Experiences with lower furnace tube cracking in a recovery boiler

ROB VESAK, BILL DOWNING, MIKE GAUTHIER, SALLY HOWARD, DOUG SPIRING, LAURA NEELS, AND HONGHITRN

ABSTRACT: The recovery boiler at the DMI Peace River Pulp Mill experienced severe cracking of composite tubes made of stainless steel 304L/SA210. Cracking occurred in tubes on the furnace floor, at primary air ports, at smelt spout openings, and at composite-to-composite butt welds in the lower furnace. The problem of cracking in the primary air ports was related to frequent temperature excursions in the tubes. These temperature variations were caused by the location and configuration of the tertiary air system and by the operation of the six-on-six interlaced secondary air system. Modifications made to the boiler have minimized the cracking problem. The elevation, size, and number of tertiary air ducts were changed, and the interlacing of the secondary air was reconfigured. A number of the SS304L/SA210 composite tubes were replaced with rotary-welded and co-extruded Inconel 625 and 825 tubes.

Application: By making modifications to the recovery boiler, mills can alleviate temperature variations that lead to cracking in boiler tubes.

At the DMI Peace River Pulp Mill, the recovery boiler has had a long history of cracking problems. Most of the lower furnace cracking has been on the stainless steel 304L-clad composite material. The cracking problems in the lower furnace include floor tubes, smelt spout openings, primary air port openings, and composite-to-composite butt welds of replacement tubes. Of these, the cracking of primary air port tubes is the most serious problem.

In collaboration with Babcock & Wilcox Canada, Oak Ridge National Laboratory, and the University of Toronto, the Peace River mill conducted several trials and investigations to identify the cause of cracking of the primary air port tubes. As a result of these studies, the mill has taken actions to alleviate the cracking of these tubes. These investigations and experiences are presented here.

BACKGROUND

The recovery boiler at the Peace River Pulp Mill of Daishowa Marubeni International (DMI) is a Babcock & Wilcox two-drum unit built in 1990. It was designed to burn 1720 metric tons of black liquor dry solids per day and to produce 250 metric tons/h of steam rated at 925 psig and 850°F (454°C).

The lower furnace walls are made of stainless steel 304L/SA210 composite tubes, 2.5 in. in diameter on 3-in. centers, up to the tertiary air level 40 ft above the sloped floor. The floor has an area of 11.2 m x 10 m. The 10 floor tubes adjacent to the side wall are made of stainless steel 304L/SA210 composite material. The remaining 98 floor tubes in the center area are studded carbon steel tubes.

The boiler burns hardwood liquor most of the time and softwood liquor three to four times a year, with 16–30 days in each run. It also burns dilute noncondensable gases at the secondary air level. Black liquor is fired at 68–75% solids at 116–125°C through four stationary nozzles, one located on each wall. The boiler has three air levels, with interlaced secondary air on the left and right walls and interlaced tertiary air on the front and rear walls. The liquor firing rate has increased over the years to about 2250 tons/day.

Although cracking in the composite tubes has not resulted in a tube leak, the boiler has been shut down biannually for complete inspections of the areas of concern as a precautionary measure. The mill shut down in the tube repair and replacement program in the lower furnace, reflecting an inspection window in the spring (March, April) and a repair window in the fall (September, October). The mill has undertaken steps to move towards a single shutdown per year, with the cracking problem of the primary air ports being the largest obstacle in the way of this initiative.

This work included several approaches, with records kept over a number of years. Metallurgical analyses were carried out to determine the main cracking mechanisms. In the primary air ports, 625 and 825 Inconel weld overlay or co-extruded tubes were installed and evaluated as to their performance. Thermocouples and flow elements were installed on several primary air port openings to monitor temperature and flow excursions. The investigation team used a video camera and a specially designed thermal probe to examine the flow dynamics and the thermal activity of the char bed near the primary air ports. Trials were also conducted to determine whether or not boiler operating variables could be tuned to reduce the frequency and magnitude of variations in tube temperature.

CRACKING EXPERIENCE

Floor tubes

Cracking has occurred in the 304L “smelt run” composite floor tubes. The cracks were found only in the 304L clad material and did not extend into the carbon steel of the tube. Most of the cracks appeared to have been associated with residual stresses remaining in the tubes from the boiler fabrication. Some cracks were found at locations where lifting lugs were welded to the floor. Other cracks appeared to have been caused by a heating torch; these cracks had a circular shape and included several tubes adjacent to one another in the sweep.

