Current Understanding Of Cracking Of Recovery Boiler Primary Air Port Composite Tubes

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ABSTRACT

Co-extruded 304L stainless steel/SA210 carbon steel tubes have found widespread use in the floors and lower walls of black liquor recovery boilers. However, cracking has been found in the stainless steel layer of these tubes, and the cracks in the tubes that form primary air port openings have been found, in some cases, to advance into the carbon steel portion of the tubes. This causes serious concern about the potential for a tube leak with the possibility of an ensuing boiler explosion. This research has been conducted so as to address possible ways to avoid this cracking: changes in operating procedures, use of alternate tube cladding materials, and modification of the air port design. Results have provided guidance on reducing the likelihood of tube cracking through selection of materials and air port design and operational changes.

INTRODUCTION AND BACKGROUND

There are approximately 160 paper mills in North America that operate on a chemical pulping process that require recovery of the pulping chemicals in order to be able to operate economically and satisfy environmental requirements. Many of these mills have more than one recovery boiler, so that there are about 250 boilers in operation. Many of these are older, lower pressure boilers built with carbon steel tubes. Because of the corrosion problems associated with higher temperature (more efficient) operation, the newer, higher pressure boilers almost always are constructed with 304L stainless steel (SS) clad carbon steel (CS) co-extruded (composite) wall tubes in the lower sections of the boiler. The composite tubes provide corrosion resistance in the higher temperature environment that was lacking in the carbon steel tubes and, from this perspective, the switch to composite tubes provided a major advancement for the paper industry [1]. Unfortunately, serious issues developed because of cracking of the outer, stainless steel layer [2,3,4,5]. To address these concerns, the U.S. Department of Energy initiated a project to determine the cause of cracking in recovery boiler composite floor tubes and to identify means to prevent further cracking of these tubes. This project was carried out by researchers at Oak Ridge National Laboratory, the Pulp and Paper Research Institute of Canada and the Institute of Paper Science and Technology. The research team has presented annual updates at the TAPPI Engineering Conferences [6,7,8,9], and additional presentations have been made at a number of international conferences [10,11,12,13]. The paper presented at the 2000 TAPPI Engineering Conference summarized the floor tube research and presented the team's best understanding of the cause of the cracking as well as recommendations on materials and operating procedures to minimize or eliminate further cracking [14].

Before the conclusion of the floor tube study, mills began reporting instances of cracking in the composite tubes that form the primary air ports on the recovery boiler side walls. This cracking was of even greater concern to boiler owners and operators because the cracks in these tubes sometimes advanced rapidly through the stainless steel and into the carbon steel portion of the tubes. In order to address this new aspect of composite tube cracking, some of the project resources were directed toward the air port tube problem. At the conclusion of the floor tube study, the research emphasis was directed totally toward the primary air port tube cracking problem. The national laboratory and the two paper institutes continued their involvement in the research, and a subcontract was placed with Process Simulations Limited to conduct recovery boiler modeling studies. This research is directed toward identifying alternate materials, air port design modifications, and process changes that appear to lessen the likelihood of cracking [15,16,17,18,19]. Other publications have addressed air port design and materials [20] and process changes [21]. However, the cracking mechanism has not been identified, and further work is underway to confirm the validity of the alternatives that appear to be beneficial. The current understanding of this problem reached by this team is presented in this paper.

CHARACTERISTICS OF CRACKING

As yet, insufficient information about the cause of cracking exists to be able to predict accurately whether any given boiler is susceptible to cracking of the composite tubes that form the primary air port openings. Cracks in these tubes have now been reported in boilers made by nearly all major manufacturers, incorporating a variety of air port opening designs. Based on careful inspection of numerous boilers by members of the research team, and reports of cracking from many other sources, there does appear to be a wide difference in susceptibility to cracking between boilers of different manufacture, and between different designs of air port opening. However, it can also be said that, even for the combination of boiler manufacture and air port design thought to be most susceptible, cracking of the primary air port opening tubes has not been reported in the majority of all such boilers. Cracking of composite tubes at air port openings has been more common, but not exclusive, to boilers made with walls of 63.5 mm (2.5 inch) diameter tubes on 76 mm (3 inch) centers.

A difficulty that has hindered accurate reporting of cracking in composite tubes in general is that of properly preparing the tubes for inspection (typically for penetrant testing or PT). Without adequate surface preparation, there is a high likelihood that cracks will not be discovered in the tubes during inspection [22,23].

When cracks are discovered, they have been found almost exclusively below the mid-point of the primary air port opening. Rarely, cracks have been discovered in the bends that form the upper half of the opening. Dye penetrant inspections are sometimes conducted on the tubes that form secondary port openings, but it has been noted that these inspections are often even less thorough than those conducted around the primary air ports. Occasionally, cracking is found in the area of the lower membrane termination welds of the secondary air ports, but cracking on the tubes is extremely unusual.

Cracks are seen in several different forms. The most widely recognized are the circumferential, relatively linear cracks and the randomly-oriented, craze or mosaic cracking. In addition, in some air port designs, it is not uncommon to see cracking in the membrane near the terminations and in the membrane to tube welds again in the area of the membrane terminations. Examples of these types of cracking are shown in Fig. 1. The depth of primary air port tube cracks has been investigated during field inspections as well as during laboratory examination of air ports removed from service. Microscopic examination consistently finds that craze cracks do not progress into the carbon steel of the composite tubes, but the circumferential cracks sometimes do continue into the carbon steel. Figure 2 pictures cross sections of circumferential cracks that continue into the carbon steel. Even though not all circumferential cracks continue into the carbon steel, inspection of the tube surface does not provide sufficient information to unequivocally predict the depth of circumferential cracks. Therefore, all of the relatively linear cracks have to be treated as if they advance into the carbon steel. For most mills, this means a grinder is used to remove some of the stainless steel in order to "chase" the crack to the point where it can no longer be detected by means of a dye penetrant examination. Depending on the depth of cracks and the repair philosophy used at each mill, a weld repair may be used to build up the carbon steel and/or to provide a stainless steel cap.

TECHNICAL APPROACH

There are several potential ways to investigate this cracking problem, but, since the best approach was not obvious, a multitask approach is being used. In order to have confidence in any recommendation for preventing primary air port tube cracking, it is essential to identify the cracking mechanism. Consequently, some of the efforts have been directed toward that task. The remaining research effort has been directed toward possible means to avoid this cracking including a switch to a more crack-resistant alloy for the outer layer of the tubes, changing operating conditions so that the environment that causes the cracking cannot develop, and implementing a different design and/or fabrication method for the air ports so that the conditions that promote cracking don't exist. The studies associated with each of these tasks are described in this paper.

TEMPERATURE STUDIES

Much of what has been accomplished in this study of primary air port cracking can be associated with the information collected from thermocouples that have been mounted on air port tubes in a number of recovery boilers in North American mills. The first installations of primary air port thermocouples were made in the fall of 1999, and a total of nine boilers have been studied in the temperature monitoring project. These studies have clearly established that significant variations occur in the temperature of the tubes at the bottom of the primary air ports. More importantly, the most severe temperature fluctuations were seen on tubes known to have a history of cracking. Some information about the nine instrumented boilers is listed in Table 1.

One of the first examples of this association between temperature fluctuations and cracking that was identified in this project is shown in Fig. 3. This figure reveals a clear pattern; the frequency and magnitude of the fluctuations are larger on the air port tubes that had previously experienced cracking. This pattern has been observed in all the instrumented boilers in which cracking of the primary air port tubes has been observed. Consequently, the magnitude of temperature fluctuations has been, and is being used as a means to determine if conditions exist where cracking of the tubes is likely to occur.

Thermocouples installed at the bends in the upper half of the primary air port openings, and along straight tubes adjacent to the tubes that form the air port opening, confirm that frequent, large temperature fluctuations are much less common, relative to those that occur on the lower half of the openings. Recently, thermocouples were installed on the tubes of four secondary air ports in a boiler that has previously experienced extensive primary air port cracking. With the exception for one day (on one thermocouple), these secondary air ports have not experienced significant temperature fluctuations over more than two months of data collection to the time of writing of this paper. A typical example of the temperature patterns seen for the four thermocouples during one day are shown in Fig. 4.

The tips of the surface-mounted thermocouples used in these studies are tightly held under a thin stainless steel pad welded to the tube surface. Tests that simulate boiler conditions have been conducted to confirm that thermocouples installed in this way were accurately reflecting conditions on the surface of the air port tubes. A tube section was built that contained a thermocouple mounted in a manner very similar to the chordal thermocouples currently used in recovery boilers as well as two of the surface mounted thermocouples attached to the tube on either side of the chordal-type thermocouple. The tube section was then heated rapidly to levels typical of the temperature spikes measured on recovery boiler tubes and the temperatures measured by the three thermocouples compared. Although there was not exact agreement in the measured temperatures, the values were close enough to conclude the surface mounted thermocouples reach temperatures representative of those measured with the chordal-type thermocouple.

