ANALYSIS OF BOILER FOULING AND BOILER CLEANING METHODS
AT THE COMMERCE REFUSE-TO-ENERGY FACILITY

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ABSTRACT
Waste-to-energy boiler fire-side fouling is a major operational issue for many facilities, including the Commerce Refuse-to-Energy Facility. The Commerce Refuse-to-Energy Facility is a 350 ton per day, mass burn waterwall facility that began operation in 1987. Fouling occurs throughout the convection sections with the highest differential pressure occurring across the generating bank. Flue gas differential pressures and temperatures have been tracked and analyzed at the facility for approximately ten years during various operating conditions. It has been determined that the rate of increase of the differential pressure across the generating bank is correlated with flue gas temperature and the extent of fouling. Several different cleaning methods have been used to clear the convection zone of ash deposits, including off-line hydroblasting, on-line hydroblasting, on-line explosives cleaning, sootblowers and sonic horns. Better understanding of the fouling trends and evaluation of cleaning methods has led the facility to use a combination of on-line hydroblasting and explosives cleaning and off-line hydroblasting. The facility is now able to operate one year between planned outages, compared to ten weeks during the initial operation of the facility. Additional savings have also been achieved by reducing induced draft fan load, and possibly a reduction in tube wastage.

INTRODUCTION
Fire-side fouling of the convection sections of waste-to-energy facilities contributes to a number of serious operational problems: 1) extensive fouling is a major impediment to extended runs, 2) heavy fouling and buildup of clinkers necessitates significant work during planned outages, and 3) ash deposits markedly reduce heat transfer, and hence plant efficiency. The causes and effects of increased flue gas pressure differential due to fouling have been examined in detail. The focus of this study has been on actual and theoretical pressure differential: 1) pressure differential is the primary negative impact of fouling on plant operation and 2) extensive plant pressure data is available. Other aspects, such as ash chemistry and heat transfer have not been examined. Ash and slag composition has not been tracked over time and it would be difficult to collect enough representative samples to correlate composition to fouling and other plant operating parameter. Heat transfer impacts, while reducing efficiency, does not lead to downtime or other major operational and maintenance issues.

Fouling of the convection section leads to increased flue gas pressure drop and reduced heat transfer. As the pressure drop increases, the induced draft fan power draw increases, leading to additional parasitic load and reduced power sales. When the pressure drop increases to the point the induced draft fan is at maximum speed, additional fouling limits combustion air flow, which may result in poor combustion. The pressure drop at which the fan is at maximum speed varies depending on the amount of in-leakage downstream of the boiler, but it can range from 2 to 5 inches water. High pressure drop across the convection zone is the determining factor in scheduling cleanings, and in some cases may force an outage.

The reduction in heat transfer that occurs as a result of fouling leads to lower boiler efficiency, loss of sufficient superheat, and hotter flue gas temperatures. Although the heat transfer impact of fouling is an important issue, heat transfer rates are easily restored to acceptable levels with an on-line waterwash or explosives cleaning at the Commerce facility.

Determination of flue gas pressure differential across the convections sections, and analysis of the causes of increased pressure differential, have been examined in three ways: 1) theoretical pressure differential; 2) trends of pressure differential relative to type of cleaning; and 3) determination of the rate of increase in pressure differential as a function of tonnage burned and flue gas temperatures.

In this paper, the term "differential pressure" refers to the difference in flue gas pressure from the generating bank outlet to the furnace. Pressure differential is measured in inches of water, which corresponds to the units logged by the plant control system.

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DESCRIPTION OF FACILITY

The Facility is located approximately 10 miles southeast of downtown Los Angeles, in an area that is predominately commercial and industrial. The facility began operation in January 1987. It is nominally rated at 350 tons per day and 10 MW net electric power.

The boiler was supplied by Foster Wheeler with grates by Detroit Stoker. Fuel quality has varied over time, ranging from nearly 100% high-BTU commercial trash to primarily post-recycling residential refuse.

The waterwalls consist of a single pass, approximately 17 feet deep by 14 feet wide, with a height from the grates to the roof of approximately 80 feet. The convective tube sections are listed in order of gas flow in Table 1. The economizer, which is downstream of the generating bank, experiences very little fouling, and the impact of ash deposition and increases in pressure differential downstream of the generating bank are not addressed in this study.

Cleaning Operations

Four methods are used to clean the convection sections. The method used depends on many factors, including the amount of fouling, length of time to the next planned outage, operational issues such as whether it is during peak power pricing periods, and cost of cleaning. Any cleaning procedure that increases downtime is avoided whenever possible.

