

The Monitoring of Circumferential Fatigue Cracking of Furnace Tubes in Supercritical Boilers

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1. Abstract

Rowan Technologies has used potential drop techniques for many years to monitor corrosion/erosion of power plant boiler tube fireside surfaces. More recently, the techniques have been refined and applied to the monitoring of fireside circumferential cracking of furnace wall tubes in supercritical boilers, as part of an Electrical Power Research Institute (EPRI) funded project.

Trials of simulated circumferential crack growth have shown that changes in measured signals are small but quantifiable under laboratory conditions. Following these successful laboratory trials, monitoring is currently underway using large-scale systems on two 800 MW supercritical boilers in the US. The monitoring systems are not only designed to detect crack propagation, but also to monitor and quantify the thermal characteristics of the tube walls, i.e. thermal instability and excessive temperatures, that are considered to be major factors contributing to tube cracking.

This paper provides an overview of the measurement techniques employed, together with results from the laboratory and on-site projects to date. The circumstances and possible root causes of circumferential crack growth are discussed in detail. Understanding the root causes of the circumferential cracking is very much a goal of this particular project, so that appropriate action can be taken to minimise it.

2. Introduction

Maintaining the basic fabric of boilers, which for large power generation units essentially comprises hundreds of miles of tubing, is a fundamental issue for boiler operators. Since the early 1990s, Rowan Technologies has been developing electrical resistance techniques to monitor the fireside integrity of boiler tube walls. Damage to the fireside tube surfaces, either from corrosion or cracking, can be a principle cause of premature tube failure and may result in unscheduled boiler shut downs for repair – a very costly undertaking.

Early work at Rowan Technologies focussed on the use of intrusive air-cooled probes to simulate and monitor fireside tube wall corrosion at point locations¹. In the late 1990s, the company adapted this technology to directly monitor the fireside corrosion rates of the boiler tubes themselves. This was achieved not simply at point locations, as with intrusive probes, but over large areas of boiler tube membrane wall, using arrays of electrodes welded to the external (cold-side) tube wall surfaces. By ‘scanning’ these sensors in sequence, complete two-dimensional maps are produced of real-time corrosion rates over large areas of wall². The longest serving system, commissioned at Drax Power station (UK) in 2001, covers some 200m² of more vulnerable areas of membrane wall. These systems not only monitor tube wall integrity, but also provide real time mapping of the wall’s thermal performance in terms of heat flux and fireside tube temperatures.

More recently, EPRI (the US Electrical Power Research Institute) has been coordinating a project, principally focussing on a supercritical boiler at Brunner Island power plant, Pennsylvania, that applies the scanner technology to the more challenging task of monitoring fireside circumferential crack growth on the membrane tube walls³. To help understand the root causes of this cracking, the scanner systems also provide a valuable insight into the thermal behaviour of tube walls in areas where cracking has been a major problem.

3. Circumferential Tube Wall Cracking in Supercritical Boilers

Supercritical boilers are high-efficiency power generation units. To help achieve greater efficiencies than subcritical units, higher boiler tube water pressures are used. At supercritical pressures (>3200psi), boiling ceases to occur. Water pressures subsequently drop below supercritical values in the high pressure turbines.

Changes in boiler operations to reduce NO_x emissions, and also the application of weld overlay to the tube wall surfaces to inhibit corrosion, has resulted in some supercritical units suffering fireside tube wall circumferential cracking. An example of circumferential cracking is shown on Figure 1. This is a section of supercritical weld-overlaid tubing, with a tube-to-tube spacing of about 40mm. The cracking tends to initiate on the fireside tube crown and becomes deeper and wider as it progresses. In extreme cases, the cracking can propagate right through the tube wall resulting in catastrophic failure.