Further attempts to characterize the temperature fluctuations included a study conducted with representatives of a North American boiler manufacturer. The results of this collaboration provided suitable mathematical characterization techniques to determine the frequency of temperature fluctuations and the amount of time the tube surface temperature was well above the temperature of the pressurized water flowing through the tubes [24]. The parameters defined as a result of this study are identified as cycles and excursions. A cycle is defined as a temperature increase of at least 75C° from the previous minimum temperature followed by a decrease of at least the same magnitude from the previous maximum temperature. The choice of this particular temperature change was based on finite element modeling studies showing 75C° is the temperature change required to take the 304L stainless steel layer on a composite tube from the yield state in compression to the yield state in tension. An excursion is defined as a data point for which the temperature is at least 450°C. Since data points are collected every ten seconds, six excursion data points would be interpreted as representing operation at a temperature of at least 450°C for an accumulated time of one minute. Selection of the 450°C temperature was based on many observations of instrumented air port tubes. Thorough documentation of each boiler showed that instrumented ports that were cracked experienced significant periods where the temperature was above 450°C. Consequently, that temperature was selected as the lower limit for the definition of excursions.

An example of how the cycle count can be used to compare results of the temperature measurements for an extended period of time is shown in Fig. 5. The data shown in the figure indicate the cumulative number of cycles measured each month for the air ports being monitored in recovery boiler “J” listed in Table 1. This representation of the data makes it clear conditions in this boiler changed throughout the year; many more temperature cycles occurred during the months of May and June than had been observed during prior months. During the month of May when the activity was the greatest, the sum of the cycles for the two thermocouples on air port LH2 was about 3,000.

Because possible cracking mechanisms require a significant number of thermal cycles to initiate cracks, the number of cycles was determined for several instrumented air ports that had cracked tubes in an extensively cracked boiler. The air ports selected were among the most active, if not the most active, of the air ports being monitored. For a six month period from fall 1999 through spring 2000, the maximum number of cycles measured for any of the thermocouples installed on the primary air port tubes was about 3,150. Previous studies of fatigue data showed that over 100,000 cycles would be required to reach the fatigue design limit for 304L stainless steel, and considerably more cycles would be required to cause cracking by a thermal fatigue mechanism [7,9,10]. Based on these measurements, it would not appear the tubes experience sufficient thermal cycles to attribute the cracking to thermal fatigue. In addition, the morphology of the cracks is generally not consistent with the pattern expected for thermal fatigue.

CAUSE OF TEMPERATURE FLUCTUATIONS

The association of the most severe temperature fluctuations with primary air ports whose tubes experience cracking raises the obvious question as to what causes the rapid changes in the temperature. Several studies have been conducted to obtain information to help determine the cause of the changes.

Effect of Boiler Operating Parameters

As described in previous papers [15,16,21], a number of mills have made changes in liquor firing properties including temperature and solids content, and definite changes in air port temperatures have been observed. For example, when the black liquor temperature was increased so that it was nearer the flash point as it left the liquor nozzle, the extent of temperature fluctuations generally decreased. More extensive studies have been conducted in which many operating parameters have been systematically varied over a period of 7-10 days. This work is described in greater detail in the section addressing the effect of operating parameter changes on tube cracking.

Video Imaging of Primary Air Port Tubes

The use of temperature patterns to monitor changes in the air port environment is now being complemented by video imaging. Team members have developed a cooled camera that is specially designed to be inserted through a primary air port into the boiler. Once in the boiler, the camera can be directed toward the surface of the air port tubes to observe what is occurring on the surface of the tubes. This camera has been used, along with the thermocouples, in an effort to determine what might be happening, physically and/or chemically, to cause the temperature changes. These studies have shown a thin coating of condensed and frozen material is always present on the fireside of the wall tubes and membranes. Molten salt frequently flows over the coated tube and membrane surfaces, and under some conditions, significant amounts flow across areas of the tubes where cracking has been observed. The camera studies have also shown rapidly varying deposition rates of black liquor char particles on the tubes at the bottom of the primary air ports. However, none of these conditions have been shown, by themselves, to consistently be the source of high temperature fluctuations on the thermocouples. A more extensive description of this research effort is given in another paper in this session [25]. This information has also been used in modeling studies to identify possible mechanisms for localized heating.

Modeling of Local Heating

A three-dimensional finite element model was used to predict the temperature variations that might occur on a primary air port composite tube subjected to localized changes in the heat flux. In keeping with the observations from the camera work, two sources of heat release at the fireside surface of the tube were considered – combustion of black liquor droplets and oxidation of Na_2S from the smelt layer.

For both cases, the model used the assumptions that the inside surface of the tube was in contact with water at 295°C and the increase in heat flux was assumed to occur over a 2 x 2 element area on the lower portion of the bent tube, as shown in Fig. 6. The area of localized heating is approximately 375 mm^2 (0.6 in^2). Furthermore, it was assumed all of the heat generated by the combustion is directly felt by the tube surface, whereas in practice the tube fireside surface is nearly always covered by a thin layer of frozen smelt – which has been documented by the video camera.

For the case of heat release from the combustion of black liquor droplets on the tube surface, the contributions from the volatile combustion and the char burning stages were considered. It was assumed the total heat generated can be approximated by a heat flux profile which increases linearly over a fairly short period of time (1.5-2.5 s), before decreasing more gradually to the initial value. It was also assumed that the entire 2 x 2 element region of the tube surface was simultaneously under the influence of liquor droplets undergoing combustion.

The variation in temperature at the tube surface due to the increased heat flux from the combustion of liquor droplets is shown in Fig. 7 for three different droplet sizes. The smaller the droplet size, the higher is the peak heat flux and the temperature increase, and also the faster is the drop in temperature to its initial value. Since the heat flux is computed using an area measure based on the initial diameter of the droplet, the smaller droplet leads to a greater heat flux. It should be noted the smaller droplet size causes a larger increase in temperature, but the duration is not very long.

The other source of heat for a localized increase in temperature considered in the analyses was the exothermic reaction of smelt oxidation, which converts Na_2S to Na_2SO_4. The maximum heat generation by the oxidation of a smelt layer on the tube surface is also estimated. It is assumed sufficient oxygen is available so all the Na_2S in the smelt is oxidized. In this case, the heat release was assumed to occur over a fixed period of 10 seconds, with a linear increase in heat flux over 3 seconds, followed by a linear decrease over the next 7 seconds. The heat flux increases with the thickness of the smelt layer as does the maximum temperature at the center of the heated region (Fig. 8). Similar to the previous case, all of the heat from the smelt oxidation is assumed to go into heating the tube surface.

The analyses described show smelt oxidation is capable of causing a fairly large increase in temperature, although it should be mentioned that the magnitudes shown are based on calculations with several simplifying assumptions. The possible insulation offered by the frozen smelt layer has not been included in the analyses, and this would lower the maximum temperature during the localized heating. Nevertheless, the modeling results show smelt oxidation can lead to a fairly high heat flux and significant increase in temperature, while the combustion of black liquor droplets leads to comparatively smaller temperature rise. Thermocouple data recorded at 10 second intervals show, in some instances, the tube surface experiences elevated temperatures for significant periods of time, whereas the temperature variations shown here last for less than a minute. These analyses only considered "single event" cases, and it may be important to consider sustained heat release due to smelt running down the tube surface or delivery of black liquor droplets to the tube surface over much longer periods of time.

ALTERNATE TUBE MATERIALS AND AIR PORT DESIGNS

Researchers from the original participating organizations have visited and continue to visit many mills during the annual (or semi-annual) shutdowns to observe the inspection of the air port tubes and to assess the condition of alternate materials being exposed in some boilers. In addition, comparisons are made between different air port designs currently being evaluated in some boilers. In some cases, selection of these alternate materials or air port designs is/was based on recommendations by the research team; in other instances, the boiler operators made changes without such input. The research team is carefully monitoring the extent of cracking and corrosion on certain air ports at each mill being monitored. These studies provide valuable information on the performance of alternate materials and air port designs.

