

Crack growth monitoring on industrial plant using established electrical resistance 'Scanner' technology

D.M. Farrell and B.J. Robbins
Rowan Technologies Ltd
216 Church Road, Urmston, Manchester, UK.
Tel: (44) 161 748 3644, E-mail: mail@rowantechnologies.co.uk

J. Stallings, S. Cardoso and W. Bakker
Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, CA, USA

Abstract

DC electrical resistance techniques (potential drop methods) are well-established methods for detecting both corrosion and crack growth during laboratory-based experiments. However, application of the techniques to large industrial plant has, to date, been somewhat limited.

Rowan Technologies has, over the past nine years, been developing and refining its scanner technology to monitor corrosion/erosion, thermal parameters and more recently crack initiation and propagation on an EPRI-sponsored project. Crack monitoring is achieved by welding matrices of electrodes to the external (air-side) metal surfaces, from which a number of high-precision measurements are made to detect and quantify changes in electrical resistance associated with crack growth.

Extensive laboratory-based work preceded a full-scale trial of the scanner on an 830MW supercritical boiler in the USA, where circumferential cracking of weld overlaid boiler tubes is of major concern. This paper discusses the background to the technique, reports on the laboratory-based results of simulated crack growth and also gives initial results from the boiler trial.

Introduction

Rowan Technologies developed corrosion probes in the early 1990s to detect and monitor corrosion in high-temperature boilers and industrial plant. Electrical resistance techniques were used to detect loss-in-thickness (corrosion or erosion) of exposed elements on the surface of probes. Probe temperatures could be controlled using compressed air to simulate the temperatures experienced by heat transfer surfaces, such as furnace tubes in boilers. These worked well but only gave a reading at the particular point where they were inserted; corrosion is frequently highly variable in industrial plant and locations only one metre apart may see vastly different rates of attack.

In the late 1990s corrosion scanners were developed by Rowan Technologies, primarily for use on heat transfer surfaces on boilers, although they are equally applicable for any surface subject to degradation. These corrosion scanners are able to directly monitor fireside corrosion, erosion and now cracking over large areas of furnace walls and whilst the boiler is operational. The output is in the form of 2-dimensional maps of the surfaces^(1,2). The scanner systems overcome the requirement

for intrusive (and cooled) insert probes to be used; the plant walls themselves take over the role of the probes.

Scanner Technology Principles

The scanner system's measurement technique is based on the well-established electrical resistance principle, where thinning of a metal increases its measured electrical resistance. A number of companies have developed so-called corrosion scanners, but these are mainly based on the premise of a single current input and output to the test area and many tens or hundreds of voltage connections in between; the potential difference being directly proportional to the resistance using Ohm's law. The current is applied and all potential differences are measured within a short period of time to enable resistances to be calculated. This method assumes that the flow of current around the test area is constant. Rowan initially investigated this method in the laboratory using test plates which were subject to corrosion, but found that the results were non-quantifiable. Areas subject to corrosion also increased in electrical resistance and this resulted in some of the current now by-passing the corroded area; this resulted in lower measured potential differences and therefore lower calculated resistances. The problem was found to be far worse where variable temperature differences were encountered (as in boilers); these also affected the electrical resistances and resulted in further errors.

Rowan concluded that current was required between each and every one of the voltage connections to build up an accurate assessment of the remaining thickness of the wall. As the electrical resistance is temperature dependent, metal temperature is also accurately measured as part of the scan process using the same electrodes, and the individual resistances compensated accordingly. The sensing electrodes used by the scanner systems are directly attached (welded) to the external boiler wall and, during the resistance measurement cycle, current is passed directly through the tube wall. The system detects small increases in resistance (measured in micro-ohms) as the tube wall thins. By installing a matrix of sensor locations, measurements can be made between adjacent sensors to build up complete maps of corrosion behaviour over large areas of boiler wall, Figure 1. Maps can be presented in a variety of formats: corrosion rate, metal loss, remaining thickness and remaining life. Systems are now available in two forms: fixed systems for continuous monitoring and portable systems for periodic monitoring of corrosion activity at different locations, for example, in chemical and refinery sites.

