PATTERN OF THERMAL FLUCTUATIONS IN A RECOVERY BOILER FLOOR †

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ABSTRACT

The floor of a black liquor recovery boiler at a mill in central Canada has experienced cracking and delamination of the composite tubing near the spout wall and deformation of the floor panels that is most severe in the vicinity of the spout wall. One possible explanation for the observed damage is impacts of salt cake falling from the convective section onto the floor. In order to determine if such impacts do occur, strain gauges and thermocouples were installed on the boiler floor in areas where cracking and deformation were most frequent. The data obtained from these instruments indicate that brief, sudden temperature fluctuations do occur, and changes in the strain experienced by the affected tube occur simultaneously. These fluctuations appear to occur less often along the spout wall and more frequently with increasing distance from the wall. The frequency of these temperature fluctuations is insufficient for thermal fatigue to be the sole cause of the cracking observed on the tubes, but the data are consistent with what might be expected from pieces of falling salt cake.

INTRODUCTION AND BACKGROUND

The 304L/SA210 composite floor of the Babcock & Wilcox 2.3MM LbDS/day black liquor recovery boiler at Weyerhaeuser's Prince Albert, Saskatchewan mill has experienced some cracking and some delamination, all primarily within a meter of the spout wall. The areas where cracking was observed during the 1994-1996 period are shown in Fig. 1,¹ and it is apparent that essentially all of the cracking is within about 1½ meters of the spout


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In addition, portions of the floor within about 3 m of the spout wall have suffered severe deformation so that the tubes are bent below the normal floor position. This boiler was put into service in 1968, and the lower boiler was rebuilt in 1984 at which time the co-extruded tubes were installed. Consequently, all this damage has occurred within the last 14 years. The causes of these problems have not been clearly defined although there has been considerable speculation as to what might be responsible.

In 1996, a two-tube section of the floor was removed because of cracking and delamination and an area with the interconnected type of cracking prompted removal of a separate, single tube; these sections were analyzed at Oak Ridge National Laboratory (ORNL). As will be described in a subsequent section, the floor tube cracking has the appearance of that often seen in floors constructed of composite tubing. Recent studies suggest cracking of this type should be attributed to stress corrosion cracking with the added possibility that temperature fluctuations may contribute to progression of these floor tube cracks. These temperature fluctuations have been documented in other boiler floors by thermocouples measuring the temperature on the membrane, above the membrane, in the tube wall or on the tube surface. As part of an effort to characterize the environment of the floor tubes, including a determination of whether thermal fluctuations occur, and to identify the causes of the floor degradation, the temperature and strain in selected areas of the floor have been measured.

Another problem encountered in this floor is one that has been seen very infrequently in other boiler floors. Between the spout wall and the first floor support beam, about 30 floor tubes near the right side wall (tubes 15-45) are bent downward. This deformation is extensive enough that many of the tubes have a slope that is negative relative to horizontal where the slope should actually be + 5.7°, which is the slope used on this boiler floor. A tube removed from this area has been examined in an effort to determine if the tube experienced any overheating or if there is any evidence of mechanical damage on the fireside. There is another area, several tubes wide and centered around tube 50 (the boiler is 86 tubes wide), where the deformation extends on both sides of the first support beam. Furthermore, there is evidence of severe loading of the first support beam; the center of the beam is bent nearly 76 mm (3 in.) below its normal position.

It has been proposed that the damage described in the two previous paragraphs results from or is exacerbated by pieces of salt cake that fall from the screen and superheater tubes. For the cracking, this association is proposed to be via the tube temperature fluctuations caused by disruption of the frozen smelt layer that serves as an insulating layer on the tubes. These fluctuations can result in tensile stresses developing in the surface of the stainless steel layer, and these stresses may help the advancement of cracks developed by a stress corrosion mechanism. For the floor deflections, mechanical damage is likely caused by very large pieces of salt cake hitting the floor at high velocity. In order to collect information that could help support or refute this idea, five thermocouple/strain gauge pairs were installed on the boiler floor, and data collection was continued for a year. In order to be certain short duration events would not be missed, data were collected for all sensors about every ten seconds. Based on the results obtained from these sensors, during the next annual shutdown an array of 25 thermocouples and four accelerometers (that were part of a leak detection system) were installed on the boiler floor. During the past year, data from this thermocouple array and the accelerometers were analyzed to better define the thermal events on the floor.