The two alternate materials being given the most serious consideration are Sanicro 38 (modified alloy 825) and Unifuse (weld overlaid alloy 625). Until the most recent inspection, no instances of air port tube cracking had been encountered with either alloy. During a spring 2003 inspection, the cracking shown in Fig. 9 was found in weld overlaid alloy 625 tubes at the top of two primary air ports. These cracks had not advanced past the carbon steel interface, but in about six months the cracks are presumed to have gone from being nonexistent, or at least immeasurably small, to extending through the weld overlay. Some caution has to be used in comparing the performance of the various materials, because there is more experience in North America with the use of weld overlaid 625 tubing for recovery boiler walls than any of the other materials that are alternatives to 304L/carbon steel composite tubing. There are reports of chromized tubing being successfully used in primary air port service, but the authors have not personally inspected any of these applications.

Thinning and localized corrosion of primary air port tubes are another issue being addressed in evaluating the alternate materials. The authors examined one boiler where the modified alloy 825 tubing suffered severe localized corrosion at the top of primary air ports on the spout wall. Thinning of the tube along the edge of the air port casting has been observed on 625 weld overlaid tubing in two boilers. An example of this thinning has been shown in previous reports [15,16], and a more extensive description of material performance has been published [17].

Within North America, inspections have yet to discover cracks in the tubes forming the primary air port openings of 10 boilers from a single manufacturer, with a particular design of air port that incorporates a long, narrow opening (and, thus, less severe bends for the tubes that form the opening), when the openings were part of the original installation. The absence of reported cracking of air port tubes in these boilers is probably due to a combination of factors that includes the differences in design of the air port opening, as well as differences in air distribution and other operating parameters. Among the many observations being made relating to temperature fluctuations and tube cracking, the information shown in Fig. 10 is of special interest. The temperature measurements were taken from one of these boilers where the longer, narrower style of primary air port was installed in all locations as part of the original construction. Clearly, these variations are significantly less frequent and much smaller in magnitude than those shown in Fig. 3.

Although this particular combination of boiler and air port design has not been offered commercially for over a decade, the observation is extremely promising, in that it suggests that cracking might be minimized, or even prevented, by optimizing the design and operation of either, or both, the boiler and air port opening. Consequently, some of the modeling work being undertaken in this project is being directed toward identifying the most important differences between various boiler types and air port opening designs.

Each boiler manufacturer has its own particular design for primary air port openings, and some manufacturers have used several different designs [20]. However, there are common features among air ports used in most boilers constructed with 2½ inch diameter tubes on 3 inch centers. The air port opening is formed by bending two adjacent tubes behind the plane defined by the tubes forming the boiler wall. Some manufacturers use a sleeve or lining inserted into the air port while others use a removable casting. All of these are intended to provide some protection to the tubes from the rodders used to clean deposits from the air ports as well as perform some of the functions of a nozzle in guiding the incoming air. In one design, bending of the tubes forming the opening is usually done on a radius on the order of 12-15 cm. In this paper, these are described as the shorter, wider air port design. In contrast, the tubes forming the primary air port openings of the other major design are bent on a radius of 25-30 cm. In comparison, these ports are longer and narrower than those described above, and these openings are described as the longer, narrower opening.

From late 1999 onwards, trials of different air port designs and different composite tibe metallurgies have been conducted within a boiler that experienced severe, significant cracking of air port openings of the short, wide design. The measurements shown in Fig. 11 are taken from primary air ports produced by different boiler manufacturers but very similar to the longer, narrower design described above and installed on the same wall of the boiler. This boiler is of a different manufacture than those described above, with significantly different air distribution and flow patterns. Minor cracking has been observed in the long, narrow air port with the fluctuation pattern shown in Fig. 11a, but the severity of cracking (in terms of number and appearance of cracks) is less than seen on wider, shorter air ports in a comparable location. The air port represented in Fig. 11b has seen relatively limited service (1/2 year vs 3-1/2 years for the air port represented in Fig. 11a), but no cracking was observed in the inspection following the first six months of operation. These observations establish that changing only the air port design is not sufficient to stop cracking of the primary air port tubes. There is some indication that the cracking frequency may be reduced, but it is definitely not eliminated.

INFLUENCE OF RESIDUAL STRESSES ON TUBE CRACKING

In composite floor tubes, residual stress measurements have shown axial stresses are compressive in the carbon steel portion of the tubes [7,12]. The lack of propagation of cracks in floor tubes from the stainless steel layer into the carbon steel layer has been attributed in large part to the presence of this compressive stress. In contrast, residual stress measurements using x-ray and neutron diffraction have shown the axial stresses in the carbon steel component at the bottom of primary air ports are mostly compressive, but can be near neutral or even slightly tensile near the SS/CS interface [18,19]. Consequently, this barrier to crack propagation may not be present in tubes at the bottom of some primary air ports.

In an effort to understand how the compressive stresses might be changed, finite element modeling studies have been conducted for the situation where there is significant overheating of the air port composite tubes. This would be a situation where steam blanketing developed briefly inside the tube in the vicinity of the bottom of the air port. The results of these calculations are presented in Fig. 12 where the stress in the carbon steel at the interface of the carbon steel and the stainless steel is shown as a function of time and operating temperature for a normal cycle to operating temperature and for a cycle where the tube is briefly heated to about 600°C. For the normal cycle to operating temperature, the stresses in the carbon steel at the SS/CS interface remain compressive after cooling to room temperature. However, if a brief excursion to 600°C is imposed on the tube after it reaches operating temperature, the stresses in this location first become more compressive but then become tensile when the tube is cooled to the operating temperature and then back to room temperature. Obviously, in addition to an association with cracking in the vicinity of the bottom of the air port, the temperature fluctuations, if severe enough, can make the tube vulnerable to penetration of the crack into the carbon steel. Experience from years of monitoring temperatures on primary air port tubes on the nine boilers has shown the air port tubes that suffer from the cracking problem have occasional fluctuations that exceed 600°C; in fact, temperatures over 750°C have been recorded.

In view of this analysis, it is important to understand the cause of the temperature fluctuations and how this can be controlled without otherwise adversely affecting boiler operation. In addition, the residual stress state of tubes in the longer, narrower air ports needs to be measured to determine if the air port design can play a major role in preventing crack propagation into the carbon steel.

INFLUENCE OF OPERATIONAL CHANGES ON TUBE CRACKING

Determination of the effect of operational parameters on the cracking of primary air port tubes has been approached in two ways – field studies and mathematical modeling.

On several occasions during the past few years, team members from Paprican have worked with operators of a particular mill to systematically vary parameters of the fuel (black liquor) supply system and the combustion air delivery system. Monitoring of the pattern of temperature fluctuations during the time the operating parameters were being changed has made it possible to identify some conditions for which the magnitude of the fluctuations is significantly changed. Figure 13 illustrates the importance of the combined effect of both the air and liquor delivery system, as it shows thermal cycles versus time for a period before and after a number of major changes were made to the operation of the boiler. Temperature cycles and excursions were high during initial operation, but cycle frequency subsequently decreased significantly following the changes that were made to boiler operation. Through this period, a number of key operational variables were changed nearly simultaneously, and subsequent trials have focused on quantifying the relative influence of the most important changes.

A thorough study of this type, during which many parameters are systematically changed, can last for a week to ten days, so this type of testing requires a major commitment of staff time, as well as a willingness on the part of the boiler owner/operator to subject the boiler to what will likely be less than optimal conditions for short periods. Analysis of the data from the trials is still in progress, but operating conditions have now been established that limit temperature fluctuations at the air port openings, relative to initial operation of the boiler and to fluctuations observed in other boilers with cracked tubes at air port openings. Parameters addressed included the liquor firing temperature, nozzle design, size, and gun angle. For the air distribution, the split between primary, secondary and tertiary air, windbox pressures, and secondary air interlacing patterns were covered in the recommendations.

A very detailed model of recovery boilers has been started, and computational fluid dynamic studies have been extended to provide considerable information about the distribution of black liquor and combustion air. The modeling results, shown in Fig. 14, reveal boilers experiencing more extensive cracking of primary air port tubes are those in which greater amounts of black liquor are deposited on the walls above and around the primary air port level. It is certainly logical that such deposition would create the conditions identified through the video imaging –

streams of molten smelt running down the walls and black liquor droplets falling on the tube surfaces. However, some improvement is still needed in the level of detail used to describe the liquor distribution and the air flow patterns at the primary air port level.

SUMMARY AND CONCLUSIONS

A significant amount has been learned about the cracking and corrosion observed on primary air ports fabricated with 304L SS/carbon steel composite tubes. Information obtained from temperature measurements suggests temperature fluctuations are essential for the cracking mechanism to be operative. However, previous studies of floor tube cracking found that well over 100,000 cycles would be required to take the material to the design limit for thermal fatigue. In many cases, cracks appear to develop in air port tubes in 6 months, but the thermocouple results do not indicate the tubes have seen a sufficient number of thermal cycles to reach the design limit much less initiate or propagate fatigue cracks. Furthermore, the crack morphology is not generally consistent with fatigue cracking. Consequently, it is likely the cracking mechanism fits the definition of corrosion fatigue, where stress cycles as well as a corrodent are required. Laboratory and field studies are in progress to identify this corrodent.