Crack Propagation within Supercritical Boilers

The development of cracks within boiler tubing can be a major issue which may result in frequent plant shutdowns and internal inspections. Supercritical power generation boilers, which are high efficiency and high output units, can be particularly susceptible to this problem:

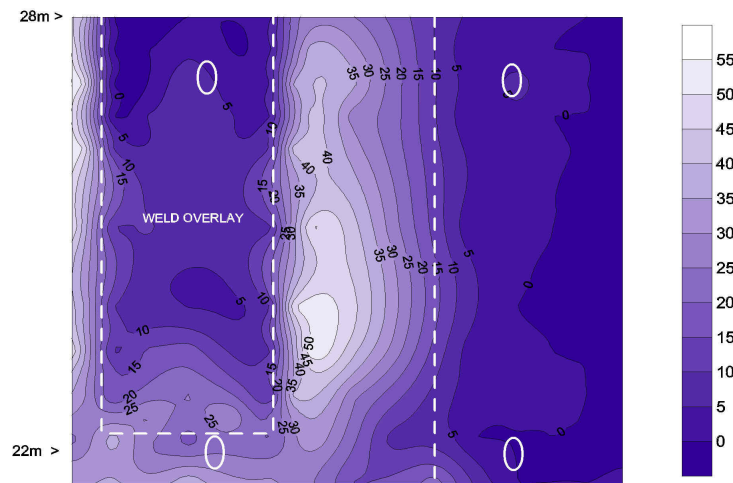


Figure 1: Typical corrosion rate map (measured in nm/hr) of a boiler wall showing excessive corrosion of the bare steel tube but minimal corrosion of the Inconel 625 weld overlay

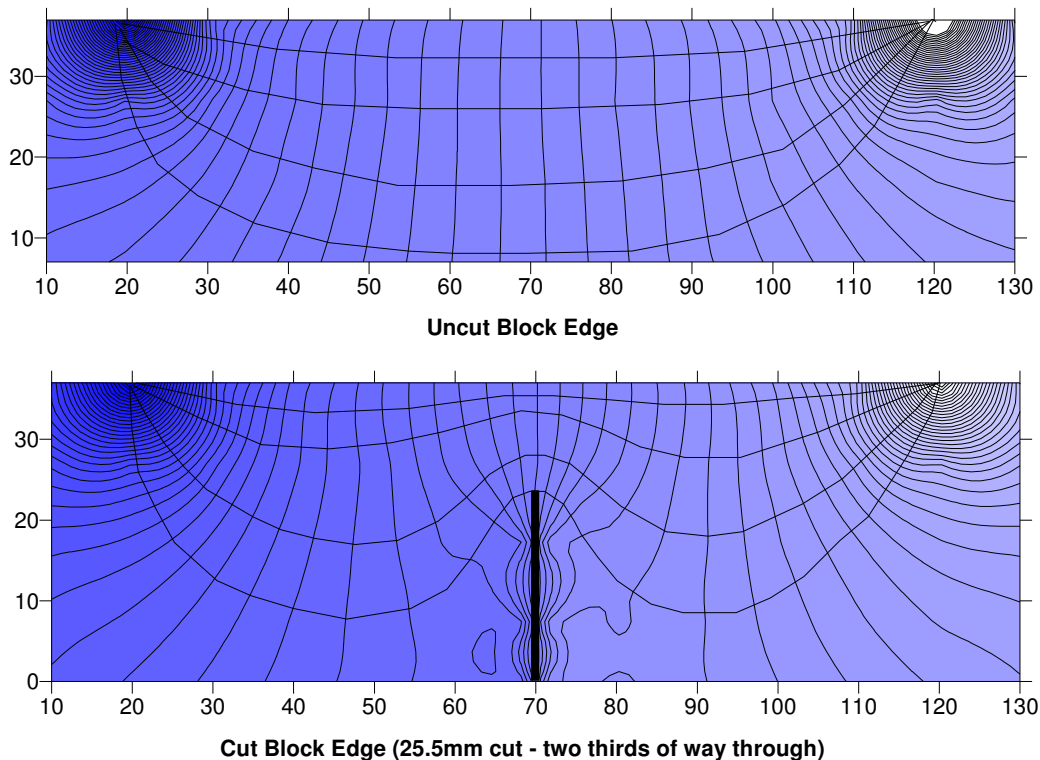
Due to a number of changes that have been made to accommodate environmental concerns, including low NO_x burners and over-fired air (OFA) systems, many of these supercritical units are now finding circumferential cracking of their weld overlaid boiler tubes in the furnace zone. The Electric Power Research Institute (EPRI) instigated a Program on Technology Innovation to find ways of detecting and measuring the cracking and to investigate the reasons for it. Rowan Technologies was asked to increase the sensitivity of its scanner technology to detect and quantify the cracking, carry out a modelling study using finite element analysis and then to use the improved scanner technology on a boiler subject to cracking. The plant selected for the site trial was a super-critical coal-fired boiler operated by Pennsylvania Power and Light in the USA; circumferential cracking of weld-overlaid tubes is an ongoing problem in this boiler, Figure 2.