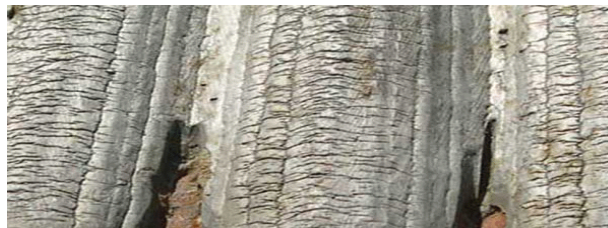


Figure 1: Typical Fireside Tube Wall Circumferential Cracking

Several mechanisms are thought to be responsible for this type of cracking: principle factors are considered to be thermal fatigue due to rapid cycling in tube temperature, creep resulting from prolonged periods at elevated temperatures and corrosion caused by deposition of reducing slag species on the tube walls.

4. Scanner Measurement Principles

For measurements of both tube wall fireside corrosion and surface cracking, the scanner systems make use of established resistance measurement techniques:

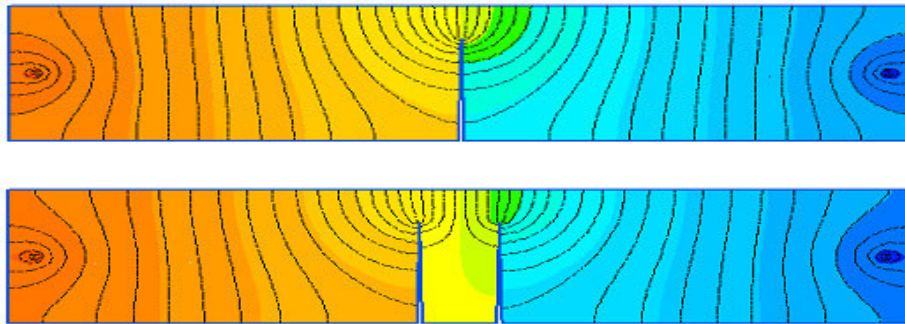
As part of the resistance measurement cycle, current passes through the tube wall via pairs of electrodes, welded to external (cold-side) surfaces and spaced roughly 1 metre apart. On entering the wall, current rapidly spreads out through the bulk metal. Thinning of a tube wall as a consequence of 'uniform' corrosion/erosion reduces the total metal cross section through which current can flow, so increasing the potential gradient for a given (fixed) current.

In the case of closely-spaced surface circumferential cracks, current flowing perpendicular to these cracks meets them as 'obstacles' which must be circumnavigated to make forwards progress, in a similar way to a runner negotiating hurdles on a race track, slowing down the runner's forward progress. A steadily increasing potential drop results as cracks propagate, although the effect is far less pronounced as compared with wall thinning.

As resistance measurements are also heavily dependent on bulk metal temperature, the systems simultaneously measure resistance and temperature and compensate for any temperature variations.

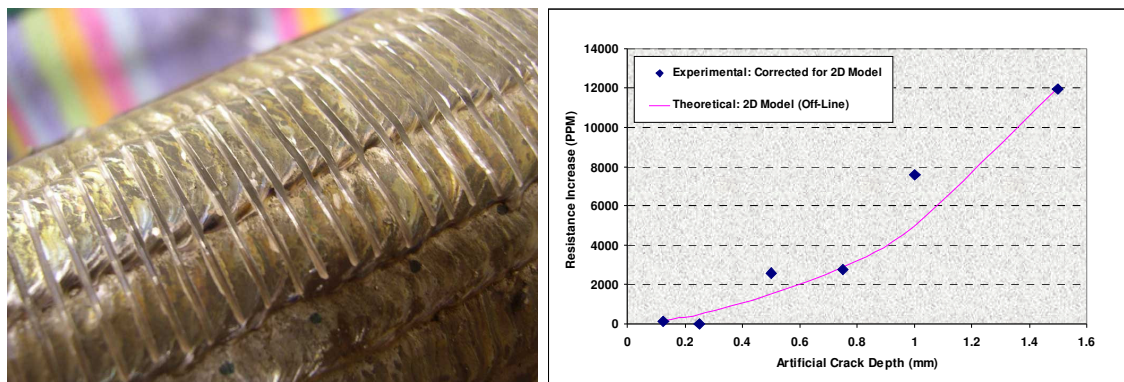
5. Circumferential Cracking – Laboratory Studies

Initial laboratory work⁴ using both experimental techniques and finite element analysis demonstrated the effect of surface cracking on current flow through a tube wall. Finite element modelling illustrates the behaviour – closely spaced deep cracks result in areas between cracks where current flow is low or virtually non-existent, Figures 2a,b. Lines of equipotential are shown in the figures, current flows perpendicular to these lines. As the cracks get deeper, changes in measured resistance accelerate.



