The boiler tubes are held in place by attachments to either adjacent tubes by slip ties on platens or to the colder steelwork on the furnace walls. These attachments are subject to thermal cycling which sometimes results in tube failures as fatigue cracks penetrate the tube walls. This failure mechanism is highly dependent on the design detail.

There are also a number expansion related issues in boiler systems. Boiler structures experience significant thermal motion. A typical large boiler is hung from roof supports and will expand downward from theses supports by 250 mm with lateral expansions in the order of 150 mm. This expansion must be accommodated by a "cold" support framework that is designed to permit this relative expansion. These supports do not generally pose a problem under two-shifting. However, these connections can be subject to cyclic bending. Another problem that can occur is load migration where load is transferred across the boiler due relaxation or failure of highly loaded supports leading to overloading and failure of individual supports.

Steam pipework systems between the boiler and turbine have to be able to accommodate the piping thermal expansion and movement of the boiler and turbine. These systems typically utilize constant load supports to accommodate the pipe movement. If these support systems seize, significant thermal creep and fatigue damage can occur under cyclic operation (e.g. at boiler or turbine terminal connections).

The report covers two-shift operating practice in some detail with comments on utilities experience in reducing startup and shutdown times. Methods of managing the thermal transients are described (e.g. off-load circulating systems to pump water slowly around the evaporative section to balance temperature variations). Improved Hot start techniques are described.

An overall approach to the local management of a station moving to two-shifting is outlined. This involves the development of an existing status database that identifies the current condition of the major plant components and their operational history. This process would also include evaluations of the water treatment system, application of monitoring systems and regular inspections, data evaluation (modeling if appropriate) to confirm components at risk, refinement of operational procedures to reduce minimum startup time with minimum physical damage to the plant and finally, an economic evaluation of plant integrity options to balance between the cost of operational constraints versus plant repair or renewal.

Typical Fatigue lives for major plant components are provided as a reference for a starting point in the evaluation of the effect of cycling.

Staff Training in operation, additional instrumentation and controls, and condition monitoring and outage/repair strategies are also outlined. Modifications to the plant that will improve cyclic performance are also discussed (e.g. size of drain connections), improved thermal insulation, boiler offload recirculation of boiler water, Boiler Hot-filling – Filling with hot water from another unit)

A typical longer term methodology to adapt a base load plant to cyclic operation is outlined. It involves [from report section 5.8]

1. Review all plant components and categorize, based on knowledge and experience, those that might be at medium or high risk of premature failure (plant status process).

2. Attach thermocouples to medium- and high-risk components to gather data for detailed operational and analytical investigations.
3. Perform two-shift trials to include a range of operating conditions; monitor pressure and temperature data for individual components.
4. Evaluate data to include operational evaluation and detailed FE stress analysis (where applicable).
5. Revise operating procedures to reduce operating time scales, and reduce thermal transients and minimize through-wall differentials.
6. Make a preliminary qualitative assessment to filter out the components in which the damage occurring is considered to be acceptable.
7. Perform a more detailed analysis of any remaining high-risk components.

The costs of cyclic operation are discussed. It is acknowledged that it is difficult to obtain cost information from operators due to the increasing commercialism that is developing in the market (competition). However some information was obtained to permit a review of a few of the factors that result in increased costs. Cyclic operating conditions can potentially result in:

Increase in capital spending due to the need for increased component replacement.

Increase in O&M costs due to higher wear and tear

Lower availability due to increased failure rates and outage times. Increased fuel usage due to reduced efficiency due to non-optimum heat rate operation.

Determining the cost of cycling is difficult due to the large variation in the design of plants and components. It is quite plant specific and thus difficult to generalize.

High-level estimates are determined by correlating annual costs to overall cyclic behavior. The report references an unpublished (as of 2001) EPRI study that gave an average Steam O&M cold start cost (unit size : 1000 MW) of $70,000, warm start costs of $4100 , hot start cost of $3,500 and , for load cycles over 60%, costs of $1,400. (all based on a !,000 MW nominal output fo a coal-fire plant).

