Cracking and corrosion performance of composite tubes and air port designs in a kraft recovery boiler

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Abstract: Alternative composite tube systems fabricated into two different port designs were installed in a kraft recovery boiler to evaluate their effectiveness in solving a composite tube cracking problem. Test ports have been examined for cracking and corrosion of the cladding/overlay every six months since the time of their installation. Test ports with co-extruded modified A825/carbon steel composite tubes, and port design designated “B” were the only one where no cracking or corrosion was found on any of the tubes after 30 months of exposure.

For one of Paprican’s member company mills, severe cracking of the 304L composite tubes has been a major problem in and around primary air ports. Cracks were discovered during the first inspection (October 1998) after start-up and have been found in every six-month inspection since [1]. The recovery boiler is a 1997 Babcock and Wilcox (B&W) unit constructed with 2¼-in. (63.5-mm) diameter tubes on 3-in. (76.2-mm) centres, a sloped floor and a single drum. The boiler’s maximum capacity rating (MCR) is 3.6 million lbs/d (1.18 million kg/d) of black liquor dry solids producing superheated steam at 619,350 lb/h (280,884 kg/h) at 1,525 psig (10,512 kPa), maximum design pressure. Cracks in this location (primary air port) can propagate into the carbon steel, thereby increasing the risk for a water leak and subsequent explosion resulting from a smelt-water reaction. This is unlike the situation for composite floor tubes where cracks propagate no further than the stainless steel/carbon steel interface [2]. Inspecting and repairing primary air ports every six months represents a significant expense for the mill.

The mill investigated three possible changes to resolve the cracking problem in and around primary air ports. These include a change in composite tube metallurgy, in air port design and/or fabrication method, and in operating conditions for the boiler. To explore the merits of using an alternative composite tube and/or port design, the mill installed several test panels containing various combinations of alternative composite tubes and port design. These panels have been examined for cracking and corrosion every six months since the time of their installation. A liquid dye penetrant method, performed by a contracted inspection company, was used to assess cracking, whereas cladding/overlay thickness measurements, performed by Paprican and ORNL, were used to assess fireside corrosion. This paper summarizes the major results of a comparative performance analysis of the test panels to date. A more detailed report is provided elsewhere [3].

Evaluation Details

Table I shows an overview of the six test panels installed. The panels were installed at primary air port locations where frequent cracking of the original co-extruded 304L stainless steel/carbon steel composite opening tubes occurred. Three different exterior layer compositions were installed, namely the conventional 304L stainless steel, Sanicro™ 38 (a modified version of Alloy 825) and Unifuse™ 625 (a weld-overlaid version of Alloy 625). The GBEST™-processed tubes were given a propriety thermal-mechanical surface treatment, prior to panel fabrication in an attempt to improve the resistance to cracking (and corrosion). Specific details pertaining to mechanical and physical properties, corrosion resistance, as well as limited case histories of these alternative composite tubes in recovery boilers, have been published by the respective supplier elsewhere [4-6].

Two different port designs were installed. As Fig. 1 shows, these two designs (A and B) are fundamentally different since the smaller bending angle and larger bending radius means that port
B has less severe bends. Port A is the conventional B&W design originally installed in the boiler, and Port B is the Kvaerner Type G design [7]. Both designs contain a casting insert that was bolted to the opening tubes from the cold side, which was sealed using a refractory compound. A different casting insert was installed on the test ports fabricated into the A design than was installed on the similarly-designed ports originally installed in the boiler to increase the contact area with the opening tubes. There are three major differences between the two casting inserts worth mentioning. First, those installed in the test panels are significantly deeper (extending farther into furnace) than those installed in the original ports. Second, the fit between the casting insert and the opening tubes is much tighter for the deep inserts than the shallow inserts. Third, an attempt was made to seal the deep inserts using a refractory compound, whereas no attempt was made to seal the shallow inserts in the originally installed ports. It is also noted that different membrane termination welding procedures were used to improve the resistance to cracking in this location. The procedure used to fabricate the GBEST/CS and A825Mod/CS panels differed from the one used for the A625WO/CS panel, which in turn was different from that used for the 304L/CS ports originally installed in the boiler.