Figure 2: Image of circumferential cracking on boiler tubes

Modelling Study and Laboratory Simulation of Crack Growth

A simple laboratory-based demonstration of the influence of a 25.5mm deep crack which affected the flow of current through a 38mm thick block of steel is shown in Figure 3. The current density is seen to be highest around the crack tip where the potential gradient is at its highest. A graph of the increase in electrical resistance as a function of the crack depth is shown in Figure 4. Note – as the crack deepens the increase in resistance accelerates and approaches infinity when it is almost through. As the crack gets deeper then its rate of propagation becomes easier to quantify.



Notes
Current Travels Perpendicular to Field Lines
Current Density Proportional to Field Line Separation

Figure 3: Measured field lines – with and without crack

The above demonstration is not representative of what may be experienced in-plant. The test block had bound edges and the crack was cut to dissect its length. In plant, walls and pipes may be boundless and the cracks may only occur on part of the exposed surface. For boiler walls, the cracks are mainly found on the fireside crown; the rest of the tube, membrane and also the back (non-exposed) of the tube are not affected - current continues to flow through these areas as normal.

A finite element (FE) program (supplied by ANSYS Inc.) was used to determine how electrical current flows around cracks in a 2-D model. Prior to cracking the original model shows how current would be expected to flow, Figure 5a. The lines on the model show lines of constant potential; the lines of constant current flow at right angles to the lines shown. The current spreads out quickly and becomes linear for the length of the model. A FE model that simulates a single crack is shown in Figure 5b. It can be seen that current flows through the top section of the model that has not been

cracked, the area around the base of the crack becomes redundant as far as current flow is concerned. The flow of current around two cracks is modelled in Figure 5c. This shows that most of the base area between cracks now becomes redundant and that multiple cracks start to behave in a similar way to general wastage as far as electrical resistance is concerned.

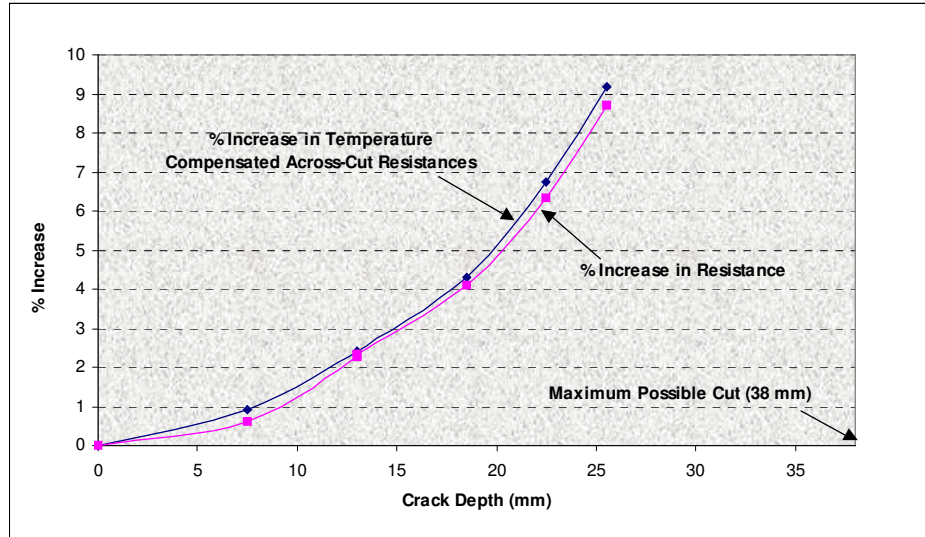


Figure 4: Typical increase in electrical resistance with increasing depth of crack for a 38mm thick steel wall