Mounting of all the thermocouples required drilling a hole in the membrane adjacent to the tube to be studied. Approximately 6 cm (2 3/4 in.) of the sheathed thermocouple was pushed through this hole and wrapped around the tube. The tip of each thermocouple reached to about the crown of the tube, and the thermocouple was held in place against the surface of the tube by a thin metal sheet that was tack welded to the tube. Strain gauges were attached to the same tubes at the same distance from the spout wall but on the crown of the vestibule side of the tubes, 180° opposite the thermocouples. Considerable care was taken in the installation of the thermocouples and strain gauges, and almost all of them functioned during the entire operating period.

RESULTS

Examination Of Tube Sections

Three sections from the boiler floor were examined at ORNL. The first two sections were removed from the floor in April, 1996, because of extensive cracking and cladding delamination. The section with extensive cracking included tubes 49 and 50 (see Fig. 2) and came from the vicinity of the spout wall. The second section came from an area on tube 33 near the center of the floor and, as shown in Fig. 3, had areas of interconnected cracking on the crown of the tube. During this inspection, this was the only tube on which any cracking was
found that was not near the spout wall. Examination of this single tube showed cracks in the stainless steel which did not always penetrate through the stainless steel layer and never advanced into the carbon steel.

Metallographic examination of the two-tube section shown in Fig. 2 revealed extensive cracking of the tube and membrane along with delamination in some areas. Figures 4-6 show, respectively, examples of cracking in the stainless steel cladding on the tube, extensive cracking of the membrane, and delamination of the tube cladding. During prior shutdowns, inspectors reportedly found 6-8 areas on tubes from which the stainless steel cladding had been completely lost.

The third tube section was removed during the April, 1997 shutdown because of severe bending in the tube. The tube actually had a wavy shape that was the result of a "downward" bending of the tube between the spout wall and the first floor support beam. The vestibule side of the portion of the floor from which the tube was taken is shown in Fig. 7. Rough measurements on the tube showed that it was bent as much as 4½ cm (1-11/16 in.) from its normal position. Microstructural examination of sections of the tube showed significant deformation of the stainless steel layer in the areas where the tube contacted the support beam, but no significant microstructural evidence of over-temperature operation was detected. This deformation of the bottom side of the tube caused by contact with the edges of the support beam is shown in Fig. 8. Each pair of micrographs clearly shows the deformation of the tube, but it can not be unequivocally determined whether the deformation was cause by a single impact or a series of impacts. Some of the evidence does support multiple impacts rather than a single impact as the cause of the deformation.

Strain Gauge/Thermocouple Data

The locations of the thermocouples and strain gauges installed in April, 1997 are shown in Fig. 9. Three sets of sensors were located in front of smelt spout openings, and the two remaining sets were placed on tube 50 at distances of 0.9 and 1.8 m (3 and 6 ft) from the spout wall. Data were collected from these thermocouples and strain gauges during the June, 1997, through April, 1998, time period. Relatively few fluctuations were detected by the sensors located near the spout wall in front of the smelt spout openings. An example showing one of the most severe temperature spikes is shown in Fig. 10, which occurred at location number 2 in late afternoon on October 4, 1997. As can be seen from the figure, the temperature increases about 175°C and the strain shows about a 90 μ change at the same time. This strain indicates a change in the shape of the tube, and it could be a result of an impact to the floor or intense heating on one side. Even though the strain returns to its original level quickly (while the temperature recovery is somewhat slower), the strain change associated with an impact would be expected to last for an even shorter period than the time indicated in this figure. Consequently, it is unlikely the strain change is due to the impact of a mass on the floor.

A second example of a temperature spike, shown in Fig. 11, was observed at location 6 on July 17, 1997. As can be seen from Fig. 11b which has an expanded time scale, a ΔT of about 115°C and a Δσ of about 55 μ units is associated with this event. In this case, the strain and temperature decrease fairly rapidly and at approximately the same time although neither returns to its initial level for many hours. It is also evident from Fig. 11b that the temperature increase occurs very rapidly suggesting the increase is not the result of gradual melting of a frozen smelt layer.

