Modifying boiler operation to reduce primary air port cracking in a recovery boiler

HONGHI TRAN, SHERY VAFA, CINDY MILBURY, BOBBIE BLANEY, FARSHAD PIROOZMAND, ARNIE ROHERTY, DAN MOTT, BLAINE ANDERSON, AND KEITH RIVERS

ABSTRACT: This systematic study examined the cause of severe cracking of SS304L/SA210 composite waterwall tubes at primary air ports in the recovery boiler at Irving Pulp & Paper's Saint John mill. The results show that the severity of the cracking problem was strongly related to the frequency and the magnitude of tube temperature excursions at the air ports. The cracking problem has been significantly reduced by operating the boiler at a lower black liquor solids content and at a higher primary air flow. These operating conditions appear to keep the char bed away from the air ports and help reduce tube temperature excursions.

Application: Mills that experience this type of primary air port cracking problem might want to try this approach; other mills may gain insights on boiler operating parameters to avoid.

Severe corrosion and cracking of waterwall SS304L/SA210 composite tubes at primary air ports has occurred in a number of recovery boilers in recent years [1,2,3]. The exact cause is not known, but most agree that the severity of the problem is related to the frequency and magnitude of temperature excursions observed on the air port tubes. Such variations at the tube surface during boiler operation may lead to excessive corrosion and to high internal stresses that may initiate new cracks and/or propagate existing cracks at the tube surface.

The recovery boiler at Irving Pulp and Paper's mill in Saint John, New Brunswick, Canada, was one of the boilers that experienced a severe primary air port cracking problem. In addition to the primary air port cracking, this boiler also experienced widespread membrane bar wastage and cracking of butt welds located between the bottom of the primary air ports and the floor. The significant effort put into solving the problem by the mill has met with great success, and all the cracking problems are now under control. This paper describes the experience of primary air port cracking problem at the mill, the possible causes, and the actions taken to minimize the problem.

CRACKING EXPERIENCE

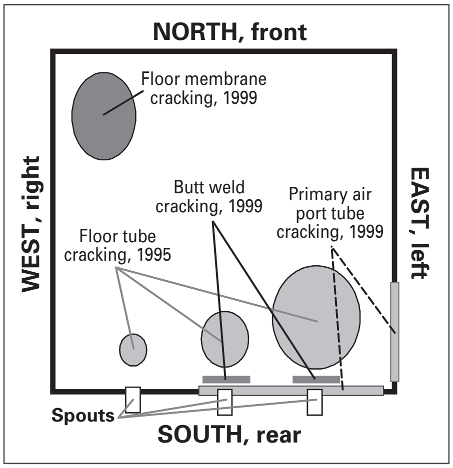
The recovery boiler is a 1970 Babcock & Wilcox UK boiler constructed with 3-in diameter tubes spaced on 4 in centers. The boiler was originally designed to burn 2.4 million lbs/day of as-fired black liquor dry solids (BLDS) and to produce 360,000 lbs/h steam rated at 825°F and 900 psig. The boiler underwent a major retrofit in 1991 to increase the firing capacity to 3.25 million lbs/day of BLDS Subsequent upgrades included the installation of a new tertiary air system, a high solids crystallizer, a saltcake purge system, precipitator upgrade and steam drum internals replacement [4]. These upgrades allowed for an increase of as-fired black liquor solids content from 68% to 72% in 1996 and to 74% in 1997. By 2000, the boiler was firing 3.7 million lbs/day of BLDS at a solids content as high as 76%, and producing 550,000 lbs/h steam.

As part of the 1991 retrofit, a new lower furnace with SS304L/SA210 composite tubes was installed. In 1995, severe localized cracking was found in the membranes and on floor tubes on the rearmost third of the floor closest to the smelt spouts (**Fig. 1**). This floor cracking prompted the mill to replace the bottom half of the composite tubes on the floor with 625 welded overlay (WOL) tubes in 1996. After six years in service, the WOL 625 tubing and membrane continues to operate without cracking or material loss.

