PERFORMANCE TESTING OF A 15-MW WOOD CHIP-FIRED BOILER USING BOILER AS A CALORIMETER

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ABSTRACT

Performance testing of solid-fuel fired boilers has historically been done by using the ASME Power Test Code 4.1 (PTC 4.1) Short Form Heat Loss Method. Recently, municipal solid waste-fired boilers have been tested using a modification of that method called the Boiler as a Calorimeter (BAC) procedure. One feature of the BAC is that the fuel higher heating value (HHV) is obtained without rigorous sampling and analysis requirements. The BAC procedure is therefore appropriate in any application where fuel variability is a factor, particularly for solid fuel boilers. This paper illustrates the application of the BAC procedure to a 15-MW wood chip-fired power plant.

INTRODUCTION

The Resource Energy System Division (RESD) of Westinghouse Electric Corporation, with the assistance of Leonard M. Grillo, Resource Recovery Consultant and ETS, Inc. conducted performance testing in July 1987 for a 15-MW wood-fired boiler in Bethlehem, New Hampshire, operated by Pinetree Power, Inc., a totally owned subsidiary of the Westinghouse Electric Corporation. The testing was conducted using the BAC procedure to reduce the uncertainty that is associated with methods requiring representative sampling and precise determination of fuel properties.

Boiler performance testing of wood-fired boilers is generally conducted using the ASME PTC 4.1 Input/Output or Heat Loss Method. Although this method is the standard for the industry, the authors believe that the BAC procedure is a more appropriate one because performance accuracy is dependent on more easily determined parameters, such as total tonnage burned, rather than the fuel's specific chemical properties.

The BAC procedure is rapidly becoming the standard for the municipal waste-fired boiler industry, where it has been shown to be more accurate than the Input/Output and Heat Loss Methods [1]. The procedure is extremely versatile and can be easily applied throughout industry for steam generating plants wherever fuel variability is a factor. In the following sections, the test protocol and reasons for applying the BAC procedure to determine the performance of the wood-fired boiler are described.

PLANT DESCRIPTION

A process flow diagram of the plant is shown in Fig. 1. Wood chips are fed from the fuel handling system through a surge bin into the semi-suspension-fired traveling grate boiler. Steam generated in the boiler drives a turbine-generator to produce approximately 15 MW of electricity. The flue gas passes through a mechanical