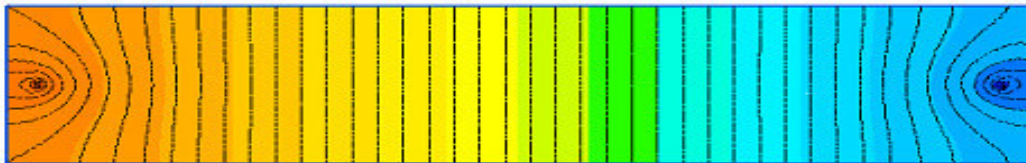


Figure 5a: No cracks

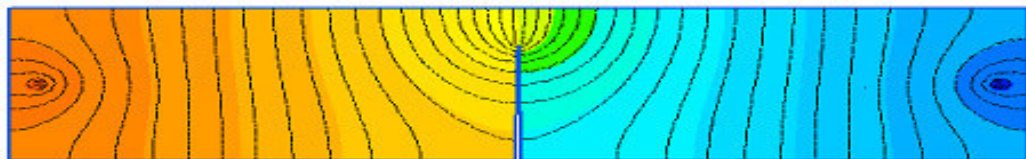


Figure 5b: Single crack

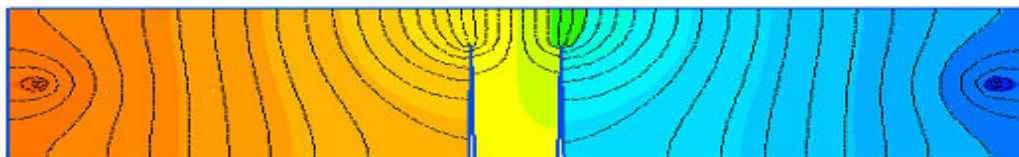


Figure 5c: Two cracks

The model was extended to 3-dimensions and sections of Inconel 625 weld-overlaid boiler tubing were obtained to carryout comparative laboratory simulations. Artificial cracks were cut into the weld overlay tubes at differing depths (ranging from 0.125mm to 1.5mm using a small diamond wheel to simulate those found on boiler tubes, Figure 6. The close relationship between the results from the model and the laboratory simulation tests is shown in Figure 7.



Figure 6: Example of artificial cracks cut into the weld overlay. Note – the cracks were shaped as penny slots (deeper in the middle) to simulate real cracks

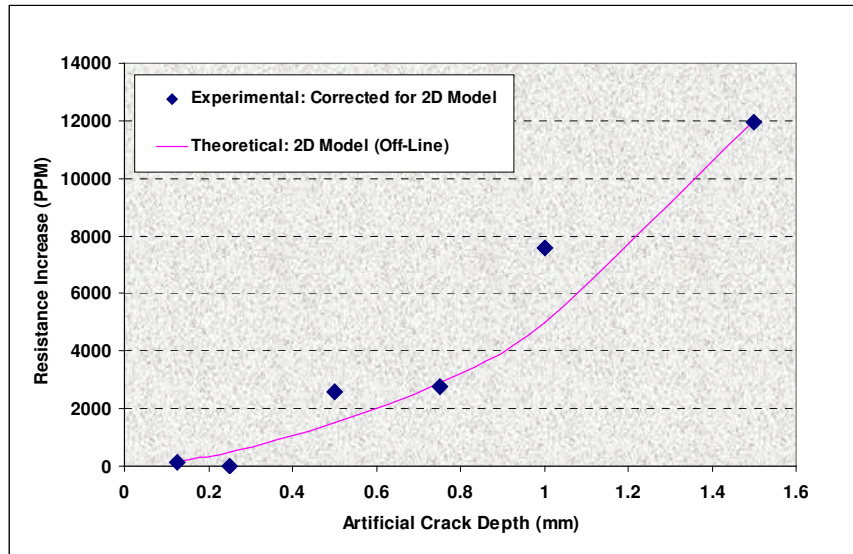


Figure 7: A graph of increase in electrical resistance with crack depth at a crack spacing of 8 per inch

Finally, 3-dimensional models were developed which related different crack depth and crack spacing to the increase in electrical resistance. A typical ‘time to detection’ graph for circumferential cracking on boiler tubes at various crack depths and 8 cracks/inch is shown in Figure 8. The sensitivity of the combined scanner and electrode arrangement was known, both for on-line and off-line assessment. Although the electronics used in the scanner are sensitive to 200ppm (when combined with the welded electrodes and without unmeasurable temperature variation), when the boiler is on-line this increases to 2000ppm. Using off-line data (which minimises temperature effects) the sensitivity is around 500ppm. For a 0.5mm deep crack this

would take around 130 weeks to reliably quantify for the on-line data and around 48 weeks for off-line data.