To minimize future floor tube cracking, the mill has started high pressure washing the furnace floor during each shutdown. The purpose is to minimize the amount of moist smelt coming in contact with the floor tubes while the boiler is warming up after a major outage.

Spout openings

Most of the tube cracking of the spout...
openings occurred on the cold side of the weld to a seal plate used for the fit up and sealing of the spouts. The problem of spout tube cracking was rectified by grinding off the seal plates and replacing them with casting inserts. This change eliminated the need for a weld attachment on these tubes.

In 1996, the spout opening tubes of 304L stainless steel were replaced with 825 Inconel co-extruded tubes. The positive experience with the co-extruded 825 tubes in this location was one of the supporting factors in the mill's decision to try co-extruded 825 tubes in the location of the primary air ports. The crotch areas of several primary air ports were discovered to have cracking problems in April 1991, after less than a year of service. Most of the cracks were in the membrane between the air port tubes, with only a few of the cracks migrating into the tubes. This area of the boiler has been consistently inspected during each subsequent shutdown. Cracks found were repaired as part of the boiler semi-annual maintenance program.

In September 1995, an emergency shutdown procedure (ESP) was performed on the boiler after a tube leak was discovered on the front wall, about 4 m above the furnace floor. (This leak was not related to the primary air port cracking.) The analysis of tubes near the leak area revealed massive copper deposits on the water side of the tubes. The boiler was shut down for 22 days for a mechanical and chemical cleaning.

During this outage, the entire lower furnace was inspected with a scanning ultrasonic testing technique. Dye penetrant tests were also carried out at every opening. The inspection revealed a significant number of cracks in the crotch areas of the primary air ports. Most of the cracks were located in the left-rear and the right-front corners of the boiler. The inspectors discovered more cracks going into the tube material during this outage than in any previous shutdown. The monitoring of this area was intensified, and the mill personnel began recording the crack depths in the tubes.

In 1996, cracks were found on the primary air ports randomly spaced down from the bottom of the port to approximately 0.15 m below it. The cracking occurred on the tube hot side inside of the crotch bends and on the crown of the tubes. This cracking did not appear to be associated with membrane welds. Figure 1 shows transverse cracks revealed by dye penetrant testing in October 1997. Several of these cracks were found to have propagated completely through the 304L layer and into the carbon steel, as shown in Fig. 2, where the cracks have been excavated.

To reduce the risk of cracking caused by weld overlay, the mill changed its crack repair procedure, leaving exposed the ground-out areas of crack excavation, as long as it did not compromise the design minimum thickness of the tube wall. Tubes were repaired or replaced where multiple cracks were found to have penetrated the carbon steel of the tube or where the crack depth breached the design minimum thickness. Future inspections of these excavation sites have shown minimal loss of carbon steel through corrosion. Only in a few cases have we observed cracks in the same location of the excavation. A significant reduction in cracking was noted in 1997 after this procedure was adopted.

In 1997, cracks were discovered on the butt welds of several tubes in the lower furnace. The tube installation technique was consequently changed to include blending any butt welds in the lower furnace to be flush with the existing tubes. All previous butt welds in the furnace were also dressed to ensure that they were flush with the tube metal. When tubes were replaced after 1997, care was taken to ensure that the lower
termination weld was located in the lower vestibule. These two procedural steps successfully minimized the problem of butt weld cracking.

Another significant step taken in 1997 was to halt the use of 304L/SA210 composite primary air port tubes. This step was taken after the discovery that tubes placed in service the previous year needed to be replaced because of cracking. The search began for a tube that would provide improved performance in the position of the primary air port.

**METALLURGICAL ANALYSIS**

Primary air port tubes from the left wall were removed and sent out to three different test facilities for metallurgical analysis in 1997. The tube inspections revealed cracks ranging in depth from shallow (0.020 in.) to deep (0.160 in.), with the deep cracks penetrating into the tube’s minimum design thickness. Figure 3 illustrates the problem.

Based on their findings at the time, the three test facilities provided different opinions of the exact cause of cracking. However, a constant theme narrowed the cause to two failure modes: mechanical and thermal cyclic fatigue.