Opening tubes installed in the six primary air port test panels were inspected for cracks using a liquid dye penetrant technique during each six-month shutdown after the panels were installed according to procedures documented elsewhere [8,9]. All cracks were documented by photographs. Crack indications identified by dye penetrant testing were carefully removed by surface grinding after each inspection. Cladding/overlay thickness measurements were made during each shutdown using an Elcometer 345 digital thickness gauge. For ports comprised of weld overlaid composite tubes, measurements were made at each weld spiral extending from five spirals below the BMT to five spirals above the TMT on each tube. For ports comprised of weld overlaid composite tubes, measurements were made at each weld spiral extending from five spirals below the BMT to five spirals above the TMT on each tube. Two measurements were taken across each tube at each elevation, one adjacent to the casting insert or membrane and the other at a distance of approximately ½-in. (12.7-mm) towards the fireside crown.

**RESULTS**

**Crack Inspections:** The results of the crack inspections are summarized in Table II as a function of time. Crack indications were classified as being either a tube crack (T) or a membrane crack (M). Tube cracks include those indications, both circumferential and craze cracks, found isolated in the tube. Membrane cracks include those indications found in either the membrane itself or in the membrane-tube weld. No tube or membrane cracks were found in the A825Mod/CS ports (LHW10-12 and RHW20-22), regardless of port design, during any of their four inspections. Tube cracks were found on more than one inspection in two of the four 304L/CS ports installed with the B design, whereas repetitive membrane cracks were found in only one these four ports. Membrane cracks were found in all six A625WO/CS ports (LHW 13-15 and RHW 10-14) after 12 months of exposure. Membrane cracks were found in all six ports at one period or another during subsequent inspections. No crack indications were found in the two GBEST/CS ports (LHW 23-24) during their first four inspections. However, during the last inspection reported, both tube and membrane cracks were found. The crack indications found in the GBEST/CS ports were located in the top membrane termination, as opposed to the bottom membrane termination, where all other crack indications reported were found. Representative photographs of the various crack indications found are included in Fig. 2.

**Corrosion Measurements:** Figure 3 compares the thickness distribution of the "worst case" opening tube from each of the six test panel as function of elevation and time. Areas of cladding thickness loss were found on co-extruded opening tubes, which depended on the metallurgy and port design. For the A825Mod/CS opening tubes (LHW 10 & 20), a loss in cladding thickness was only observed on the tubes fabricated into the port design A (LHW 20), and it occurred in a range from the BMT to an elevation corresponding to the bottom of the casting opening. In contrast, for the 304L/CS opening tubes fabricated into port design B (RHW 25), the major thickness changes (losses) occurred in a range from and to an elevation corresponding to the top of the casting opening to the TMT, respectively. One notes that this corrosion
occurred during the last reported six-month interval, coinciding with a degraded seal between the casting insert and the opening tube. A loss in overlay thickness was found on both weld-overlaid composite tubes, A625WO/CS (RHW 11 and LHW 13) and GBEST/CS (LHW 24), fabricated into port design A. This corroded area (elevation) is similar to the corroded area found on the A825Mod/CS tubes (LHW 20) fabricated into the same port design. The A625WO/CS tubes fabricated into port design A had the greater cladding/overlay thickness loss of all alternative composite tube-port design combinations. The majority of this loss occurred during the first 12 months of exposure. Significant changes were made to the liquor delivery system and the combustion air system during this time, which may have affected corrosion. Interestingly, similar losses in cladding thickness were not observed for any of the 304L/CS opening tubes fabricated into port design B during this period. At elevations not within the aforementioned thinning range, thickness measurements were reproducible on both types of composite tubes (co-extruded and weld overlaid). For example, both sets of measurements (October 2000 & April 2003) made on the A825Mod/CS opening tubes installed during the October 2000 shutdown (LHW 10 & LHW 20) mapped the local variations in cladding thickness that were introduced by the bending operation.