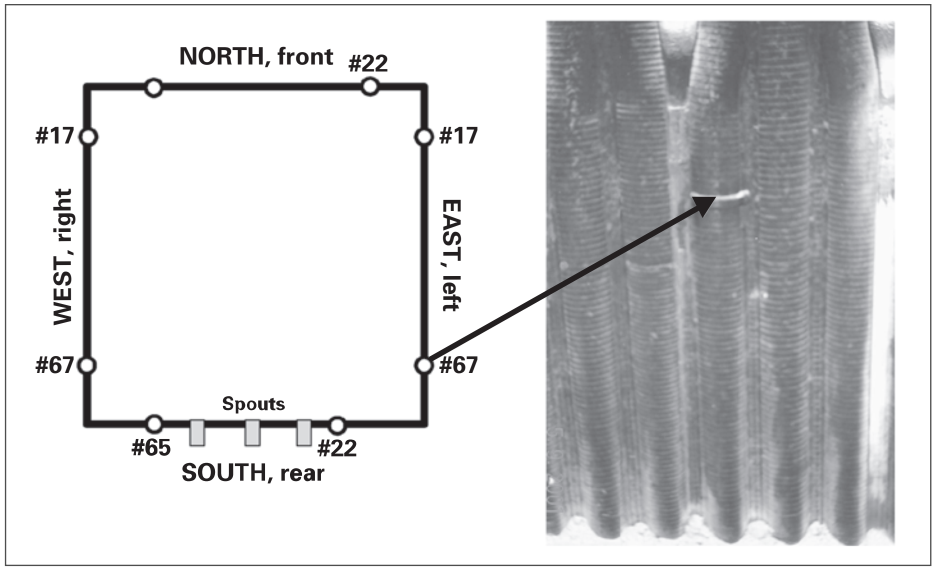
In May 1998, cracking of primary air port tubes was found in the southeast (SE) or rear-left corner of the boiler (Fig. 1). Initially, only a small area was affected, but the extent of cracking problem increased drastically with each subsequent outage. In May 1999, extensive primary air port cracking was found in the east (left) sidewall and along the south (rear) wall. In addition to the primary air port cracking, extensive butt weld cracking was found over two smelt spouts (between the smelt spout openings and the primary air ports) that required the welds to be cut out and short replacement tubes installed.

A planned boiler inspection in November 1999 revealed extensive primary air port cracking, butt weld cracking, and membrane bar wastage that required replacement of 20 m (60 ft) of membrane bar in the rear left corner (**Fig. 2**). Due to the continuing deterioration of these wall panels, the mill decided to replace the south (rear/spout) wall and east (left) wall with WOL 625 tubing during the April 2000 outage. During this outage, eight crown thermocouples were installed just below the primary air ports to monitor tube temperatures and thermal conditions near the air ports (**Fig. 3**). Tubes East 67 and South 22 were selected as these tubes were in the center of the major problem areas. The remaining six thermocouples were installed using the same tube spacing from their respective corners. Compilation of tube temperature data was important because frequent, high tube temperature excursions are believed to be the main cause of cracking.

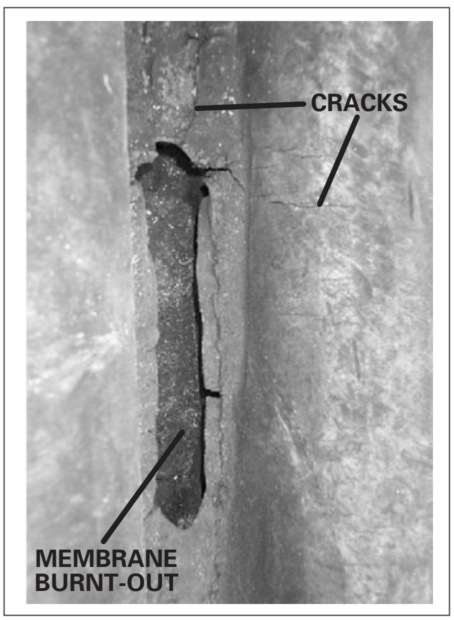
Following the April 2000 shutdown, a study program was developed to monitor the thermal variations (temperature spiking) in the lower furnace, and to determine which operating parameters, if any, correlate to the thermal variation. Extensive trials were subsequently conducted in which the black liquor solids content was held at 76%. The results were inconclusive, mainly due to the extreme thermal conditions in the SE corner of the boiler. Changes were made in several boiler operating parameters, but none



1. Locations of cracking in the lower furnace.



3. Locations of crown thermocouples installed on primary air port tubes during April 2000 boiler shutdown. Photo showing the crown thermocouple installed on WOL 625 tube E67.