From an operational perspective, it was difficult to understand how the mechanical cyclic fatigue could have been the cause, since the cracking areas did not appear to be exposed to any greater cyclic loading than any other area of the furnace. The only time the boiler may experience mechanical cycles of any significance would be during startup and shutdown. Although this theory would explain why so many cracks were discovered after the boiler ESP in 1995, it did not explain the cracking found in 1996 or 1997. Furthermore, if the cracking was caused by mechanical cyclic fatigue, we should have seen a reduction after the number of water washes changed from four times a year to twice a year.

We therefore directed our main focus on resolving cracks caused by thermal cyclic fatigue.

**IMPROVED METALLURGY**

Based on the results of material performance studies at Oak Ridge National Laboratory and PAPRICAN [1, 2], we selected the 625 rotary-welded Inconel-clad tubes as our preferred replacement metal, followed in later years by co-extruded 625 and 825 Inconel. In 1998, the first 625 rotary-welded Inconel tubes were installed in several primary air port locations. These tubes were inspected after six months in operation and were found to have held up well compared to the 304L/SA210 composite tubes.

Subsequent inspections in 1999 showed that the 625 Inconel tubes performed well, although cracking was found at the crotch of the tubes in the membrane. Figure 4 shows an example.

There were also indications of cold side corrosion between the port casting and the back side of the port.

Several 625 rotary-weld tubes awaiting installation in the furnace were inspected. This inspection revealed cracks in the crotch of the primary air port membrane even before it had seen service. This finding introduced another variable into the mix of problems that could be causing cracking in the tubes. This problem, however, was simpler to resolve because we were able to work with the tube supplier. The tube supplier changed the in-shop welding procedure to minimize the probability of cracking. On our part, we changed our acceptance criteria to include tube inspection at the supplier’s shop prior to delivery.

Air port tubes made of 625 rotary-weld material with a “G-Best” treatment were installed during the boiler outage in Fall 2000. No cracks were found in these tubes during the inspection in Spring 2001. However, a rapid thinning was noted on a tube metal adjacent to a trial primary air port casting installed six months earlier. The tube metal was grooved at the interface of the primary port casting with a wall loss of approximately 1.5 mm in six months. Figure 5 shows an example from April 2001.
After we changed the trial air port casting back to the original design, we noted little or no further tube loss.

In Fall 2001, after five years of successful use of the 825 Inconel co-extruded tubes for smelt spout openings, we decided to try them in the location of primary air port No. 29 on the left wall. At the same time, we installed the 625 Inconel co-extruded tubes in an air port nearby for comparison purposes. The design of the air port was also changed to one that had an opening slightly taller than the original openings, with a gradual slope towards the crotch of the port, as shown in Fig. 6.

Even with the superior tube materials and designs used, primary air port cracking has occurred in the same corners of the boiler. This experience led us to believe that it is difficult to correct the cracking problem with design and metallurgical changes alone.

The intensity of the cracking problem may be expressed as cumulative crack depth, which is the sum of all crack depths measured on air port opening tubes during each major inspection. This number is reset to zero when the tubes are replaced with new ones. Figure 7 shows the cumulative crack depth of various primary air ports on the left-hand wall of the boiler since 1995. The cumulative crack depth of Port No. 28 dropped from 0.6 in. to zero in Fall 1998 as original 304L stainless steel tubes were replaced with 625 Inconel overlay tubes. The replaced tubes did not experience any cracking until Spring 2000, when their cumulative crack depth was about 0.1 in. The cracks were ground out, and the tubes have only seen minor cracking since then.

**TUBE TEMPERATURE AND WATER FLOW**

During the September 2001 outage, twelve thermocouples were installed on the lower bend of primary air port tubes on the side walls to monitor tube temperatures. (There were two thermocouples per port and three ports per each side wall: two near corners and the other at the center.) As Fig. 8 shows, the data obtained from these thermocouples consistently showed a much greater thermal activity (i.e., larger and more frequent temperature spiking) in the left-rear and the right-front corners of the boiler than in other locations. The location of this higher thermal activity coincided with the locations of the worst cracking in the furnace.