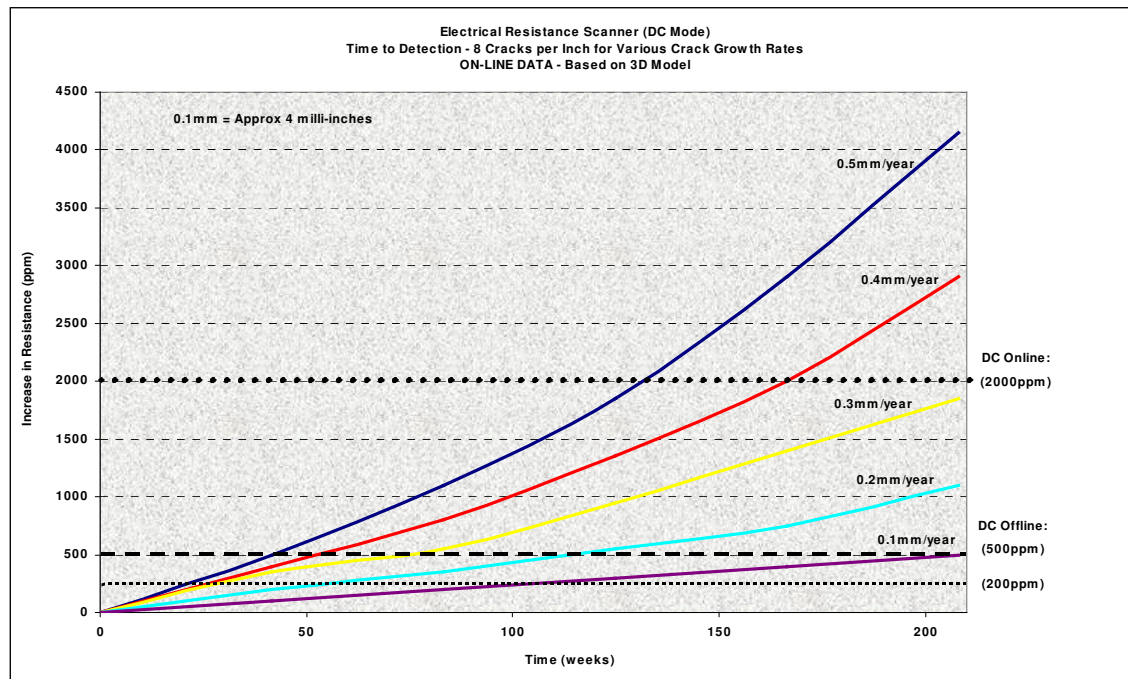


Figure 8: Time to detection for crack growth for a boiler when on-line with a DC system. Note – resistance increases have been reduced by a factor of 4 to account for the crack length being only a quarter way around the fireside segment

Circumferential Crack Monitoring in a Supercritical Boiler

Rowan Technologies and EPRI subsequently initiated a monitoring project to investigate circumferential cracking on bare and weld-overlaid boiler tubes on a supercritical boiler at the Brunner Island Power Station. The work involved the design and installation of a scanner system to monitor two large areas on both the front and right walls of the boiler. The work included an ongoing analysis of the data to investigate both the occurrence of cracking and also its possible causes.

During the resistance measurement cycle, current is first passed vertically through the tube wall and then passed horizontally through the same area of wall. The principle here is that the vertical flow of current 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 flow of current which runs parallel to any cracks.

The first type of analysis involved temperature compensating the individual resistances. The second type of analysis used the ratio of the two measurements to provide a useful indicator of crack propagation through the tube wall. This second method overcomes the requirement to temperature compensate the individual resistance readings. This latter system worked well in the laboratory, but on-site significant differences in temperature, and variation in these differences, were

experienced between adjacent electrodes. The first method was subsequently used for the on-site work.