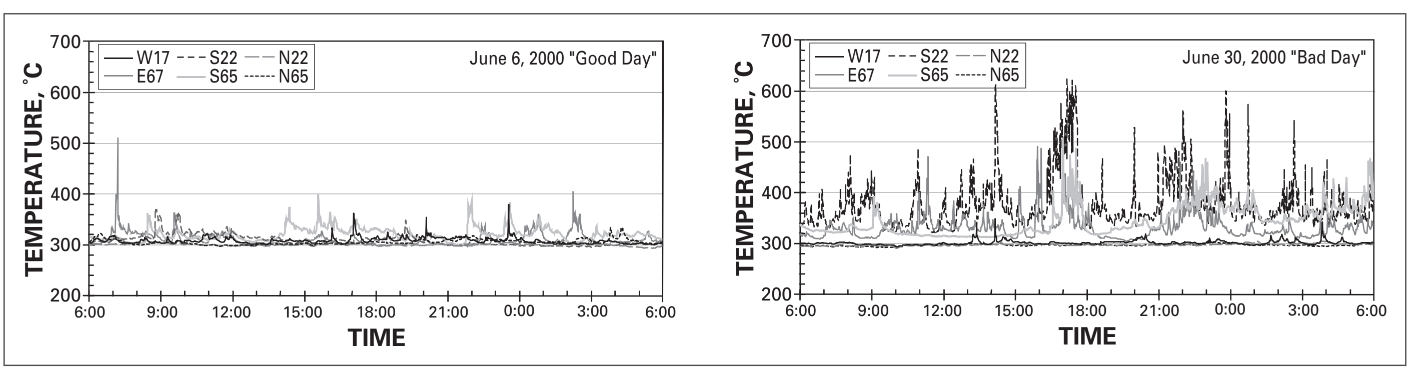
2. Burned-out SS304L membrane bar on the east (left) sidewall, just below the primary air port, November 1999. Note cracks on the SS304L/SA210 composite tube and the membrane bar.

appeared to have an effect on temperature spiking. The crown thermocouples in the SE corner burned out at the end of June 2000, after less than two-and-a-half months in operation.

The thermal activity near the air ports varied widely from day to day. **Figure 4** shows temperature variations registered by crown thermocouples at various primary air ports for two extreme days. On the "good" day (June 6, 2000), the thermal activity near the primary air ports was relatively calm and little temperature spiking was observed. On the "bad" day (June 30, 2000), the frequency of temperature spikes increased markedly and the magnitude of spiking increased, particularly at air ports on the south and east walls of the boiler. At air ports on the north side (N22 and N65) and at one on the west side (W17), no temperature spikes were observed. The thermal activity was consistent with the cracking pattern in the boiler: the problem was much more severe on the south and east walls than on the north and west walls (Fig. 1).

The December 2000 planned shutdown revealed cracking in several membrane bars in the rear left (SE) corner below the primary air ports on the new WOL 625 walls (**Fig. 5**). The problem was confined to the membrane bars, and none of the cracking was observed on the tubes. Approximately 10 m (30 ft) of membrane bars were replaced during this shutdown, along with the crown thermocouple shields that had burned off.

Following the December 2000 shutdown, the mill established an investigation team to systematically study the cause of temperature spiking and to develop strategies for controlling the cracking problem. The study was conducted in collaboration with Babcock & Wilcox Canada and the University of Toronto. It involved i) reviewing boiler operating data from the past few years, ii)



4. Tube surface temperatures at various primary air ports on a good day (left) and a bad day (right).

monitoring tube temperatures at various air ports, iii) relating boiler operating parameters to tube temperature excursions, and iv) conducting trials to examine if the extent of tube temperature excursions can be reduced by adjusting the parameters which were identified as being responsible for the tube temperature excursions.

STUDY PLAN

To systematically analyze the problem, the investigation team followed the principles used in Juran's quality improvement process and Kepnor-Tregoe's problem solving process. Data on various operating parameters were thoroughly examined to determine which parameters could be eliminated as a cause of temperature excursions, and which parameters could be considered as having a high probability, medium probability, or low probability of causing the problem. The timeline of data collection was defined by asking the question, "when did the problem first occur?" Since cracks were first noticed on primary air port SS304L/SA210 tubes in May 1998, the conditions causing them would have been in place in the boiler by at least late 1997. To test that presumption, we compiled and analyzed the 1995-2000 boiler operating data. The analysis revealed several important operational changes:

- The total air flow to the boiler was decreased in December 1995 when the mill implemented a consumed air strategy.
- In order to minimize carryover and plugging, the primary air flow and secondary air flow were decreased by 5% each in mid 1997, with the equivalent amount of air flow directed toward the tertiary air to keep the total air flow constant.
- The black liquor solids content was increased from 72% to 74% in early 1997, and to 76% in 2000;
- The as-fired black liquor load was increased from 3.5 million lbs/day to 3.7 million lbs/day in 2000.

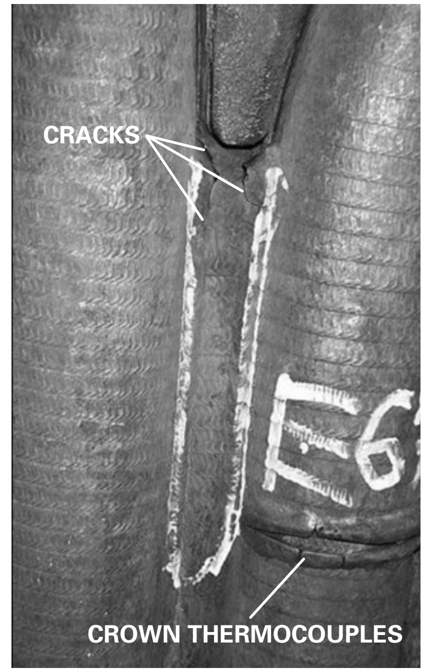
These changes—the increase in liquor firing load, the increase in liquor solids content, and the decrease in primary air—most likely caused the cracking problem, because they would probably increase the char bed size and the probability of char bed buildup near primary air ports.

