MPLUS Project MC-01-005
Final Report
January 2002

Recovery Boiler Wall Tube Temperature Measurements*

Gorti B. Sarma, Kimberly A. Choudhury, James R. Keiser
Oak Ridge National Laboratory
Oak Ridge, TN 37831

Frank E. Steinmoeller, Keith B. Rivers, C. Malcolm Mackenzie, Bryan B. Stone, John A. Kulig
Babcock & Wilcox
20 S. Van Buren Ave., Barberton, OH 44203

Summary

Thermocouple data collected from various locations in the vicinity of black liquor recovery boiler primary air ports have been analyzed using two methods, one for estimating the amount of time spent at high temperatures, and the other for estimating the number of thermal fatigue cycles. A simplified method for counting the thermal fatigue cycles is shown to match the more rigorous "rainflow" method quite well. The two methods of analyses provide a simple and quick way to quantify the relative activity of the thermocouples.

*Research sponsored by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Industrial Technologies, Advanced Industrial Materials Program, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

Introduction

Paper mills use recovery boilers to burn black liquor in order to recover certain chemicals used in the pulping process, and to generate process steam. The floor and walls of the recovery boiler are made of tubes that are connected to each other by membranes. Composite tubes and membranes, which have a protective clad layer covering the SA210 carbon steel, are used to withstand the corrosive environment in the lower portion of the boiler [1]. Development of cracks in the 304LSS composite tubes forming the boiler floor has received much attention over the last few years. More recently, cracking has been observed in 304LSS composite tubes forming the primary air ports in the walls of the boiler. Cracks appear to form more often in the lower portion of the primary air port opening, in the tubes that are bent sideways and back behind the adjacent straight tubes to form the opening for the air port.

In an effort to study the temperature changes experienced by the tubes forming air ports, thermocouples were installed at several locations on these tubes. A number of air ports in several different recovery boilers were instrumented to study the differences between air ports as a function of their location in the boiler. The objective of this project was to analyze the thermocouple data collected from one of these recovery boilers in an effort to quantify the thermal fluctuations observed at various locations, and to develop the future ability to correlate the fluctuations with boiler operating conditions.

Analyses of Thermocouple Data

The possible locations of various thermocouples at a primary air port, along with the locations of instrumented air ports in the subject boiler are shown schematically in Figure 1. The number of thermocouples at each air port was not the same, with some air ports being instrumented at almost all locations indicated, while other air ports had fewer thermocouples. Thermocouple data were recorded at ten second intervals, so that a given day had up to 8640 values for each thermocouple location. A portion of the raw data for May 3, 2001 is shown in Figure 2. Over several months, the large amounts of data collected made it necessary to come up with some means to analyze and quantify certain trends in the temperature variations.