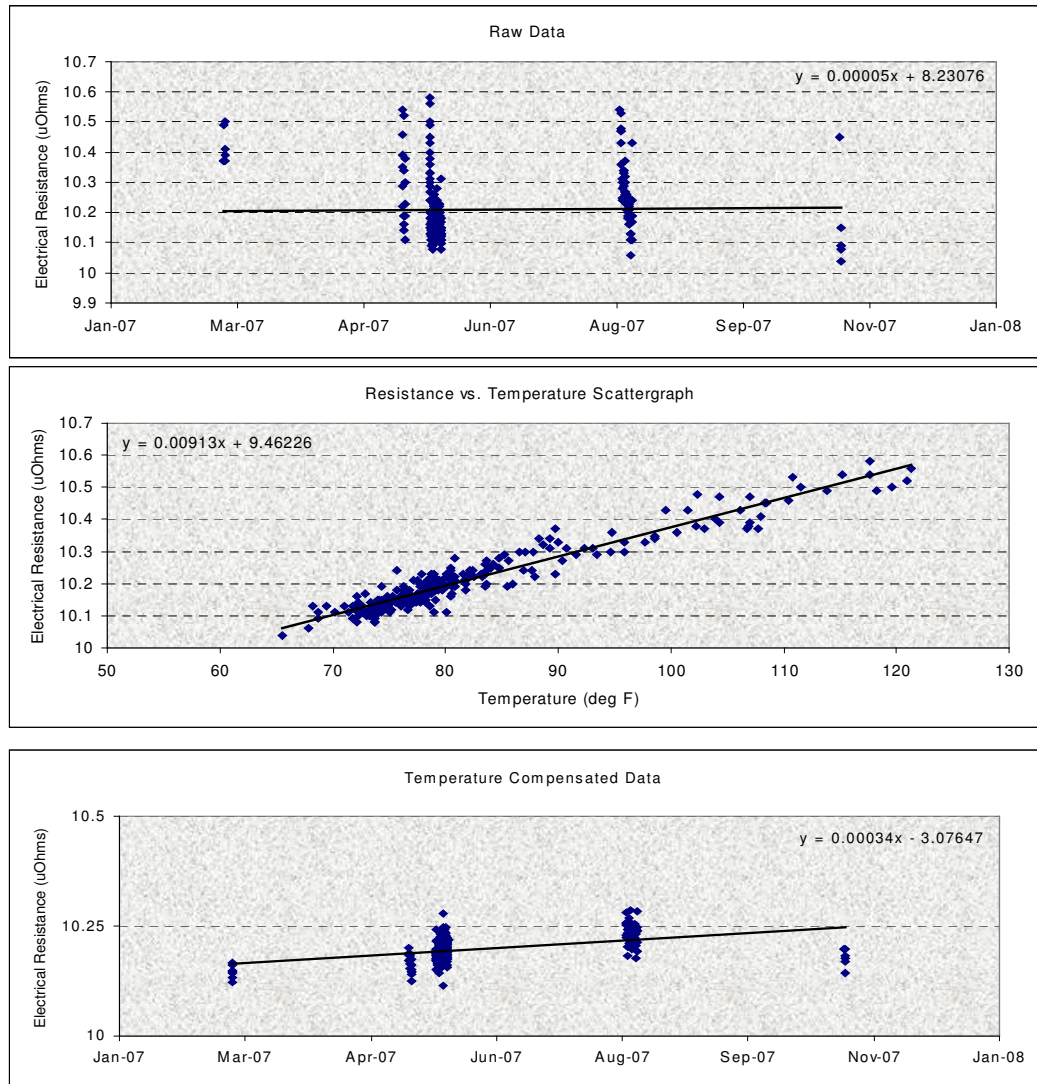


Figure 9: Typical analysis of electrical resistance data – the raw data is temperature compensated to produce the real electrical resistance

The system was commissioned in January 2007 and the results to December 2007 indicate that a few areas of the walls may be subject to crack initiation and growth. The most consistent data was for the off-line periods and using individually temperature compensated data. An example of the off-line electrical resistance data is shown in Figure 9. The raw data (without temperature compensation) is shown in the top trace. The data (resistance vs. temperature) is next plotted to produce a 'scattergraph'; the gradient of which is the temperature coefficient of resistance for the particular alloy (or in this case weld-overlaid construction) in this temperature range. This method is preferable to determining the constant from laboratory work as it also takes into account the geometry and other factors (such as the weld overlaid construction), which will contribute to variations in electrical resistance. This coefficient is then used to temperature compensate the raw resistance data. The temperature compensated data showed a small increase in electrical resistance which

may be associated with crack growth. An example 2D map of the test area on the front wall, giving the change in electrical resistance, is shown in Figure 10. From the initial laboratory-based simulation of circumferential cracking⁽³⁾ and using a density of 16 cracks/inch, this equates to a maximum depth (on the right side of the test area) of between 0.25 to 0.5mm (9 to 18 milli-inches) on the fireside crown of the weld-overlaid tubes. This is close to the detection limit of the scanner. Further monitoring is currently being carried out to quantify the rate of crack growth on this boiler.