Another cost estimate provided by Aptech showed a very large cost range depending on the size and type of plant. The provided estimates were:

Cold Start: $US 15,000 to 500,000

Hot Start: $US 4,000 to 90,000

It is suggested that he best way to establish the cycling cost of a particular unit is to examine or test the specific plant. It is noted that where such assessments have be performed, the author's surveys indicate that the cycling cost have been significantly higher than the operator's own estimates with the variation being between a factor of 2 to as high as 10.

Forced outage due to cycling was considered in the study. Some statistics were obtained by surveys. A review of the statistics received was provided. The time lag between a peak in cyclic loading and a subsequent peak in EFOR was found to be about 7 years initially and then reduce three years and then to continue to reduce as the plant ages. A similar review of FOR indicated an initial delay of approx 9 or 10 years to about a 4 year delay as the plant ages.

A review of Operation and Maintenance costs related to cycling was also performed. Some survey data was found to imply that cyclic operation does not have a major impact on the O&M trend and suggests that other factors (e.g. management strategies for reducing staff numbers and changes in maintenance methods) may be more important in determining annual budgets. It was suggested that ideally, the longer term must be considered.

Capital and Major Item replacement costs were reviewed. Based on the limited information available, (one small oil-fired unit), a capital related cost of $3,600 per start was calculated.

The report provides some commentary on the Modeling of Costs. The existence of detailed cost models developed by Aptech and EPRI is noted. Both models have developed high-level (top-down) and detailed (bottom-up) methodologies.. These models are comprised of the following main elements:

- Establish a historical cycling pattern at a high level (for example, hourly MW data)
- Collate, analyze, and "smooth" available historical cost data
- Establish a base cycle to compare and relate to actual cycles and determine equivalent base cycles
- Introduce a damage accumulation model that includes terms covering steady-state (creep),cyclic (fatigue), and, optionally, off-load (corrosion) conditions
- Determine the cost of the equivalent base cycle and, using the degree of deviation of the actual cycle from the base case, estimate the cost of each type of start or load change

Two examples of the type of output that can be obtained from these types of analyses are provided. Of particular interest is the commentary on the relative costs of cold:warm:hot starts. The ratios obtained were 1:0.68:0.52 and 1:0.67:0.57 for the cases examined. The variation is not very large in that a cold start is only about twice as damaging as a hot start. It is stated that generally, a typical cold:hot ratio of about 4:1 or more would be expected and that this is some evidence that warm starts may be more damaging than cold starts (1:1.19 cold:warm).

The effects of load following were also reviewed. For the data reviewed, it was found that one cold start was the equivalent of 10 and 31 load cycles (i.e. 1:10 and 1:31 for the two cases reviewed). The variation may reflect significant differences in load change rates or the extent of the load change. It was noted that a recent high level EPRI model (for steam-only O&M costs) produced vary different ratios in cost terms (17:20:50 for warm:hot:large load cycle (>60%) to one cold start). It was thus suggested that high level modeling without a sound damage accumulation aspect may have inherent limitations and require further investigation.

A cost model was considered beyond the scope of the study outlined in the report. However, it was proposed that a simplified method for positioning a plant within a large cost range may be possible through a simple ranking system. The ranking could be based initially on simple criteria such as plant size, age of plant, quality of historical maintenance (based on EFOR) and percentage of starts outside of OEM procedures. These criteria could then be used to determine the relative cost of cyclic operation of a particular plant within a group. Considerations related to the detail design of individual components (e.g. welded rotors) and the overall design of the plant could be also be incorporated. Weighting factors could be used to account for the variation in effect on cycling costs amongst the various criteria.

In summary, this report provides an overview of the considerations to be made when changing from base load to cyclic load operation. The damage mechanisms are outlined and implications on operation cost are discussed. While the report suggests a strategy for ranking a given plant within a range of plants with regard to cyclic operation, it does not address the ranked operational costs of a given component within a plant.

End of Review Information.

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