From the temperature measurements, the modeling work and the observations of cracking patterns, it is apparent that primary air ports having temperatures above 450°C for a significant time period are more likely to experience cracking of the stainless steel layer. Furthermore, when the temperature reaches a level in the vicinity of 600°C, the stresses in the carbon steel are changed such that cracks can more easily advance into the carbon steel.

The temperature measurements, the video observations, and the effect of operating parameters on the temperature activity suggest deposition of black liquor on the boiler walls provides the source of material responsible for the temperature fluctuations, whether it is burning of the organic component of the liquor droplets or the oxidation of the sodium sulfide that is released when the droplets are burned. Consequently, it appears that limiting the deposition of liquor on the walls above and around the primary air ports is one approach that could be used to control the cracking of primary air port tubes.

Observation of alternate materials utilized in primary air ports and exposed for extended periods of time have not shown any cases of cracks developing in composite tubes fabricated from modified alloy 825, and only very limited cracking has been seen on tubes weld overlaid with alloy 625. However, no alloy used to date has been entirely immune from cracking or corrosion in all service applications. Minor cracking is commonly reported for tubes in smelt spout openings made from the modified alloy 825 tubes, and limited cracking has been found on the weld overlaid primary air port and smelt spout opening tubes after a few years service. Additionally, localized corrosion adjacent to the air port casting has been observed in some cases for the tubes overlaid with alloy 625, and in one boiler, severe corrosion of the modified alloy 825 wall tubes has occurred.

The data available for comparison of the two most common primary air port designs suggests the longer, narrower design may be less likely to crack, but it is clear that use of this type of air port alone is not sufficient to prevent cracking of 304L stainless steel. Clearly, the liquor and air distribution characteristics of the boiler do have a significant influence on whether or not air port cracking is likely to occur.

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REFERENCES

1.Sharp, W.B.A., TAPPI Journal, 64 (7), pp. 113-115 (1981).

2. Klarin, A., "Floor Tube Corrosion In Recovery Boilers", TAPPI Journal, 76 (12), pp. 183 (1993).

3. Pohjanne, P., Mäkipää, M., Ehrnstén, U., and Hänninen, H., "Cracking Of Compound Tubes In Black Liquor Recovery Boilers", proceedings from the 7th International Symposium on Corrosion in the Pulp and Paper Industry, Atlanta, Georgia (1992).

4. Mäkipää, M., Nenonen, P., Salonen, J., and Hakkarainen, T., "Studies With TEM, SEM and Optical Microscope on the Cracking of BLRB Composite Floor Tubes", proceedings from the 8th International Symposium on Corrosion in the Pulp and Paper Industry, Stockholm, Sweden (1995).

5. Hänninen, H., Pohjanne, P., and Nieminen, P., "Cracking And Corrosion Problems In Black Liquor Recovery Boilers", International Symposium On Plant Aging And Life Predictions Of Corrodible Structures, May 15-18, 1995, Sapporo, Japan (1995).

6. Keiser, J.R., Taljat, B., Wang, X.-L., Maziasz, P.J., Hubbard, C.R., Swindeman, R.W., Singbeil, D.L., Prescott,R., "Analysis Of Composite Tube Cracking In Recovery Boiler Floors", proceedings from the 1996 TAPPI Engineering Conference, Atlanta, Georgia.

7. Keiser, J.R., Taljat, B., Wang, X.-L., Swindeman, R.W., Maziasz, P.J., Thomas, R.L., Payzant, E.A., Singbeil, D.L., Prescott, R., " Analysis Of Cracking Of Co-Extruded Recovery Boiler Floor Tubes", proceedings from the 1997 TAPPI Engineering & Papermakers Conference, Nashville, Tennessee.

8. Singbeil, D.L., Prescott, R., Keiser, J.R., and Swindeman, R.W., "Composite Tube Cracking In Kraft Recovery Boilers – A State-of-the-Art Review", proceedings from the 1997 TAPPI Engineering Conference, Atlanta, Georgia.

9. Keiser, J.R., Wang, X.-L., Swindeman, R.W., Sarma, G.B., Hoffmann, C.M., Maziasz, P.J., Singbeil, D.L., Prescott, R., Eng, P., Frederick, L.A., Singh, P.M., Mahmood, J., "Status Report On Studies Of Recovery Boiler Floor Tube Cracking", proceedings from the 1999 TAPPI Engineering/Process & Product Quality Conference, Atlanta, Georgia.

10. Swindeman, R.W., Keiser, J.R., Maziasz, P.J., "Fatigue Cracking Of Coextruded 304L/CS Tubes", proceedings from 9th International Symposium on Corrosion in the Pulp and Paper Industry, Ottawa, Ontario (1998).

11. Prescott, R., Eng, P., Singbeil. D.L., "Stress Corrosion Cracking Of Type 304L Stainless Steel In Kraft Recovery Boiler environments", proceedings from 9th International Symposium on Corrosion in the Pulp and Paper Industry, Ottawa, Ontario (1998).

12. Taljat, B., Zacharia, T., Wang, X.-L., Keiser, J.R., Swindeman, R.W., Hubbard, C.R., "Mechanical Design Of Steel Tubing For Use In Black Liquor Recover Boilers", proceedings from 9th International Symposium on Corrosion in the Pulp and Paper Industry, Ottawa, Ontario (1998).

13. Keiser, J.R., Taljat, B., Wang, X.-L., Swindeman, R.W., Maziasz, P.J., Meyers, L.E., Thomas, R.L., Elliott, S.T., Singbeil, D.L., Prescott, R., Gorog, J.P., "Causes And Solutions For Cracking Of Coextruded And Weld Overlay Floor Tubes In Black Liquor Recovery Boilers", proceedings from 9th International Symposium on Corrosion in the Pulp and Paper Industry, Ottawa, Ontario (1998).

14. Keiser, J.R., Sarma, G.B., Wang, X.-L., Hubbard, C.R., Swindeman, R.W., Singbeil, D.L., Singh, P.M., "Why Do Kraft Recovery Boiler Composite Floor Tubes Crack?" proceedings from the 2000 TAPPI Engineering Conference, Atlanta, Georgia.

15. Keiser, J.R., Singbeil, D.L., Sarma, G.B., Singh, P.M., Choudhury, K.A., Ely, T.M., Hubbard, C.R., Kish, J.R.,

Perdomo, J. J., “Recent Observations Of Recovery Boiler Primary Air Port Cracking And Characterization Of Environmental Conditions”, proceedings from TAPPI 2001 Engineering, Finishing/Converting Conference, San Antonio, Texas.

16. Keiser, J.R., Singbeil, D.L., Sarma, G.B., Choudhury, K.A., Kish, J.R., Frederick, L.A., Hubbard, C.R., Singh, P. M., “Relationship Of Recovery Boiler Parameters And Primary Air Port Cracking”, proceedings from the TAPPI 2002 Fall Conference, San Diego, California.

17. Kish, J.R., Singbeil, D.L., and Keiser, J.R., “Experience Using Composite Tubes In Lower Furnace Of Kraft Recovery Boilers”, proceedings from PAPTAC Pacific Coast Branch Parksville Mini-Conference 2003, Parksville, British Columbia.

18. Keiser, James; Singbeil, Douglas; Sarma, Gorti; Choudhury, Kimberly; Singh, Preet; Hubbard, Camden; Swindeman, Robert; Ely, Thomas; Kish, Joseph; Kenik, Edward; Maziasz, Philip; Bailey, Sarah, “Comparison Of Cracking In Recovery Boiler Composite Floor And Primary Air Port Tubes”, proceedings from International Chemical Recovery Conference, Whistler, British Columbia (2001).

19. Keiser, J.R., Singbeil, D.L., Choudhury, K.A., Sarma, G.B., Hubbard, C.R., Ely, T.M., Kish, J.R., Singh, P.M., Kenik, E.A., Hall, L.M., “Characterization Of Primary Air Port Cracking In Black Liquor Recovery Boilers”, proceedings from 10th International Symposium on Corrosion in the Pulp and Paper Industry, Helsinki, Finland (2001).

20. Shenassa, R., Haaga, K., Tuiremo, J., “Primary Air Port Tube Integrity – A Critical Review Of Primary Air Port Design And The Effect Of Boiler Design Parameters”, proceedings from the TAPPI 2002 Fall Technical Conference, San Diego, California.