INVESTIGATION OF POSSIBLE CAUSES

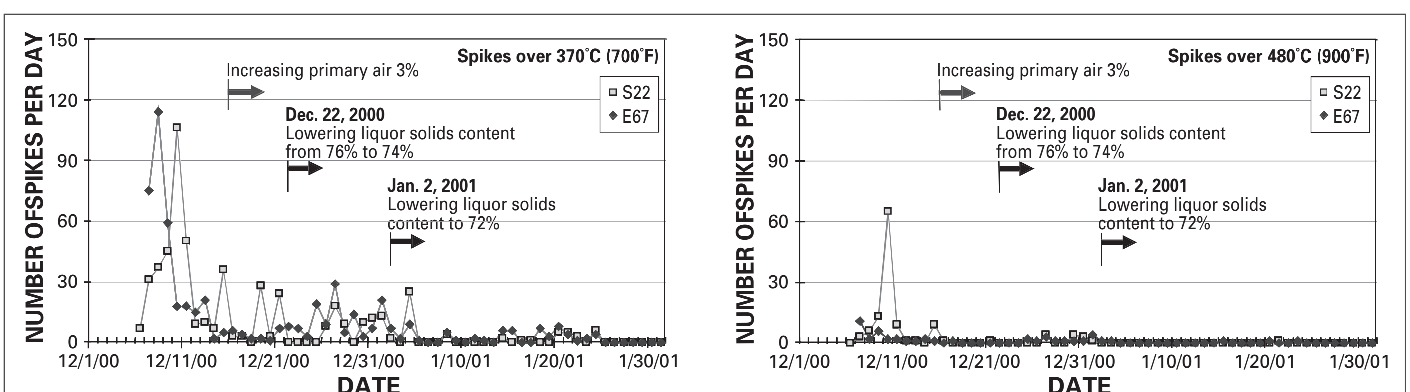
While the increase in liquor firing load appeared to be an important cause of temperature spiking, lowering the firing load was not a viable option for the mill to adopt. Therefore, a study was performed to determine if lowering the liquor solids content and increasing the primary air flow would reduce the frequency and magnitude of temperature excursions observed on primary air port tubes, particularly those in the SE corner of the boiler.

In mid-December 2000, the primary air flow was increased 3% from a primary/secondary/tertiary air split of about 32/39/29 to 35/35/30, while the total air flow was kept constant. On December 22, 2000, the liquor solids content was lowered from 76% to about 74% by setting the boiling point rise (BPR) of the liquor in the high solids concentrator (HSC) from 18ºC to 17ºC (30ºF). On January 2, 2001, the solids content was lowered further, from 74% to 72%, by setting the BPR of the HSC liquor to 16ºC (28ºF) to determine if the temperature spikes could be further reduced.

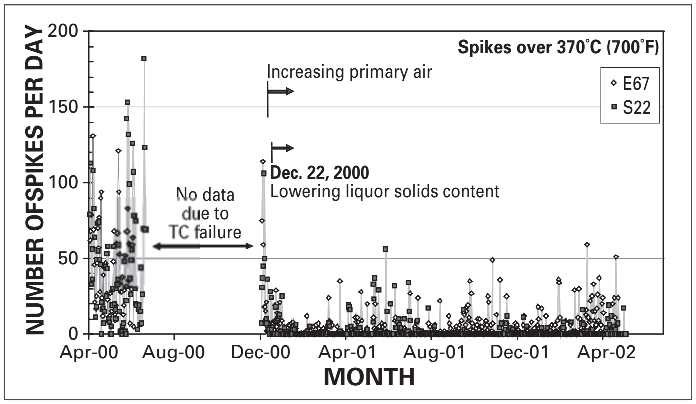
We evaluated the effect of changing these boiler operating parameters based



5. Arrows showing cracking of membrane bar adjacent to Tube E67 during the December 2000 planned shutdown. Note the crown thermocouple burned off on Tube E67.



6. Thermal activity at thermocouples below the primary air ports in the rear-left (southeast) corner of the boiler during the months of December 2000 and January 2001. Left: Number of spikes above 370°C (700°F). Right: Number of spikes above 480°C (900°F).



