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MONITORING AND IMPROVING COAL-FIRED POWER PLANTS USING THE INPUT/LOSS METHOD - PART III

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ABSTRACT

The Input/Loss Method allows for complete thermal understanding of a power plant through explicit determinations of fuel and effluent flows, fuel chemistry including ash, fuel heating (calorific) value and thermal efficiency. Fuel and effluent flows are not directly measured. The Method is designed for on-line monitoring, and enables continuous improvement of unit heat rate.

The base technology of the Input/Loss Method was documented in companion ASME papers, Parts I & II (1998-IJPGC-Pwr-33 and 1999-IJPGC-Pwr-34). Accurate determination of boiler efficiency is an important aspect of this Method. The current paper explains, defends, and expands the Input/Loss Method of determining boiler efficiency. Expansion of the Method includes: 1) defense of the use of "gross" versus "fuel" efficiency; 2) a generic and high accuracy approach to stack loss computations; 3) variable Heats of Formation; and 4) development of lower heating (net calorific) value calculations commonly used in Europe, maintaining consistency with computed fuel flows using higher (gross calorific) values.

Although the Input/Loss Method employs principles from both the Input-Output and Heat-Loss (Heat-Balance) approaches of ASME Power Test Codes, this paper notes several conceptual differences. Fundamental concepts are discussed, followed by calculational methods. It concludes with examples demonstrating 0.2% to over 0.4% error in efficiency if using traditional protocols.

General methods of this work rely on review of earlier efforts (Parts I & II). Understanding Part III methods clearly requires study of its combustion equation and nomenclature. Review of PTC 4.1 (or the longer PTC 4) is also strongly advised.

NOMENCLATURE

Molar Quantities Related to Stoichiometrics

x = As-fired fuel per 100 moles dry gas product, solution "base"
 a = Molar fraction of combustion O_2 , moles/base.
 n_i = Molar quantity of substance i , moles/base.
 N_j = Molecular weight of compound j .
 α_k = Mole of As-Fired fuel constituent k ; $\sum \alpha_k = 1.0$, $k=0,1,\dots,10$.
 b_A = Moisture in entering combustion air, moles/base.
 βb_A = Moisture entering with air leakage, mole/base.

b_z = Water/steam in-leakage from working fluid, moles/base.
 b_{pLS} = Molar fraction of pure limestone ($CaCO_3$).
 γ = Molar ratio of excess $CaCO_3$ to stoichiometric $CaCO_3$.
 z = Moles of H_2O per effluent $CaSO_4$, specified on input.
 σ = Kronecker function: unity if sulfur present in fuel.
 β = Air pre-heater dilution factor, a ratio of air leakage to true combustion air, a molar ratio.
 $\beta \equiv (R_{Act} - 1.0) / [aR_{Act}(1.0 + \varphi_{Act})]$
 R_{Act} = Ratio of total moles of dry gas from the combustion process before entering the air pre-heater to gas leaving; defined as the air pre-heater leakage factor.
 φ_{Act} = Ratio of non-oxygen gases (nitrogen and argon) to oxygen in the combustion air; $\varphi_{Act} \equiv (1.0 - A_{Act}) / A_{Act}$
 A_{Act} = Concentration of O_2 in combustion air local to the system.

Quantities Related to System Terms

BBTC = Useful Energy Flow Delivered derived directly from the combustion process, Btu/hr.
 ΔH_{f-77}^0 = Heat of Formation at 77 F, Btu/lbm or Btu/lb-mole.
 ΔH_{f-Cal}^0 = Heat of Formation at T_{Cab} , Btu/lbm or Btu/lb-mole.
HBC = Firing Correction (i.e., "energy credit"), Btu/lbm_{AF}.
HHV = As-Fired (wet-base) higher heating value, Btu/lbm_{AF}.
HHVP = As-Fired (wet-base) higher heating value corrected for constant pressure combustion process, Btu/lbm_{AF}.
HNSL = Non-Chemistry & Sensible Heat Losses, Btu/lbm_{AF}.
HPR = Enthalpy of Products (HHV- or LHV-based), Btu/lbm_{AF}.
HRX = Enthalpy of Reactants (HHV- or LHV-based), Btu/lbm_{AF}.
HR = System heat rate (HHV- or LHV-based), Btu/kWh.
HSL = Stack Losses (HHV- or LHV-based), Btu/lbm_{AF}.
J = Joule's conversion, 778.16926 ft-lbf/Btu.
 L_m = Specific heat loss term for a process m , Btu/lbm_{AF}.
LHVP = As-Fired (wet-base) lower heating value corrected for both a constant pressure combustion process and rejected fuel effects, Btu/lbm_{AF}.
 m_{AF} = As-Fired fuel mass flow rate (wet with ash), lbm_{AF}/hr.
 Q_{SAH} = Energy flow delivered to steam/air heaters, Btu/hr.
 R = Gas constant, 1545.325 ft-lbf/lb-mole/R.
 T_{Stack} = Exit boundary temperature for combustion products, F.

T_{Cal} = Calorimetric temperature referencing the laboratory determined or computed heating value, F.
 T_{RA} = Reference temperature to which sensible heat losses and traditional PTC 4.1 "boiler credits" are based, F.
 W_{FD} = Brake fan power associated with in-flowing streams (e.g., FD fans) within the system boundary, Btu/hr.
 W_{ID} = Brake fan power associated with out-flowing streams (e.g., ID & gas recirculation fans), Btu/hr
 WF_k = Weight fraction of component k, --.
 η_B = Boiler efficiency (HHV- or LHV-based), --.
 η_C = Combustion efficiency (HHV- or LHV-based), --.
 η_A = Boiler absorption efficiency, --.

INTRODUCTION

The Input/Loss Method is a unique process which allows for complete thermal understanding of a power plant through explicit determinations of fuel and effluent flows, fuel chemistry including ash, fuel heating value and thermal efficiency (Lang, 1994-99, 1998 & 1999). Fuel and effluent flows are not directly measured. The Method is designed for on-line monitoring, and hence continuous improvement of unit heat rate.

For coal-fired power plants, direct fuel metering with the accuracy required for acceptable thermal performance monitoring has always eluded the industry, to say nothing of determining coal heating values in real-time. Given intrinsic inaccuracies, traditional coal flow metering is worthless for thermal performance monitoring. The Input/Loss Method developed by Exergetic Systems employs turbine cycle energy flows, boiler efficiency independent of fuel flow, routine emissions and an indicated Air/Fuel ratio. With this and other information, plant improvement is achieved through application of Fuel Consumption Indices, an established technique which distributes irreversible losses on a system-wide bases leading to incremental heat rate changes (Lang & Horn, 1991).

This Part III paper discusses the critically important determination of **boiler efficiency**. Indeed, boiler efficiency, if thermodynamically accurate, will guarantee consistent system mass/energy balances. From such consistencies, fuel flow and effluent flow can then be determined ... with greater accuracy than obtained from direct measurements. In summary, routine plant and effluent measurements coupled with accurate boiler efficiency allow the Input/Loss Method to produce the following information **on-line**:

Thermal:

- As-Fired Fuel Chemistry and Heating Value
- Fuel Flow
- Boiler Efficiency
- Turbine Cycle Heat Rate
- Gross Unit Heat Rate
- Fuel Consumption Indices for all major components (true losses in the system, and their fuel cost)
- Tube Failure Model, detects both flow & location.

Emissions:

- Effluent Emission Rates (in terms of lb_{effluent}/hr and lb_{effluent}/million-Btu_{fuel})
- Total Effluent Mass and Volumetric Flow Rates
- Error analysis of effluent instrumentation, ambient conditions and system assumptions.

POWER TEST CODE BOILER EFFICIENCY

Before discussing details of the recommended boiler efficiency procedures it is useful to examine ASME's Power Test Code (PTC) 4.1, Steam Generating Units. The general procedures followed by PTC 4.1 are found in the new PTC 4, and are also used in PTC 4.4 Heat Recovery Steam Generators and PTC 22 Gas Turbine Power Plants.

Using PTC's Heat-Loss Method (now termed the Heat-Balance Method), higher heating value efficiency is defined as:

$$\eta_{B\text{-HHV}} = \frac{\text{HHVP} + \text{HBC} - \sum \text{Losses}/m_{\text{AF}}}{\text{HHVP} + \text{HBC}} \quad (1A)$$

$$\eta_{B\text{-HHV}} = \frac{\text{BBTC} / m_{\text{AF}}}{\text{HHVP} + \text{HBC}} \quad (1B)$$

As interpreted by the methods of this paper, the above imply that the input energy flow in fuel and "credits" $m_{\text{AF}}(\text{HHVP} + \text{HBC})$ less $\sum \text{Losses}$, describes the "Useful Energy Flow Delivered" (BBTC) from combustion as a thermodynamic process. This is not a trivial statement, for, as demonstrated below, a countering PTC viewpoint when evaluating these same terms allows arbitrary accounting of system in- and out-flows of energy. As applied, the PTC view tacitly assumes $\text{HHVP} \neq f(T_{\text{RA}})$. PTC 4.1 allows for a user defined (arbitrary) reference temperature affecting only HBC and Loss terms. PTC 4's preferred methods include fixing the reference temperature at 77F for all fuels; ignoring the HBC term altogether, advocating a so-called "fuel" efficiency. Demonstrated in this paper is that evaluation of the HBC term and Losses is integrally connected with combustion as a thermodynamic process. Their evaluation is dependent on the definition of heating value ... indeed whose energy, and thus the energies of all system streams, must be referenced to the calorimetric temperature which defines by reference the fuel's energy (see Notes & Errata, item 1). As a practical matter when analyzing high energy coals, PTC assumptions may have little impact. However, the generalist approach is advocated herein, and believed required with high water fuels and/or unusual combustion situations.