21. Tran, H., Vafa, S., Milbury, C., Blaney, B., Piroozmand, F., Roherty, A., Mott, D., Anderson, B., Rivers, K., “Modifying Boiler Operation To Reduce Primary Air Port Cracking In A Recovery Boiler”, proceedings from the TAPPI 2002 Fall Technical Conference, San Diego, California.

22. “Inspection For Cracking Of Composite Tubes In Black Liquor Recovery Boilers”, Technical Information Paper 0402-30, TAPPI Press, Atlanta, Georgia (2001).

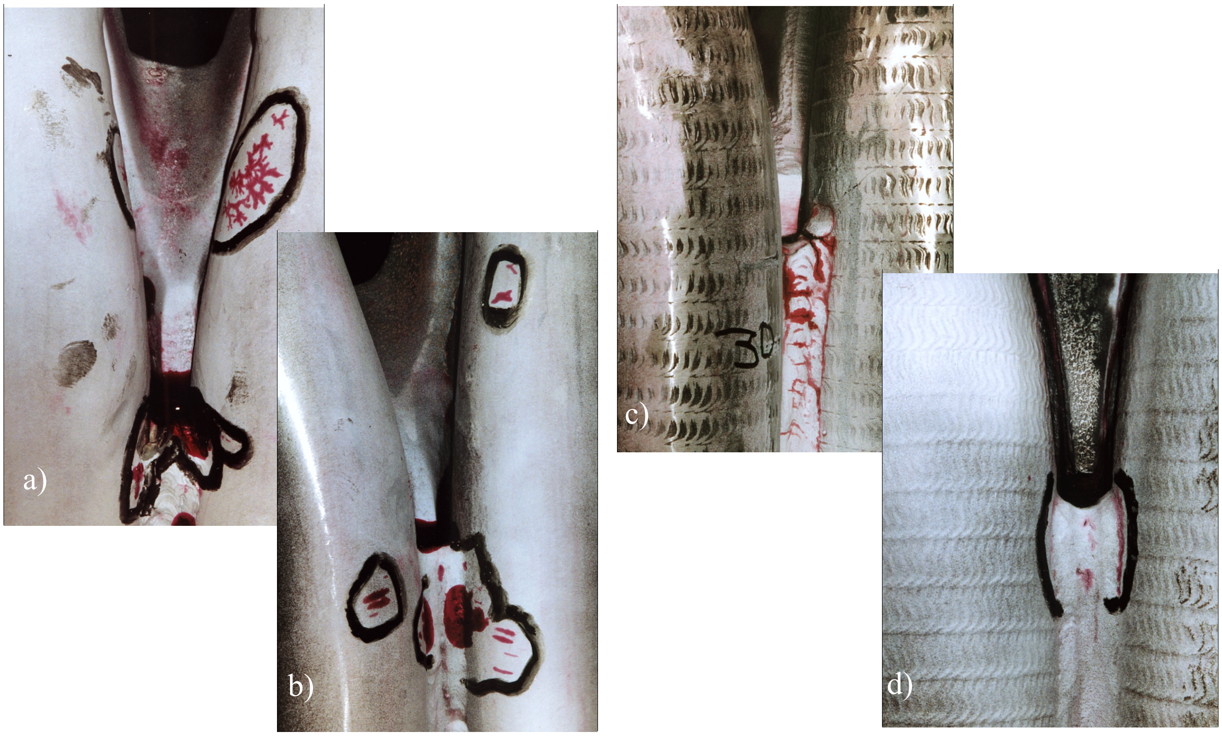
23. Wensley, A and Woit, B, “Inspection of Primary Air Port Opening Tubes in Recovery Boilers”, proceedings from the 2001 TAPPI Engineering Conference, TAPPI, Atlanta, Georgia.

24. Sarma, G.B., Choudhury, K.A., Keiser, J.R., Steinmoeller, F.E., Rivers, K.B., Mackenzie, C.M., Stone, B.B., Kulig, J.A., “Recovery Boiler Wall Tube Temperature Measurements”, MPLUS project report MC-01-005, Oak Ridge National Laboratory, Oak Ridge, TN (2002).

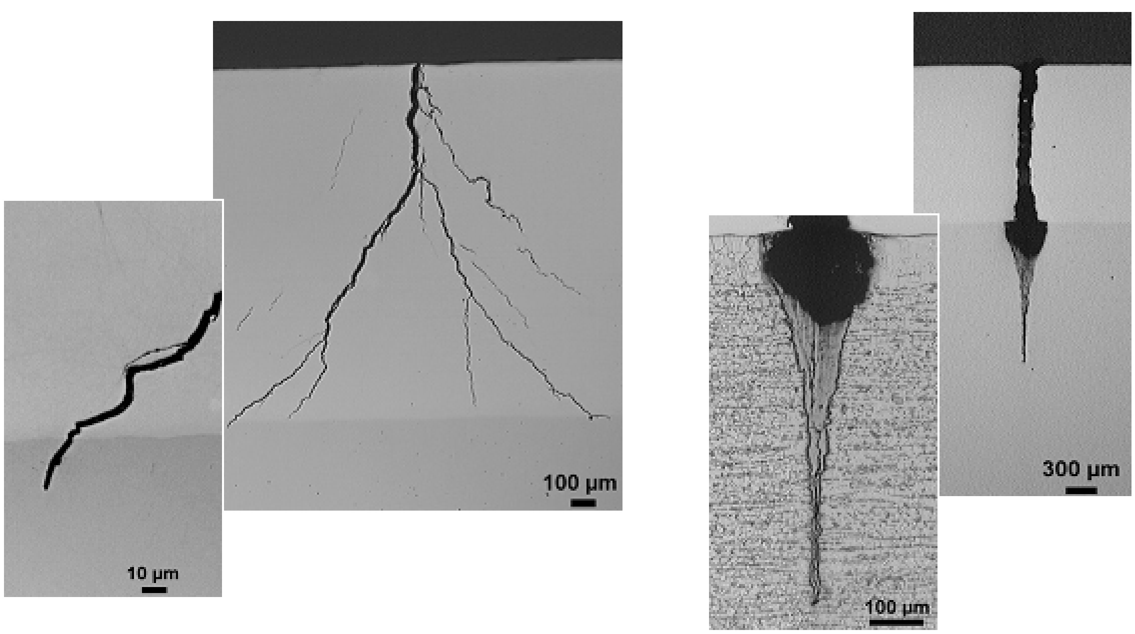
25. Frederick, L., Singbeil, D., Kish, J., “Using An In Situ Video Camera To Diagnose The Cause Of Temperature Fluctuations On Air Port Tubes In Kraft Recovery Boilers”, proceedings from the 2003 TAPPI Fall Technical Conference: Engineering, Pulping & PCE&I, Chicago, Illinois.

Table 1. Recovery boilers instrumented with primary air port thermocouples as part of this study

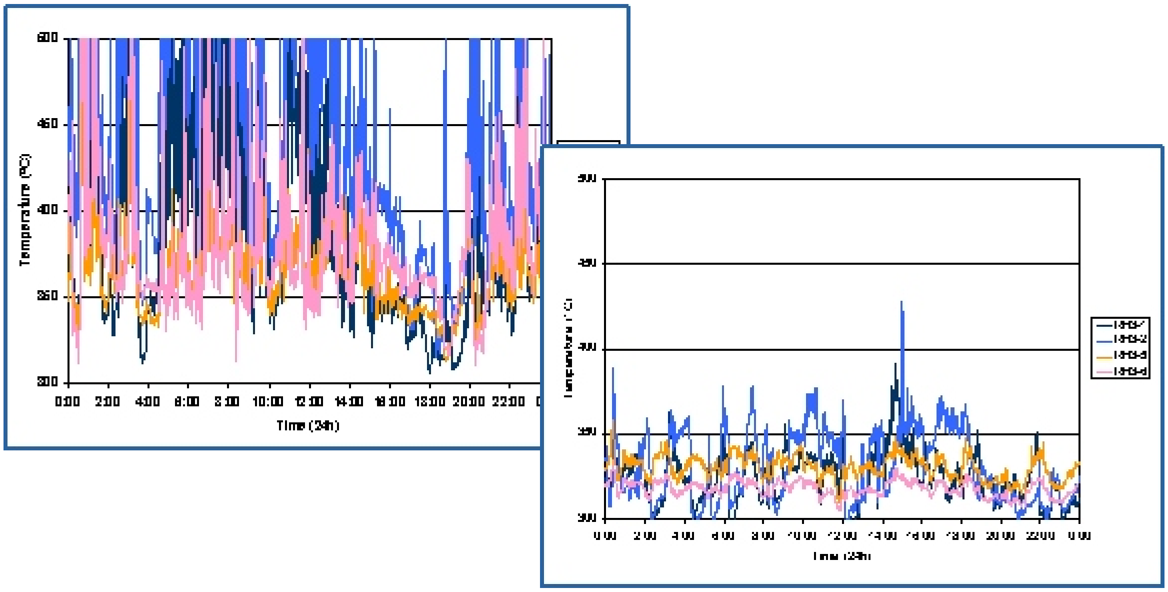
Boiler ID	Nominal Capacity MLbDS/Day	Operating Pressure (psig)	Floor type	Primary air port (PAP) type	Sleeve/insert type	Extent of PAP cracking
A	3.79	925	Sloped	Short, wide	Casting	Considerable
B	3.80	1250	Sloped	Short, wide	Casting	Negligible
C	3.95	1250	Sloped	Short, wide	Casting	Extensive
D	2.67	880	Decanting	Short, wide	Welded sleeve	Considerable
E	3.50	850	Decanting	Short, wide	Casting	Considerable
F	4.50	900	Sloped	Long, narrow	Casting	None
G	5.40	1300	Sloped	Short, wide	Casting	Considerable
H	4.50	1300	Decanting	Short, wide	Welded sleeve	None
I	5.67	700	Decanting	Short, wide	Casting	None