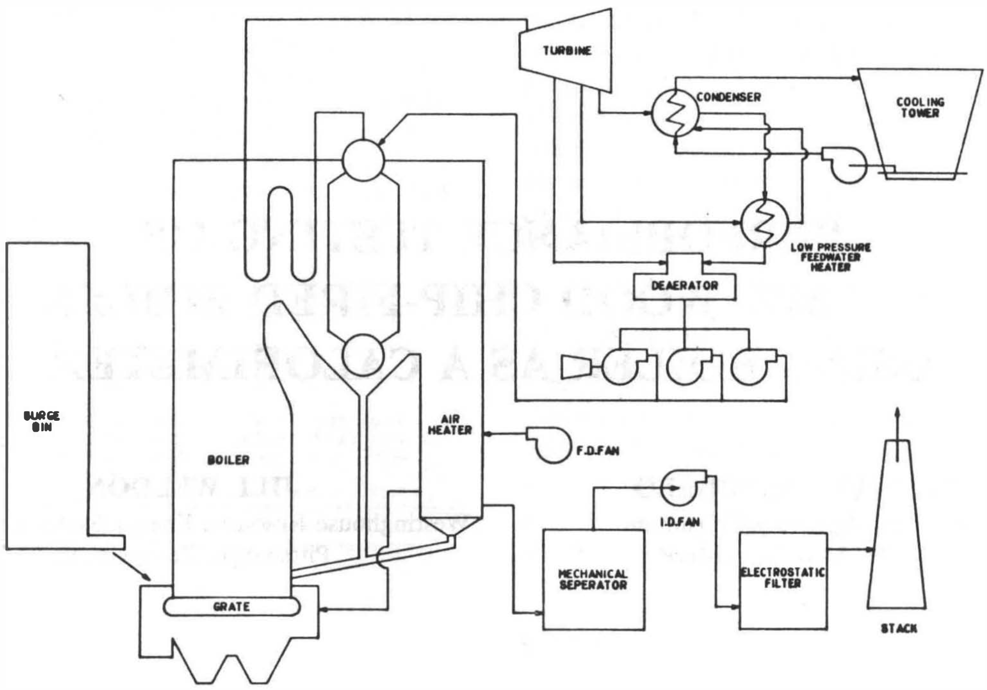

FIG. 1 PROCESS FLOW DIAGRAM OF BETHLEHEM WOOD-FIRED POWER PLANT

separator and electrostatically-augmented gravel bed filter (EFB) to remove the particulate matter to meet an emission limit of 0.1 lb/MBtu. The cleaned flue gas exits to the atmosphere through a 197.5-ft stack.

DESCRIPTION OF THE BOILER AS A CALORIMETER PROCEDURE

The basis for testing boilers and waste incineration systems is contained in ASME Power Test Code 4.1—Steam Generating Units (PTC 4.1) and ASME Power Test Code 33—Large Incinerators (PTC 33), respectively. The BAC procedure is developed from information contained in these two codes.

PTC 4.1 describes two methods for determining boiler efficiency: the input-output and heat loss methods. The input-output method determines efficiency by the following equation:

$$\text{efficiency} = \frac{\text{heat output}}{\text{heat in fuel} + \text{heat credits}}$$

and requires the accurate measurement of the quantity and HHV of the fuel. The heat loss method determines efficiency by the following equation:

$$\text{efficiency} = 100 - \left(\frac{\text{heat losses}}{\text{heat in fuel} + \text{heat credits}}\right) \times 100$$

and requires the determination of the ultimate analysis and HHV of the fuel.

In the BAC procedure, the equations from PTC 4.1 are rearranged to eliminate the requirements for determining the fuel heating value, moisture content and ultimate analysis. In a boiler system, the total chemical heat input from the fuel can be determined by the following equation:

$$\text{heat in fuel} = \text{heat output} + \text{heat losses} - \text{heat credits}$$

The HHV of the fuel can be determined by dividing the measured "heat in the fuel" by the weight of fuel fired during the test. The efficiency can be determined by substituting the above equation into that for the input-output method, resulting in the following:

$$\text{efficiency} = \frac{\text{heat output}}{\text{heat output} + \text{heat losses}}$$

These two equations are the basis of the BAC procedure. Although the procedure is not described in

PTC 4.1 or PTC 33, the equations and instructions for the measurements are taken from PTC 4.1 and PTC 33. This has been generally accepted as a procedure for determining refuse HHV and boiler efficiency by the solid waste industry, and has now been applied to a wood chip combustion facility.

APPLICATION OF THE BAC TO WOOD CHIP-FIRED BOILERS

The Heat Loss and Input/Output tests of the ASME PTC 4.1 have historically been applied to the wood chip-fired boiler industry. Those tests were developed to test the performance of fossil fuel-fired steam generators, where the fuel is generally consistent and the HHV and ultimate analysis are determined accurately and easily.

In wood chip-fired systems, however, the fuel has a highly variable moisture content and HHV. The HHV of the wood chips is similar to that of refuse, in that it may vary widely during a performance test. Figure 2 shows the actual percent variation of the HHV of wood chip grab samples taken hourly during the performance test. The coefficient of variation of HHV and moisture for wood chip samples taken during the performance test were calculated and compared to previously reported [2] coefficients of variation for refuse in Table 1.

Because the BAC procedure for boiler performance testing is the preferred test for variable HHV MSW plants, it follows that it should be the preferred test for wood chip-fired plants, also.

TABLE 1 COMPARISON OF VARIABILITY BETWEEN WOOD CHIP AND REFUSE FUEL HHV

Property	Coefficient of Variability MSW (1)	Wood Chips (2)
HHV	+/- 12.2 percent	+/- 8.7 percent
Moisture	+/- 28.0 percent	+/- 21.3 percent

(1) Between same day pairs of bags (Reference 2)
(2) Between hourly grab samples during the test

TEST PROCEDURES

The wood chip HHV determination requires the accurate measurement of the weight of fuel fired during the test. The weight is not needed to perform an efficiency test using the BAC. However, since the wood chip HHV was desired, the fuel weight was needed.