Six water flow elements were also installed on the side walls to determine if there was any anomaly in water flow inside tubes during upset conditions. The circulation of water flow in the wall tubes at all six locations during normal operation showed little variability, with some indications of unstable flow during startup periods. Changes in boiler water circulation were not observed during periods of high thermal activity on the tubes. The flow indications in the tubes allowed us to rule out water circulation as a contributing variable. These results were consistent with those found in other boilers [3].

**BOILER OPERATION TRIALS**

In collaboration with Babcock & Wilcox Canada and the University of Toronto, we conducted three trials to determine if we could reduce the thermal spikes by adjusting the boiler operating parameters. During the first trial in October 2001, we used a thermal probe and a video camera to record the gas temperatures and char bed dynamics near the primary air ports. The second and third trials were conducted in June 2002 and April 2003 with distributed control system and visual confirmation of the thermal events indicated by tube thermocouples.
Secondary air distribution
Of all parameters tested, the one that appeared to have the most impact in reducing the frequency and magnitude of temperature spikes was the change in the secondary air configuration. The original design of the secondary air port was an interlaced six-on-six configuration, as illustrated in Fig. 9. We tested various configurations to find one that would not only reduce thermal spiking but would also provide stable boiler operation, an even O₂ distribution, low carryover, lower dregs, and low SO₂ emissions.

In the effort to improve the distribution of the secondary air, two additional secondary air ports were installed in the side walls during the Fall 2002 outage. The openings were identical in design and shape to the existing secondary air ports. The new ports were located in the right front and left rear approximately 30 in. from the front and rear walls. The air configuration in Fig. 10 was trialed between Oct 2002 and March 2003. During boiler air trials, these ports were found to reduce the frequency of thermal spikes in the corners somewhat. However, they created problems with the bed and the side-to-side oxygen distribution.

When the third trial was completed in April 2003, a new configuration was discovered that provided greater thermal stability and a reduction in side-to-side O₂ deviation. Illustrated in Fig. 11, it is a two-on-two secondary air arrangement. Small adjustments of one to two notches are occasionally required on several of the secondary air dampers to reduce thermal spiking events. Other configurations resulted in an unstable char bed, side-to-side O₂ splits, or high SO₂ emissions and/or high carryover.

The main concern over the two-on-two secondary air configuration is that the floor tubes are bare in the center of the furnace. Operating with exposed carbon steel pin-studded tubes for extended periods of time can result in excessive tube stud waste and possible damage of the floor tubes. By reducing the side-to-side oxygen deviation, we reduced the gas swirl in the furnace.

Changes were also made in the air splits for better air distribution. The new air splits evenly divided the air between the primary, secondary, and tertiary levels. The increased air pressure and flow from the primary air port now acts to keep the bed further away from the port tubes, in turn reducing the frequency of thermal spikes.

Liquor nozzles
Multiple configurations of liquor distribution were tested to find the liquor setup that best fit the air configuration. Trials were carried out in which we altered the nozzle design, the liquor temperature, the splash plate angle, and the liquor gun angle. The results showed that the 38 liquor guns at a 45° angle provided the best liquor distribution when we were running the two-on-two secondary air configuration. The results also showed that liquor nozzle angles played a significant role in bed stability and boiler excess oxygen.

There was a good relationship between excess oxygen, carryover, and the angle of the liquor nozzle on the right side wall. High carryover was usually observed on the left side of the furnace, indicating that a greater degree of combustion could be taking place on that side. When the liquor gun on the right wall was raised to –2° from –17°, an immediate decrease in O₂ concentration on the right side of the furnace was observed. On the other hand, the O₂ concentration increased immediately when the liquor gun was lowered to –20°. We found that we could maintain the oxygen deviation at a split of less than 0.5% O₂ by decreasing the gun angle to –30°.

Possible cause of primary air port cracking
Most of the tube cracking for the primary air ports occurred in the left-rear and right-front corners of the boiler where high thermal activities usually prevailed. This circumstance indicates that temperature spiking could play an important role in tube cracking. The most probable cause of temperature spiking was the smelt activity and flow directly below the primary air ports.

Results of the boiler operating trials, tube temperature measurements, observations of char bed dynamics near the air ports, and the experiences of primary air port cracking at another mill [3] indicated that the circulation of the furnace combustion gas was an important parameter. The tertiary air, the interlaced six-on-six secondary air system, and air splits between the primary, secondary, and tertiary air ports contributed greatly to the cracking of the primary air port tubes.