**COMPARATIVE PERFORMANCE**

It is stressed here that several major changes to the boiler’s operation, liquor delivery and combustion air arrangement in particular, were made to reduce the occurrence of cracking in the mill’s boiler after the installation of the test panels. These changes did coincide with a significant reduction in the number of cracking indications of the 304L/CS opening tubes originally installed in the boiler. Consequently, the test panels were not exposed to same boiler operating conditions that were present prior to and during their

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**TABLE II. Results of liquid dye penetrant crack inspections.**

<table>
<thead>
<tr>
<th>Port Opening</th>
<th>Composite Tube</th>
<th>May 00</th>
<th>Oct. 00</th>
<th>Apr. 01</th>
<th>Oct. 01</th>
<th>Apr. 02</th>
<th>Oct. 02</th>
<th>Apr. 03</th>
</tr>
</thead>
<tbody>
<tr>
<td>RHW-10</td>
<td>A625WO/CS</td>
<td>None</td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>N/M</td>
<td>R/B</td>
<td></td>
</tr>
<tr>
<td>RHW-11</td>
<td>A625WO/CS</td>
<td>None</td>
<td>M</td>
<td>None</td>
<td>T,M,M</td>
<td>M</td>
<td>N/M</td>
<td>R/B</td>
</tr>
<tr>
<td>RHW-12</td>
<td>A625WO/CS</td>
<td>None</td>
<td>M</td>
<td>None</td>
<td>T,M,M</td>
<td>M</td>
<td>N/M</td>
<td>R/B</td>
</tr>
<tr>
<td>RHW-13</td>
<td>A625WO/CS</td>
<td>None</td>
<td>M</td>
<td>M</td>
<td>T,M,M</td>
<td>M</td>
<td>N/M</td>
<td>R/B</td>
</tr>
<tr>
<td>RHW-14</td>
<td>A625WO/CS</td>
<td>None</td>
<td>M</td>
<td>None</td>
<td>T,M,M</td>
<td>M</td>
<td>N/M</td>
<td>R/B</td>
</tr>
<tr>
<td>LHW-13</td>
<td>A625WO/CS</td>
<td>None</td>
<td>M</td>
<td>None</td>
<td>M</td>
<td>M</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>LHW-14</td>
<td>A625WO/CS</td>
<td>None</td>
<td>M</td>
<td>None</td>
<td>T,M,M</td>
<td>M</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>LHW-15</td>
<td>A625WO/CS</td>
<td>None</td>
<td>M</td>
<td>None</td>
<td>None</td>
<td>M</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>LHW-20</td>
<td>A825Mod/CS</td>
<td>N/I</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>LHW-21</td>
<td>A825Mod/CS</td>
<td>N/I</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>LHW-22</td>
<td>A825Mod/CS</td>
<td>N/I</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>LHW-23</td>
<td>GBEST/CS</td>
<td>N/I</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>T</td>
<td></td>
</tr>
<tr>
<td>LHW-24</td>
<td>GBEST/CS</td>
<td>N/I</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>T,M</td>
<td></td>
</tr>
<tr>
<td>RHW-25</td>
<td>304L/CS</td>
<td>T^2</td>
<td>T^3</td>
<td>T^2</td>
<td>T</td>
<td>None</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>RHW-26</td>
<td>304L/CS</td>
<td>T</td>
<td>M</td>
<td>None</td>
<td>T,M,M</td>
<td>T,M</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>RHW-27</td>
<td>304L/CS</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>RHW-28</td>
<td>304L/CS</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>T</td>
<td></td>
</tr>
<tr>
<td>LHW-10</td>
<td>A825Mod/CS</td>
<td>N/I</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>LHW-11</td>
<td>A825Mod/CS</td>
<td>N/I</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>LHW-12</td>
<td>A825Mod/CS</td>
<td>N/I</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>

1. Associated with membrane
2. Associated with thermocouple weld
3. Associated with crimp (mechanical damage)
T = Cracks in tube (circumferential and/or craze)
M = Cracks in membrane or in membrane-tube weld
N/I = Not Installed; N/M Not Measured; R/B Removed from Boiler

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**FIG. 2. Photographs taken during the inspection showing the nature of cracking found.** (A) Linear tube cracks and membrane crack found (October 2001) in the 304L/CS tubes fabricated into port design B, (B) Membrane cracks found (October 2001) in A625WO/CS tubes fabricated into port design A, and (C) Tube cracks found (April 2003) in GBEST/CS tubes fabricated into port design A.
installation. This must be taken into consideration when interpreting the relative performance history. Specific details of the changes to the boiler’s operation and their resulting influence on cracking will be the focus of a future report. It is recognized also that port location within the boiler cannot be ruled out as having an influence on performance.