7. Number of spikes/day above 370°C (700°F) at thermocouples below the primary air ports in the southeast corner of the boiler in the period between April 2000 and May 9, 2002.

on the number of temperature spikes that occurred above 370°C (700°F), and above 480°C (900°F) in a day. In this study, a "spike above 370°C" is defined as a single thermal event in which the tube temperature increases above 370°C and then drops back below 370°C. Similarly, a "spike above 480°C" occurs when the tube temperature exceeds 480°C and then drops back below 480°C. **Figure 6** shows the results for the thermocouples installed on Tube S22 and Tube E67 in the southeast corner. The number of spikes above 370°C decreased significantly, from more than 50 spikes/day to less than 20 spikes/day, after the primary air flow was increased and the black liquor solids content was lowered on December 22, 2000. The number decreased further, to less than five spikes/day, after the solids content was lowered further to 72% on January 2, 2001. The effect was more dramatic on the number of spikes above 480°C; only a few spikes were observed in December 2000 after the changes were made, and virtually no spikes were observed during the entire month of January 2001.

The results were so encouraging that a decision was made to keep the operation of the boiler at 72% to 73% solids and the primary/secondary/tertiary air split of about 35/35/30. The average number of spikes exceeding 370°C (700°F) observed on Tube S22 and Tube E67 has been low (**Fig. 7**), averaging about two and five spikes/day, respectively. What is really important is that *the cracking problem appears to have stopped*. No further cracking was found during planned inspections in May 2001 and in May 2002.

Note that during the period from December 22, 2000, to the end of January 2001, the liquor temperature was held constant to eliminate it as a dominant cause of thermocouple activity. Beginning in February, changes were made to the digester controls, which lowered the residual alkali content of the black liquor. As a result, at the target % solids content, a higher liquor temperature was needed to control the bed size. The operator control strategy was to increase the liquor temperature if there was an indication of increasing liquor viscosity or increasing bed size. Thus, the liquor temperature became a secondary control parameter which could be altered, whereas, the % solids content was a primary control parameter which was to be held constant.

The small number of temperature spikes and the absence of cracking problem since the adoption of lower solids, higher primary air operation in December 2000 clearly suggest that the strategy works. Unfortunately, the same strategy resulted in an increase in carryover, more fouling in the superheater, and hence, lower boiler thermal efficiency. Therefore, we needed to find a compromise that would minimize temperature spikes and also generate more steam with minimal additional carryover. This may be possible by increasing the liquor solids content.

HIGHER LIQUOR SOLIDS TRIAL

Procedure

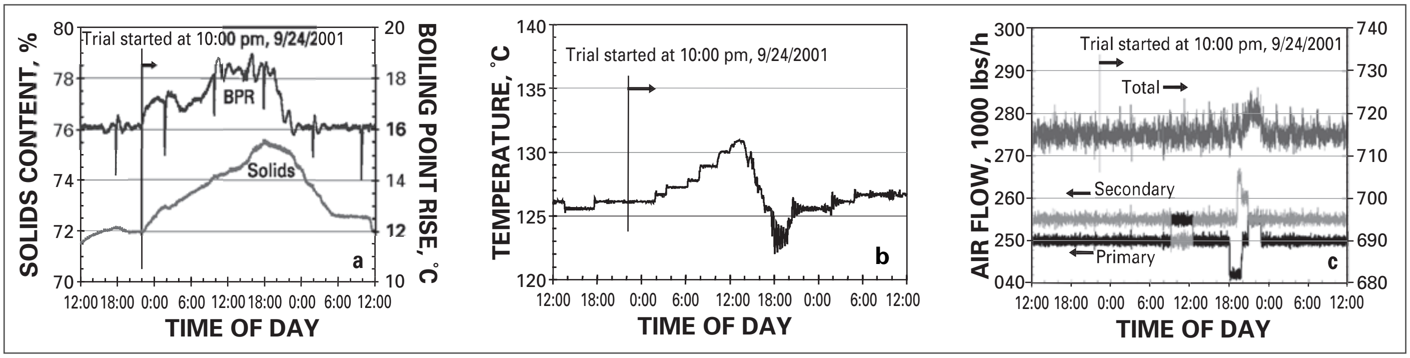
A higher-solids-firing trial was conducted on September 24, 2001 to examine if the number of temperature spikes can be maintained at a low level while the liquor solids content is increased. At 10 p.m. that day, the heating steam flow to the black liquor concentrator was increased to increase the liquor solids content. As is shown in **Figure 8a**, the solids content of the as-fired black liquor (measured by an on-line refractometer) increased gradually from an initial value of 72% to 75.5% at 6 p.m. on September 25, 2001 and then gradually decreased to 73% at about 6 a.m. on September 26, 2001. The change in liquor solids content was confirmed by the change in BPR of the concentrator liquor.