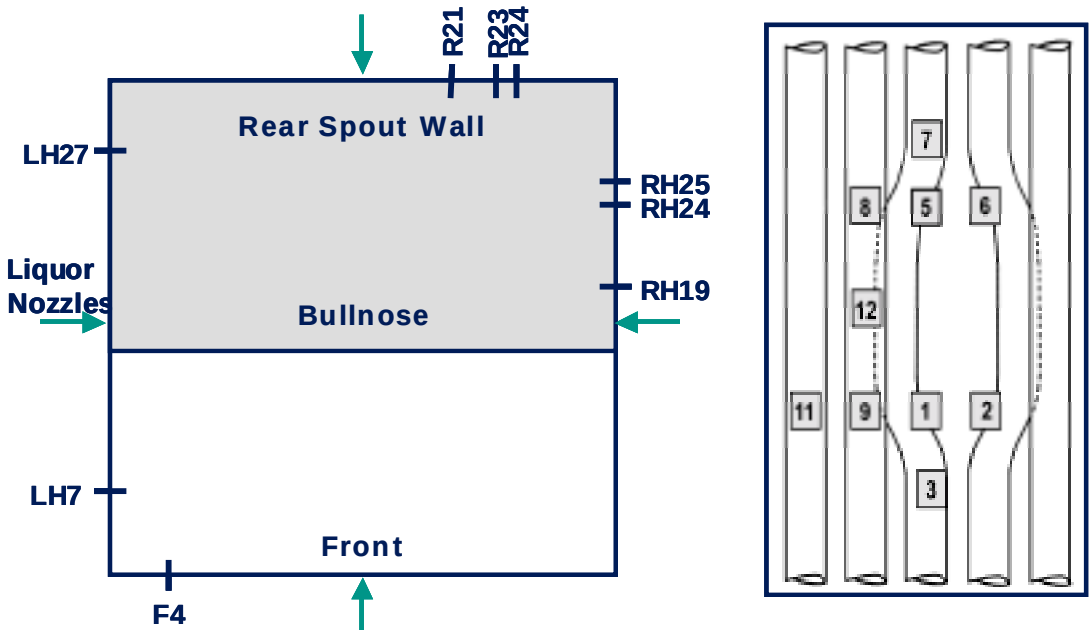

Figure 1: Schematic of recovery boiler showing primary air ports that have been instrumented and locations of thermocouples at each air port.

Date	Time	LH7-2	LH7-3	LH27-5	LH27-2	LH27-3	R21-1	R21-2	R21-3	LH27-7	R23-3
5/3/2001	0:00:10	335.8	317.9	364.3	323.5	347.1	374.0	383.3	361.1	343.7	366.7
5/3/2001	0:00:20	333.6	317.8	364.0	323.6	346.7	377.1	384.2	364.3	343.7	368.4
5/3/2001	0:00:30	332.1	317.8	363.6	323.3	345.8	377.1	385.0	364.7	343.3	369.2
5/3/2001	0:00:40	332.0	317.7	363.0	323.1	345.2	378.2	384.8	364.9	342.8	369.1
5/3/2001	0:00:50	332.9	317.7	362.7	322.9	344.9	376.8	384.6	363.5	342.5	367.7
5/3/2001	0:01:00	332.4	317.6	362.5	323.0	345.2	376.4	384.5	362.3	342.5	367.3
5/3/2001	0:01:10	332.3	317.7	362.4	322.9	345.4	375.8	382.1	360.4	342.8	367.0
5/3/2001	0:01:20	333.1	317.7	362.4	322.9	345.4	373.6	379.6	358.8	343.1	366.2

Figure 2: A portion of the spreadsheet showing raw data collected on May 3, 2001 from thermocouples located on primary air ports.

The temperature variation at each location has been plotted over 24-hour periods starting at midnight for each day, after condensing the data by choosing one out of three data points. It should be emphasized that the points were chosen every 30 seconds only for the purpose of plotting the temperature fluctuations. The data analyses discussed in the following sections were all performed with the full data sets considering all data points. Figures 3 and 4 show the temperature variations for thermocouples at air port R24 (#24 on the rear wall) based on data collected on May 17 and May 20, 2001, respectively. Examination of such plots for the various air ports showed that all thermocouples experience some thermal fluctuation, with certain locations showing lower "baseline" temperature with greater frequency and amplitude of fluctuations, while others had a higher "baseline" temperature with smaller and less frequent fluctuations. Due to the complexity of the temperature variations on any given day, as well as the large quantities of data collected, it was felt that a more quantitative measure of the temperature fluctuations would be useful.