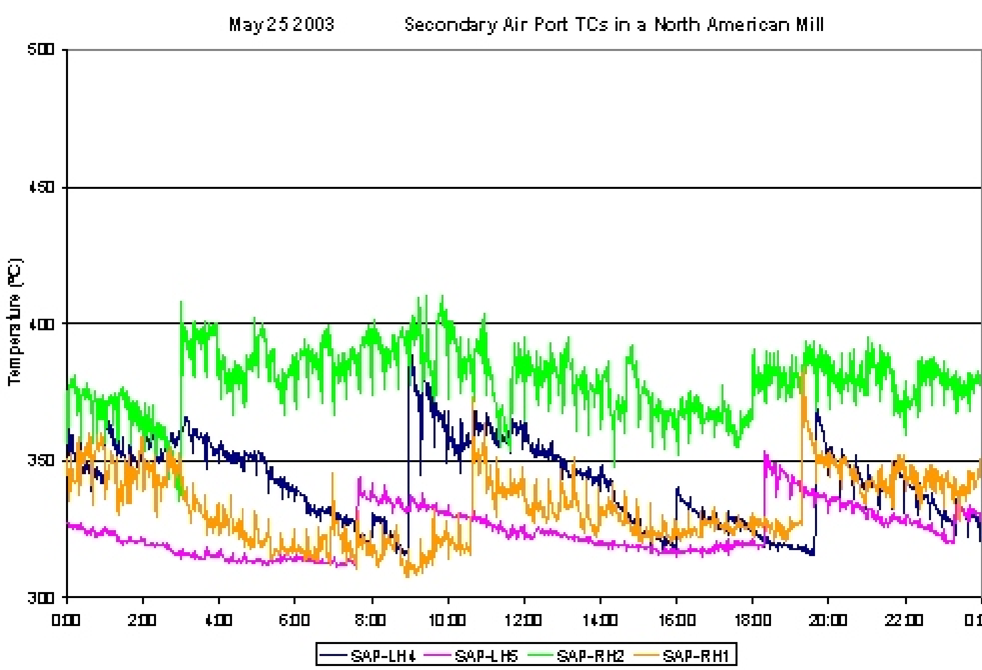
1. Examples of cracking in primary air port composite tubes a) craze cracks, b) circumferential cracks, c) membrane cracks, and d) tube-membrane weld cracks.



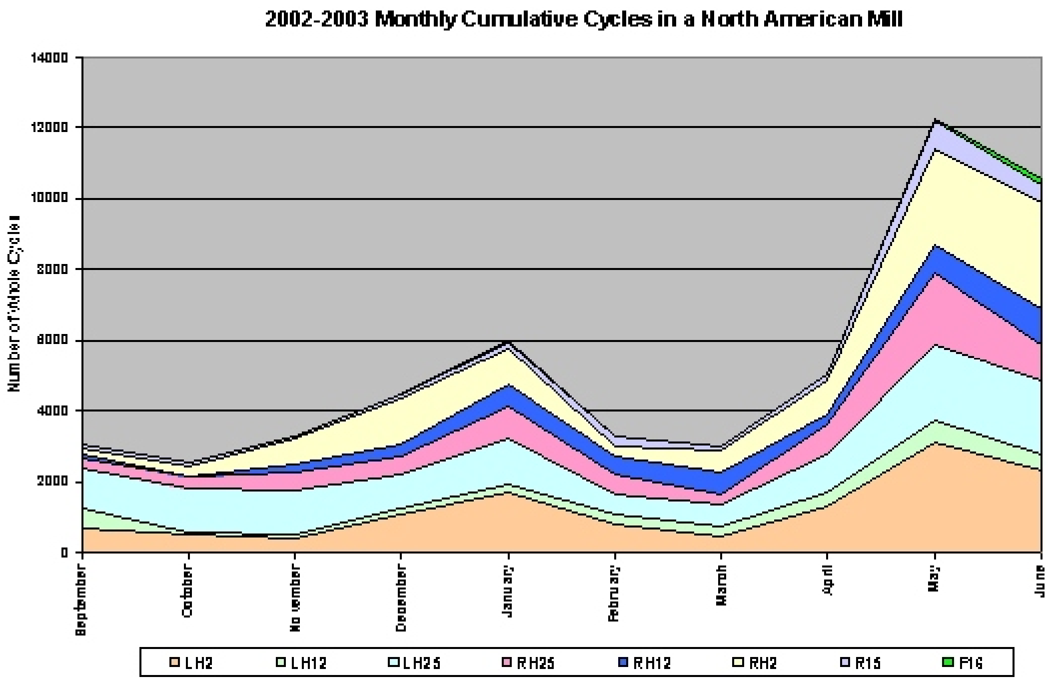
2. Examples of circumferential cracks continuing into the carbon steel.



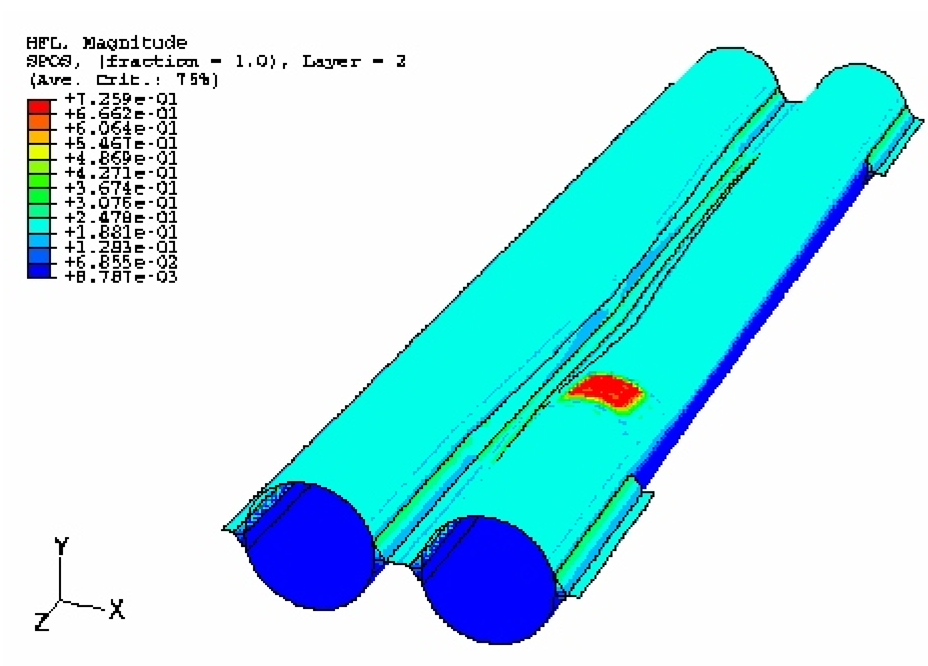
3. Temperature fluctuations during one day period for a) primary air port tube with history of cracking and b) primary air port tube with no history of cracking.