The test duration and fuel feed rate can be determined in the following two ways:

(a) Set the test duration and determine the fuel weight fired during that time period.

(b) Set the weight of fuel and determine the test duration as the time needed to combust that known quantity of fuel.

In the case of the Pinetree Power Plant, the latter method is more precise and was used for the test. An eight-hour test duration was desired. Sufficient wood was collected, based on the estimated fuel feed rate, to provide approximately an eight-hour fuel supply. At the end of the test, the actual duration was determined to be 7 hr and 57 min.

Nontest wood chips were fed until about ten minutes prior to the desired test start. The conveyors were purged of nontest chips during the 10-min period prior to start, and test chips were loaded onto the conveyors but not allowed to reach the surge bin.

The test began when the low level alarm in the surge bin sounded. Weighed chips were then fed continuously to the boiler until all of the weighed chips were combusted and the conveyors purged of test chips. The test ended and normal operation resumed when the surge bin low level alarm sounded. In this manner, the quantity of wood chips fed to the plant was known with reasonable accuracy.

The BAC procedure requires that the boiler outputs, losses and credits be determined for the duration of the test. The reference point numbers used throughout this paper referring to the outputs, losses and credits are taken from Fig. 1 from PTC 4.1. The nomenclature used is consistent with that in PTC 4.1 and is shown in Table 2.

Outputs

Of the four outputs defined in PTC 4.1, the following two were applicable to the Pinetree facility and accounted for in the test procedure:

(a) Heat in primary steam (q_{s32}).

(b) Heat in blowdown (q_{w35}).

Losses

Of the fifteen losses defined in PTC 4.1, the following seven were applicable to the Pinetree facility and accounted for in the test procedure:

(a) Unburned carbon in refuse (residue) (L_{uc}).

(b) Heat in dry gas ($L_{G'}$).

(c) Moisture in fuel (L_{mf}).

(d) Moisture from burning hydrogen (L_H).

(e) Moisture in air (L_{mA}).