1. Major Outage Wash and Sandblasting During annual or semi-annual scheduled outages, a thorough cleaning is done of the entire furnace and boiler. The furnace waterwalls are brush sandblasted to remove slag and dust. The convection sections are washed with high-pressure water until the tubes are substantially down to bare metal. Usually there is a small amount of material left on the walls, or in difficult to access locations. The thorough sandblasting and cleaning results in a very low differential pressure and low gas temperatures with improved heat transfer. This type of cleaning is the only method that allows for an extended run of four to eight months.

Cleaning Equipment

Numerous mechanisms are and have been used to reduce or prevent fouling in the convection sections. The success of each varies and can be difficult to determine. Currently sootblowers in the evaporator, rappers and sonic horns in the superheater, and sonic horns in the generating bank are used to reduce fouling. Table 2 summarizes the history of devices that have been used at the facility.

<table>
<thead>
<tr>
<th>Bank</th>
<th>Approximate Dimensions Height x Width x Depth</th>
<th>Number of Tubes</th>
<th>Tube Outside Diameter</th>
<th>Description of Observed Fouling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screen</td>
<td>18' x 14' x 1.5'</td>
<td>40 total, 3 deep in staggered pattern</td>
<td>3&quot;</td>
<td>Some scaling and some buildup from the walls. Not normally a significant problem.</td>
</tr>
<tr>
<td>Evaporator</td>
<td>17' x 14' x 4.5'</td>
<td>19 wide x 8 deep</td>
<td>3&quot;</td>
<td>Some scaling and some buildup from bottom and top and outside walls. Not normally a significant problem.</td>
</tr>
<tr>
<td>Primary</td>
<td>17' x 14' x 5'</td>
<td>26 wide x 14 deep</td>
<td>2.125&quot;</td>
<td>Significant buildup on the tubes including a large fin on leading edge. Eventually leads to chunks and bridges forming between tubes.</td>
</tr>
<tr>
<td>Superheater</td>
<td>First Bank</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary</td>
<td>18' x 14' x 6'</td>
<td>26 wide x 16 deep</td>
<td>2.125&quot;</td>
<td>Significant buildup on the tubes including a large fin on leading edge. Eventually leads to chunks and bridges forming between tubes.</td>
</tr>
<tr>
<td>Superheater</td>
<td>Second Bank</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary</td>
<td>18' x 14' x 5'</td>
<td>26 wide x 14 deep</td>
<td>2.125&quot;</td>
<td>Significant buildup on the tubes including a large fin on leading edge. Eventually leads to chunks and bridges forming between tubes.</td>
</tr>
<tr>
<td>Generating</td>
<td>Bank</td>
<td>36 wide x 20 deep</td>
<td>2.5&quot;</td>
<td>Buildup on tubes eventually leads to significant blockage across the bank, primarily in front half. Buildup from top and bottom drums is also significant problem.</td>
</tr>
</tbody>
</table>

TABLE 1. TUBE BANKS
2. Short Outage Wash When there is a forced outage that is expected to last more than 36 to 48 hours and the critical path work is not in the convection sections, the downtime is occasionally utilized to do a high-pressure wash of the tubes. Normally the focus is on the generating bank. The quality of the cleaning varies depending on the time available. While this type of wash can improve heat transfer in the convection sections, flue gas temperature at the inlet of the convection section remains high. The length of run after this type of cleaning varies.

3. On-line Wash Periodically the convection sections are washed while the plant is on-line. A long lance ending in a tee is used to manually wash any locations accessible through access doors. The on-line wash improves heat transfer and removes significant quantities of ash, but due to limited access to the generating bank, resulting improvements in pressure drop may not be significant. In addition, it has no effect on flue gas inlet temperatures. On-line washes have been reduced in frequency since explosives cleaning began in late 2005.

4. Explosives Cleaning On-line explosives cleaning has been performed periodically on a trial basis since October 2005. The cleaning is done using a detonation cord placed in a water- and air-cooled aluminum tube and extended into the boiler through access hatches. This type of cleaning is very effective at removing large amounts of material and can reduce pressure drop to acceptable levels even when the boiler is badly fouled. Unlike a full outage with sandblast, it has no effect on flue gas inlet temperatures.

<table>
<thead>
<tr>
<th>Number and Location</th>
<th>Operation</th>
<th>History</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporator / Screen Sootblowers</td>
<td>Two, located between the screen and evaporator banks 1/3 and 2/3 the distance between the bottom and top of the banks.</td>
<td>Once per Shift</td>
</tr>
<tr>
<td>Superheater Rappers</td>
<td>One rapper at the bottom of each loop. A total of 22 on each side.</td>
<td></td>
</tr>
<tr>
<td>Superheater Sonic Horns</td>
<td>Four, two each on the south side between the Pri. 2nd bank and Secondary Bank.</td>
<td>Once per hour.</td>
</tr>
</tbody>
</table>

**TABLE 2. SUMMARY OF TUBE CLEANING DEVICES**

**PRESSURE DROP CALCULATIONS**

**Theoretical Pressure Differential**

Calculations were made of the pressure drop across the tube banks using fluid dynamics principals in an attempt to gain insight into the effects of fouling.