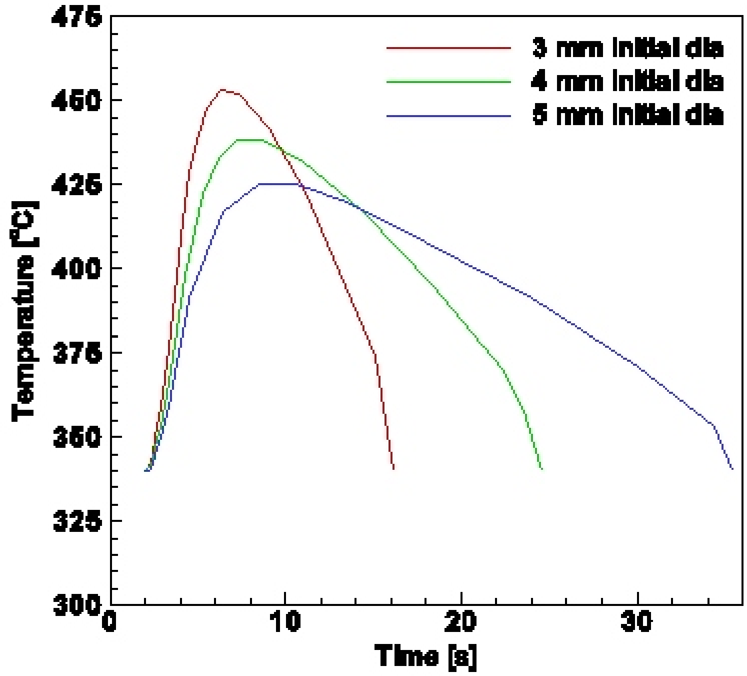
4. Temperatures measured by thermocouples in secondary air ports of boiler with history of primary air port cracking. The cycle associated with rodder operation is apparent.



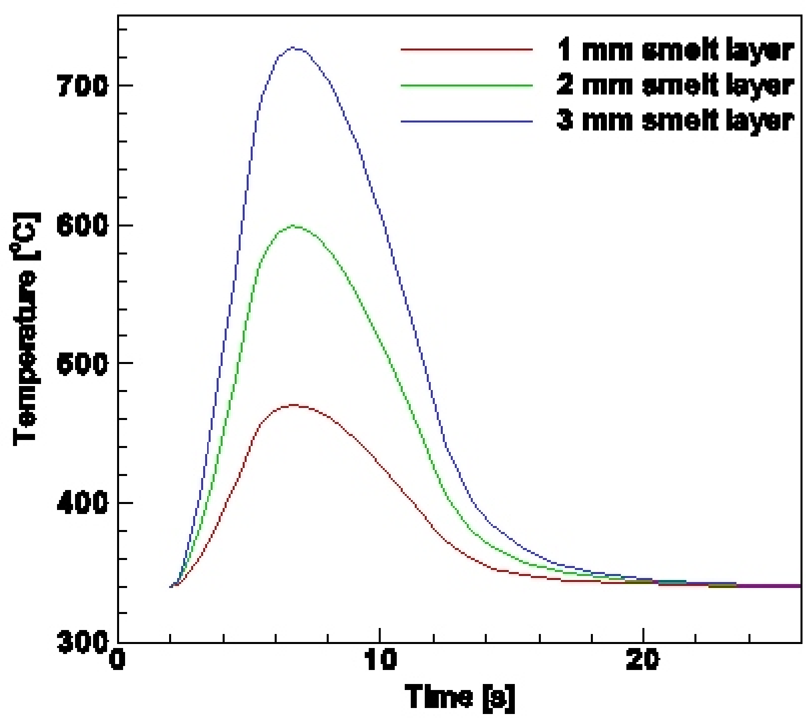
5. Monthly cumulative cycle count for eight monitored primary air ports (16 thermocouples) in a recently rebuilt recovery boiler. Note that the cycle count was much higher to recent months.



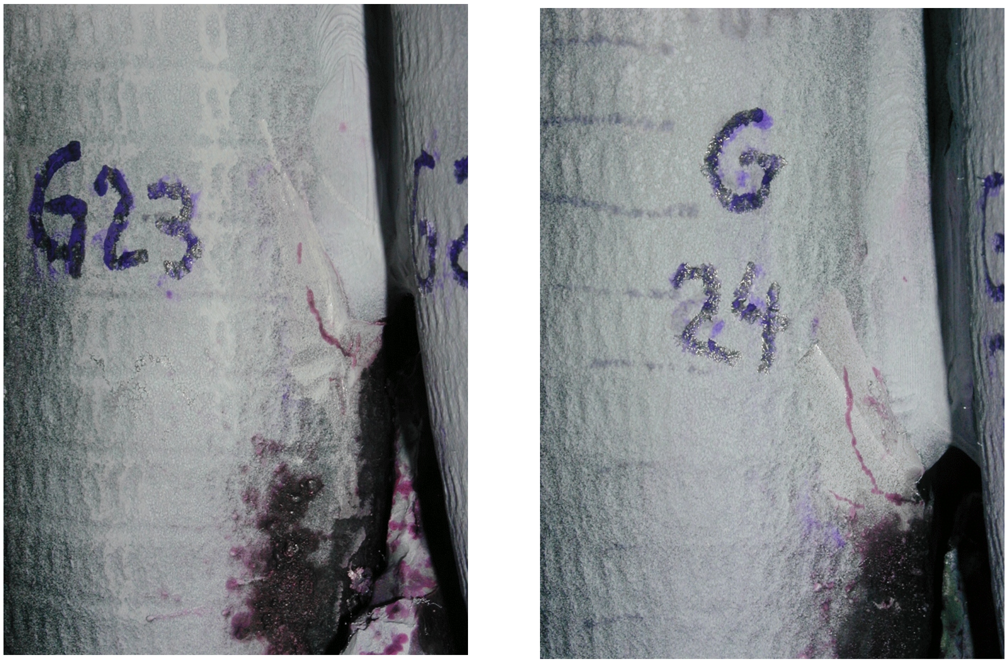
6. Heat flux [W/mm^2] variation on the tube surface showing a region of 2 x 2 elements on the lower portion of the bent tube where localized heating was assumed to occur.



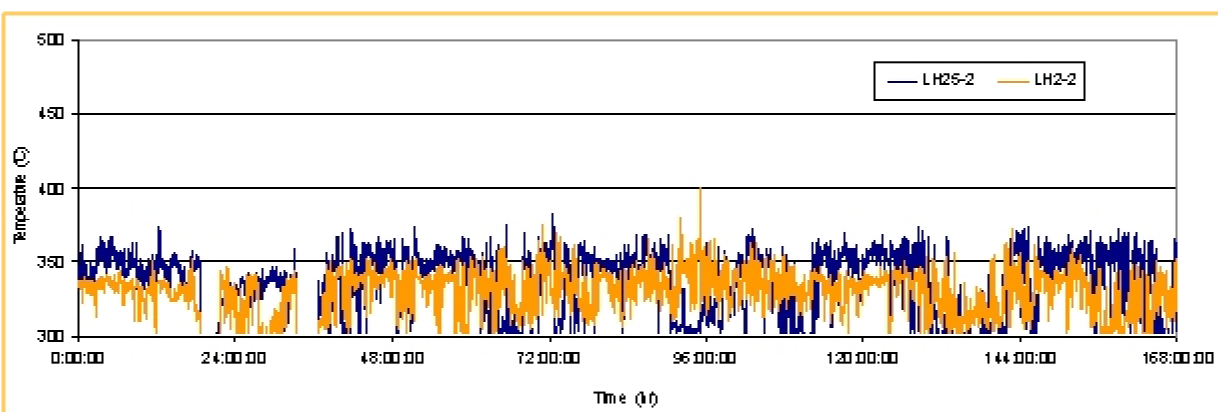
7. Temperature variation at the fireside crown of the tube due to combustion of black liquor droplet for different initial droplet sizes.