Thermal fluctuations of the type shown in Figs. 10 and 11 were relatively infrequent at the locations studied. The frequency of the individual spikes can be deduced from the information in Table 1 which gives the number of thermal spikes that occurred during the period June 10 through November 30, 1997, as a function of the ΔT associated with the spike. The data in this table clearly indicate that spikes did occur at all locations monitored, but there was less activity near the smelt spout openings along the front wall than there was at positions 4 and 6 which were approximately 1 and 2 meters away from the spout wall.

The most frequent events were single spikes (like those described in the previous paragraphs) that were fairly isolated from any other event. However, there were infrequent periods during which the average temperature seemed to increase and frequent spikes were observed. An example of this behavior, shown in Fig. 12, was collected at location 6 on October 17. Both the strain and the temperature show quite a bit of activity over a ten hour period. The baseline temperature during this period is about 20-25°C above its "normal" level before and after this period. In addition, there are 5 spikes during this period that are 40-50°C above the adjusted baseline. Currently, there is no explanation for what caused this period of higher activity.
The information obtained from the thermocouple/strain gauge pairs showed that thermal and mechanical excursions did occur, generally simultaneously, but that they were relatively infrequent. However, the information provided did not resolve the question of whether the temperature changes were likely caused by impacts of material falling onto the floor or by rivulets of smelt running across the floor and changing directions frequently. With the intent of obtaining information that would address this question as well as provide some insight as to the cause of the floor tube bending, additional thermocouples were added during the April-May, 1998 outage. In addition, in order to collect information on floor deflections, four accelerometers that will ultimately be part of a leak detection system were put into service before the rest of that system was ready for operation. These accelerometers were mounted on rods that were attached to the floor membranes and extended downward through the vestibule floor. An accelerometer served each quadrant of the floor. It was hoped that these accelerometers might give some indication of the "building shaking" events that were reported to occur very infrequently.

Data From Thermocouple Array

Thermocouples were installed in the array shown in Fig. 13 during the April-May, 1998 shutdown. The thermocouples are arranged in a 5 x 5 array with one foot spacing between adjacent thermocouples. The accelerometers are positioned at roughly the center of each quadrant of the recovery boiler floor. Because of hardware and software problems, only a very limited amount of data was collected during the first 3½ months after installation. Once these problems were resolved, data were collected on a fairly continuous basis.

Temperature measurements of five separate events are given in Figs. 14-18. In these figures, temperature isotherms are shown as shades of gray with higher temperatures being shown as progressively darker gray. As indicated in the upper left plot in each figure, the intersection points of the lines on the grid coincide with the positions of thermocouples on the floor. The horizontal lines on the grid represent, from top to bottom, tubes 44, 47, 50, 53, and 56 while the vertical lines represent, from left to right, positions 2, 3, 4, 5, and 6 feet away from the spout wall where the thermocouples were positioned. Thus, these grids provide a perspective of the boiler floor as viewed from above looking down on the floor. The elapsed time for each display is given in seconds by the number above the display. Not shown on these figures are the results of the accelerometer measurements. The experience with the accelerometers has been that, in some instances, they indicate a significant event at the time a temperature spike begins, but in other cases, no accelerometer signal occurs at the time of a spike. Because the duration of a signal from a floor impact is expected to be very short, it can be argued that, since the accelerometer results are not collected continuously, some will be totally missed. Further work is planned to evaluate this possibility, and changes to the data collection system might be proposed.

The event shown in Fig. 14 occurred shortly after 1:30 pm on September 9, 1998. At the 49147 second mark, floor temperatures ranged from 260 to 330°C. Ten seconds later, the temperature at thermocouple 4 on tube 50 increased over 10°C. Over the next minute, the temperatures dropped to near their initial level, and, during the subsequent 3 minutes, they dropped about another 20°C.

The event shown in Fig. 15 is similar to that shown in Fig. 14 except it occurred on the second thermocouple on tube 50 just before 1:30 am on September 19, 1998. The first indication of the thermal spike is seen at the 5098 second mark. As shown in Fig. 15, the temperature decreased rapidly after the initial spike so that 4½ minutes later the floor temperatures were at or below their initial levels.

