View from the Penthouse

The DNFM Technical News Letter

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Load Cycling

As many coal-fired power plants designed for baseload service are forced to cycle, unforeseen stresses have been introduced to boiler pressure parts. Understanding the effects and implementing mitigation strategies could prevent premature component failures and keep facilities operating reliably. On August 3, 2015, the U.S. Environmental Protection Agency (EPA) finalized the Clean Power Plan, which calls for cuts in carbon pollution from existing power plants. This rule, coupled with low natural gas prices, could result in natural gas–fired facilities being used more frequently for baseload power and coal-fired plants being cycled, more than ever before, to meet grid requirements.

The majority of coal-fired units were designed and constructed as baseload units, without any anticipation of significant load changes. But combustion turbines and heat recovery steam generators offer higher thermal efficiencies (about 60%) than coal-fired boilers (the best steam plants may operate at a maximum efficiency of about 40%), which is also contributing to a change in dispatch tendencies. Although coal-fired power plants are still in high demand, alternative sources are also very attractive from an economic and environmental point of view. Increasing renewable energy resources such as solar and wind power along with combined cycle combustion turbines (CCCT) is causing additional stress on coal-fired plants due to load-following. Load cycling in coal-fired plants causes long-term and short-term effects on equipment reliability and availability.

What is Load Cycling?

Load-cycling may consist of low-load conditions, hot start-up, warm start-up and/or cold start-up. Low-load condition is when the unit is reduced and operated at a minimum load without being shutdown. During hot start-up, the unit is usually cycled every day. Warm start-up consists of operating the unit for four to five days continuously, and shutting down during weekends. Cold start-up consists of shutting down the unit for an extended period of time for maintenance, usually with a layup procedure.

Effects of Load Cycling

Utility boilers are constructed using different materials and thicknesses. These materials expand and contract at different rates. In addition to creep damage, high temperature components such as superheaters and reheaters experience thermal and mechanical fatigue. The cumulative effect is known as creep fatigue. The resulting damage is much more severe than standalone creep or fatigue damage. Under cyclic loading, tube-to-header welds develop cracking due to a combination of fatigue stresses and hoop stresses. Fatigue stresses can result from relative movement between the components, specifically during heating-up or cooling down, or when load changes occur due to transient stresses. Fatigue stresses are also present from inadequate tube leg flexibility, defective supports/attachments or rigid attachments on the pressure parts. The individual high temperature superheat (SH) and reheat (RH) tubes may operate at different temperatures because of variations in heat distribution, slagging, fouling and misalignment. Therefore, steam enters into the header at different temperatures. Load cycling exacerbates the temperature difference between the individual tubes, since the firing rate is adjusted during load changes to maintain pressure and temperature. During load increase, the boiler is temporarily over fired and this will be reversed when the load is reduced. This causes transient thermal shocks to the header, resulting in ligament cracking. In addition to these thermal stresses, the external stresses associated with header expansion and contraction can cause damage on cycling units, resulting in fatigue cracks at the attachments. An additional fatigue component usually exists wherever components are joined via welding since different parts expand and contract at different rates. Although the fatigue component is within the endurance limit, it will affect the creep properties of the components.

Creep-strength-enhanced ferritic steels (CSEFs) like T91 and T23 are very popular in modern power plants because of higher allowable stresses and superior creep properties than their ancestor grade steels such as T22 and T11. Note that there are some inherent long-term maintenance issues with the CSEF steels. The use of CSEFs in heavy cycling units, specifically in reheat circuits, significantly affects the superior properties obtained through precise heat treatment, resulting in premature failures. Dissimilar-metal welds (DMWs) are very frequently used in high temperature circuits to facilitate material transitions. Load swings produce significant transient thermal and differential stresses on the DMWs. These welds are not only subjected to creep, but also susceptible to creep fatigue failure. Load cycling significantly reduces the useful life of a DMW.

Thermal fatigue is an important consideration during load cycling. Condensate usually collects in the remote sections of SH and RH circuits, resulting in two major issues; thermal fatigue and short-term overheating. The temperature difference exists between the hot headers versus cold steam, or vice versa, produces thermal fatigue cracking and ligament cracking. Warm start-ups produce significant thermal fatigue damage since the temperature difference is usually higher. As shown in **Figure. 1**, rapid start-up conditions may lead to short-term overheating failures, specifically when condensate collects in the low-spots or loops. The tensile strength of the steel drops significantly beyond the design temperatures. Rapid start-ups and shutdowns as well as load changes can cause exfoliation of the ID oxide scale. If the exfoliation is excessive, it may lead to pluggage of bends or erosion damage in the turbine. At low temperature regions of the boiler, load cycling also causes thermal fatigue cracking in economizer inlet headers or tubes, lower furnace wall tubes or headers, and steam drum internals. This fatigue cracking primarily occurs from the ingress of cold water into hot boiler components or vice versa.