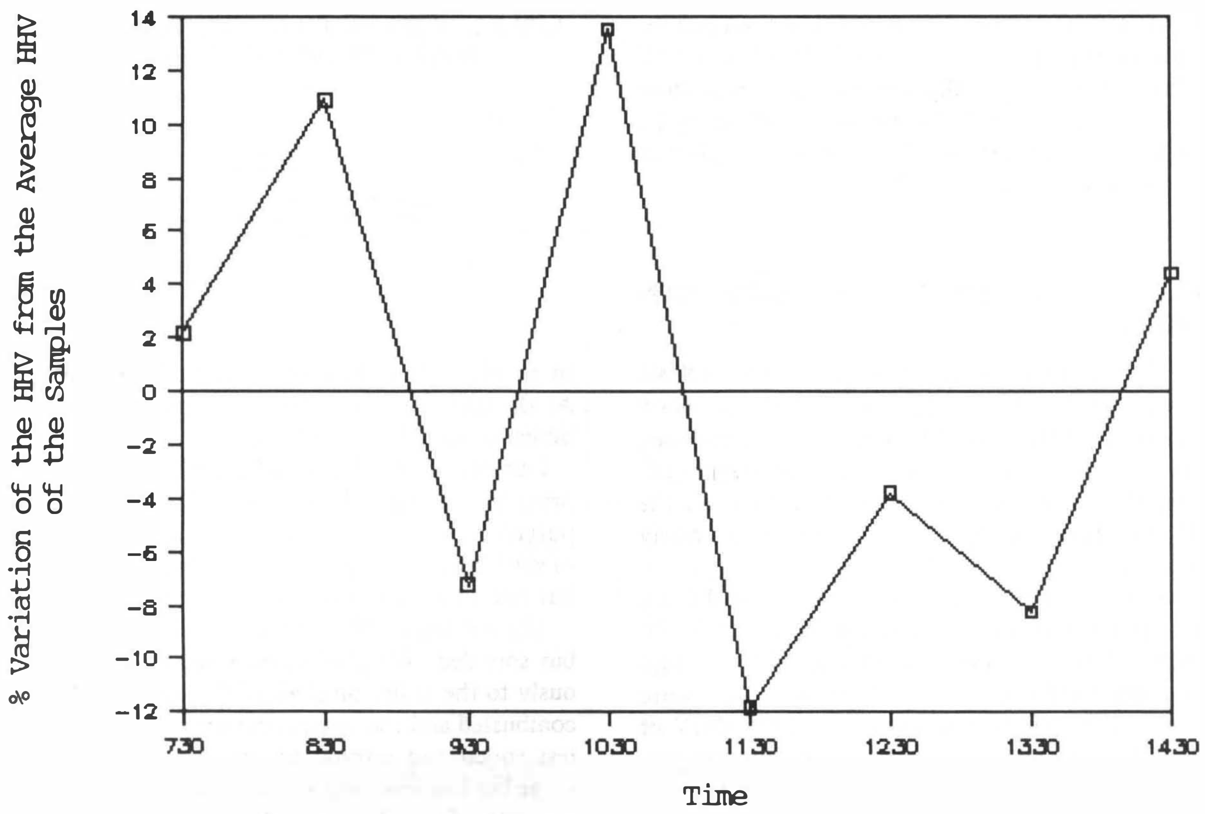

FIG. 2 PERCENT VARIATION OF THE WOOD CHIP HHV DURING THE BOILER EFFICIENCY TEST

(f) Radiation and convection (L_β).
(g) Sensible heat in flue dust (L_d).

To determine the loss due to unburned carbon in the residue, the quantity and HHV of the combined residue produced during the test were measured. The sampling and testing procedure for residue is discussed later.

The flue gas flow, temperature and composition were measured to determine losses due to the dry gas and moisture. With the BAC method, an ultimate analysis of the fuel is not available; therefore the losses due to fuel moisture and moisture formed from fuel hydrogen cannot be determined separately. Instead, the moisture present in the stack gases is measured and attributed to all moisture losses.

The flue gas flow rate was determined by performing pitot tube traverses across the stack flue using EPA Method 2 procedures. Flue gas composition was measured using Orsat apparatus by EPA Method 3 procedures. The flue gas moisture sample was taken over 1-hr periods at a single point at the center of the flue. Moisture content was determined using EPA Method 4 procedures.

Radiation and convection losses were determined based on Fig. 8 in PTC 4.1.

The sensible heat in the dry residue was determined from the temperature of the residue at each discharge point. Plant personnel indicated that about 90% of the ash was collected by the mechanical separator and EFB, and 10% from the grate. The temperature of the air heater outlet was 400°F and the temperature of ash from the grate was estimated at 1300°F, so a weighted average of 500°F was applied to the total ash stream to determine the sensible heat content.

Credits

Of the nine credits defined in PTC 4.1, the following three are applicable to the Pinetree facility and accounted for in the test procedure:

(a) Heat in entering air ($B_{A'}$).
(b) Sensible heat in fuel (B_f).

TABLE 2 NOMENCLATURE

A	:	Air
A'	:	Dry air
B	:	Heat credits in the form of sensible heat
c	:	Specific heat (BTU/lb-°F)
CO_2	:	Percent carbon dioxide per volume of dry flue gas
e	:	Elapsed time (for the test duration)
F	:	Factor
F1	:	Factor 1: pounds of nitrogen per pound of standard air (= 0.7685, PTC 4.1, Page 73)
f	:	Fuel
G	:	Flue gas
G'	:	Dry flue gas
H	:	Higher heating value (BTU/lb)
H_2O	:	Percent moisture per volume of flue gas
h	:	Enthalpy (BTU/lb)
L	:	Heat loss which could have been added to the working fluid
M	:	Molecular weight of any substance (lb/mole)
m	:	Moisture content (weight percent)
N	:	Pounds of nitrogen per pound of A.F. fuel
N_2	:	Percent nitrogen per volume of dry flue gas
O_2	:	Percent oxygen per volume of dry flue gas
P	:	Pressure
p	:	Ashpit refuse (residue)
p'	:	Dry pit refuse (residue)
q	:	Heat
R	:	Reference
s	:	Steam
t	:	Temperature (Fahrenheit)
UC	:	Unburned carbon in residue
V	:	Volume of any substance
v	:	Vapor
W	:	Weight
w	:	Water
x	:	Auxiliary
β	:	Radiation and convection
γ	:	Gas specific weight (lb/cf)
'	:	Dry

(c) Heat supplied by moisture in entering air (B_{mA}).