The pressure differential was calculated from (equation 7.72 in [1]):

\[
\Delta p = N_L \chi (\rho V_{\text{max}}^2 / 2) f
\]

\(N_L\) is the number of tubes in the direction of flow. \(\chi\) is a "correction factor" which is a function of transverse and longitudinal pitch of the tubes and Reynolds number and is approximately 0.5 to 3 for most conditions for the Commerce tube banks and \(f\) is the friction factor which is approximately 0.25 for most banks. The flue gas density is \(\rho\) and \(V_{\text{max}}\) is the average flue gas velocity between the tubes. It should be noted that this equation does not take into account losses at the walls, only the pressure drop created by flow moving across the tubes.

In order to model the effect of fouling on the pressure differential, ash buildup was assumed to occur in the following paradigms that could be incorporated into the calculation of pressure differential. The model of fouling is uniform buildup on the outer surface tubes, effectively increasing the diameter of the tube, and for purposes of the calculation is expressed as the thickness of the ash on the tube. In addition to increasing the velocity between the tubes, this type of fouling also affects the Reynolds number and the factors \(\chi\) and \(f\) in eq. (1), all of which are functions of tube diameter. Figure 1 is a rendering of this type of buildup. The
The second form of fouling is blockage of the open space between the tubes, which for purposes of calculation is expressed as a percentage of the duct that is blocked in a bank. This type of blockage has the effect of forcing the flow into the remaining open portion of the bank, thereby increasing velocity through that remaining portion in proportion to the amount that is blocked. It is assumed, for calculation purposes, that the portion blocked is completely blocked and the portion open is completely open (other than tube buildup, if any.) Figure 2 is a photograph of the generating bank showing the lower portion of the tube bank blocked off by ash. The terms “blockage” or “duct blockage” are used to describe this type of fouling.

Table 3 shows the calculated pressure differential using eq. (1) across each bank for five different fouling conditions at typical full-load operations. The first column is for a completely clean convection section, and the total differential of 0.58 inches water is in the general range of what has been measured after thorough cleanings. The last column is an approximation of the conditions observed with the highest differential. The intermediate columns show other combinations of fouling. It can be seen that under all scenarios the generating bank experiences the highest pressure drop, accounting for about three-fourths of the overall differential. The generating bank tends to foul more quickly than the other banks, and it is possible the generating bank contributes proportionately more flow resistance when the convection section is dirty.

Figures 3 and 4 illustrate the relationship between duct
blockage, tube buildup and pressure drop calculated using eq. (1). In order to achieve critical levels of fouling, it is more realistic that the primary cause is duct blockage rather than tube buildup. When dirty, the observed level of tube buildup is typically in the 0.1-0.4 in. range, and the amount of duct blockage is in the 60-80% range. Even at 60% blocked, it would require 0.6-0.7 in. of buildup to create the high differential that is measured when fouling is severe. This level of buildup has not been observed. Conversely, with a realistic 0.3 in. of buildup, blockage would be in the 70-80% range, which is approximately what has been observed. Therefore, efforts to minimize fouling should focus on reducing blockage between the tubes rather than keeping the tubes themselves clean.

Long Term Trend

Figure 5 shows the trend of differential pressure for an approximate 10 year period, with the x axis units being tons burned. Periods with no data points shown are when no valid data was collected.

From 1998 until 2005, corresponding to the first 800,000 tons on the trend, the facility was primarily using major outage waterwashes (every 4-6 months) supplemented by on-line waterwashes and occasional quick washes during forced outages. The effect of the on-line waterwashes is not visible in this chart, as the impact on fouling is relatively small. Increasing pressure drop during each run was a determining factor for scheduling a major outage, and normally three were required each year. Starting in fall of 2005, explosives cleaning in combination with planned outages once per year, occasional cleanings during short outages and on-line washes, were used to minimize fouling. The on-line explosives cleaning has enabled the facility to operate a full year between planned outages.