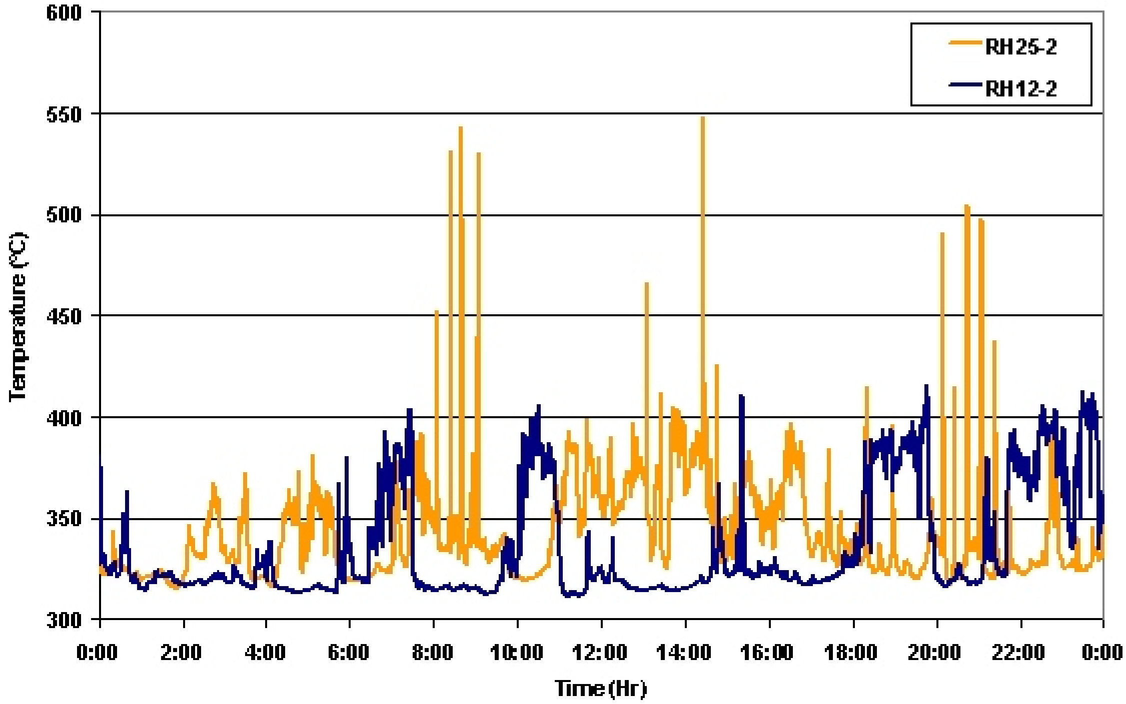
8. Temperature variation at the fireside crown of the tube due to smelt oxidation for different smelt layer thickness.



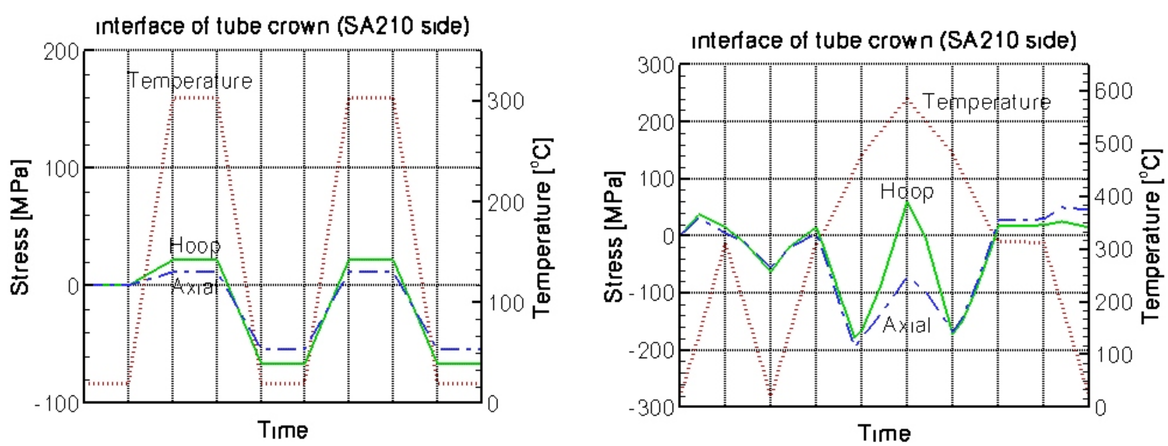
9. Cracking observed at the top of primary air ports in alloy 625 weld overlaid tubes. The tubes had been in service for 2½ years at the time of the inspection when the cracks were found. Note that some of the tube has been ground off in the effort to eliminate the cracks.



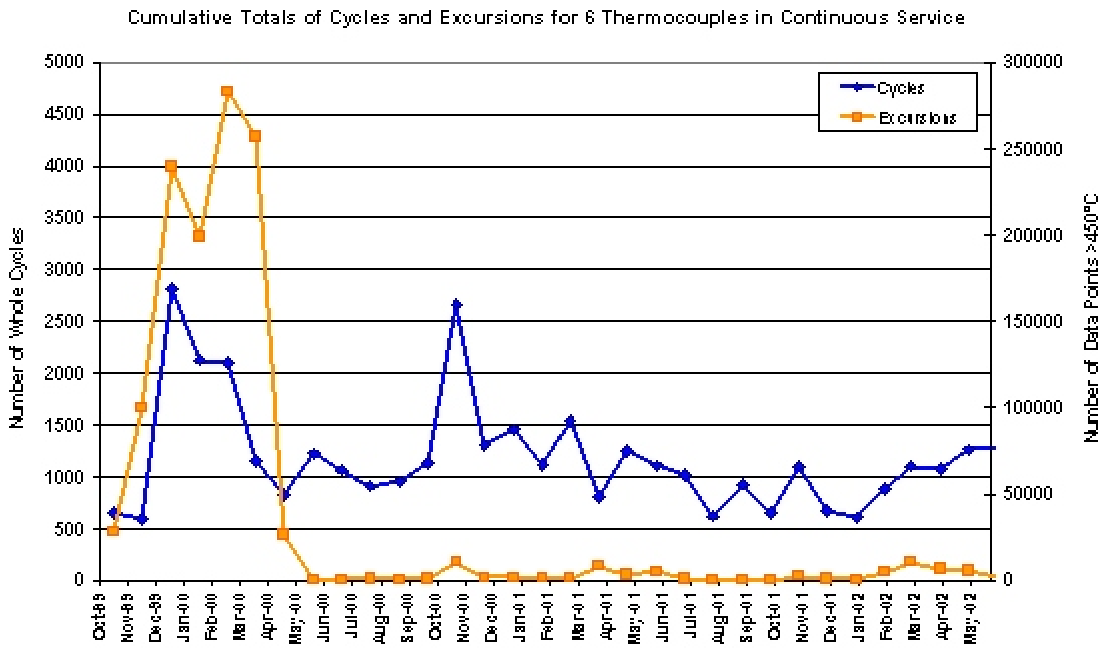
10. Temperature measurements made on composite tubes that form longer, narrower type primary air ports in a boiler initially constructed with the longer, narrower type of primary air ports.



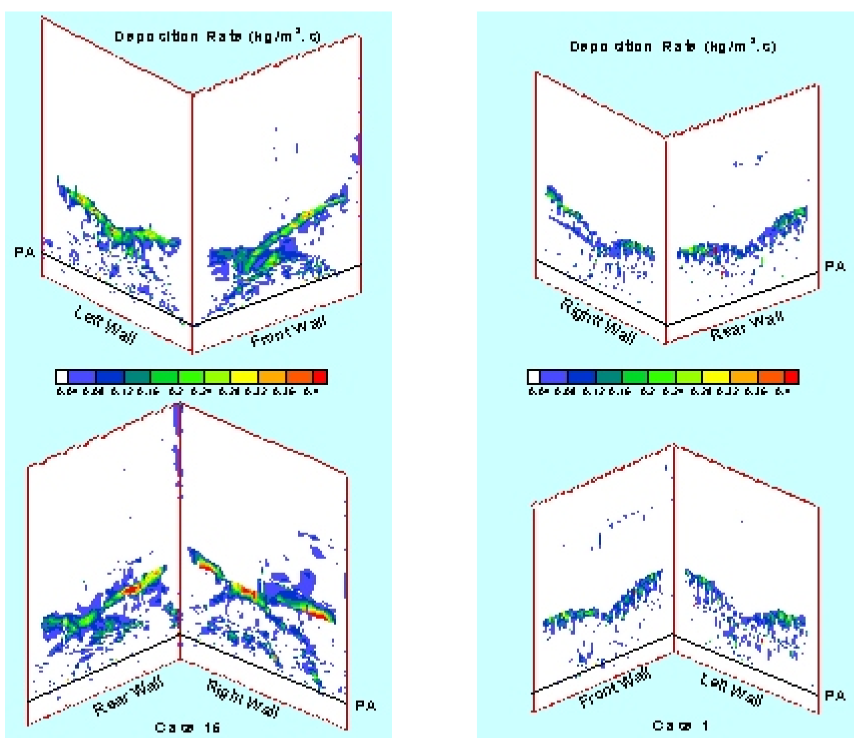
11. Temperature measurements made on composite tubes that form longer, narrower type primary air ports in a boiler initially constructed with shorter, wider type of primary air ports.



12. Calculated residual stresses in the carbon steel at the stainless steel to carbon steel interface. After normal operation, these stresses are compressive whereas the stresses become tensile after a severe temperature excursion.



13. Thermal cycles measured on selected thermocouples before and after a change in liquor nozzle type in a boiler that had experienced extensive primary air port tube cracking.



14. Black liquor deposition rate calculated for two boilers - boiler #1 that has experienced primary air port cracking and boiler #2 that has not shown significant amounts of primary air port cracking.