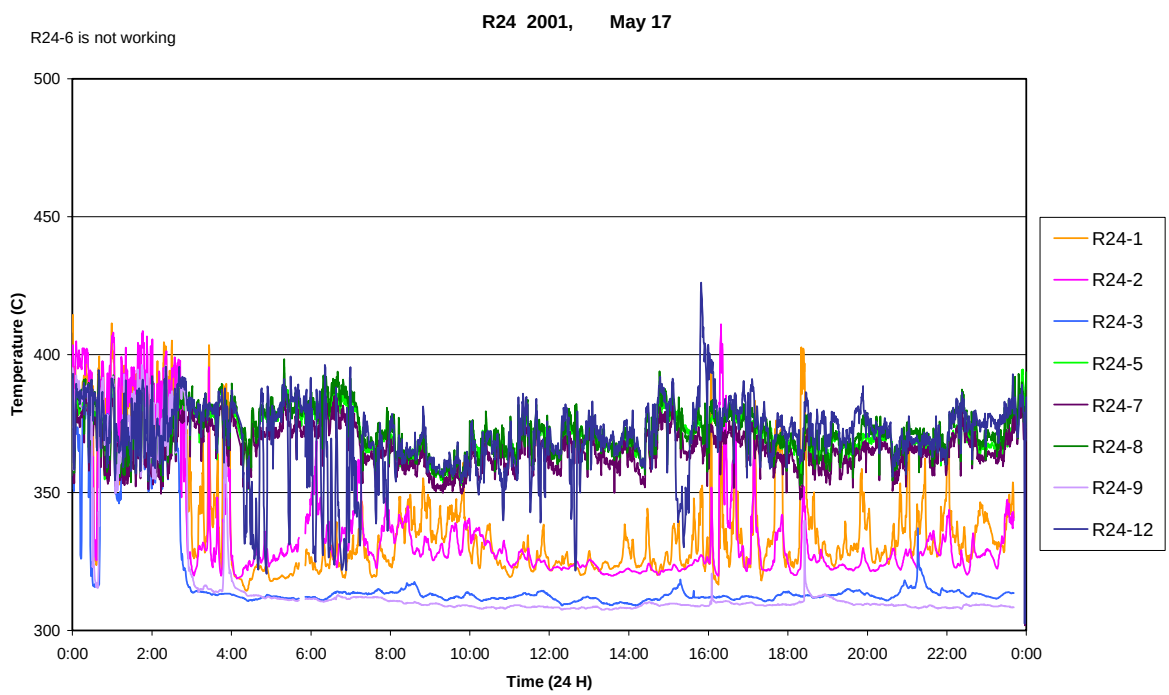

Figure 3: Variation of temperature measured by thermocouples at air port R24 on May 17, 2001.