To study the thermodynamic nuances of heating value, the concept of Enthalpies of Products and Reactants is now introduced. This is a key feature of the Input/Loss Method. Such quantities both define heating value and justify the HBC "credit" term as being intrinsically required for any definition of boiler efficiency.

Recall that higher heating value is the amount of energy released given complete combustion; for a solid fuel in a constant volume bomb, where the process occurs about (or is corrected to) the "calorimetric temperature". This process **is the difference** between the enthalpy of ideal products ($\text{HPR}_{\text{Ideal}}$) less reactants (HRX_{Cal}) both evaluated relative to the calorimetric temperature, T_{Cal} . Correction from a constant volume process (HHV) associated with a bomb calorimeter, if applicable, to a constant pressure process (HHVP) associated with the As-Fired condition is made with the $\Delta H_{\text{V/P}}$ term, of Eq.(39). See Notes & Errata, items 2 thru 4.

$$\oint \delta_{T\text{-cal}} Q = - \text{HHV} = - \text{HHVP} + \Delta H_{\text{V/P}} \quad (2A)$$

$$\text{HHVP} = - \text{HPR}_{\text{Ideal-HHV}} + \text{HRX}_{\text{Cal-HHV}} \quad (2B)$$

Only when fuel is actually fired at T_{Cal} is the thermodynamic definition of heating value truly conserved. At any other temperature the so-called "fuel" efficiency (ignoring a HBC correction), is thermodynamically inconsistent. It is argued by Entwistle (1988) and others that efficiency should give a numerical result that is associated with the ratio of output to pure fuel energy. This author agrees, but insists that indeed the definition of HHV, as pure fuel energy measured at T_{Cal} , but fired at T_{Fuel} , be strictly maintained; thus $\text{HPR}_{\text{Ideal}}$ & HRX_{Cal} must be corrected to achieve this concept. This work maintains that only when fuel is actually fired at exactly T_{Cab} and whose ideal combustion products are cooled to exactly T_{Cab} is the thermodynamic definition of heating value strictly conserved. At any other firing temperature, a **Firing Correction** (HBC) term must be applied to HRX_{Cal} . At any other temperature associated with effluent products, the $\text{HPR}_{\text{Ideal}}$ term must be corrected for both actual products and sensible heats relative to T_{Cal} . At any other temperature, use of a "fuel efficiency" is thermodynamically inconsistent.

When a fossil fuel is fired at a temperature other than T_{Cab} the Firing Correction term HBC must be added to each side of Eq.(2B):

$$\text{HHVP} + \text{HBC} = -\text{HPR}_{\text{Ideal-HHV}} + \text{HRX}_{\text{Cal-HHV}} + \text{HBC} \quad (3A)$$

Eqs.(1A) & (3A) imply that for any As-Fired condition, the systems' thermal efficiency is unity provided the $\text{HPR}_{\text{Ideal}}$ term is conserved (i.e., system losses are zero, with ideal products being produced at T_{Cal}). For an actual combustion process, the $\text{HPR}_{\text{Ideal}}$ term of Eq.(3A) must be corrected for actual system losses, thus forming the basis of boiler efficiency:

$$\eta_{\text{B-HHV}} (\text{HHVP} + \text{HBC}) = -\text{HPR}_{\text{Ideal-HHV}} - \sum \text{Losses}/m_{\text{AF}} + \text{HRX}_{\text{Cal-HHV}} + \text{HBC} \quad (3B)$$

This work recognizes that the $\text{HPR}_{\text{Ideal}}$ term of Eqs.(2B) & (3A), and thus (3B), is key in accurately computing boiler efficiency implied by Eq.(3B). This term, defining the enthalpy of ideal combustion products, must be evaluated at T_{Cal} . All terms comprising Eq.(3B) must be evaluated with methodology consistent with a boiler's energy flows, but also, and most importantly, in such a manner as to not impair the numerical consistency of $\text{HPR}_{\text{Ideal}}$ as referenced to T_{Cal} .

The PTC procedures do not appreciate the consistent use of T_{Cal} as establishing the thermodynamic reference of energy levels as affecting the major terms comprising boiler efficiency (and thus the consistent use of $\text{HPR}_{\text{Ideal}}$). It is believed, in general, that the power industry evaluates fuel heating value, and especially for coal, only to classify fuels. Boiler efficiencies are determined as relative quantities. Accuracy in heating value and in the resultant computed fuel flow has not been required, only accuracy in the total system fuel energy flow (i.e., Btu/hr). The accuracy needed in boiler efficiency by the Input/Loss Method, given that fuel chemistry, fuel heating value and fuel flow are all computed, requires a more consistent approach (see Notes & Errata, item 5). Further, commercial needs for high accuracy boiler efficiency was not required until recent deregulation of the electric power industry which has now necessitated improved accuracy. Higher heating value boiler efficiency follows directly from Eq.(3B), noting that: $\text{HRX}_{\text{Act-HHV}} \equiv \text{HRX}_{\text{Cal-HHV}} + \text{HBC}$:

$$\eta_{\text{B-HHV}} = \frac{-\text{HPR}_{\text{Ideal-HHV}} - \sum \text{Losses}/m_{\text{AF}} + \text{HRX}_{\text{Act-HHV}}}{\text{HHVP} + \text{HBC}} \quad (3C)$$

To illustrate, consider a simple system firing pure carbon in dry air, having losses only of dry gas, effluent CO and unburned carbon. Assume FD and ID fans of W_{FD} & W_{ID} energy flows. Applying PTC 4.1 §7.3.2.02, but using nomenclature of this work, dry gas loss is evaluated at T_{RA} the arbitrary reference temperature of PTC 4.1. The PTC's term L_{G} is given by:

$$L_{\text{G}} = C_{\text{P/Gas}} (T_{\text{Stack}} - T_{\text{RA}}) M'_{\text{Gas}} \quad (4)$$

Incomplete combustion is described (PTC 4.1 §7.3.2.07) as the fraction of CO produced relative to total possible CO₂ effluent, times the difference in Heats of Combustion of carbon and CO. Note: PTC 4.1 assumes 14540 Btu/lbm_c for carbon and 4380 Btu/lbm_c for CO; consistent $\Delta H_{\text{c-68F}}^0$ values are 14085.22 and 3957.38 Btu/lbm_c.

$$L_{\text{CO}} = (\Delta H_{\text{c-CalCO}_2}^0 - \Delta H_{\text{c-CalCO}}^0) M'_{\text{CO}} \quad (5)$$

Unburned carbon is described in PTC 4.1 §7.3.2.07, as the flow of refuse carbon times its Heat of Combustion:

$$L_{\text{UC}} = (\Delta H_{\text{c-CalCO}_2}^0) M'_{\text{C/Fly}} \quad (6)$$

For our simple example, and assuming unity fuel flow, the so-called boiler "credits" are determined by PTC 4.1 procedures as:

$$\text{HBC} = C_{\text{P/Fuel}} (T_{\text{Fuel}} - T_{\text{RA}}) + C_{\text{P/Air}} (T_{\text{Amb}} - T_{\text{RA}}) M'_{\text{Air}} + W_{\text{FD}} \quad (7)$$

In these equations the various weight fractions, relative to As-Fired fuel, M'_i , have direct translation to 4.1 usage. PTC 4.1 efficiency is then given by the following, after combining the above quantities in Eq.(3C), and re-arranging terms:

$$\eta_{\text{B-HHV}} = \frac{[-\text{HPR}_{\text{Ideal-HHV}} - C_{\text{P/Gas}} (T_{\text{Stack}} - T_{\text{RA}}) M'_{\text{Gas}} - W_{\text{ID}} - (\Delta H_{\text{c-CalCO}_2}^0 - \Delta H_{\text{c-CalCO}}^0) M'_{\text{CO}} - (\Delta H_{\text{c-CalCO}_2}^0) M'_{\text{C/Fly}} + \text{HRX}_{\text{Cal-HHV}} + C_{\text{P/Fuel}} (T_{\text{Fuel}} - T_{\text{RA}}) + C_{\text{P/Air}} (T_{\text{Amb}} - T_{\text{RA}}) M'_{\text{Air}} + W_{\text{FD}}]}{(\text{HHVP} + \text{HBC})} \quad (8)$$

Eq.(8) illustrates a few of PTC 4.1 discrepancies, but at the same time suggests the general approach followed by Input/Loss.