During the trial, while the solids content of the as-fired black liquor was changed, the total liquor firing load to the boiler was kept constant by adjusting the liquor volume flow rate. The steam production, pressure and temperature were constant throughout the trial. As the liquor solids increased throughout the day, the liquor firing temperature was increased to control the bed height (Figure 8b). The airflow distribution (primary airflow and secondary airflow) were occasionally changed to examine its effect on temperature spiking (Figure 8c). Char bed activity was documented using two camcorders to videotape the char bed through the primary air ports near tubes E67 and tube W67, and occasionally through the air port near tube S22.

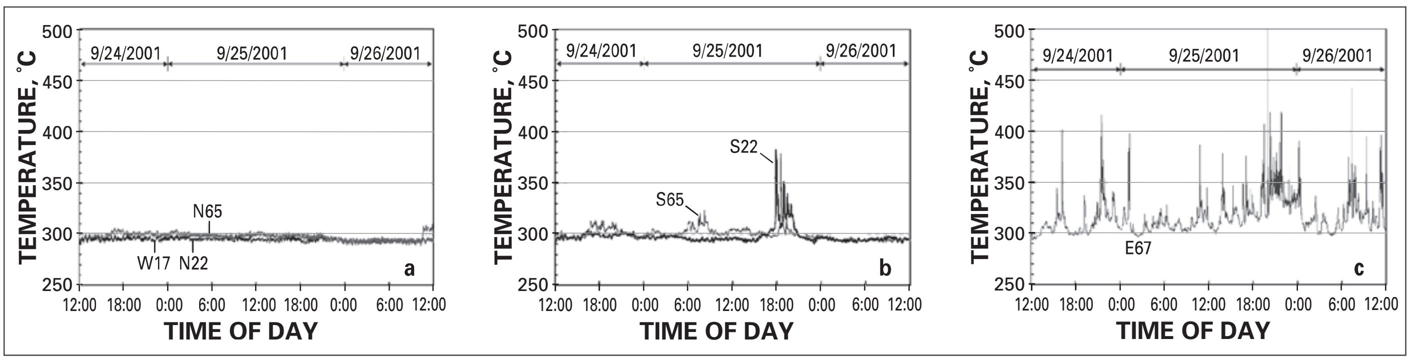
Results

Figure 9 shows the trial results. No temperature spike was observed on Tubes W17, N22 and N65 (Fig. 9a). This was consistent with the fact that no tube cracking has been experienced at primary air ports on the west (right) and north (front) walls of the boiler. On the south (rear) wall where smelt spouts are located, the thermal activity near Tubes S22 and S67 was also relatively low until 6 p.m. on September 25, when temperature excursions started to occur and last for 3 h (Fig. 9b). In contrast, Tube E67 on the east (left) wall showed erratic temperature variations with many temperature spikes observed between 6 p.m. on September 25, and 1a.m. the next day (Fig. 9c).

The on-set of high temperature excursions at 6 p.m. coincided with the time when the black liquor solids content reached the highest level, 75.5%, the black liquor temperature was at the lowest value, 123°C (253°F), and when the primary air was lowered from 250,000 lbs/h to 242,000 lbs/h (Fig. 8). These drastic operating changes were intentionally induced to allow the char bed to grow so that the effect of char bed on temperature spiking could be examined.



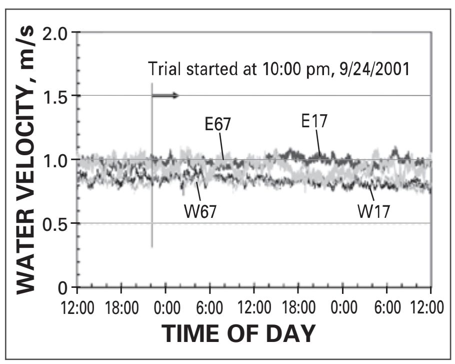
8. Firing conditions during September 24, 2001, trial, (a) as-fired black liquor solids content and boiling point rise; (b) as-fired black liquor temperature; (c) primary air, secondary air, and total air flow rates (tertiary air was not changed).



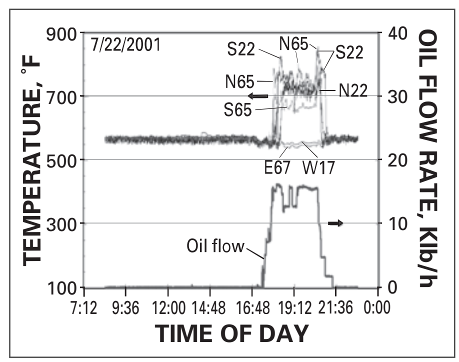
9. Tube temperatures at various primary air ports during the high-solids firing trial.