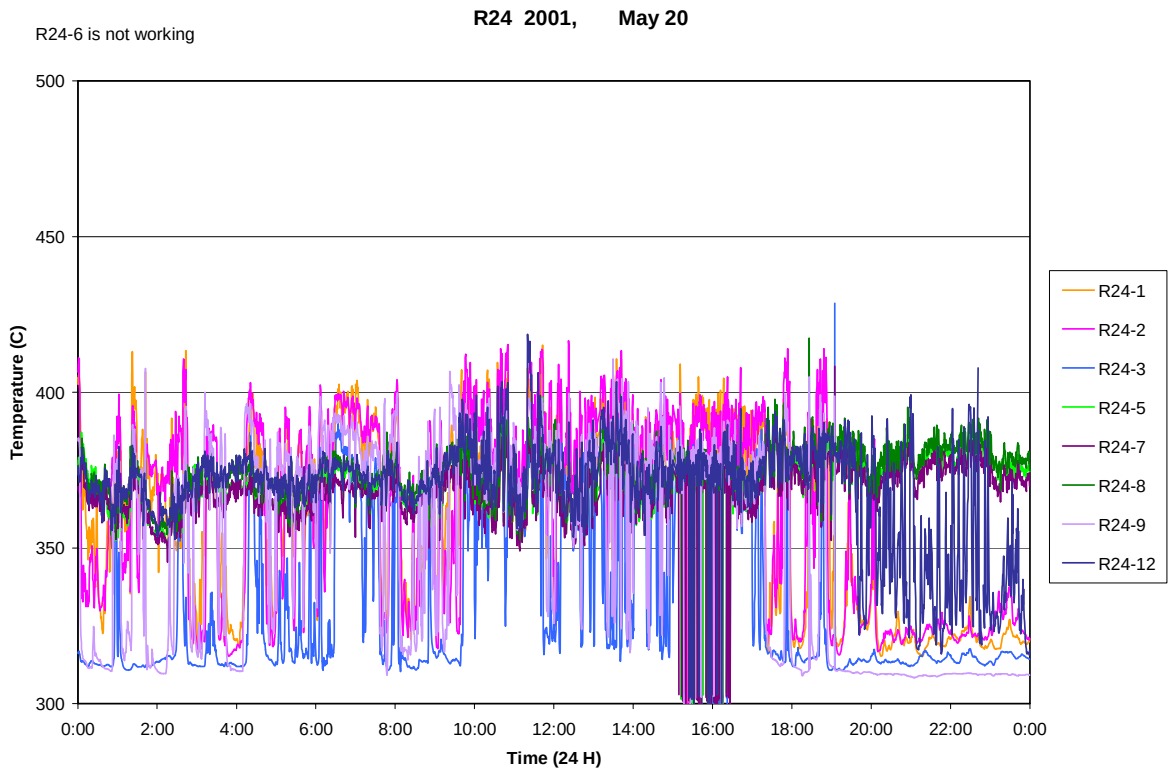

Figure 4: Variation of temperature measured by thermocouples at air port R24 on May 20, 2001.

Count of number of high temperature data points

One of the simplest methods of identifying if a thermocouple is relatively calm or active is to count the number of data points recorded at that location which exceed a given critical temperature. Examination of data during relatively "calm" periods indicated the "baseline" operating temperature to be between 325 and 375 °C. Earlier work on modeling the cooling of floor tubes from operating temperature during boiler shutdown [2] suggests a temperature drop of about 75 °C is sufficient to cause the stress at the crown of the 304LSS composite tube to change from compressive to tensile yield. Based on this result, and considering a temperature increase of 75 °C above the upper limit of the "baseline" operation regime to be critical, any temperature value above 450 °C was determined to be a "thermal excursion," and a count of the number of such "excursions" was made for each thermocouple. Figure 5 shows the results of the thermal "excursion" count for the thermocouple at position 2 on air port F4 (#4 on the front wall) for the month of May 2001. The first few days shows a number of active days with high numbers of "excursions."

It must be noted that if the temperature at a particular location rose above 450 °C and stayed up for a long period of time, all those data points were counted as "excursions." The number of high temperature readings therefore does not provide a complete picture, since a thermocouple could be reading a higher temperature with minimal fluctuation, and all readings would still count as "excursions." However, the count does provide some useful information, since it indicates which locations are spending a lot of time at high temperatures, which could be detrimental to the tubes if one considers damage due to corrosion. Also, if there are periods when the same thermocouple records fewer "excursions," and this could be correlated to some change in operating parameters, it could help in choosing the operating conditions such that the high temperature "excursions" are minimized.