Figure 1. Several secondary tube failures due to short-term overheating during start-up periods

Load cycling exacerbates corrosion fatigue on waterwall tubes since the differential stresses on waterwall tubes are higher during start-ups and load swings. Corrosion fatigue is not only a reliability issue, but also a safety concern since failures usually occur on the cold side of the boiler. In order to have corrosion fatigue, either the boiler water oxygen concentration is too high or the pH is out of the control range at the same time that stresses are high enough to break the magnetite layer, as shown in **Figure 2**. Corrosion fatigue occurs when operating or residual stresses break the protective magnetite (Fe_3O_4) layer, exposing the bare steel to the corrosive environment. These stresses are highest during transient periods.

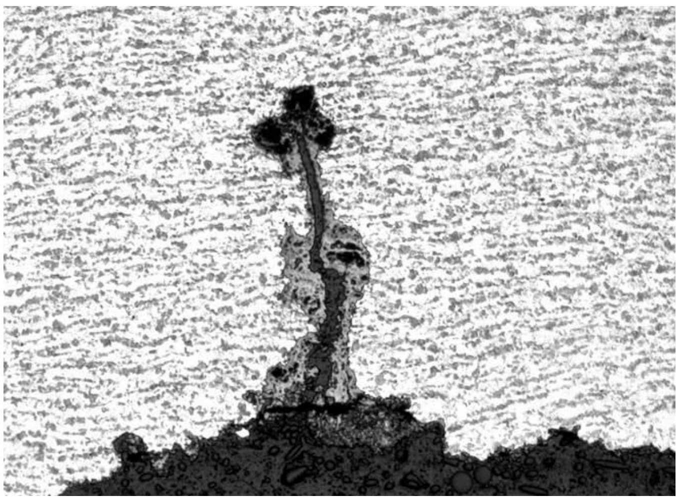

Figure 2. A tube surface that has begun to crack as a result of corrosion fatigue

Caustic gouging is a well-known issue in natural circulation units, specifically during low-load conditions. Repetitive upsets in coolant flow due to load swings cause caustic gouging of waterwall tubes, resulting in significant wastage. In natural circulation units, the coolant flow is biased to certain tubes since it operates on the density difference between the hot and cold fluids. Low-load conditions play a major role in caustic gouging. The flow upsets cause caustic to concentrate at the edges of steam bubbles. Caustic concentrations remove the protective layer of iron oxide, resulting in tube wastage, as shown in **Figure 3**. Phosphate hideout, one of several forms of under-deposit corrosion (UDC), usually occurs when units are operating with phosphate-based treatment. Phosphate hideout causes ionic phosphate to disappear or absorb during high load conditions; it will dissolve into boiler water when the heat rate is reduced. Phosphate hideout promotes acid phosphate corrosion. Hideout becomes evident during load swings or start-ups while changing heat input. Dirty boilers are susceptible to phosphate hideout and acid phosphate corrosion.

Figure 3. Caustic attack in a cyclone inlet roof tube. The plant commenced load cycling about one year prior to this failure

Mitigation Strategies

As discussed earlier, there will always be some adverse effects on equipment reliability whether it is a low-load condition, hot start-up, warm start-up or cold start-up. Each of these conditions will affect the integrity of pressure parts one way or another. It is observed across the board that the warm start-ups adversely affect equipment since the temperature difference is higher and there is greater susceptibility to air in-leakage during shutdown periods.

Fatigue stresses often occur as a result of inadequate tube leg flexibility between the tube penetrations and the header, and also from rigid attachments on the tube. More flexibility and better attachment design will reduce the fatigue stresses. Sometimes it may require header relocation to provide more flexibility. Many older units were designed with rigid attachments; slip type attachments should be used instead to accommodate differential thermal expansion. Several older plants were designed with closely spaced, unsymmetrical tube penetrations which are susceptible to ligament cracking. It is well known that the evenly spaced larger ligaments are less susceptible to creep fatigue damage, see **Figure 4**. Redesign of tube-hole penetrations and tube-to-header weld configuration, especially by eliminating the lack-of-fusion notch at the end of the tube penetration, can also increase creep fatigue resistance. The inclusion of a smooth chamfer at the ID of the header bore hole reduces stress concentration, improving creep fatigue resistance, as shown in **Figure 5**. Good attachment design is vital minimizing creep fatigue. Periodic inspections to check that the *proper* condition of attachments will reduce fatigue related issues. Note that the majority of piping related problems is associated with the hangers and support system; therefore, periodic inspections should be scheduled. Terminations of attachments should taper to the surface to reduce the localized stress concentrations. Lack-of-penetration in attachment welds can result in them running hot or can increase stress concentrations. Good weld design and adherence to welding procedures are essential.