Figures 2a and 2b: FE Modelling of Single and Double Cracks

Further detailed studies included resistance measurements of simulated cracking on weld-overlaid tubing, Figure 3. Slots were cut into the tubing using a fine cutting disc. Slot width and depth were increased in stages and subsequent increases in resistance recorded. Typical results, comparing experimental results with theoretical modelling, are presented in Figure 4.

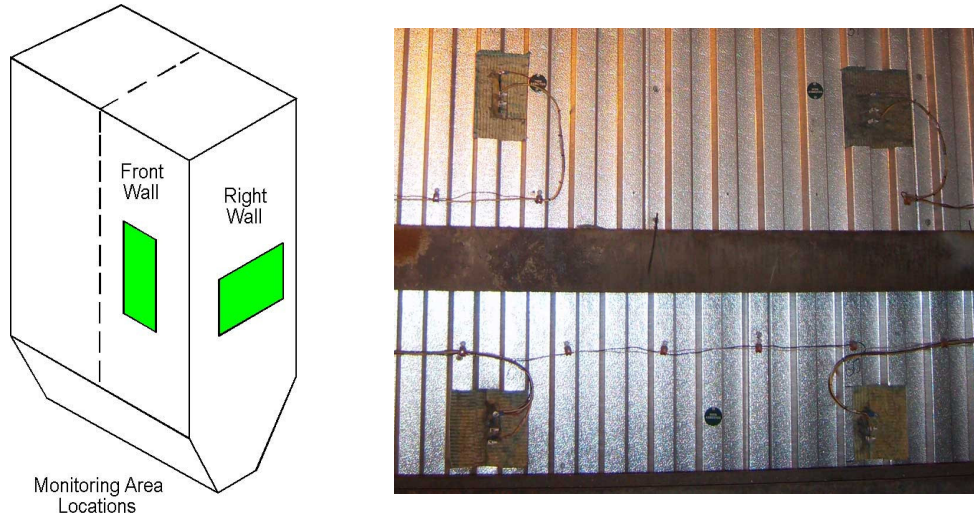


Figures 3 and 4: Simulated Crack Growth and Typical Experimental Results

The studies showed that changes in measured values due to circumferential cracking were small but measurable in a laboratory environment. On-site measurements were likely to be influenced by additional signal ‘noise’ in the form of thermal instabilities and possibly a small amount of electrical interference.

6. System Design – Brunner Island

Scanner systems use rectangular arrays of sensors welded to the external surfaces of the boiler membrane walls. Arrays can consist of up to a hundred or more sensor locations. Brunner Island has two monitoring areas, using arrays of 81 and 91 sensor locations. The monitoring locations are shown in Figure 5 and cover roughly 140m² of membrane wall. Typical sensor locations are shown in Figure 6.



Figures 5 and 6: Monitoring Areas and Typical Sensor Locations on Unit 3

For monitoring of circumferential crack growth using the scanner technology, two approaches are possible: the first approach uses a resistance ratio technique where current is passed vertically, and then horizontally, through a localised area of tube wall. The principle here is that vertical current flow runs perpendicular to, and is more influenced by, the presence of any circumferential cracks (reflected by an increase in measured electrical resistance) as compared to the horizontal current flow that runs parallel to any cracks. The second approach uses temperature compensation of vertical resistance measurements, and is now the adopted method at Brunner Island due to more stable results.

The scanner temperature sensor arrangement also allows predictions of wall heat flux and fireside tube wall surface temperatures. The scanner's ability to predict fireside tube temperatures from external (cold-side) thermal data is a major feature of these systems: the technique used has been devised and refined during the evolution of the scanner technology. High and variable fireside tube wall temperatures are thought to be key factors in the initiation and propagation of tube wall cracking.