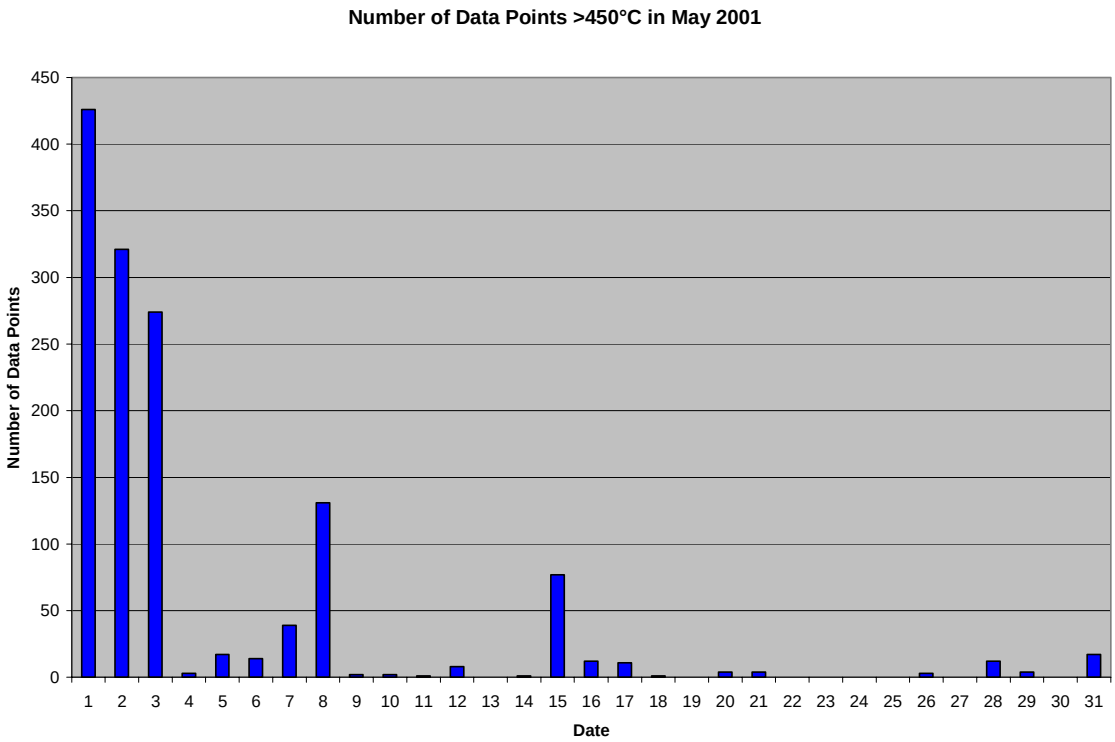

Figure 5: Bar chart showing the number of thermal "excursions" above 450 °C at F4-2 during May 2001.

Count of time spent in thermal fluctuation

Based on an examination of the plots showing the temperature variation, it was determined that most thermocouples have a "baseline" operating temperature, which is the temperature recorded when the activity is relatively calm with minimal fluctuations. Due to wide variations in temperature values among different thermocouples, as well as for different days for the same thermocouple, a representative value that matched most of the thermocouples was used as the "baseline" temperature range. Choosing the "baseline" temperature to be between 325 °C and 375 °C, the thermocouple data were analyzed to estimate the amount of time spent within the "baseline" temperature, and the amount of time spent in fluctuations above the "baseline" temperature. In these calculations, data points that fell below 200 °C or exceeded 1000 °C were ignored. The time was calculated in hours for each day, and a typical result is shown in Figure 6 for thermocouples 2 and 3 at air port F4 for data from May 2001.

Count of number of half-cycles

Among the possible causes for cracking of air port tubes are thermal fatigue and corrosion fatigue, both of which require stress cycles. It therefore becomes necessary to estimate the number of fatigue cycles experienced by the tube. Based on some earlier work on modeling the changes in temperature and stresses in composite floor tubes [2], it was determined that for tubes made of 304L stainless steel over SA210 carbon steel, a temperature change of about 75 °C is sufficient to cause the stress in the outer stainless steel layer to go from compressive to tensile yield or vice-versa. Based on this, a method to count the number of temperature cycles was devised. A half-cycle is defined as the increase or decrease in temperature of more than 75 °C from the previous lowest or highest value, respectively. Any fluctuations in temperature less than 75 °C are ignored, and the up- and down-cycles occur in sequence alternately. Figure 7 shows the plot of half-cycle count for the different thermocouples for May 2001. The number of half-cycles varies depending on both location of the air port in the boiler and location of the thermocouple at the air port.