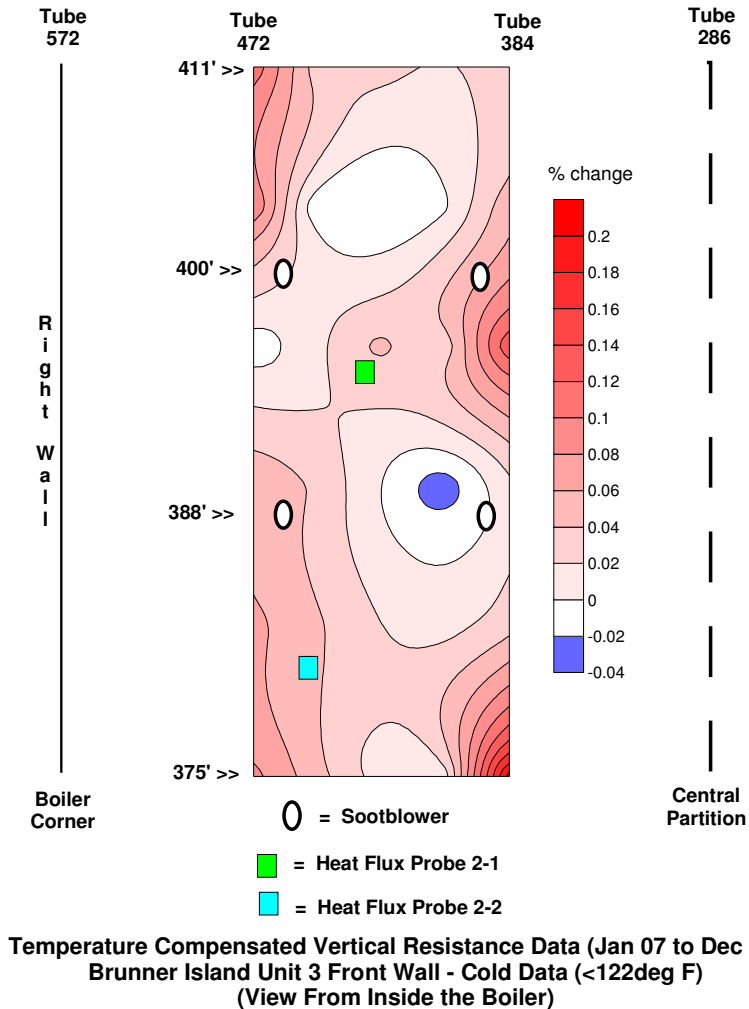


Figure 10: Temperature compensated vertical resistance data

Typical thermal data from the scanner (at one location only) is shown in Figure 11. This shows four thermal spikes relating to the fireside temperature of the tube, two of which correlate with increases in boiler load and two of which occur at full load. A 2D map of the front wall test area during one of these thermal spikes is shown in Figure 12. This shows the highest membrane temperatures around the middle of the test area. These thermal events, which will contribute towards the stress resulting in fatigue cracking are occurring on the fireside and are due to operational factors, such as slag shedding, flame impingement or increased radiation from the fireball⁽⁴⁾.