- 1) The enthalpy terms $\text{HPR}_{\text{Ideal}}$ & HRX_{Cal} as referenced to the calibration temperature, when "corrected" to system boundary conditions using $(T_{\text{Stack}} - T_{\text{RA}})$ & $(T_{\text{Fuel}} - T_{\text{RA}})$ is wrong since $T_{\text{RA}} \neq T_{\text{Cal}}$. The effects on HPR from the $\sum \text{Losses}/m_{\text{AF}}$ term, as referenced to T_{RA} further increases error. See PTC 4.1 §7.2.8.3 and §7.3.2.02.
- 2) PTC 4.1 addresses unburned fuel and incomplete combustion through Heats of Combustion. Although numerically correct as referenced to $\text{HPR}_{\text{Ideal}}$ a more logical approach is to describe actual products - their effluent concentrations and specific Heats of Formation, $\Delta H_{\text{f-Cal}}^0$ evaluated at T_{Cal} , not T_{RA} . See PTC 4.1 §7.3.2.01, -07, etc.
- 3) HHV reflects formation of ideal combustion products at T_{Cab} ; water thus formed must be referenced to $\Delta H_{\text{f-Cal/liq}}^0$ and $h_{\text{f-Cal}}$ (not

shown). Of course water's Heat of Formation varies from -6836.85 Btu/lbm at 40F to -6811.48 Btu/lbm at 100F; h_r from 8.02 to 68.05 Btu/lbm. These terms are held constant per PTC 4.1 §7.3.2.04.

- 4) PTC 4.1 §7.3.2.13 pulverizer rejected fuel losses are described by the rejects weight fraction times rejects heating value, HHV_{Rej} (not shown). This is correct only if HHV_{Rej} is the same as the As-Fired. If mineral matter is concentrated in the rejects (reflected in HHV_{Rej}), then fuel chemistry (and HPR & HRX terms) must be affected.
- 5) PTC 4.1 offers some confusion over "credit" and loss terms. For example, if the system encompasses a FD fan, its energy inflow, W_{FD} , must carry the same sense as $\int dh$ reactant terms; thus correcting HRX_{Cal} see above. In like manner, the W_{ID} term must follow the sense of $\int dh$ products as affecting outflows, but with a negative sign, thus correcting HPR_{Ideal} ; see Notes & Errata, items 1c & 2. PTC 4.1's generic use of B_{XE} per §7.2.8.5 is ill-advised given its lack of specificity.

Of course, one could equate T_{RA} to T_{Cal} (not suggested by PTC 4.1 nor 4), and solve some of these issues. However, combustion using high excess air would tax PTC 4.1 assumptions when using C_p values for "standardized" combustion products. Molecular weights suggested by PTC 4.1 are oxygen-based; they invoke inconsistencies with all published thermodynamic properties since the carbon-base standard was established some 38 years ago. Numerous thermodynamic constants invoked by PTC 4.1 are inaccurate or at least questionable: carbon & hydrogen Heats of Combustion, Btu/kWh conversion, the gas constant, assumed O_2 in ambient air, heat capacities from 1936 & 1954 research, an assumed calorimetric temperature of 77F (§7.2.6.2), etc. Taken as a whole, these discrepancies aggravate accuracy when considering variations to common combustion.

PTC 4.1's Input-Output Method is, of course, not practical for coal-fired units given its reliance on measured fuel flow. Its application to oil- and gas-fired units is flawed if computed efficiencies are not correctly referenced. For example, if oil and gas units are both burning 18,000 Btu/lbm fuel at 52F producing the same delivered energy flow, BBTC, their efficiencies are not comparable (the oil's HHV being referenced to 68F and the gas to 60F). Given different T_{Cal} , HBC for these cases will be different - by definition - thus creating a differences in boiler efficiency and in computed fuel flows.

As suggested by Eq.(8), rearrangement of its terms when obtained from a consistent combustion equation provides the nucleus for Input/Loss modeling. First, the issue of possible inconsistency between ideal and actual products is addressed by simplifying (for the example sited) the entire numerator of Eq(8) to $[-HPR_{Act} + HRX_{Act}]$. In this, the Enthalpy of Products, HPR_{Act} , encompasses effluent sensible heat and ΔH_{f-Cal}^0 terms associated with actual products, including all terms associated with incomplete combustion. The Enthalpy of Reactants, HRX_{Act} , is defined by the third line of Eq.(8), $[HRX_{Cal-HHV} + HBC]$; noting that $HRX_{Cal-HHV}$ is evaluated as $[HHVP + HPR_{Ideal-HHV}]$ as strictly defined by Eq.(2B). Second, use of the $[-HPR_{Act} + HRX_{Act}]$ concept allows ready introduction of the calorimetric temperature as affecting both $\int dh$ and ΔH_{f-Cal}^0 terms, versus the arbitrary T_{RA} . Third, the $[-HPR_{Act} + HRX_{Act}]$ concept

provides generic methodology for any combustion situation, for any fuel, bearing any amount of water. It is believed the elimination of individual loss terms associated with the *combustion process* greatly reduces error when determining total *Stack Losses*, including the significant dry gas loss. Note that: $\sum(\text{Stack Losses})/m_{AF} = HHVP + HBC - [-HPR_{Act-HHV} + HRX_{Act-HHV}]$.

As an aside, the use of the word "credit" is believed misleading since terms comprising HBC intrinsically correct the fuel's calorimetric energy base to the As-Fired conditions. The HBC quantity is herein termed a "Firing Correction". HBC is not a convenience nor arbitrary; it should not be viewed as another "system energy flow". HBC can not be eliminated (as argued by some), it is required for HHV consistency and thus allows for valid mass/energy balances.

In conclusion, although the basic philosophies of PTC 4.1 and 4 are useful and have been employed by the Input/Loss Method, the specifics are not thermodynamically consistent if applying a strict definition of heating value. PTC methods are applicable to the higher quality fuels. For applicability to all fuels, all firing conditions, and all methods of determining heating value (i.e., evaluated at any T_{Cal}), the following is advocated:

- an ordered approach to boiler efficiency calculations employing the basic measuring of heating value through consistent treatment of energies of products & reactants;
- accurate and consistent thermodynamic properties, referenced to the calorimetric temperature; and
- a high accuracy thermodynamic approach to determining total effluent flows (never based on direct measurement).

INPUT/LOSS BOILER EFFICIENCY, INTRODUCTION

The Input/Loss Method determines boiler efficiency, η_B , by dividing its definition into two components, a combustion efficiency and boiler absorption efficiency:

$$\eta_B = \eta_C \eta_A \quad (9)$$

To develop the combustion efficiency term, the Input/Loss Method employs an energy balance uniquely about the flue gas stream (i.e., the combustion process). This balance is based on the difference in enthalpy between actual products HPR_{Act} and actual reactants HRX_{Act} . Actual, As-Fired, Enthalpy of Reactants is defined in terms of Firing Corrections: $HRX_{Act} \equiv HRX_{Cal} + HBC$. Combustion efficiency is defined in terms which are independent of fuel flow but akin to PTC 4.1's Input-Output Method; its terms are fully integrated with those of a combustion equation, such as found in Eq.(19).

$$\eta_{C-HHV} \equiv \frac{-HPR_{Act-HHV} + HRX_{Act-HHV}}{HHVP + HBC} \quad (10)$$

This formulation was developed to maximize accuracy. Typically for coal-fired units, over 95% of the boiler efficiency's numerical value is comprised of η_C . All individual terms comprising η_C have the potential of being determined with high accuracy. HPR_{Act} is determined knowing effluent temperature, complete stoichiometric balances, and accurate combustion gas and water properties. HRX_{Act} is dependent on heating value and Firing Corrections. HBC

applies needed corrections for reactant's sensible heat: fuel, combustion air, limestone, water in-leakage and energy inflows ... all referenced to T_{Cal} (detailed below) such that $(- \text{HPR}_{\text{Act}} + \text{HRX}_{\text{Act}})$ is conserved.

The boiler absorption efficiency is developed from the boiler's "Non-Chemistry & Sensible Heat Loss" term, HNSL; the product's sensible heat of non-combustion processes. See Notes & Errata, item 6. It is defined such that it, through iterative techniques, can be computed independent of fuel flow:

$$\eta_A \equiv 1.0 - \frac{\text{HNSL}}{- \text{HPR}_{\text{Act-HHV}} + \text{HRX}_{\text{Act-HHV}}} \quad (11)$$

$$= 1.0 - \frac{\text{HNSL} / \eta_{\text{C-HHV}}}{\text{HHVP} + \text{HBC}} \quad (12)$$

HNSL comprises radiation & convection losses, pulverizer rejected fuel losses (or fuel preparation processes), and sensible heats in: bottom ash, fly ash, effluent dust and effluent products of limestone. HNSL is determined using a portion of PTC 4.1's Heat-Loss Method.