Prior to the tertiary air upgrades and relocation, combustion flow modeling was performed on the boiler. The results showed that the tertiary air level created a significant downward air flow that disrupted the air flow patterns at the secondary air level. Similar modeling work completed for the new air port design indicated a significant reduction in disturbance and down draft. This change in the tertiary air may have contributed to the reduction from 1998 to 2001 in the number of tubes that have cracks. This trend is presented in Fig. 12.

Temperature spikes occurred after material dropped from the walls and was pushed toward the primary air ports. The liquor distribution and furnace combustion gas flow caused the bed material to build up on the walls in the two corners of the boiler at the liquor gun level. When a large char buildup on the wall fell onto the bed, tube temperatures spiked. This phenomenon was witnessed and verified during the boiler operation trials. Although the spike did not occur every time material dropped from the walls, it did occur often enough to suggest that this kind of event was one of the main causes of temperature spikes.

The tubes with the most severe cracking problem (the left-rear and right-front corners of the boiler) are located directly across from secondary air jets. The secondary air level directly above the cracking primary air ports was a blank wall of tubes. By closing down on secondary air ports S6 and N6 (Fig. 11), or shutting them completely, we were able to reduce the swirl in the furnace, and the buildup on the walls above these corners was reduced. The material still builds up, but when it drops off the wall it is less likely to be pushed into the front of the primary air port, because of the opposing
secondary air and the combustion gas swirl in the furnace. The increased primary air pressure also assists in keeping the material away from the port.

**REMEDIAL MEASURES AND RESULTS**

The trials indicated that the secondary air configuration had the greatest influence on the thermal spiking at the primary air ports. Several actions were taken in trying to solve the problem of composite tube cracking in this boiler. Determining the relative benefit of any one of the following actions is difficult, but collectively, they are felt to have reduced the severity of cracking:

- Relocating the tertiary air ports and changing the air port layout in 1998
- Changing the secondary air system configuration to a two-on-two configuration
- Reallocating the division of air between the primary, secondary, and tertiary air levels, thus increasing the primary air flow by 8%
- Using improved metallurgy for port tube cladding
- Modifying the air port design to one with a gentle transition toward the primary air port crotch
- Changing the procedures for repairing primary air port tubes in 1997 and for replacing them in 1996.

The changes have reduced the magnitude and frequency of primary air port cracking. Cracking was reduced from a high of 67 tubes discovered with cracks in 1996 to an average of less than 10 tubes with cracks per inspection in 2003. The cumulative crack depth was also reduced from a high of 1.5 in. in October 1995 to less than 0.100 in. in June 2003.

The changes in the boiler operation, port design, fabrication process, and metallurgy of the port opening were all needed to reduce the cracking of the primary air ports to an acceptable level. In 2003, we changed the shutdown from a six-month cycle to a nine-month cycle. In 2004 we have successfully moved to a single shutdown per year. TJ

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**INSIGHTS FROM THE AUTHORS**

Boiler tube cracking represents a high cost and a high risk to the pulp and paper industry. The causes of cracking in the lower furnaces of recovery boilers are probably similar from mill to mill. The approach we took to solving the problems may be helpful to mill engineers contending with the same kind of difficulties.

The greatest challenge in this research was the sampling period. Inspections of the primary air ports were being completed every six months. Changes were made to the furnace, and the positive results of the changes could not be seen until the unit was inspected six months later. The most surprising discovery was how sensitive the furnace was to what appeared to be minor operational changes.

We will keep monitoring the primary air ports to ensure that the cracking continues to diminish in size and frequency. Tube replacement will be done on an as-needed basis until most of the primary air ports with a tendency to crack are upgraded to an improved metallurgy.

Mill personnel may benefit from this work by gaining a better understanding of the issue and putting that knowledge to work in inspecting for cracking problems. We hope they will find our experiences helpful in trying to solve the cracking problems that may be occurring in their own furnaces.

Vesak, Downing, Gauthier, Howard, Spirig, and Neels (photo not available) are with the Daishowa-Marubeni International Peace River Pulp Mill, Peace River, AB, Canada. Tran is with the Pulp & Paper Centre, University of Toronto, Toronto, ON, Canada. Email Veska at rveska@prpddmi.com.