The reference temperature for the test was 60°F. The credits for sensible heat and moisture in entering air are based on the dry bulb temperature at the air inlet to the forced draft fan. Wet and dry bulb temperatures were taken as near as possible to the fan inlet to determine specific humidity. The sensible heat in fuel was assumed to be at the outside ambient dry bulb temperature that was measured near the truck dump.

LOCATION AND FREQUENCY OF MEASUREMENTS

Control Room Data

Control room data were taken every 10 min and consisted of information monitored by the plant control system. These data included:

(a) Totalized primary steam flow (pounds for the test duration).

(b) Primary steam temperature (F).

(c) Primary steam pressure (psig).

(d) Feedwater temperature (F).

(e) Steam drum pressure (psig).

(f) Combustion air inlet temperature (F).

(g) Air heater outlet temperature (F).

Blowdown flow could not be measured directly and was estimated to be 1% of the steam output.

Noncontrol Room Data

The weigh station monitor was responsible for collecting gross and tare weights of all trucks entering or leaving the site which pertained to the test.

A plant "rover" collected noncontrol room data for the duration of the test. The data were collected hourly and include the following:

(a) Wet and dry bulb temperatures at air inlet (F).

(b) Ambient dry bulb temperature at the wood chip delivery area (F).

(c) Residue samples for laboratory determination of moisture and HHV.

The wet and dry bulb temperatures were measured using a sling psychrometer. The readings were taken as near as possible to the inlet to the combustion air fans. The wet and dry bulb temperatures are used to determine specific humidity (moisture) in the entering air. The temperature of the entering air used in the combustion calculations was the combustion air inlet temperature taken in the control room. The ambient dry bulb temperature at the wood chip delivery area represents the temperature of the fuel.

Ash Sampling, Preparation, and Testing

Ash samples were collected hourly at the discharge of the ash conditioner. The ash production rate was determined in a manner similar to the way in which the wood chip feed rate was determined, by weighing the truck loads produced for a definite time period. Samples were sent to a laboratory for moisture, HHV and ultimate analysis determinations.

Assumed Data

PTC 4.1, modified to use the BAC, requires that certain assumptions be made. The following assumptions were made for this test:

(a) Radiation and convection loss (F_β) = 0.40%.

(b) Blowdown flow (W_{we35}) is equal to 1% of the steam flow (= 12,000 lb).

(c) Wood chip HHV (H_f) = 4500 Btu/lb (which was used only for the calculation of radiation and convection loss).

(d) Moisture content of fuel (m_f) = 50% (which was used only to determine the heat capacity of the fuel).

(e) Nitrogen concentration in wood chips (N) = 0.03%.

Pretest Conditions

Prior to the start of the test, the plant was required to meet certain criteria to assure that the test would produce a representative and accurate assessment of the plant performance. All plant instruments were calibrated less than two weeks prior to the start of the test. The boiler operated for a sufficient period to allow the heat transfer surfaces to foul. Immediately prior to and after the test, the facility was operated in a stable mode at rated capacity for more than 4 hr.

DATA

All of the data were collected in the manner described above and are presented in reduced form. For example, steam flow is total flow for the test, temperature is the average of the readings taken, etc. The results of the data collection and reduction are shown in Table 3.