7. Resistance Measurements - Results to Date

Using the technique of temperature-compensating resistance measurements, mentioned above, small increases in values have been detected at Brunner Island. Measurements taken when the boiler is off-line (i.e. cold) are the most stable due to the absence of dynamic temperature variations through the tube wall when the boiler is operational, although the number of opportunities for off-line measurements is dictated by the need for shut-downs for maintenance or repair.

An example 2D map from the front wall monitoring area, showing changes in compensated resistance as a function of time, is shown in Figure 7. Based on a density of 16 cracks/inch, the

largest resistance increases shown equate to a maximum crack depth of between 0.25 to 0.5mm. This is close to the detection limit of the scanner.

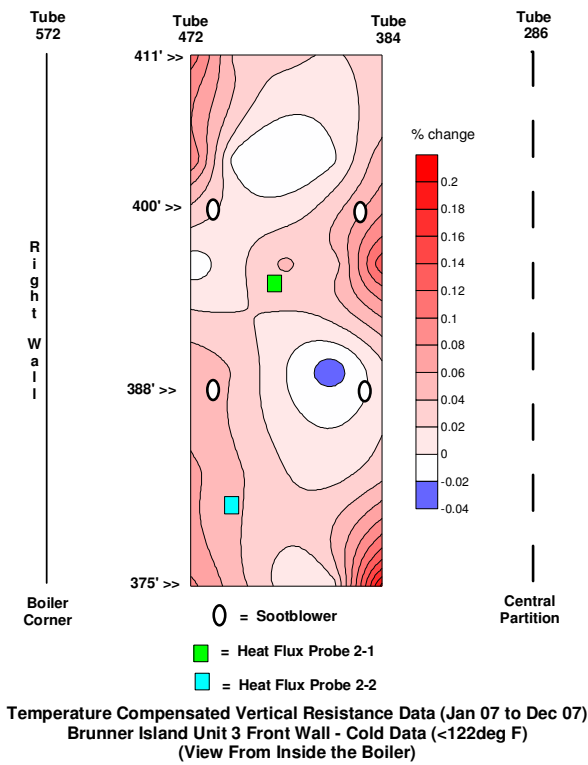


Figure 7: Temperature-Compensated Vertical Resistance Data

9. Thermal Data – Understanding the Root Causes

The scanner has the ability to acquire thermal data from all sensor locations on the Brunner Island installation in less than a minute, the equivalent of about three measurements per second. Such fast thermal ‘scan’ speeds enables more rapid thermal transients to be detected and quantified. The newly acquired scan data is directly uploaded to the plant information system (historian). From the historian, data can immediately be processed to produce real-time maps of wall heat flux or estimated front face temperatures using dedicated scanner software. The sensor arrays have sufficient spatial information to enable high quality two-dimensional maps to be produced.

Also, analysis of thermal data from individual (point) sensor locations enables localised time-dependant thermal behaviour to be quantified and correlated with boiler operations.

As mentioned earlier, high tube wall temperatures, rapid temperature changes and large temperature differences are all thought to be contributing factors to circumferential cracking. By processing the scanner’s thermal data in a variety of ways, clues can be determined as to why the cracking is occurring.

10. Elevated Tube Wall Temperatures

At elevated tube wall temperatures, the tube's yield strength is reduced and so 'excessive' temperatures that might compromise tube integrity are undesirable. Brunner Island has chosen to apply weld overlay to much of the tube walls to inhibit corrosion, but the resulting wall thickening will tend to increase fireside surface temperatures. The actual process of applying weld overlay also results in additional residual stresses within the tube walls that may encourage surface cracking or crack propagation.

The scanner's thermal mapping abilities are able to highlight occasions when tube fireside wall temperatures become 'excessive'. Figure 8 shows what appears to be flame impingement of the tube wall, this particular event lasted some thirty minutes before subsiding. Estimated fireside tube crown temperatures appear to exceed about 650⁰C (1200⁰F - defined by the white areas), which compares with typical operating temperatures of around 480⁰C (900⁰F). Metallurgical analysis of failed tubes (as a result of cracking) has confirmed that the tube metal does indeed exceed 650⁰C on occasions.