Three distinct periods can be seen on the trend:
- 1997-2001 (0-300,000 tons) was a period when the plant was operating well and burning relatively high-BTU refuse.
- During the period 2001-2005 (300,000-800,000 tons), the refuse quality dropped and production suffered. Overall, it appears this resulted in slower fouling. In addition, there was a six-month period near 600,000 tons during which problems with the ID fan (unrelated to fouling) limited production. During this time, the pressure differential was almost flat.
- Starting in 2005 (approximately 800,000 tons) refuse quality increased, resulting in higher loads and temperatures. By coincidence this is also when explosives cleaning started, and the combination of the two events has resulted in frequent cleanings and rapid rises in pressure differential. The fact that the explosives cleanings have allowed the plant to run one year between major outages has also contributed to the rapid increases between cleanings.

Data Collection and Reduction

Data was compiled from plant instruments using the Bailey DCS. Fifteen-minute averages for the period of December 30, 1997 through February 7, 2007 were compiled into valid two-hour averages. For each two-hour average only selected 15-minute averages were used. Criteria to validate the 15-minute average included: near full-load operation; no gas usage; no sootblowing; and valid data for the critical parameters of stack flow, pressure readings, etc. A minimum of three valid 15-minute averages were required to calculate a valid two-hour average. As a result, a total of 19,935 valid two-hour averages were generated. A corrected pressure differential was also calculated for each data point which accounted for fluctuations in flue gas flow.
ANALYSIS OF PRESSURE DIFFERENTIAL RATE OF INCREASE

Plant data was analyzed in an attempt to elicit factors that affect increases in pressure drop. The focus was on eventually being able to reduce or stop any increase in pressure drop as the plant operated. As long as the rate of increase was low enough, the need for cleaning or outages would be reduced regardless of the level of fouling. Conversely, even a very low pressure differential is not beneficial unless the rate of increase is also low.

From the two-hour averages, increases in pressure drop were calculated using fifty data point average change in pressure differential versus tonnage burned. Tonnage burned was used as the measure of the amount of plant operation as it was felt this is the best indicator of the amount of fouling that takes place over time as the plant operates. Other measures such as time or power generation would not take into account downtime, operation on gas, operation at reduced load, etc. This step in data reduction resulted in 276 data points.

It has been observed that as the pressure differential increases, the rate of increase accelerates. Figure 6 shows the relationship between the rate of increase and the pressure differential. A very clear correlation can be seen, with little variation in the data at higher differentials. This supports the observation that once the fouling reaches a certain point, it increases rapidly and predictably.

Figure 7 shows how the increase varies with temperature. For this chart the average of the generating bank inlet and generating bank outlet temperatures was used. There appears to be a correlation between the rate of increase and the temperature, and in particular a slight step change can be observed at approximately 850 F. Temperature is also related to the amount of fouling, so this chart does not necessarily
illustrate a separate cause and effect relationship between temperature and increasing fouling. Using the data shown in Figures 6 and 7, a reasonable projection can be made of the differential pressure trend if the starting differential and the flue gas temperatures are known. The flue gas temperature has a significant effect especially when the boiler is clean. An increase of 100 F in temperature may cause the slope of the change in pressure differential to increase by a factor of 5 or 10 (Figure 7). At higher levels of fouling, the effect of temperature is less (as a percent) due to the fact that the slope is already high.

Figure 8 shows conditions typical for four types of cleanings and operating conditions calculated using correlations developed from the data in figures 6 and 7. The trends are consistent with what has been observed and indicate that reducing flue gas temperature should be considered when attempting to reduce the upward trend in fouling.
CONCLUSION

Analysis of the trend of flue gas pressure differential across the convection sections at the Commerce Refuse-to-Energy Facility has led to insight into the factors that increase fouling and have resulted in improved methods for cleaning and extended the interval between outages required for cleaning. By determining the acceleration rate and the effect of temperature on the differential, a more accurate assessment of various cleaning equipment and methods can be made.

Ongoing monitoring of plant operations and optimization of cleaning methods continue, including:

- Superheater rappers will be restored to full operation in May 2007 which is expected to reduce fouling in the superheater and reduce the flue gas temperature into the generating bank, both of which will lead to a slower increase in pressure differential between cleanings.
- The interval between explosives cleanings will be adjusted in order to determine the optimum interval.
- On-line washes, which have been almost eliminated since beginning explosives cleaning, may be re-started in order to reduce the flue gas temperature into the generating bank.
- The economics of various combinations of cleanings is being evaluated in order to minimize the overall cost. It is possible the plant will return to a semi-annual outage schedule. Two outages per year will result in substantial downtime cost, which may be more than offset by the reduction in on-line cleanings and cleaning expense during forced outages.
- Efforts continue with optimization of sonic horn operation and evaluation of their effectiveness.

Future analysis will include addressing possible adjustments to plant operations and further investigation into heat transfer.

REFERENCE