The definition of η_A allows the classical definition, Eq.(1A), to be evaluated using HPR_{Act} and HRX_{Act} terms. Since $\text{HSL} = \text{HPR}_{\text{Act-HHV}} - \text{HPR}_{\text{Ideal-HHV}}$ it follows from Eq.(2B) that: $[- \text{HPR}_{\text{Act-HHV}} + \text{HRX}_{\text{Act-HHV}}] = \text{HHVP} + \text{HBC} - \text{HSL}$, which is incorporated into the combined Eqs.(9), (10) & (11):

$$\eta_{\text{B-HHV}} = \frac{- \text{HPR}_{\text{Act-HHV}} + \text{HRX}_{\text{Act-HHV}}}{\text{HHVP} + \text{HBC}} \cdot \frac{- \text{HPR}_{\text{Act-HHV}} + \text{HRX}_{\text{Act-HHV}} - \text{HNSL}}{- \text{HPR}_{\text{Act-HHV}} + \text{HRX}_{\text{Act-HHV}}} \quad (13A)$$

$$= \frac{- \text{HPR}_{\text{Act-HHV}} + \text{HRX}_{\text{Act-HHV}} - \text{HNSL}}{\text{HHVP} + \text{HBC}} \quad (13B)$$

$$= \frac{\text{HHVP} + \text{HBC} - \text{HSL} - \text{HNSL}}{\text{HHVP} + \text{HBC}} \quad (13C)$$

$$= 1.0 - \frac{\sum \text{Losses} / m_{\text{AF}}}{\text{HHVP} + \text{HBC}} \quad (13D)$$

$$= \frac{\text{BBTC} / m_{\text{AF}}}{\text{HHVP} + \text{HBC}} \quad (14)$$

where, of course, $\sum \text{Losses} \equiv m_{\text{AF}}(\text{HSL} + \text{HNSL})$. Again, the Useful Energy Flow Delivered, BBTC, is $m_{\text{AF}}(\text{HHVP} + \text{HBC})$ less $\sum \text{Losses}$.

With a computed boiler efficiency the As-Fired fuel flow rate, m_{AF} , can then be back-calculated from Eq.(14) which is of critical importance to Input/Loss Methods.

$$m_{\text{AF}} = \frac{\text{BBTC}}{\eta_{\text{B-HHV}} (\text{HHVP} + \text{HBC})} \quad (15)$$

Assuming T_{Cal} is not known and an arbitrary reference temperature (T_{RA}) must be used, $T_{\text{Cal}} = T_{\text{RA}}$, then the practicality of any boiler efficiency method should be demonstrated through the sensitivity of the denominator of Eq.(15) with the assumed reference temperature. Fuel flow, BBTC, and HHVP are constants for a given system evaluation. Regards fuel flow, the use of an arbitrary T_{RA} is compatible with Input/Loss Methods provided the computed fuel flow of Eq.(15) is demonstrably insensitive to reasonable changes in the reference temperature, T_{RA} . By reasonable changes is meant the likely range of the actual calorimetric temperature (e.g., 68F to 95F

for solid or liquid fuels). This is not to suggest that effects on η_{B} and HR may be ignored if fuel flow is found insensitive; the insensitivity of η_{B} and HR must also be demonstrated, through the $\text{HPR}_{\text{Ideal}}$ term before a given T_{RA} is justified. However, if η_{B} is mis-evaluated through mis-application of T_{RA} , effects on fuel flow are not proportional given the influence of the HBC term evaluated using Input/Loss Methods. A 1% change in η_{B} (e.g., 85% to 84%) caused by a change in T_{RA} will typically produce a 0.2% to 0.4% change in fuel flow ($\Delta m_{\text{AF}}/m_{\text{AF}}$) using Input/Loss Methods. Further, Eq.(15) also illustrates that the use of a fuel efficiency (in which $\text{HBC} \equiv 0.0$), in combination with an arbitrary reference temperature is flawed: since $\eta_{\text{B}} = f(T_{\text{RA}})$, and BBTC & HHVP are constants, changes in computed fuel flow are then related to some arbitrary T_{RA} , and quite wrong. The effects on HR given mis-application of T_{RA} will compound (add) the erroneous effects from η_{B} and fuel flow.

Once fuel flow is correctly determined, stoichiometric balances are then used to resolve all boiler inlet & outlet mass flows, including effluent flows required for regulatory reporting. Unit heat rate associated with a power plant follows from Eq.(15).

$$HR_{\text{HHV}} \equiv \text{BBTC} / (\eta_{\text{B-HHV}} \text{Power}) \quad (16)$$

$$= m_{\text{AF}}(\text{HHVP} + \text{HBC}) / \text{Power} \quad (17)$$

Given objectives to calculate consistent fuel & emission flows and unit heat rate, the importance of accurately determining boiler efficiency is obvious. The further objective of determining on-line heating values, based on sophisticated error analysis, demands integration of stoichiometrics with accurate efficiency. See Notes & Errata, item 7.

FOUNDATIONAL PRINCIPLES AND NOMENCLATURE

Thermodynamic Properties

For background material, this section discusses the determination of Heats of Formation used for the consistent determination of boiler efficiency. Thermodynamically, the most common assumption is that Heats of Formation at absolute zero, ΔH_{f-0}^0 , are an additive function of the various atomic groups comprising the substance (Reid & Sherwood, 1965). However, by international convention, standardized Heats of Formation are referenced to 77.0F (25C) and 1.00 bar pressure. For typical fossil combustion, pressure corrections are justifiably ignored. Thus to convert to any temperature from 77F, assuming an additive principle (Danner & Daubert, 1983):

$$\Delta H_{f-T}^0 = \Delta H_{f-77}^0 + \int_{77}^T dh_{\text{Compound}} - \sum \int_{77}^T dh_{\text{Elements}} \quad (18)$$

Use of the 77F-base standard is important as it allows consistency with published values. This is not trivial, consistent ΔH_{f-T}^0 values for CO_2 , SO_2 and H_2O allow consistent evaluation of the difference between the As-Fired heating value plus Firing Corrections, and $[- \text{HPR}_{\text{Act}} + \text{HRX}_{\text{Act}}]$... thus intrinsically accounting for Stack Losses, HSL, including the vagaries of coal pyrolysis given unburned fuel, see Eqs.(13B) & (13C). The finest

compilation of Heats of Formulation and other properties is the so-called CODATA work (Cox, Wagman, & Medvedev, 1985); it is the recommended basis for any study of fossil combustion. Enthalpy integrals used in Eq.(18) and elsewhere herein are obtained from the work of Passert & Danner (1974); also used as API standards. A difficulty could arise if using ASHRAE air psychrometric properties. ASHRAE has chosen 0.0F as the thermodynamic dead state for dry air enthalpy, but concurrently for water its traditional triple point (32.018F). All fluid components in the system (e.g., combustion gases, water in the combustion effluent, moist combustion air, gaseous constituents of air) must use a consistent dead state for thermodynamic property evaluations. The Input/Loss Method employs a uniform dead state for all properties at 32.018F and 0.08872 psiA (e.g., the defined zero enthalpy for dry air, gaseous CO₂, saturated liquid water, etc.). Thermodynamic properties are evaluated in the usual manner; for example from T_{Dead} to T_{Ca_b} and from T_{Dead} to T_{Stack}, thus the net evaluation from T_{Ca_l} to T_{Stack}.

Given such foundations Heats of Formation can then be computed for any calorimetric temperature. For gaseous fuels the industrial calorimetric standard is 60F and 14.73 psiA; refer to ASTM D1071, §2.2, and GPA 2145. For coal and coke heating values, determined by adiabatic or isoperibol bomb calorimeter following ASTM D5865, §13, the reference is 77F (25C) as based on ASTM Research Report D05-1013. Earlier ASTM standards D2015 & D3286 used 68F (20C). For coal heating values following ISO 1928:1995(E) the reference is 77F (25C). For oil fuels, following ASTM D240, the reference is 68F (20C). ASME PTC 4.1 assumes 68F; PTC 4 assumes 77F ignoring gaseous fuel standards. This is not to suggest that codified standards for coal are used by labs regards standard reference temperatures - **they are not**. Further, typically the ASTM standards do not specify how T_{Ca_l} is to be achieved. In practice the author has found various labs using: 27C (80.6F), 28.5C (83.3F), 30C (86.F) or 35C (95F); noting that modern bomb calorimeters can run at an adjustable T_{Ca_l}. The author has yet to find any lab determining coal HHV at 68F or 77F. However, knowing the calorimetric temperature (whatever it is), all system energy terms affecting boiler efficiency can then be consistently computed - T_{Ca_l} simply needs to be reported.