The performance of the test panels was evaluated simply in terms of the comparative cracking and corrosion history. Table III. Included in the table is the exposure time at which the indication (cracking and/or corrosion) was first observed. It is noted that although membrane cracks in 304L/CS opening tubes fabricated into port B were first detected after 24 months of exposure, they were detected after 6 months of service during later inspections. Of the various combinations considered, only the A825Mod/CS opening tubes fabricated into port design B have yet to crack or corrode during the exposure time reported. This observation implies that both composite tube metallurgy and port design may influence performance. Supporting evidence is provided below.

**Composite Tube Metallurgy:** For both port designs, the difference in performance between 304L/CS opening tubes and their alternatives is most pronounced in the tube cracking history. When fabricated into port design A, both tube and membrane cracks were found in every six-month exposure period under study. This clearly was not the case with the three alternatives fabricated into port design A, particularly with the tube cracking history. Of the alternatives, tube cracks were found only in GBEST/CS opening tubes. However, their detection was significantly delayed relative to 304L/CS opening tubes fabricated into the same port design (30 months versus 6 months) and they occurred in an unusual location (near TMT versus near BMT). The improved resistance to tube cracking of the alternatives is also reflected in the comparative performance history of the two test panels fabricated with port design B. Tube cracks were detected in the 304L/CS opening tubes after just six months exposure. In contrast, no tube cracks were found on the A825Mod/CS opening tubes in these ports.

Comparing the membrane cracking of 304L/CS opening tubes fabricated into port design A with the alternatives is not meaningful since different weld termination procedures were used. However, a comparison between GBEST/CS and A825Mod/CS ports is meaningful since both alternatives were fabricated with a similar weld procedure. Membrane cracks were found in GBEST/CS ports after 30 months of service, whereas no membrane cracks were found in the A825Mod/CS ports during the same service period. The improved resistance to membrane cracking of the alternatives relative to 304L/CS
is clearly demonstrated by the comparative performance history of the test panels fabricated with port design B. Membrane cracks were detected in the 304L/CS opening tubes after just six months of exposure. In contrast, no membrane cracks were found on the A825Mod/CS opening tubes in similar ports.

Regarding corrosion resistance, it is unclear from Table III whether or not the alternatives fabricated into port design A represent an improvement over the conventional 304L/CS. Corrosion of all three alternatives, including A825Mod/CS, was observed after 12 months exposure. However, it is clear from Fig. 3 that amongst the alternatives fabricated into port design A, A825Mod/CS opening tubes has the highest relative resistance to corrosion. For port design B, it is clear from Table III that the alternative A825Mod/CS represents an improvement over the conventional 304L/CS. The quality of the seal between the casting insert and the opening tubes can influence the resistance to corrosion, and may be responsible in part for the relative differences.

**Port Design:** The influence of port design can be gauged by considering the relative cracking and corrosion resistance of 304L/CS and A825Mod/CS opening tubes fabricated into both port designs. Port design had little influence on cracking, regardless of composite tube metallurgy. For 304L/CS ports, tube cracks and membrane cracks were detected after just 6 months of service in both port designs. For A825Mod/CS ports, no tube or membrane cracks were detected in either of the two port designs. In contrast, port design appears to have had an influence on corrosion resistance. Corrosion was detected on A825Mod/CS opening tubes fabricated into port A after 12 months, whereas no corrosion has been found on A825Mod/CS opening tubes fabricated into port B after 30 months of exposure.

**DISCUSSION**

The propagation of cracks in conventional 304L/CS primary air port opening tubes is believed to be a result of a corrosion fatigue mechanism, which requires a cyclic tensile stress and contact with a corrosive liquid [2]. The thermal expansion difference between the 304L stainless steel cladding and the carbon steel is likely the major contributor to the required tensile stress. Random, yet frequent, temperature excursions during operation are the likely contributor to the cyclic behaviour required with this mechanism. Unlike the case for floor tubes, a strong correlation between temperature excursions and cracking has been found for primary air port opening tubes [2]. Such a correlation suggests that the required liquid phase is formed during operation, as opposed to a start-up or shutdown. Neither the cause of the thermal excursions nor the chemical environment is well-understood at this time.