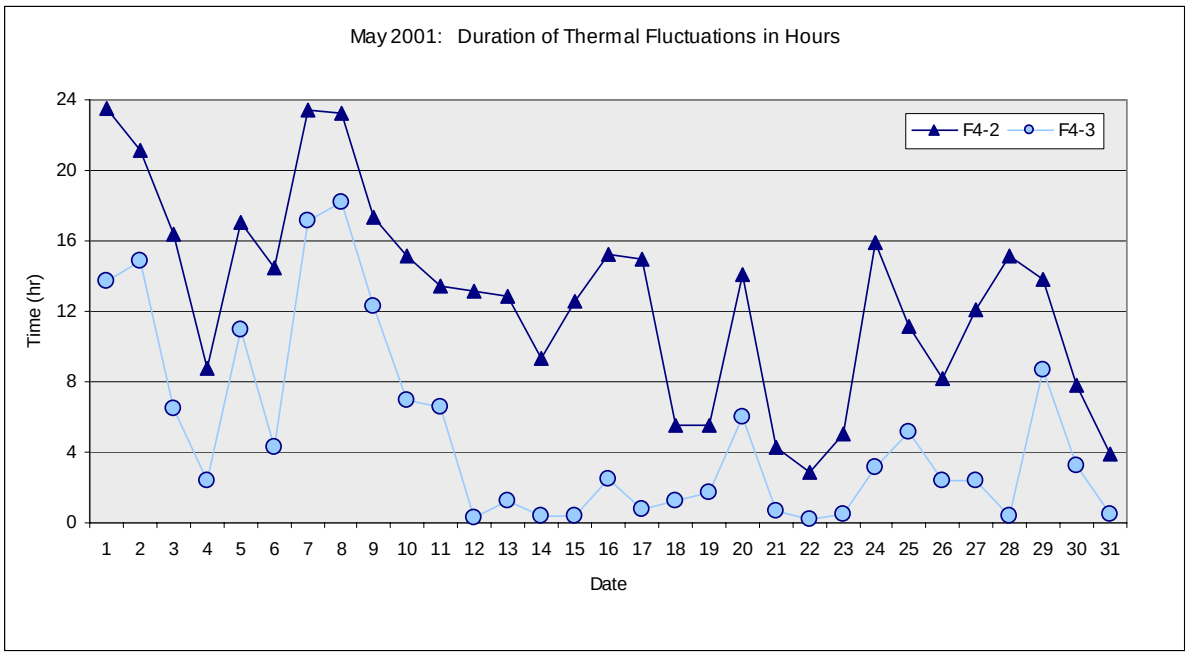

Figure 6: Time spent above "baseline" temperature in thermal fluctuations based in data collected at F4-2 and F4-3 for various days in May 2001.