Shortly after 10:00 am (36661 seconds) on September 6, 1998, a sudden temperature increase of about 50°C was indicated by the second thermocouple on tube 50 (see Fig. 16). Twenty seconds later, another temperature spike was indicated by the fourth thermocouple on the same tube, and the heating effect from both perturbations caused heating of the thermocouples on tubes 47 and 53. In addition to the heating effects centered around thermocouples 50-2 and 50-4, the thermocouples at 56-1 and 53-1 showed evidence of other heating near the spout wall. About thirty seconds later (36712), the temperatures of thermocouples 50-2 and 50-4 dropped considerably. The evidence of these temperature excursions was nearly gone less than three minutes later (36876).

About four hours earlier (22218 seconds) on the same morning, the floor thermocouples displayed nearly uniform temperature over the portion of the floor being studied. Ten seconds later, as shown in Fig. 17, a sharp temperature spike was seen at thermocouple 50-4 that extended toward thermocouple 50-3. After an additional ten seconds, the temperature at 50-4 remained fairly high and the temperature of thermocouple 50-2 had
increased. About a minute later, the temperature all along tube 50 had dropped, with the decrease being as much as 70°C in the hottest areas. Six and a half minutes later, the temperature was nearly back to the initial levels over the entire floor. This series of temperature profiles may be indicative of smelt flowing from the vicinity of thermocouple 50-4 toward the smelt wall. However, heating of the floor tubes that occurs near the spout wall is less than toward the center of the area being studied.

The last example is shown in Fig. 18. In this case, which occurred about 30 minutes after midnight on September 8, 1998, the floor was somewhat warmer than in some of the previous examples. The beginning of a temperature spike was seen at 1879 seconds on thermocouple 47-4, and ten seconds later a fair amount of heating was shown on thermocouples 47-3 and 47-4. Within 2½ minutes, the temperature distribution across the portion of the floor being studied nearly returned to the initial state.

DISCUSSION

Thermocouple, strain gauge and accelerometer measurements have been collected intermittently over an 18 month period. Measurements during the first year were made in front of the smelt spout openings and, during the second year, in an area of the floor where severe cracking had been seen. The latter measurements were made over an approximately 1.5 m² (16 ft²) area of the floor in which cracking and deformation of tubes had been seen previously. The results from the first year indicated that the sensors located about 0.9 and 1.8 m (3 and 6 ft) from the spout wall experienced more thermal fluctuations than did the tubes that were near the spout wall and in front of smelt spout openings.

Results collected during the subsequent period confirmed that temperature fluctuations do occur on the floor and that, for the limited area studied, the frequency is less near the spout wall than it is away from the wall. Although the area studied was fairly limited, it appears that more frequent fluctuations that cover larger areas of the floor occur toward the center of the boiler floor. Based on the shape of the char bed that is thought to exist in this recovery boiler, the area of the floor where the thermocouples indicate the greatest frequency of fluctuations also corresponds to the area where the char bed is expected to have significant depth.

CONCLUSIONS

Cracking in the vicinity of the spout wall on the 304L/CS composite floor tubes is typical of that usually seen in this material. The cracks originate at the OD surface, advance transgranularly through the stainless steel, and do not continue into the carbon steel.

Deflections in the floor tubes in certain areas also result in deformation on the vestibule side where the tubes contact the support beam. It is not possible to positively determine if the deformation was the result of a single impact or of multiple impacts. No evidence was found indicating overheating of the fireside of the tubes, but the slope of some of the tubes is such that it might be possible to trap steam if it were generated in that area. Presumably, the water at the point is still relatively cool, and the velocity is sufficient to prevent steam from accumulating.

The frequency of thermal spikes, particularly in the area where cracking has been found, is relatively small and is not sufficient for thermal fatigue caused by the thermal spikes to be the cause of the cracking seen in the 304L stainless steel layer on the composite floor tubes.

The temperature patterns seen during the measurements with the thermocouple array suggest that, in most cases, the thermal spikes are the result of impacts on the floor that break through the layer of frozen smelt rather than to a rivulet of molten smelt flowing across the floor in a constantly changing path. If a rivulet of molten smelt were causing the thermal spikes, significant temperature changes would be expected to occur on a number of adjacent tubes.