Visual inspection of the primary air ports in the southeast (rear-left) corner of the boiler at the moment the temperature spike at 6 p.m. occurred showed that the char bed was quite large, and was touching the tube E67. Examination of videotapes of the char bed recorded through the primary air ports near Tubes E67 and S22 also revealed that the conditions at these ports were extremely turbulent when the temperature excursions occurred. The char bed appeared to move toward the air ports, with a large pool of molten smelt present on the bed surface. In contrast, the conditions on the other side of the boiler (right sidewall) near Tube W67 were "calm;" the char bed appeared to be "normal" and was located away from the air port.

The trial confirmed that the high liquor solids content and the low liquor temperature are important factors in char bed growth, particularly when the primary air rate is low. If the char bed grows and burns intensely near the air ports, turbulent conditions with a large pool of molten smelt will result, which may lead temperature spiking. This is consistent with the observations by Falat [1] in his pioneering work on the mechanism of localized corrosion at primary air port tubes, which related the severe tube corrosion to the existence of relatively long-lived temperature excursions.



10. Velocities of cooling water in various tubes during the September 24, 2001, trial.



11. Effect of oil firing on tube temperature excursions (July 22, 2001).

EFFECT OF WATER CIRCULATION

The boiler is equipped with pitot tubes to monitor the water velocity in several tubes in the lower furnace. Extensive studies tried to find a correlation between water circulation and temperature spiking. No correlation has been found to date, suggesting that water circulation was not a cause of the cracking problem at the mill. **Figure 10** shows an example of the studies. During the high liquor solids trial, the water velocity in tubes that were monitored was relatively constant, 0.8-1 m/s. Tube E67 is of particular interest. No significant change in water velocity was found in this tube, despite a large number of temperature spikes observed (Fig. 9c).

EFFECT OF OIL BURNERS

There is an interesting phenomenon observed at this mill that may indirectly help identify the cause of temperature excursions. The tube temperatures at several primary air ports were found to consistently increase every time oil burners were operated. **Figure 11** shows an example of that. In this case, four of the six crown thermocouples showed an abrupt increase in tube temperature from 570°F to 750°F as the oil flow rate reached 16,000 lbs/h, and a sudden drop in temperature as the oil flow rate decreased. The magnitude of the temperature increase depended on the location of the oil burners that were in use and the oil flow rate burned at the time.

Mills operate oil burners only during boiler startup and shutdown, and when the black liquor flow is insufficient to maintain a steam production target. Since they are not in use most of the time, oil burners cannot be the cause of temperature spiking, and hence, tube cracking. However, the consistent occurrence of temperature excursions when oil burners were on implies that if a thermal condition similar to that encountered during oil burning occurred, there would be a tube temperature excursion. Although it is not clear what the thermal condition may be, flame impingement, radiation, and/or intense combustion near the tube surface may be a contributing factor.

IMPLICATIONS

The experience and results of studies at the mill clearly show that the severity of the primary air port cracking problem depends strongly on the frequency and magnitude of tube temperature excursions. By operating the boiler at conditions that produce few temperature spikes, the mill has brought the cracking problem under control. In this case, the two main operational changes that helped minimize temperature spikes are i) lowering the liquor solids content and ii) increasing primary air flow. In order to understand the root cause of the cracking problem, it is important to examine how these operational changes could lead to the observed decline in temperature excursions in the southeast corner of the boiler.

Under normal conditions, the tube surface temperature in the lower furnace is stable at about 300°C (570°F), due to the cooling effect of the saturated water that flows inside the tubes. In principle, in order for a temperature spike to occur on a tube at any location in the lower furnace, there must be a heat transfer imbalance at that location. In other words, the tube surface must be abruptly heated at a rate greater than the saturated water inside can cool it. Possible causes of heat transfer imbalance may include the following:

- A sudden increase in heat input to the boiler (sudden increase in liquor firing load, liquor heating value, etc.)
- Flame impingement on the tube
- Spalling and falling of char/frozen smelt from the waterwall, exposing the tube surface to the combustion gas
- Poor water circulation inside the tube
- Sudden contact of the tube with molten/flowing smelt and the subsequent oxidation of sulfide in the smelt
- Intense burning of black liquor directly on the tube
- Radiation from intense combustion that occurs near the tube.

The first three possible causes are unlikely to be important. If they were, cracking would not have been confined to locations near primary air ports. The fourth possible cause, poor water circulation, was not an issue in this case, as discussed earlier.

The last three causes are more plausible because these mechanisms require air, a condition that always prevails near the primary air ports. The experience at Irving Pulp & Paper suggests that the dynamics of the char bed near air ports may play an important role in the occurrence of temperature spikes. During the time when high tube temperature excursions occurred, the bed was highly unstable and turbulent, contained a larger quantity of molten smelt, and was located closer to the air ports than normal.