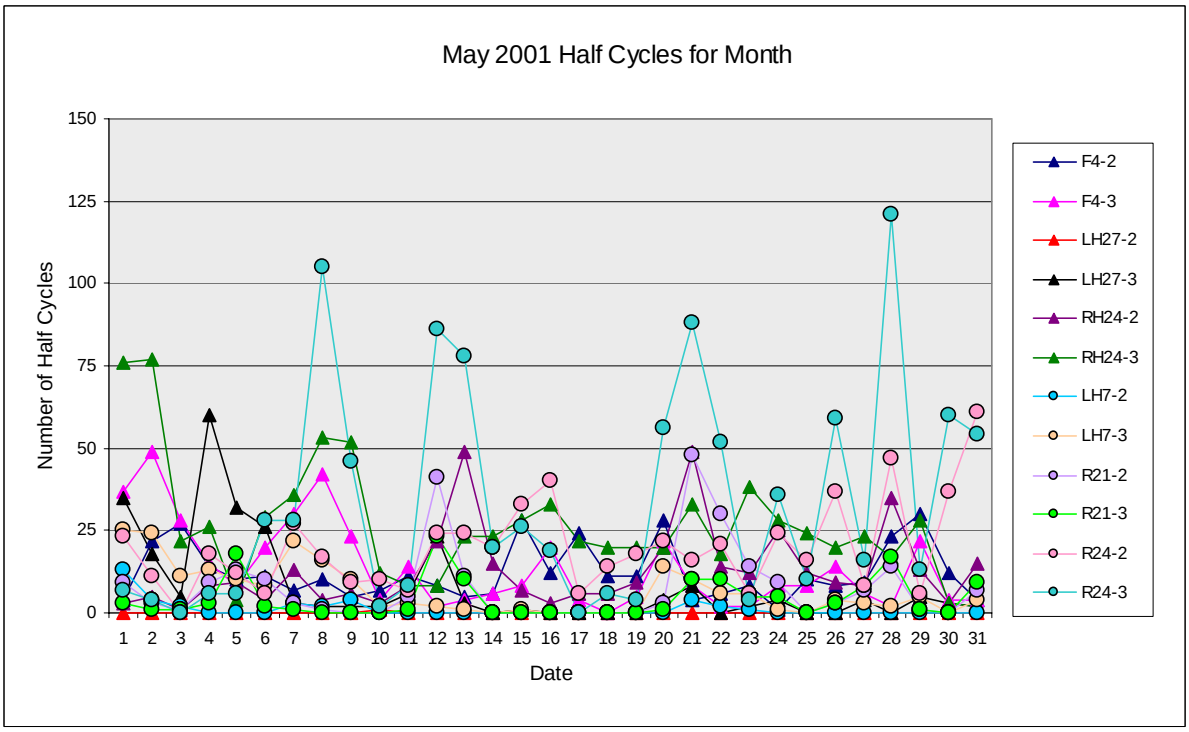

Figure 7: Half-cycle count based on data collected during May 2001 at the different thermocouple locations.

The half-cycle method (labeled "Gorti") was originally set up to always start with an up-cycle, so that the first half-cycle due to a temperature drop was ignored. That method was subsequently modified to include the first up-cycle also (labeled "Tony"). A comparison of the two methods is shown in Figure 8 for data from thermocouple F4-2 for the month of May 2001, and it is observed that the two methods are almost identical, and the difference between the two methods is at most one half-cycle.

An alternate and more rigorous method for counting thermal fatigue cycles is based on the ASTM "rainflow cycle" counting method used widely to characterize mechanical fatigue [3]. It was first developed to identify closed hysteresis loops in the stress-strain response of a material subjected to cyclic loading. If the strain-time history is drawn such that the time axis is oriented vertically, with increasing time downward, one could imagine that the strain history forms a number of "pagoda roofs." Cycles are then defined by the manner in which rain is allowed to "drip" or "fall" down the roofs, based on certain rules imposed on the dripping rain so as to identify closed hysteresis loops. The disadvantage of the ASTM method is that the data must be sorted so that the first data point is the maximum in the range. Also shown in Figure 8 is a plot of the rainflow method for cycle counting (identified as "Whole Cycle"). There is a good correspondence between the half-cycles and the rainflow method. The number of cycles obtained by dividing the half-cycle count by two differs from the rainflow method by at most one. Therefore, the half-cycle method provides a good indication of the days on which there are a greater number of temperature fluctuations that could be damaging from fatigue considerations. However, the half-cycle count does not have any information regarding how much time is spent at the higher temperatures, which is a consideration in assessing corrosion issues.