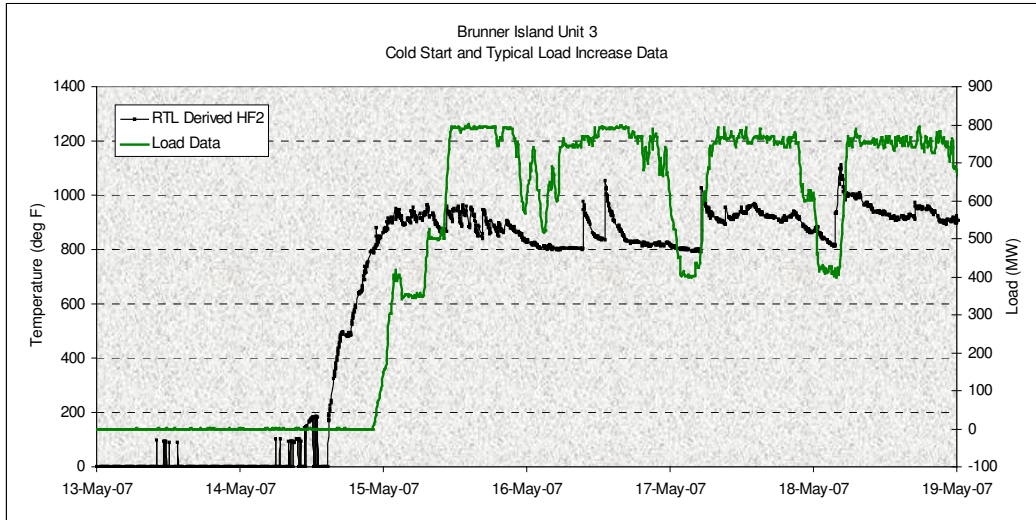


Figure 11: Thermal data from Brunner Island Unit 3, front wall

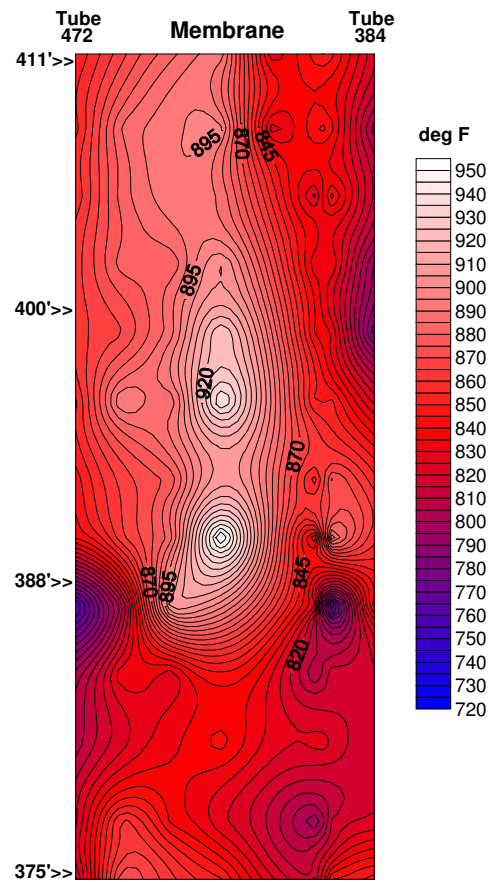


Figure 12: 2D thermal map of Brunner Island Unit 3, front wall after start of second thermal event

Discussion

Supercritical boilers are high-efficiency and high output units, which fire pulverised fuel to heat the cooling medium (supercritical fluid) in the furnace tubes. The critical point for water is 3200psia and at temperatures above 374°C (705°F) the cooling medium exists as a supercritical fluid, where the properties of the gaseous and liquid phases become similar. However, due to the boiler's design and operation they are more prone to high fireside metal temperatures than subcritical drum boilers. This may result from either, the cooling medium flow becoming unstable (resulting in under-cooling) and/or slag falls or excessive radiation incident on the tube walls (resulting in over-heating). Some of these problems have reportedly been overcome by the use of internally ribbed tubes, sliding pressure operation and more lately, spiral type waterwalls. However, many supercritical boilers are still suffering thermally-related problems on the furnace walls.

Expansion and contraction of the furnace walls during these overheating events can result in excessive stresses leading to fatigue. The problem may be compounded where the overheating is highly localised to one, or a low number, of tubes and the adjacent tubes are restricting the normally elastic strain. The use of weld overlay on the tubes may exacerbate the problem as there is invariably a difference in expansion coefficients between the parent and weld overlay, as well as possible weld-related residual stresses.

The largest temperature variation on the walls occurs during a hot or cold start. Unit 3 at Brunner Island is a base-load boiler and only seven shutdowns were experienced during 2007. However, thermal spikes (or events) on the fireside walls, at already high operating temperatures, are also highly damaging for the fireside walls. These may result in the fireside tube wall passing its elastic limit and being subject to plastic strain. Repeated thermal events, resulting in high fireside temperatures may thus result in fatigue cracks initiating on the fireside walls, and in particular when weld overlay is employed, as the fireside temperatures are increased.

Most of the circumferential cracking has been observed in the 'corrosive' areas between the burners and the OFA and sulphur has been detected in the blunt-tipped fatigue cracks of failed tubes. Corrosion fatigue (a combination of corrosion and stress) can occur at lower levels of stress than fatigue alone. It is documented that corrosion fatigue can occur in hot gases where hydrogen sulphide is prevalent: as expected in the reducing environment prior to the OFA. It is therefore probably that corrosion may be contributing to the fatigue mechanism.

The initial data from the scanner appears to be identifying areas where crack initiation and growth may be occurring. This should become easier to detect as the cracks become deeper and more off-line data becomes available. The use of the corrosion scanner for detecting and quantifying crack initiation and growth in industrial plant is still in its infancy. The system has been fully proven in the laboratory where temperature variation is low. However, in boilers where the temperature variation is far higher, extended monitoring is required before quantifiable data can be obtained.

Conclusions

1. The electrical resistance technique has been proven for detecting cracks in laboratory and modelling tests. On site, if the location of cracks are known and the plant's future integrity needs to be monitored the scanner system may be used in combination with suitably-placed electrodes. If the presence of cracks is unknown, then a more extensive array of electrodes will be required to detect their presence.
2. The electrical resistance monitoring on the Brunner Island supercritical boiler has identified areas where crack initiation and growth may be occurring on the weld overlaid tubes. However, this cannot yet be fully confirmed as the data used to predict the crack growth spans a period of only nine months.
3. The boiler has been found to be subject to high temperature thermal events, which are contributing to cyclic stresses on the tube walls. These stresses are most probably contributing to the circumferential fatigue cracking on the fireside crowns.
4. Most of the cracking is occurring on weld overlay, which has been applied in the corrosive areas between the burners and the OFA. The application of weld overlay results in higher fireside crown temperatures but the indications are that the corrosive conditions also contribute to the cracking.
5. It has not yet been possible to identify the root cause of the thermal events, although some of them coincide with soot blowing and some of them coincide with load increases. All the indications from the thermal data indicate that these events are associated with operational conditions, such as increased fireside activity (flame impingement, increased radiation, slag shedding) as compared with decreased cooling activity in the tubes.

Acknowledgements

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