Combustion Equation

The following combustion equation is presented here for assistance in understanding nomenclature used in the following section which details procedures. Refer to prior works for additional clarity. The nomenclature used is unique in that brackets are included for clarity. For example, the expression "α₂[H₂O]" means the fuel moles of water, algebraically α₂. Quantities comprising the combustion equation are based on 100 moles of dry gaseous product.

$$\begin{aligned}
 & x\{\alpha_0[C_{YR}H_{ZR}] + \alpha_1[N_2] + \alpha_2[H_2O] + \alpha_3[O_2] + \alpha_4[C] + \alpha_5[H_2] + \alpha_6[S] \\
 & + \alpha_7[CO_2] + \alpha_8[CO] + \alpha_9[H_2S] + \alpha_{10}[ash]\}_{As-Fired\ Fuel} \\
 & + b_z[H_2O]_{In-Leakage} + [(1 + \beta)(a[O_2] + a\phi_{Act}[N_2] + b_A[H_2O])]_{Air} \\
 & + \{(1 + \gamma)b_{PLS}[CaCO_3]\}_{As-Fired\ PLS} \\
 = & d_{Act}[CO_2] + g_{Act}[O_2] + h[N_2] + j_{Act}[H_2O] + k_{Act}[SO_2] \\
 & + \{e_{Act}[CO] + f[H_2] + l[SO_3] + m[NO] + p[N_2O] + q[NO_2] \\
 & + t[C_{YP}H_{ZP1}] + u[C_{YP2}H_{ZP2}]\}_{Minor\ Components} + x\alpha_{10}[ash] \\
 & + \sigma b_{PLS}[CaSO_4 \cdot zH_2O] + \{(1 - \sigma + \gamma)b_{PLS}[CaO]\}_{Excess\ PLS} \\
 & + v[C_{Refuse}] + \{\beta a[O_2] + \beta a\phi_{Act}[N_2] + \beta b_A[H_2O]\}_{Air\ Leakage} \quad (19)
 \end{aligned}$$

Note that Eq.(19) contains terms which allow consistent study of any combination of effluent data, especially the principle "actual" effluent measurements d_{Act} , g_{Act} , j_{Act} and the system terms β , ϕ_{Act} & R_{Act} . As has been discussed in Parts I & II, these terms are considered of critical importance when describing fossil-fired systems - they allow data on either side of the air pre-heater to be employed, in any mix, with total consistency. This allows the stoichiometric base of Eq.(19), of 100 moles of dry gas, to be conserved at either side of the air pre-heater: dry stack gas = 100 moles, and dry boiler gas = 100 moles. Several computational options are provided for: 1) input of excess air; 2) input of O₂ and minor pollutants; or 3) input of CO₂, O₂ and minor pollutants.

INPUT/LOSS BOILER EFF., DETAILED PROCEDURES

Absorption efficiency, η_A , is based on the Non-Chemistry & Sensible Heat Loss term, HNSL, whose evaluation employs several PTC 4.1 procedures. HNSL is defined by the following:

$$HNSL \equiv L_\beta + L_p + L_{d/Fly} + L_{d/Prec} + L_{d/Ca} + L_R - W_{ID}/m_{AF} \quad (20)$$

HNSL bears the same numerical value for both higher or lower heating value calculations, as does η_A ; see Notes & Errata, item 8. Exceptions to PTC 4.1 usage includes the following: L_β is referenced to the total gross (corrected) higher heat input, (HHVP + HBC), not HHV; the L_w term of PTC 4.1 is combined with the ash pit term L_p ; $L_{d/Fly}$ is sensible heat in fly ash; $L_{d/Prec}$ is the sensible heat in stack dust at collection (the assumed electrostatic precipitator), considered a separate stream from fly ash; and $L_{d/Ca}$ is the sensible heat of CaSO₄·zH₂O and CaO effluents given limestone injection. The L_R and W_{ID} terms are discussed below. Note that all terms of Eq.(20) are evaluated relative to unity As-Fired fuel. Numerical checks of all effluent ash is made against fuel mineral content (and optionally can re-normalize the fuel's chemistry).

The radiation & convection factor, $\beta_{R\&C}$, is determined using either: the American Boiler Manufacturers' curve (PTC 4.1); the work of Gerhart, Heil & Phillips (1991); direct measurement; or judgement. The resulting L_β loss term is computed using the (corrected) higher heating value plus Firing Corrections:

$$L_\beta \equiv \beta_{R\&C}(HHVP + HBC) \quad (21)$$

The coal pulverizer rejects loss term, L_R , is based on the gross (corrected) higher heat input plus Firing Corrections of the rejected fuel, [WF_{Rej} (HHVP_{Rej} + HBC)], given rejects contain condensed water. Further, it is assumed the grinding action could result in a concentration of mineral matter (ash) in the reject, thus the fuel chemistry is renormalized based on a corrected fuel ash, $\alpha_{10-corr} = f(WF'_{Ash-AF})$; Eq.(19). This is based on the weight fraction of ash downstream of the pulverizers (true As-Fired), WF'_{Ash-AF} : whose value derives from the weight fraction of rejects/fuel, WF_{Rej} ; ash in the supplied fuel, $WF_{Ash-Sup}$; and corrected heating values. For lower heating value computations, the ratio HHV_{Rej}/HHV_{Sup} in Eq.(22A) is replaced by LHV_{Rej}/LHV_{Sup}.

$$\begin{aligned}
 WF'_{Ash-AF} = & WF_{Ash-Sup} [(1.0 - WF_{Rej})HHV_{Rej}/HHV_{Sup} \\
 & - (WF_{Rej}/WF_{Ash-Sup})(1.0 - HHV_{Rej}/HHV_{Sup})] / (1.0 - WF_{Rej}) \quad (22A)
 \end{aligned}$$

The assumption of the L_R loss being based on the higher heating value, although convenient for the HNSL term, implies, given the possibility of renormalized fuel chemistry, that LHVP must be corrected for differences in fuel water's latent heat. This correction is described below as applied in Eq.(22B). The $\Delta H_{L/H}$ term of Eq.(22C) is evaluated using As-Fired chemistry corrected for rejected fuel, see Eq.(40). The correction ξ is given as $(1 - WF'_{Ash-AF}) / (1 - WF'_{Ash-Sup})$. ξ also corrects Eqs.(39) thru (42). See Notes & Errata, item 9 for a derivation of $\Delta H_{corr-LHV}$. These same procedures are applicable for a fuel cleaning process where fuel ash is removed.

$$LHVP = LHV + \Delta H_{V/P} - \Delta PV_{L/H} - \Delta H_{corr-LHV} \quad (22B)$$

$$\Delta H_{corr-LHV} = \Delta H_{L/H} (\xi - 1.0) / \xi \quad (22C)$$

The steam/air heater energy flow term, Q_{SAH} , is assigned to HBC provided the system encompasses this heater, thus allowing BBTC to be defined in the classical manner (i.e., throttle less feedwater, hot less cold reheat); best seen equating Eqs.(13B) & (14):

$$BBTC = m_{AF} (-HPR_{Act} + HRX_{Act} - HNSL) \quad (22D)$$

If HHV and $HRX_{Cal-HHV}$ are to be conserved (and thus $HPR_{Ideal-HHV}$), the effects of BBTC must be corrected for that energy flow solely attributable to combustion: thus $HRX_{Act-HHV}$ through HBC includes a $+Q_{SAH}$ term, noting that $(BBTC - Q_{SAH})$ is net system output.

The ID fan energy flow term, W_{ID} , where thermal energy is imparted to gas outflow streams (e.g., ID or recirculation fans), the HPR_{Act} term must be corrected with a $-W_{ID}$ through HNSL of Eq.(12) such that the fuel's energy is again properly conserved.

The coal pulverizer shaft power is not accounted as no thermal energy is added to the fuel. Crushing coal increases its surface energy. For a \approx brittle material, no appreciable changes in internal energy occur. The increased surface energy and any slight changes in internal energy are well accounted for through the process of determining heating value (again, HPR_{Ideal}). If using ASTM D2013, samples are prepared by grinding to a #60 sieve (250 μ m) ... as in pulverizing. Indeed, inconsistencies would arise if the bomb calorimeter samples were prepared atypical of actual firing conditions.

Miscellaneous shaft powers are not accounted if not affecting HPR_{Act} or HRX_{Act} . Indeed, the use of heat rates incorporating electrical house loads (the B_{XE} term of PTC 4.1), is not advised for understanding the thermal performance of systems. The presence of an FD Fan will always improve efficiency given a higher Firing Correction. The presence of an ID Fan will not affect η_B .

Having evaluated HNSL, Eq.(20), the absorption efficiency is determined from either HHV- or LHV-based parameters:

$$\eta_A = 1 - \frac{HNSL}{-HPR_{Act-HHV} + HRX_{Act-HHV}} = 1 - \frac{HNSL}{-HPR_{Act-LHV} + HRX_{Act-LHV}} \quad (23)$$

At the system-level, HNSL through η_A corrects the quantity $[-HPR_{Act} + HRX_{Act}]$ to the actual useful output, $BBTC/m_{AF}$.