Figure 9 shows another example of elevated temperatures (>650⁰C) that occurred after wall cleaning (sootblowing) operations. In this example, wall cleaning from three adjacent sootblowers within the right wall monitoring area have exposed the tube wall to very high radiant heat. Gradually slag will start to re-form and temperatures will subside once again.

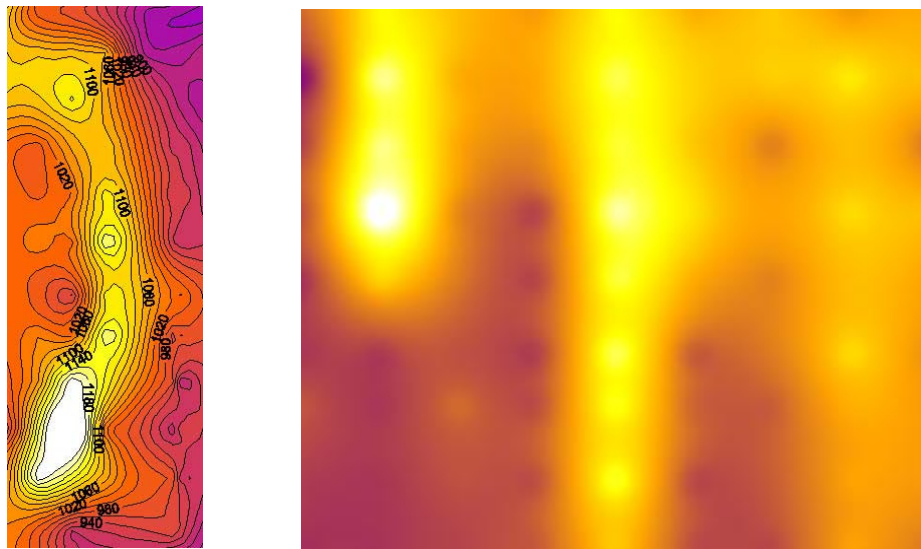


Figure 8 (Left) shows an Arc of Flame Impingement within the 12m High Front Wall Monitoring Area. Figure 9 (Right) shows Areas of Tubing Exposed to High Temperatures following Wall Cleaning of the 8m High Right Wall Monitoring Area. Brighter colours indicates higher Fireside Tube Temperatures – White corresponds to 650⁰C (1200⁰F) or Greater.

Another possible cause of elevated or excessive tube wall temperatures is where coolant flow instabilities result in loss of heat transfer through the tube wall to the cooling medium. Rapid, and possibly damaging increases in tube wall temperature result. At Brunner Island, possible flow instabilities that may result in tube damage, particularly during boiler start-up and shut down, are the subject of investigation. The scanner's thermal data provides a valuable reference source for these investigations.

11. Temperature Dynamics

Rapid temperature fluctuations and large temperature gradients between adjacent parts of the tube wall results in areas of differing expansion, so inducing considerable stresses and contributing to stress fatigue. These cyclic, cumulative effects on the tube metal, combined with elevated tube surface temperatures, may ultimately result in the formation of microscopic circumferential cracks. It is thought that the influence of corrosive species within the surface slag and continued stress cycling gradually enlarge these cracks.

Thermal data from the Brunner Island scanner has highlighted both rapid temperature fluctuations together with highly localised (spatial) temperature differences that can result from wall cleaning, natural slag shedding, flame impingement etc. In the case of natural slag shedding, localised slag falls can expose some tubes to high radiant heat whilst adjacent tubing remains covered by slag and are considerably 'cooler'. The central column of brighter temperatures of Figure 8 is one such localised slag fall initiated by wall cleaning. The hotter, exposed tubing will want to expand whilst the cooler tubing will not; large tube-to-tube wall stresses may result. Research has shown that large tube-to-tube temperature differences can result in circumferential cracking⁵.