The improved resistance to tube cracking of the alternatives relative to 304L/CS opening tubes is consistent with reported modeling and laboratory studies on the cracking of composite floor tubes [10, 11]. To create tensile stresses in straight tubes, finite element modeling has demonstrated that more severe thermal cycles are required for Alloy 825 and Alloy 625 composite tubes than for 304L stainless steel composite tubes [10]. It is noted that co-extruded Alloy 625-based composite opening tubes systems have cracked in service [3]. Furthermore, Alloys 825 and 625 was found to be as susceptible to cracking as 304L stainless steel and in laboratory tests simulating floor tube stress corrosion cracking [11]. Unlike with floor tubes, the initial stress state of opening tubes is influenced by the bending operation and the non-uniform tube seal weld. Both of these factors influence the stress state that develops upon thermal cycling. It is possible that the larger bending radius utilized in port B design produces a lower initial stress state in a given composite opening tube, correspondingly imparting a higher cracking resistance. However, the results reported herein do not support this hypothesis since, for a given composite tube, no difference in the cracking resistance was found between the two port designs in this boiler.

Traditionally, corrosion of 304L/CS opening tubes occurs on the cold-side of primary air ports, however, it has also been observed on the fireside [12, 13]. Such corrosion has been attributed to molten NaOH [12, 13]. In a reported corrosion study, of the various alternative alloys considered here, Alloy 625 exhibited the highest corrosion resistance, even in its welded state [14]. Thus, the fireside corrosion of alternative opening tubes reported herein is inconsistent with attack by molten NaOH. Cladding/overlay thickness measurements made on A625WO/CS and A825Mod/CS opening tubes suggest that Alloy 825 has a higher resistance to corrosion than welded Alloy 625. This discrepancy suggests that some other liquid environment, which forms during operation, is responsible for the observed corrosion. It appears as though the corrosion resistance of A825Mod/CS opening tubes was influenced by port design. A possible explanation for the difference is the quality of the seal between the casting insert and the opening tubes.

**CONCLUSIONS**

1. Conventional 304L/CS primary air ports had a poor resistance to cracking and corrosion in this recovery boiler, regardless of port design. Tube cracks, membrane cracks, and corrosion were detected after just six months of exposure in both port designs.

2. No non-membrane related tube cracks were detected in any of the A825Mod/CS and A625WO/CS opening tubes installed in this boiler, regardless of port design. This result suggests that composite tube metallurgy may have a stronger influence on the cracking resistance than port design. It is noted that co-extruded modified Alloy 625/carbon steel composite opening tubes installed with a different port design in another recovery boiler have cracked in service.

3. Significant corrosion of the 304L/CS opening tubes was detected. The majority of corrosion occurred during the first 12-month interval under study. A reduction in corrosion coincided, in particular, with a major change in the boiler’s operation, liquid delivery and combustion air system.

4. A825Mod/CS opening tubes had a higher corrosion resistance than the A625WO/CS opening tubes when the entire length of service is taken into consideration. The observation is consistent with reported corrosion studies in molten NaOH. The discrepancy suggests that some other corrosive liquid is responsible for the fireside corrosion observed.

5. A825Mod/CS opening tubes fabricated into port design B had a higher resistance to corrosion than those fabricated into port design A. This difference may be accounted for by the quality of seal between the casting insert and the opening tubes.

6. Of the various composite tube metallurgy and primary air port design combinations considered, the A825Mod/CS opening tubes fabricated into port design B had the best performance history. No cracks or corrosion have been found to date on any of the six opening tubes installed in this test panel.

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**LITERATURE**


Résumé: Dans une chaudière de récupération kraft, nous avons installé d’autres types de systèmes de tubes composites dotés de deux orifices de combustion différents, afin d’évaluer s’ils pouvaient nous permettre de régler les problèmes de fissuration de ces tubes. Nous avons par la suite vérifié tous les six mois si le placage ou le revêtement de ces orifices présentait des signes de fissuration ou de corrosion. Les orifices d’essai dotés de tubes composites en acier ordinaire ou modifié A825 co-extrudé et l’orifice B étaient les seuls où nous n’avons trouvé ni fissuration ni corrosion dans aucun des tubes après 30 mois d’exposition.


Keywords: KRAFT MILLS, RECOVERY BOILERS, PIPING, COMPOSITES, FRACTURE, CRACKS, AIR JETS, OPENINGS, MACHINE DESIGN, CORROSION, CARBON STEEL.