Combustion efficiency is determined by the following, as either HHV- or LHV-based:

$$\eta_{C-HHV} \equiv \frac{-HPR_{Act-HHV} + HRX_{Act-HHV}}{HHVP + HBC} \quad (24)$$

$$\eta_{C-LHV} \equiv \frac{-HPR_{Act-LHV} + HRX_{Act-LHV}}{LHVP + HBC} \quad (25)$$

All unburned fuel downstream of the combustion process proper (e.g., carbon born by ash) is treated by the combustion efficiency term, as are all air, leakage & combustion water terms. For accuracy and Method consistency, stack losses are not independently computed; however to clarify, they relate to η_{C-HHV} using PTC 4.1 nomenclature as:

$$\eta_{C-HHV} = 1.0 - \frac{HSL_{HHV}}{HHVP + HBC} \quad (26)$$

$$HSL_{HHV} = [L_G + L_{mG} + L_{mF} + L_{mA} + L_{mCa} + L_Z + L_H + L_{CO} + L_{UH} + L_{UHC} + L_{UC1} + L_{UC2}]_{HHV} \quad (27)$$

where: the L_{mG} term is moisture created from combustion of chemically-bound H/C fuel; L_{mCa} is fuel moisture bound with effluent $CaSO_4$; L_{UC1} is unburned carbon in fly ash; L_{UC2} is unburned carbon in bottom ash; all others per PTC 4.1. Non-combustion energy flows are not included (see HNSL). Terms of Eq.(27) as fractions of $(HHVP + HBC)$ or $(LHVP + HBC)$, are computed by back-calculation after η_C is determined, presented for monitoring of individual effects.

Development of the combustion efficiency term, computed based on HPR_{Act} , HRX_{Act} & HBC and involving systematic use of a combustion equation, is believed an improved approach versus individual "stack loss" terms. Most importantly, system mass and energy balances are assured.

Boiler efficiency is defined as either HHV- or LHV-based.

Note that its definition, given both Firing Correction and HNSL definitions, conserves the thermodynamic meaning of heating value. Thus fuel flow *must compute identically* from either efficiency base.

$$\eta_{B-HHV} = \eta_{C-HHV} \eta_A \quad (28)$$

$$\eta_{B-LHV} = \eta_{C-LHV} \eta_A \quad (29)$$

$$m_{AF} = \frac{BBTC}{\eta_{B-HHV} (HHVP + HBC)} = \frac{BBTC}{\eta_{B-LHV} (LHVP + HBC)} \quad (30)$$

Given the nature of the modeling employed, computations of Eq.(30) using both efficiencies is an important numerical overcheck.

As observed above, once HNSL is computed only three principle quantities remain to complete boiler efficiency: HPR_{Act} , HRX_{Act} and HBC which are defined in the following paragraphs.

To fully understand the formulations comprising HPR_{Act} , HRX_{Act} and HBC, note the subscripts associated with the individual substances. When considering water product created from combustion, n_{Comb-H_2O} in Eq.(31), its Heat of Formation (saturated liquid phase) at T_{Cal} must be corrected for boundary (stack) conditions via $[h_{Stack} - h_{f, Ca}]$. The Enthalpies of Reactants of Eqs.(34) & (35) derive from the definition of heating value $[HHVP + HPR_{Ideal-HHV}]$ at T_{Cal} , Firing Corrections then applied. Firing

Corrections are closely defined and only relate to terms which correct HRX_{Cal} to the actual firing conditions.

Differences in formulations required for higher or lower heating values should also be carefully reviewed. Note that higher heating values require use of the saturated liquid enthalpy evaluated at T_{Cal} ; lower heating values require the use of saturated vapor at T_{Cal} . Water bound with effluent $CaSO_4$ is assumed in the liquid state at the stack temperature; whereas its reference is the heating value's base (fuel water being the assumed source for the $z[H_2O]$ term). The quantities which are not so corrected are the last two terms in Eqs.(31) & (32): water born by air and from in-leakage undergo no transformations, having non-fuel origins. Heating values and energies are, of course, associated with the system boundary: the As-Fired fuel (or the "supplied" in the case of fuel rejects), ambient air and location of CEMS and stack temperature measurements. See Notes & Errata, item 10.

Enthalpy of Products (HPR_{Act})

For higher heating value calculations:

$$HPR_{Act-HHV} \equiv \sum HPR_i + [n_{Comb-H_2O}(\Delta H_{f-Cal}^0 + h_{Stack} - h_{f-Cal}) + n_{Fuel-H_2O}(h_{Stack} - h_{f-Cal}) + n_{Lime-H_2O}(h_{f-Stack} - h_{f-Cal}) + n_{CAir-H_2O}(h_{Stack} - h_{g-Cal}) + n_{Leak-H_2O}(h_{Stack} - h_{Steam})]_{H_2O} N_{H_2O} / (xN_{AF}) \quad (31)$$

For lower heating value calculations:

$$HPR_{Act-LHV} \equiv \sum HPR_i + [n_{Comb-H_2O}(\Delta H_{f-Cal}^0 + h_{Stack} - h_{g-Cal}) + n_{Fuel-H_2O}(h_{Stack} - h_{g-Cal}) + n_{Lime-H_2O}(h_{f-Stack} - h_{g-Cal}) + n_{CAir-H_2O}(h_{Stack} - h_{g-Cal}) + n_{Leak-H_2O}(h_{Stack} - h_{Steam})]_{H_2O} N_{H_2O} / (xN_{AF}) \quad (32)$$

where:

$$HPR_i = \text{Enthalpy of non-water product } i \text{ at the stack.} \\ \equiv [\Delta H_{f-Cal}^0 + \int_{T_{Cal}}^{T_{Stack}} dh_i] n_i N_i / (xN_{AF}) \quad (33)$$

n_{Comb-H_2O} = Molar water found at the stack (boundary) created directly from combustion

$$\equiv x(\alpha_0 ZR/2 + \alpha_5 + \alpha_9) - f$$

n_{Fuel-H_2O} = Molar water found at stack born by As-Fired fuel (as total inherent and surface moisture)

$$\equiv j_{Act} - [b_A + b_Z + \sigma b_{PLS,Z} + x(\alpha_0 ZR/2 + \alpha_5 + \alpha_9) - f]$$

n_{Lime-H_2O} = Water bound with effluent $CaSO_4$ ($\sigma b_{PLS,Z}$)

n_{CAir-H_2O} = Molar water found at the stack born by combustion air and air in-leakage

$$\equiv b_A (1.0 + \beta)$$

n_{Leak-H_2O} = Water found at the stack from in-leakage (b_Z)

$(h_{Amb} - h_{Cal})_{Air}$ = Δ Enthalpy of combustion air relative to T_{Cal}

h_{f-Amb} , h_{g-Amb} = Sat. water enthalpies at ambient dry bulb.

$h_{Stack-H_2O}$ = $f(P_{Stack-H_2O}, T_{Stack})$, where $P_{Stack-H_2O}$ is water's partial pressure per the wet molar:

$$P_{Stack-H_2O} = P_{Amb} (j_{Act} + \beta b_A) / (1.0 + j_{Act} + \beta b_A).$$

Enthalpy of Reactants (HRX_{Act})

For higher heating value calculations:

$$HRX_{Act-HHV} \equiv HHVP + HBC + HPR_{CO_2-Ideal} + HPR_{SO_2-Ideal} + \Delta H_{f-Cal}^0 (\alpha_0 ZR/2 + \alpha_5 + \alpha_9) N_{H_2O} / N_{AF} + HRX_{CaCO_3} \quad (34)$$

For lower heating value calculations:

$$HRX_{Act-LHV} \equiv LHVP + HBC + HPR_{CO_2-Ideal} + HPR_{SO_2-Ideal} + \Delta H_{f-Cal}^0 (\alpha_0 ZR/2 + \alpha_5 + \alpha_9) N_{H_2O} / N_{AF} + HRX_{CaCO_3} \quad (35)$$

where:

$HPR_{CO_2-Ideal}$ = Energy of CO_2 ideal product from complete combustion at the calibration temperature.

$$\equiv \Delta H_{f-Cal}^0 (\alpha_0 YR + \alpha_4 + \alpha_8) N_{CO_2} / N_{AF}$$

$HPR_{SO_2-Ideal}$ = Energy of SO_2 ideal product from complete combustion at the calibration temperature.

$$\equiv \Delta H_{f-Cal}^0 (\alpha_6 + \alpha_9) N_{SO_2} / N_{AF}$$

HRX_{CaCO_3} = Energy of injected pure limestone, $CaCO_3$, at T_{Cal} ; use of ΔH_{f-Cal}^0 anticipates Heats of Formation associated with limestone products via use of Eq.(33).