The database used for these conclusions came from measurements on a very limited portion of the recovery boiler floor. Nevertheless, there is no reason to believe the results are not representative of the remainder of the floor at the same distance from the spout wall. It is anticipated that additional measurements will be made, and efforts will be made to correlate the data with sootblower operations.
ACKNOWLEDGMENTS

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**TABLE 1**

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<th>ΔT</th>
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<th>Location 2</th>
<th>Location 4</th>
<th>Location 6</th>
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<td>Tube 33, in front of spout #2, about 30 cm (1 ft.) from spout wall</td>
<td>Tube 54, in front of spout #3, about 30 cm (1 ft.) from spout wall</td>
<td>Tube 50, about 91 cm (3 ft.) from spout wall</td>
<td>Tube 50, about 183 cm (6 ft.) from spout wall</td>
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* For the period June 10 through September 30, 1997, as experienced by thermocouples mounted on selected recovery boiler floor tubes.
Figure captions

1. Pattern of cracking that developed on the floor of black liquor recovery boiler #1 during the 1994-1996 time period at Weyerhaeuser's Prince Albert, Saskatchewan mill.
2. Two-tube section of floor panel taken from near the spout wall a) as received at ORNL and b) after dye penetrant testing.
3. Interconnected or spider web cracking found on tube 33 near the center of the boiler floor.
4. Cross section of tube from Prince Albert recovery boiler floor showing interconnected cracking found on tube 33 near the center of the boiler floor.
5. Cross section of membrane from Prince Albert recovery boiler floor showing cracking of the stainless steel layer.
6. Cross section of tube from Prince Albert recovery boiler floor showing area where delamination occurred.
7. Area of recovery boiler floor where severe deformation of the tubes occurred.
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10. Results of strain gauge and thermocouple measurements for location 2 on October 4, 1997.
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12. Results of strain gauge and thermocouple measurements for location 6 on October 17, 1997, showing an extended period of increased activity.
14. Temperature profiles of a portion of the Prince Albert recovery boiler floor from early afternoon on September 9, 1998. As indicated in the upper left display, the horizontal lines represent tubes with the tube number shown on the left axis while the vertical lines indicate thermocouple numbers which correspond to one less than the distance (in feet) from the spout wall. The elapsed time (in seconds) is given by the number above each profile.
15. Temperature profiles of a portion of the Prince Albert recovery boiler floor from very early morning on September 19, 1998. As indicated in the upper left display, the horizontal lines represent tubes with the tube number shown on the left axis while the vertical lines indicate thermocouple numbers which correspond to one less than the distance (in feet) from the spout wall. The elapsed time (in seconds) is given by the number above each profile.
16. Temperature profiles of a portion of the Prince Albert recovery boiler floor from late morning on September 6, 1998. As indicated in the upper left display, the horizontal lines represent tubes with the tube number shown on the left axis while the vertical lines indicate thermocouple numbers which correspond to one less than the distance (in feet) from the spout wall. The elapsed time (in seconds) is given by the number above each profile.
17. Temperature profiles of a portion of the Prince Albert recovery boiler floor from about 6:00 am on September 6, 1998. As indicated in the upper left display, the horizontal lines represent tubes with the tube number shown on the left axis while the vertical lines indicate thermocouple numbers which correspond to one less than the distance (in feet) from the spout wall. The elapsed time (in seconds) is given by the number above each profile.
18. Temperature profiles of a portion of the Prince Albert recovery boiler floor from early morning on September 8, 1998. As indicated in the upper left display, the horizontal lines represent tubes with the tube number shown on the left axis while the vertical lines indicate thermocouple numbers which correspond to one less than the distance (in feet) from the spout wall. The elapsed time (in seconds) is given by the number above each profile.
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Figure 8. Micrographs showing cross sections of the bottom side of a floor tube where it contacted the floor support beam.
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Figure 14. Temperature profiles of a portion of the Prince Albert recovery boiler floor from early afternoon on September 9, 1998. As indicated in the upper left display, the horizontal lines represent tubes with the tube number shown on the left axis while the vertical lines indicate thermocouple numbers which correspond to one less than the distance (in feet) from the spout wall. The elapsed time (in seconds) is given by the number above each profile.
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