Even when the boiler was operated at a high liquor solids content, a low liquor temperature, and a reduced primary air flow (Fig. 8 at 6 p.m., September 25, 2002), only the primary air ports in the southeast corner near Tube E67 and Tube S22 suffered from high tube temperature excursions. The primary air ports at other locations had no temperature spiking problem. This suggests that it is not the high liquor solids content or the low liquor temperature, or the reduced primary air, per se, that caused temperature spikes, but rather the dynamics of the char bed (turbulent conditions, movement and size) resulting from the combined effects of these parameters are responsible for temperature excursions. The turbulent char bed conditions make it easier for the molten smelt to be in direct contact with the tube surface, and/or for the char and black liquor to burn near or directly on the tube surface. The heat released from direct combustion or from oxidation of sulfide in molten smelt may result in an enhanced heat transfer from the furnace to the tube, causing the tube temperature to rise at the moment of contact. Therefore, it is critical to operate the boiler under conditions that keep the char bed away from the air ports. Lowering the liquor solids content, increasing primary air flow and increasing the liquor temperature are all the operating parameters that help make the char bed smaller and/or prevent the char bed from build-up near the air ports.

SUMMARY

This systematic study examined the cause of severe cracking of SS304L/SA210 composite waterwall tubes at primary air ports, membrane bar wastage, and cracking of butt welds located between the bottom of the primary air ports and the floor in the recovery boiler at the Saint John mill. The results show that the severity of the problem was strongly related to the frequency and the magnitude of tube temperature excursions at the air ports, which were greatly affected by the char bed dynamics near the air ports.

The cracking problem has been significantly minimized by operating the boiler at a lower black liquor solids content and at a higher primary air flow. These conditions appear to keep the char bed away from the air ports and help reduce tube temperature excursions.

In addition to the operational changes described above, computational fluid dynamic modeling has been used to examine the air flow and liquor spray patterns in the lower furnace. Based on the modeling results, two additional air ports were installed to the secondary air system during the May 2002 shutdown; one was near the rear-left (SE) corner of the boiler and the other near the front-right (NW) corner. These ports were installed in an effort to eliminate the recirculation flow patterns in both corners of the furnace to minimize carry-over, while maintaining the thermocouple activity low to avoid the primary air port cracking. The effect of these new ports on temperature spiking and boiler operation is being evaluated, although the data obtained to date shows that the number of temperature spikes in the rear-left (SE) corner of the boiler has been drastically reduced. **TJ**

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LITERATURE CITED

1. Falat, L., *TAPPI J.* Vol. 79(2): 175(1996).
2. Keiser, J.R., Singbeil, D.L., Chowdhury, K.A., et al., "Characterization of primary air port cracking in black liquor recovery boilers", Proceedings of the 10th International Symposium on Corrosion in the Pulp and Paper Industry, Vol. 1, p. 89-102, 2001, VTT, Finland.
3. Keiser, J.R. et al, "Recent observations of recovery boiler primary air port cracking and characterization of environmental conditions," Proceedings of the 2001 TAPPI Engineering Conference, Session No. 24, TAPPI PRESS, Atlanta, Georgia, USA.
4. Mackenzie, C.M. Hiner, L., Wessel, R., Constable, G., and Diduch, G., "Irving recovery boiler upgrade: advanced designed techniques to increase capacity and improve cleanability," Proceedings of 1997 TAPPI Engineering Conference, TAPPI PRESS, Atlanta, p. 1365-1394.

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INSIGHTS FROM THE AUTHORS

We selected this topic to research because it is a very important subject from a boiler operation point of view and because it fits well with our expertise. This work helped me greatly in devising critical experiments at the university to determine the main factors causing high tube temperature excursions and cracking near primary air ports.

The most difficult aspect of this research was to determine the interaction between one boiler operating variable and another in the recovery boiler. It is often difficult to pinpoint the exact cause of the problem. We needed to conduct a systematic analysis of boiler operating conditions and use our knowledge of boiler operation and black liquor combustion.

Despite the complexity of the problem, we were fortunately able to sort out the main boiler operating parameters that led to the cracking problem.

As a further step, we will closely monitor the cracking conditions of the tubes and make sure that the problem is under control. We will also conduct experiments in the laboratory to verify some of the hypotheses and to examine if we can reproduce the tube cracking conditions in the laboratory.

— Honghi Tran

Tran and Vafa are with the University of Toronto, Toronto, Ontario, Canada; Milbury, Blaney, Piroozmand, Roherty, and Mott are with Irving Pulp & Paper Ltd., Saint John, New Brunswick, Canada; and Anderson and Rivers are with Babcock & Wilcox Canada, Cambridge, Ontario, Canada. Email Tran at tranhn@chem-eng.toronto.edu.


Tran


Vafa


Milbury


Blaney


Piroozmand


Roherty


Mott


Anderson


Rivers