$$\equiv \Delta H_{f-Cal}^0 b_{PLS} (1.0 + \gamma) N_{CaCO_3} / (xN_{AF})$$

Enthalpy of Firing Corrections (HBC)

$$HBC \equiv C_p(T_{AF} - T_{Cal})_{Fuel} + (Q_{SAH} + W_{FD}) / m_{AF} + [(h_{Amb} - h_{Cal})_{Air} a (1.0 + \beta)(1.0 + \phi_{Act}) N_{Air} + (h_{g-Amb} - h_{g-Cal})_{H_2O} b_A (1.0 + \beta) N_{H_2O} + (h_{Steam} - h_{f-Cal})_{H_2O} b_Z N_{H_2O} + C_p(T_{Amb} - T_{Cal})_{PLS} b_{PLS} (1.0 + \gamma) N_{CaCO_3}] / (xN_{AF}) \quad (36)$$

HEATING VALUE CONVERSIONS

Several industrial standards and "coal" textbooks employ simplifying assumptions regarding HHV conversions. For example, a constant is sometimes used to convert from a constant volume process HHV (i.e., bomb calorimeter), to a constant pressure process HHVP (i.e., the As-Fired). Fuel oxygen is sometimes ignored. Some labs convert HHV to HHVP using a constant value, and contrary to ASTM D5865 which requires reporting the "gross calorific value at constant volume". Refer to: PTC 4.1, §9.6 (PTC 4, §5.8, assumes 4.1 procedures); ASTM D5865, §13 & 14 as referencing Research Report D05-1013; and ISO 1928:1995(E), §E.2 & E.3. The following is recorded for completeness to this work. Underlying this presentation is that the latent heat at constant volume (Δu_{fg-Cal}) is used for HHV to LHV conversions, and the latent heat at constant pressure (Δh_{fg-Cal}) is used for HHVP to LHVP conversions (for further discussion and examples see Notes & Errata, item 12).

To convert solid and liquid fuel heating values from a constant volume to a constant pressure process use:

$$HHVP = HHV + \Delta H_{V/P} \quad (37)$$

$$LHVP = LHV + \Delta H_{V/P} - \Delta PV_{L/H} \quad (38)$$

$$\Delta H_{V/P} \equiv RT_{Cal-Abs} (\alpha_5/2 - \alpha_1 - \alpha_3) / (\xi J N_{AF}) \quad (39)$$

$$\Delta H_{L/H} \equiv \Delta h_{fg-Cal/H_2O} (\alpha_0 ZR/2 + \alpha_2 + \alpha_5 + \alpha_9) N_{H_2O} / (\xi N_{AF}) \quad (40)$$

$$\Delta U_{L/H} \equiv \Delta u_{ig-Ca/H_2O} (\alpha_0 ZR/2 + \alpha_2 + \alpha_5 + \alpha_9) N_{H_2O} / (\xi N_{AF}) \quad (41)$$

$$\Delta PV_{L/H} \equiv \Delta H_{L/H} - \Delta U_{L/H} \quad (42)$$

where $T_{Cal-Abs}$ is the absolute temperature, and molar quantities are employed (see Eq.(19) for nomenclature).

For gaseous fuels, the only correction needed is the compressibility factor Z assuming ideally computed heating values: $HHVP = HHV_{ideal-HHV} Z$; (refer to AGA procedures for evaluation of Z , and $HHV_{ideal-60F}$). The nominal industrial procedure is to divide $[m_{AF} HHV_{ideal-HHV}]$ by Z to convert the energy flow to the ideal for traditional billing purposes. Typically Z will vary from 0.998 to 0.990 for natural gases.

To convert from a higher (gross) to a lower (net) heating value, the following are exact and consistent with Eqs.(37) & (38):

$$LHV = HHV - \Delta U_{L/H} \quad (43)$$

$$LHVP = HHVP - \Delta H_{L/H} \quad (44)$$

RESULTS

The following presents numerical results, including comparing the Input/Loss Method to PTC 4.1. However, considered the most important result of this work is the development of its approach to boiler efficiency, using the HPR_{Act} , HRX_{Act} and HBC terms.

Confirmations and Sensitivities

The Input/Loss Method employs, in part, Exergetic Systems' EX-FOSS program for steam generator analysis (Lang, 2000). Using EX-FOSS, numerous sensitivity analyses were completed demonstrating differential effects, and several for calculational sanity.

To illustrate the effects of mis-using calorimetric temperature Table 1 presents the results of a methane-burning boiler. As observed, boiler efficiency is insensitive to slight changes in heating values provided T_{Cal} is not varied in any other term which might effect η_B ; this, of course, is thermodynamically inconsistent with Eq.(2B). However, when consistently applying T_{Cal} (as its impacts HPR_{ideal}), results indicate serious differences in boiler efficiency. One may not establish a reference temperature for the fuel's base chemical energy, at T_{Cab} and then not consistently apply it to other energy terms, including boiler Losses. Conversely, one may not reference boiler Losses to a reference temperature and then ignore the dependency HPR_{Act} and HRX_{Act} have on T_{Cal} . If randomly applied as suggested by Table 1, errors in η_B and unit heat rate will be assured. Given a computed η_B , use of Eq.(15) as derives from Eqs.(10) & (11), demands consistency with HPR_{Act} , HRX_{Act} and HBC. The same system can not have a difference in computed fuel flow given some randomly chosen T_{RA} .

Table 2 presents typical effects on boiler efficiency and unit heat rate of mis-use of calorimetric temperatures on a variety of coal-fired power plants. These computations are based on EX-FOSS, varying only T_{Cal} . Data was obtained from actual plant conditions, monitored by Input/Loss Methods. The effects (of a 9 ΔF change) are indicative of a linear response (i.e., 25C to 20C, or 25C to 30C).

Table 1: Calorimetric Temperature Effects on Boiler Efficiency

Computed Heating Value for Methane at 77F or 60F	Eff. at 77F	Eff. at 60F	All Terms $f(T_{Cal})$ Effecting $\Delta\eta_{B-HHV}$
23867.31 at 77F	83.318%	82.893%	-0.425%
23891.01 at 60F	83.333%	82.908%	-0.425%
Difference in efficiency if ignoring T_{Cal} (T_{Cal} only effecting the computed HHV)	-0.015%	-0.015%	

Table 2: Effects on Boiler Efficiency and Unit Heat Rate of Mis-Use of Calorimetric Temperature

Unit	$T_{Cal}=77F$	$T_{Cal}=68F$	$\Delta\eta_B$ Effect	$\Delta HR/HR$ Effect
110 MWe CFB, Coal	86.086%	85.874%	-0.212%	+0.237%
300 MWe Lig-B, LHV	78.771%	78.426%	-0.345%	+0.438%
800 MWe Coal Slurry	81.364%	81.099%	-0.265%	+0.335%

Table 3 lists computational overchecks of higher and lower heating value calculations, verifying that the computed fuel flow rates of Eq.(30), are numerically identical. These simulations were selected from Input/Loss' installed base as having unusual complexity, based on actual plant conditions. The only changes in these simulations was input of HHV or LHV, and an EX-FOSS option flag; LHV or HHV are automatically computed by EX-FOSS given input of the other.

Table 3: EX-FOSS Calculational Overchecks (efficiencies & fuel flow, lbm/hr)

Unit	HHV Eff. & Flow	LHV Eff. & Flow
300 MWe Lignite-B	59.104% 1,383,259.9	78.426% 1,383,260.0
800 MWe Coal Slurry	81.097% 1,104,329.4	88.761% 1,104,329.7

The repeatability accuracy of modern calorimetric instruments is between $\pm 0.07\%$ to $\pm 0.10\%$. They typically use benzoic acid powder for calibration testing. Such calibration tests and routine runs are typically analyzed using the well-known Washburn corrections (Hubbard, Scott and Waddington, 1954). Based on these procedures, NIST Standard Reference Material 39j certification for benzoic acid makes a multiplicative temperature correction: $[1.0 - 45.0 \times 10^{-6} (T_{\text{cal}} - 25^\circ\text{C})]$. Such corrective coefficients (e.g., 45.0×10^{-6}) were computed for a number of coals, using average chemistries for different coal Ranks, and with methane. For example, a correction of 122×10^{-6} implies a 0.122% change in HHV over $10\Delta\text{C}$. As observed below in Table 4, heating values with increasing fuel moisture are generally increasingly sensitive to calorimetric temperature, especially for gaseous fuels and poor quality lignites. Effects on HHVs associated with the higher energy coals is not great. However, as seen in Table 4, the sensitivity of temperature on $\text{HPR}_{\text{ideal}}$ is appreciable; computed using EX-FOSS. This sensitivity demonstrates the fundamental cause for effects observed in Tables 1 and 2. See Note & Errata item 11.