CALCULATIONS

Nitrogen Balance to Determine Total Air

The total combustion air entering the system boundaries is difficult to measure because it enters from several sources and changes continuously. The total air is determined more accurately by a nitrogen balance. The fuel nitrogen content (N), which is insignificant in comparison to the air nitrogen, was estimated at 0.03% for the balance. The following calculation was used to determine total dry air, in pounds:

$$W_{A'e} = \frac{(V_{Ge})(1 - H_2O)/100)(N_2)(\gamma_{N2G}) - (N/100)(W_{fe})}{F_1}$$

where

γ_{N2G} is the nitrogen specific weight in flue gas in lb/cf, calculated as follows:

$$\gamma_{N2G} = \frac{(M_{N2})(14.7)}{(10.73)(t_G + 460)}$$

The total moisture in the air is calculated from the total dry air as follows:

$$W_{mAe} = (W_{A'e})(m_{a'})$$

Boiler as a Calorimeter Calculations

The equations below are solved from the information developed previously. All outputs, credits and losses are reported in Btu/lb as-fired fuel.

Heat Outputs

q_{s32} = Net Heat Output to Steam

$$q_{s32} = \frac{(W_{se32})(h_{s32} - h_{w24})}{W_{fe}}$$

$$= 3260.1 \text{ Btu/lb}$$

q_{w35} Net Heat Output to Blowdown

$$q_{w35} = \frac{(W_{we35})(h_{w35} - h_{w24})}{W_{fe}}$$

$$= 7.1 \text{ Btu/lb}$$

Heat Credits

$B_{A'e}$ = Heat Credit from Sensible Heat in Dry Air

$$B_{A'e} = \frac{(W_{A'e})(c_{A'})(t_{A'7} - t_{RA})}{W_{fe}}$$

$$= 62.6 \text{ Btu/lb}$$

B_{mAe} = Heat Credit from Sensible Heat in Air Moisture

$$B_{mAe} = \frac{(W_{mAe})(c_s)(t_{A'7} - t_{RA})}{W_{fe}}$$

$$= 1.4 \text{ Btu/lb}$$

B_{fe} = Heat Credit from Sensible Heat in Fuel

$$c_f = (c_{f'})(1 - m_f/100) + (c_w)(m_f/100)$$

$$= 0.665 \text{ Btu/lb-F}$$

$$B_{fe} = (c_f)(t_f - t_{RA})$$

$$= 6.7 \text{ Btu/lb}$$

Heat Losses

L_{UC} = Heat Loss Due to Unburned Carbon in Residue

$$L_{UC} = \frac{(W_{p'e})(H_{p'})}{W_{fe}}$$

$$= 97.6 \text{ Btu/lb}$$

TABLE 3 RESULTS OF DATA COLLECTION

Control Room Data

W_{Se32} (total steam flow):	1,201,000 lb
t_{32} (average steam temperature):	756 °F
P_{32} (average steam pressure):	634 psia
t_{24} (average feedwater temperature):	270 °F
P_{31} (average steam drum pressure):	695 psia
t_{G14} (average air heater outlet temperature):	390 °F
$t_{A'7}$ (combustion air temp. at A.H. inlet):	106 °F

Non-Control Room Data

W_{fe} (total weight of fuel fired):	421,080 lb
W_{pe} (total wet ash weight):	6,599 lb
$t_{A'7}$ (air dry bulb temperature near A.H.):	96 °F
t_{A7} (air wet bulb temperature near A.H.):	72 °F
t_f (fuel temperature):	70 °F

Ash Laboratory Data

$H_{p'}$ (dry ash HHV from lab):	7748 BTU/lb
m_p (ash moisture content from lab):	19.58 Pct

Stack Data

CO_2 (volume percent CO_2 in dry flue gas):	13.71
O_2 (volume percent O_2 in dry flue gas):	6.36
N_2 (volume percent N_2 in dry flue gas):	79.93
H_2O (volume percent moisture in flue gas):	19.10
t_G (flue gas temperature):	386 °F
V_{Ge} (wet flue gas flow):	62,535,320 ACF

Other Data

Heat capacities, in BTU/lb-F are as follows:

$c_{A'}$ (dry air, PTC 4.1, Figure 3):	.24
$c_{f'}$ (dry fuel, PTC 33, Table 2):	.33
$c_{G'}$ (dry flue gas, PTC 4.1, Figure 7):	.24
$c_{p'}$ (dry ash, PTC 33, Section 7.1):	.20
c_s (steam, PTC 4.1, Figure 6):	.47
c_w (water):	1.00