Statistical analysis of scanner data has helped to show the extent of spatial temperature variations across the tube wall. An example of these spatial differences is shown in Figure 10. The figure shows on-line temperature difference data from tubes spaced about 0.7 metre apart. Given the nature of localised slag removal and heat exposure, it is likely that similar differences are occurring at a much more localised level.

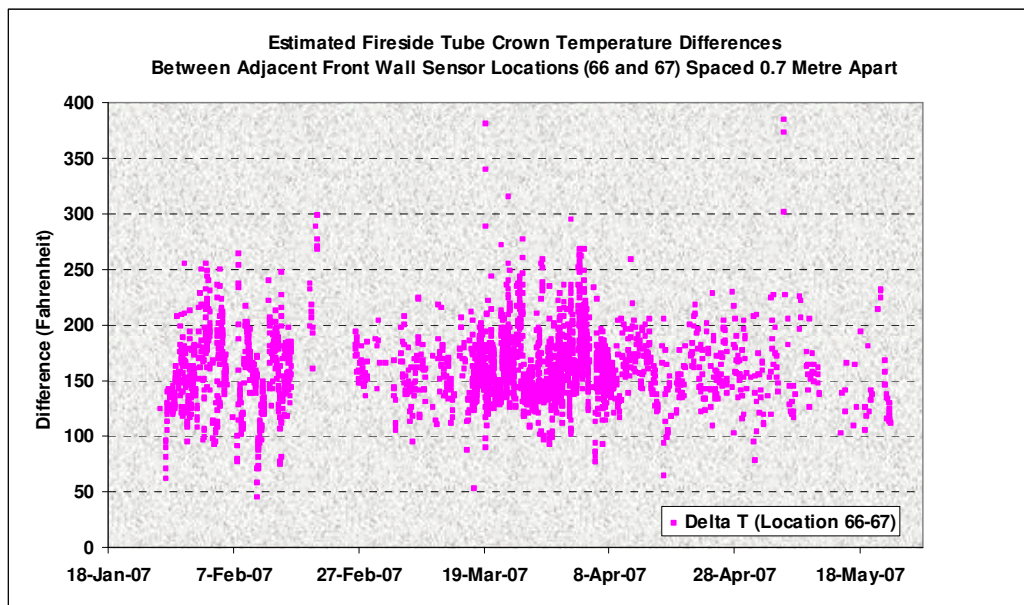


Figure 10: Example Fireside Tube Temperature Differences between Adjacent Sensor Locations

Extremely localised and substantial temperature differences may also exist in the form of membrane-to-crown differences for the same tube. For example, slag deposits that accumulate in the sheltered recesses between tubes at the membrane (i.e. the 'fins' between tubes that are welded to form a continuous tube wall), sheltering the membranes from more 'aggressive' temperatures, whilst more exposed tube crowns experience much higher temperatures.

Independent modelling of possible damage mechanisms that might result in tube wall cracking has shown that some of the characteristics of the thermal behaviour of the tube walls at Brunner Island are indeed capable of initiating cracking.

10. Discussion and Conclusions

The scanner technology has a proven record of monitoring boiler wall fireside corrosion using electrical resistance techniques. Work is still on-going to prove/demonstrate the technique's viability in monitoring circumferential cracking of fireside boiler tube walls. Changes in measured resistance values as a consequence of surface cracking are considerably smaller than those from surface thinning corrosion. The fundamental physics shows that for both corrosion and cracking, changes in measured values accelerate as they both progress and so detection and quantification becomes easier.

For this EPRI project, clues that help establish the root causes of the cracking are fundamental aims so that steps can be taken to minimise or even eliminate it completely. The scanner's data has provided a clear insight into the boiler wall thermal behaviour at Brunner Island and provided evidence of high and dynamic fireside surface temperatures attributable to a variety of phenomena such as natural and forced slag removal.

Following the findings of the research project, operational changes to tackle the cracking problem on Unit 3 have included use of the scanner's thermal data to help provide more careful control of the operating parameters. These seem to be having the desired effect, outages due to tube leaks have dropped dramatically over the last 12-18 months as a result.

11. References

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