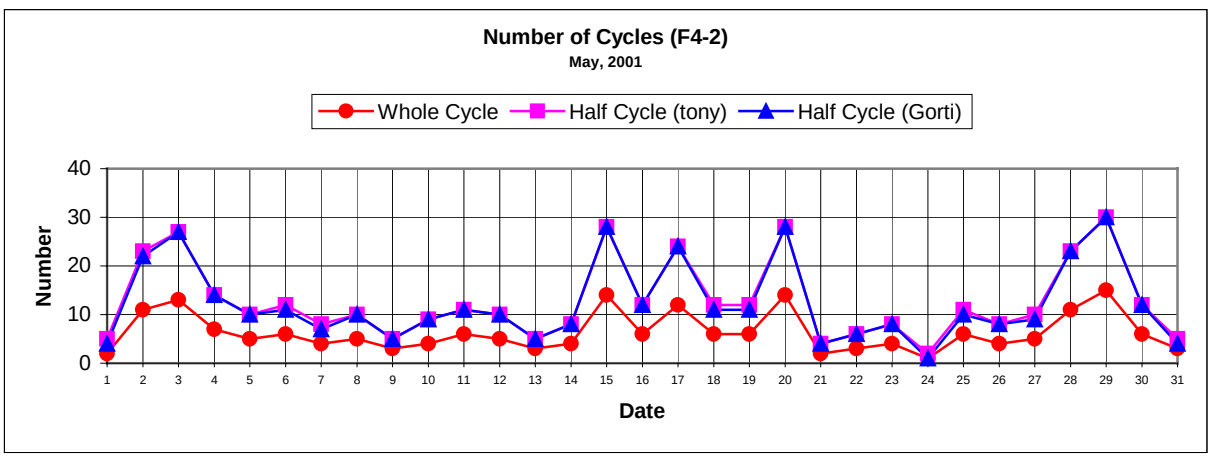

Figure 8: A comparison of different cycle counting methods to estimate the thermal fatigue cycles based on data collected at location F4-2 during May 2001.

Conclusions

Thermocouple data collected from primary air ports of a recovery boiler have been analyzed using two different methods. The first method provides a count of the number of data points above a certain temperature, thus indicating how much time each thermocouple location spends at high temperatures. The second method estimates the number of thermal fatigue cycles per day at each location. Each method by itself lacks certain information, but taken together, these two methods provide a quantitative basis to determine the relative activity of the thermocouples at different locations.

Since the ultimate objective is to minimize cracking of the air port tubes, these methods can be used to quickly identify specific periods when the "excursions" or half-cycles are high. Those periods can then

be examined in more detail using the ASTM "rainflow" method in order to assess potential fatigue damage, and to see if the greater thermal activity can be correlated with any changes in boiler operation. This would in turn help in determining the operating conditions that lead to minimal activity or fluctuations.

Recommendations for Further Work

Analyses of the thermocouple data have been limited to air ports of one particular boiler. Similar data are available from other boilers, and it is necessary to apply the methods of analyses discussed here to those data, in order to gain a better understanding of the thermal environment in the vicinity of air ports. In particular, it would be very important and useful to find correlations between locations where cracking is frequently observed and certain trends in data, such as high cycle count or large time spent in thermal fluctuations.

The criterion used for half-cycle counts was a change in temperature of 75 °C, which was based on the transient analysis of cooling of floor tubes from operating temperature during boiler shutdown [2]. However, the change in temperature required to cause stresses to change from compressive to tensile yield may depend on the initial temperature, and this needs to be investigated further through some modeling studies. From fatigue considerations, a cycle with temperature change of 150 °C would be worse than one with 75 °C change. It may therefore be necessary to also perform cycle counts with different values for the temperature change.

The other important task is in establishing cause and effect relationship between changes in operating parameters and changes in temperature data. As seen from the limited analyses presented here, on some days there is increased activity at all thermocouple locations, while on other days there is greater activity only at some locations. Correlating the changes in operating conditions to changes in thermal activity is another area that requires further effort.

References

1. D.L. Singbeil, R. Prescott, J.R. Keiser, and R.W. Swindeman, "Composite Tube Cracking in Kraft Recovery Boilers: A State-of-the-Art Review," Technical Report ORNL/TM-13442, Oak Ridge National Laboratory (1997).
2. B. Taljat, T. Zacharia, J.R. Keiser, and X.-L. Wang, "Modeling Studies of a Composite Tube Floor in Black Liquor Recovery Boilers," *TAPPI Journal*, 82 (12), pp. 99–108 (1999).
3. "Standard Practices for Cycle Counting in Fatigue Analysis," ASTM Designation: E 1049 – 85 (Reapproved 1990).