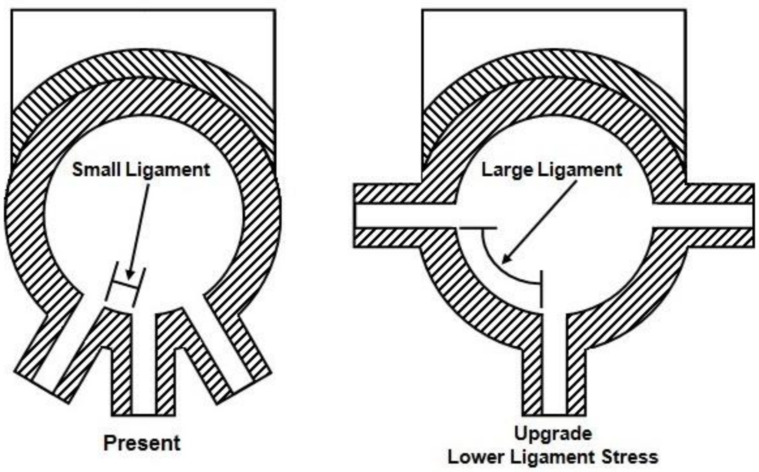

Figure 4. Larger ligaments are less susceptible to creep fatigue damage

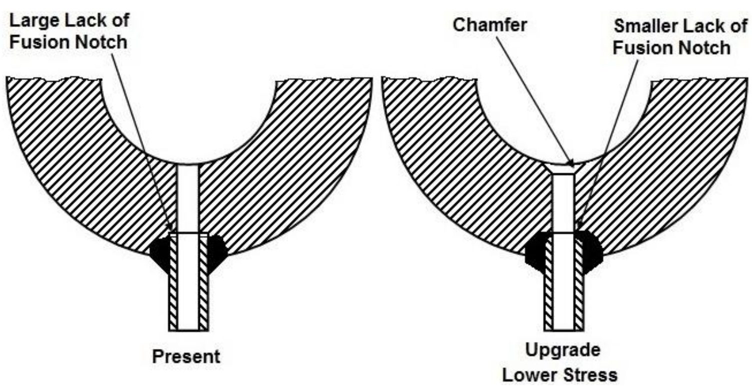

Figure 5. Elimination of the lack-of-fusion notch at the end of tube penetrations and including a smooth chamfer at the inner diameter of the header bore hole can improve creep fatigue resistance

Transient stresses due to load cycling affect the useful life of a DMW. Transient stresses can be reduced with slower start-ups. A DMW can be made with or without filler metal which will have a finite life. It is anticipated that the DMWs made with EPRI P87 or Inconel filler metal are expected to have a longer life than those without these filler metals. The DMW made using the nickel-based filler metal compromises the difference in thermal expansion between the stainless steel and ferritic steel. Stresses and temperatures are the critical factors in the life span of a DMW; performance can be improved by controlling these factors. The weld joint can be relocated to a position where it is exposed to lower temperature. Frequent inspection and maintenance of tube hangers, supports, and spacers can be performed to reduce secondary loads.

Condensate in the high temperature circuits creates major problems during start-up periods. The tubes should be baked for long enough to evaporate the condensate before increasing the heat input. Reduce the thermal gradient between the fluid and metal during start-up periods. Note that the load cycling plays a major role in thermal fatigue. Once the component reaches equilibrium, thermal fatigue will not be a significant factor.

The use of rifled tubing in areas susceptible to under-deposit corrosion can provide better flow mixing to avoid potential corrosion issues. Load cycling significantly increases the susceptibility of waterwall tubes to corrosion fatigue. Fast start-ups increase the transient stresses since different parts expand and contract at different rates, breaking protective oxides and exposing the bare tubes to the corrosive environment. Pad welds are to be avoided in regions which are susceptible to corrosion fatigue. The residual stresses from welding exacerbate corrosion fatigue. It is critical to ensure that water chemistry is within range for pH and oxygen content, especially during start-ups or load shifts, to reduce the risk of corrosion fatigue. Boiler cleanliness must be maintained to reduce the risk associated with phosphate hideout. Use tri-sodium phosphates in place of mono or di-sodium phosphates to bump the phosphate readings. The addition of tri-sodium phosphates does not cause acid phosphate corrosion, but the addition of mono and di-sodium phosphates can promote acid phosphate corrosion. During start-ups, mainly use tri-sodium phosphates to bump the phosphate readings. Avoid heavy blowdowns, which will significantly affect the sodium phosphate ratios and aggravate the situation in units which are susceptible to acid phosphate corrosion. Perform periodic deposit weight density (DWD) testing to know how dirty the boiler is. Boiler cleanliness will significantly reduce majority of waterside issues.