Enthalpies in BTU/lb were taken from ASME Steam Tables:

h_{S32} (enthalpy of steam):	1382.0
h_{W24} (enthalpy of feedwater):	239.0
h_{W35} (enthalpy of blowdown):	489.7
h_{vG14} (enthalpy of vapor in flue gas at 1 psia):	1235.2
h_{Rv} (enthalpy of vapor at reference point):	1087.7
h_{Rw} (enthalpy of water at reference point):	28.1

Molecular weights, in pounds per mole, were used in the calculations:

M_{CO2} (Molecular weight of CO_2):	44.01
M_{O2} (Molecular weight of O_2):	32.00
M_{N2} (Molecular weight of N_2):	28.02
M_{H2O} (Molecular weight of water):	18.02
M_A (Molecular weight of air):	28.84

Other factors used include:

Fl (pounds of nitrogen per pound of standard air, from PTC 4.1)	0.7685
F_{beta} (radiation and convection loss from PTC 4.1 Figure 8)	0.4
$m_{A'}$ (specific humidity in the entering air, calculated from the wet and dry bulb temperatures, in pounds of water vapor per pound dry air	0.0113

Results of Nitrogen Balance:

$W_{A'e}$ (weight of dry air)	2,387,400 lb
$W_{G'e}$ (weight of dry flue gas)	2,495,901 lb
W_{mGe} (weight of moisture in flue gas)	348,547 lb
W_{mAe} (weight of moisture in air)	26,978 lb

$L_{G'}$ = Heat Loss Due to Sensible Heat in Dry Flue Gas

$$L_{G'} = \frac{(W_{G'e})(c_{G'})(t_{G14} - t_{RA})}{W_{fe}}$$

$= 469.4$ Btu/lb

L_{mG} = Heat Loss Due to Sensible Heat in Moisture in Flue Gas

$$L_{mG} = \frac{(W_{mAe})(h_{vG14} - h_{Rv}) + (W_{mGe} - W_{mAe})(h_{vG14} - h_{Rw})}{W_{fe}}$$

$= 929.3$ Btu/lb

L_{β} = Heat Loss Due to Radiation and Convection

$$L_{\beta} = (F_{\beta}/100)(H_f)$$

$= 18.0$ Btu/lb

$L_{p'}$ = Heat Loss Due to Sensible Heat in Dry Residue

$$L_{p'} = \frac{(W_{p'e})(c_{p'})(t_p - t_{RA})}{W_{fe}}$$

$= 1.1$ Btu/lb

Wood Chip HHV and Boiler Efficiency

The wood chip HHV is determined as follows:

$$\text{Total outputs} = q_{s32} + q_{w35}$$
$$= 3267.2 \text{ Btu/lb}$$
$$\text{Total credits} = B_{A'e} + B_{mAe} + B_{fe}$$
$$= 70.7 \text{ Btu/lb}$$
$$\text{Total losses} = L_{UC} + L_{G'} + L_{mG} + L_{\beta} + L_{p'}$$
$$= 1515.5 \text{ Btu/lb}$$

$$\text{Wood chip HHV} = \text{outputs} + \text{losses} - \text{credits}$$
$$= 4712.0 \text{ Btu/lb}$$

The boiler efficiency is determined as follows:

$$\text{Boiler efficiency} = \frac{\text{outputs}}{\text{outputs} + \text{losses}}$$
$$= 68.3\%$$

CONCLUSIONS

Procedures to determine boiler efficiency and HHV for the Pinetree Power, Inc. wood chip-fired boiler using a modified version of ASME PTC 4.1, known as the Boiler as a Calorimeter Procedure, were described in the paper. The BAC procedure is appropriate for wood-fired boilers because wood fuel is highly variable in moisture content and HHV. The variability of wood fuel is comparable to that of refuse fuel where the BAC procedure has been accepted as the industry standard. The BAC procedure should therefore be considered in performance testing of wood chip-fired boilers as a useful alternative to the standard heat loss or input-output method of ASME PTC 4.1.

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