Table 4: Temperature Coefficients for Heating Value Corrections & $\text{HPR}_{\text{ideal-HHV}}$ Temperature Sensitivity

Coal Rank	Fuel Water (%)	Fuel Ash (%)	Avg HHV at 25C (Btu/lbm)	HHV Temp Coef. ($\times 10^{-6}/1\Delta\text{C}$)	$\frac{\Delta\text{HPR}_{\text{ideal}}}{\text{HPR}_{\text{ideal}}}$ ($\times 10^{-6}/1\Delta\text{C}$)
an	3.55	9.85	12799.75	19.56	376.6
sa	1.44	16.51	12466.17	30.10	285.0
lvb	1.74	13.24	13087.76	39.22	347.7
mvb	1.75	11.48	13371.75	41.88	380.5
hvAb	2.39	10.86	13031.61	47.77	444.2
hvBb	5.61	11.83	11852.63	56.53	446.7
hvCb	9.89	12.32	10720.40	60.18	450.6
subA	12.85	8.71	10292.89	51.16	398.3
subB	17.87	9.57	9259.75	61.15	408.0
subC	23.79	10.67	8168.69	75.14	423.3
ligA	29.83	9.64	7294.66	83.56	439.4
ligB-P	28.84	22.95	4751.83	122.17	481.3
ligB-G	54.04	19.30	2926.82	246.01	685.2
Methane	.00	.00	23867.31	105.39	424.3

Table 5: Effect on Computed Fuel Flow, Eq.(15), Given Changes to Reference Temperature

Coal Rank	Effect on Fuel Flow ($T_{\text{RA}} = 68$ to 77F)	Effect of Fuel Flow ($T_{\text{RA}} = 68$ to 95F)
an	+0.0051%	+0.0148%
hvCb	-0.0251%	-0.0758%
subC	-0.0273%	-0.0824%
ligB	-0.1118%	-0.3371%

The Input/Loss Method has been formulated to cause an insensitivity in computed fuel flow when varying an arbitrary reference temperature, T_{RA} , at least over a reasonable range. Table 5 demonstrates this for several coal Ranks, assuming T_{RA} changed from 68F to 77F, and from 68F to 95F. Such effects on fuel flow are additive to those associated with boiler efficiency when considering net effects on unit heat rate.

Table 6: Consecutive Sensitivity Studies Presenting Incremental PTC 4.1 and EX-FOSS Effects

Description	PTC 4.1 $\Delta\eta_{\text{B}}\%$	EX-FOSS $\Delta\eta_{\text{B}}\%$	Loss & Firing Correction Terms with Notes
Pure C, 77F stack, $T_{\text{RA}} = T_{\text{Cal}} = 77\text{F}$, $T_{\text{Air}} = 77\text{F}$	---	---	$\eta_{\text{B}} = 100\%$, HHV = 14085.33
Pure C, 350 F and 0% O_2 at Stack.	5.867	5.800	L_{G} , $\Delta\Delta\eta_{\text{B}}=0.067\%$
Pure C, 5% O_2 at Stack	1.686	1.693	L_{G}
Fuel: 0.89474C, .08421A, .02105H	2.139	2.148	L_{dFly} and L_{mf} , HHV = 12639.47
Fuel: 0.8500C, .0800Ash, .0200H and .0500 H_2O	1.024	1.021	L_{mf} , As-Fired HHV = 11407.21
Unburned C at 2.5% in Fly Ash	0.241	0.229	L_{UC}
1.0% Rejects at 9000 Btu/lb	0.789	0.806	L_{R} , As-Fired HHV = 11431.53, with .078039Ash
0.4% Rad. & Conv	0.400	0.400	L_{p}
500 ppm stack CO	0.236	0.238	L_{CO}
Fuel Temp at 117F	-0.013	-0.009	B_{FE}
Dry Air at 87F	-0.035	-0.031	B_{AE}
Saturated Air at 87F.	0.408	0.413	B_{mAE} and L_{mA} , $\Delta\Delta\eta_{\text{B}} = +0.034\%$
T_{RA} at 87F	-0.300	0.000	T_{cal} is constant for EX-FOSS calc
T_{RA} at 97F	-0.298	0.000	$\Delta\Delta\eta_{\text{B}} = -0.598\%$ for a total $20\Delta\text{F}$.
T_{RA} at 107F	-0.302	0.000	$\Delta\Delta\eta_{\text{B}} = -0.900\%$ for a total $30\Delta\text{F}$.

Input/Loss Results versus PTC 4.1

Table 6 presents results of consecutive sensitivity studies, beginning with the theoretical burning of pure carbon (graphite), ending with a \approx realistic combustion. Once a sensitivity is established its presence is then maintained for all subsequent analyses (e.g., stack temperature at 350F is maintained from the second analysis thereafter). Studies begin assuming $T_{\text{cal}} = T_{\text{RA}} = 77\text{F}$, heating values were calculated at 77F as were fuel and air temperatures. Stack loss effects are integrally computed via Eq.(31), listed here as $\Delta\eta_{\text{B-HHV}}$ effects (HNSL terms considered for Table 6 only include: $L_{\text{d/Fby}}$, L_{R} and L_{β}).

As seen in Table 6, results indicate reasonable consistency, the greatest differences do not exceed 0.07% $\Delta\eta_{\text{B-HHV}}$ (typically 0.01%) for the high quality coal assumed - provided PTC 4.1's reference air temperature is set to T_{cal} . When floating T_{RA} the effect can cause - 0.30% $\Delta\eta_{\text{B-HHV}}$ error per every 10 ΔF increase in the assumed "reference temperature". These effects are caused solely by changes in $\int dh$ and $\Delta H_{\text{f-cal}}^0$ terms, not the through the numerical value of HHV. For example, on a hot summer day if the power plant's monitoring procedures employ PTC 4.1 using T_{RA} based on ambient air temperature, boiler efficiency could be in error by $\approx 1\%$ $\Delta\eta_{\text{B-HHV}}$. Given this, the argument for using PTC 4.1 even for relative comparisons should be the subject of review, based on the fuel's characteristics and accuracy required.

CONCLUSIONS

This work demonstrates a systemic approach to determining boiler efficiency. It validates the concept of defining boiler efficiency in terms of the Enthalpies of Products and Reactants, and Firing Corrections (HPR_{Act} , HRX_{Act} and HBC), and, it is believed, provides accuracy. Higher accuracy is needed by the Input/Loss Method, and indeed for the improvement of fossil combustion in a competitive marketplace. The HPR_{Act} , HRX_{Act} and HBC concept forces an integration of combustion effluents and system effects with fuel chemistry. The following highlight conclusions reached.

Determination of Boiler Efficiency

- ❑ Boiler efficiency evaluated by PTC 4.1, if using a justifiable T_{RA} as the fuel's calorimetric temperature, and computed correctly, can be reasonably accurate yielding less than $\pm 0.07\%$ $\Delta\eta_{\text{B}}$ error.
- ❑ Boiler efficiency computations should reference the heating value's calorimetric temperature, T_{cal} . Corrections from T_{cal} should be made to the HPR_{Act} , HRX_{Act} and HBC terms. No attempt should be made to correct measured coal or oil heating values to a T_{RA} (use the "as-measured" T_{cal}).
- ❑ If PTCs are incorrectly used: by allowing T_{RA} to float or set constant, by simplifying stack loss calculations, by unqualified use of B_{XE} , by mis-use of the L_{R} term, etc., differences of 1% compared to consistent treatment can be easily reached. For coal-fired units mis-use of T_{RA} by only 5 ΔC (9 ΔF) results in 0.2 to over 0.4% $\Delta\eta_{\text{B}}$ error. For gas-fired units the $\Delta\eta_{\text{B}}$ differences will range from 0.35 to 0.45% (77F vs. 60F). These results are solely related to $\int dh$ and $\Delta H_{\text{f-cal}}^0$ effects.

- ❑ Comparing the calculations of boiler efficiency by many boiler vendors appears highly inconsistent to the author. Suggested as a new section of PTC 4, is presentation of typical consecutive sensitivities of loss terms (e.g., Table 6), allowing comparison of numerical results.
- ❑ Input/Loss Methods involving the HPR_{Act} and HRX_{Act} concept should replace PTC boiler methods - not only to correct errors and assumptions - but, most importantly, to provide a systemic approach to stack losses. This directly impacts the accurate determination of effluent flows. The interpretation of \approx nine individual stack loss terms has led to inconsistent industrial use. The Input/Loss approach represents:
 - use of a systemic approach to boiler efficiency;
 - use of consistent and accurate properties; and
 - a high accuracy approach to the determination of effluent flow (without direct measurement).
- ❑ Use of a FD Fan will always improve boiler efficiency. Use of an ID Fan or a gaseous recirculation fan will always degrade boiler efficiency.

Determination of Heating Values

- ❑ The determination of heating values by bomb calorimeter requires recognition and recording of the calorimetric temperature, and proper calibration testing. Industrial standards should mandate that calorimetric temperatures be recorded with all reported heating values.
- ❑ Calorimeter instrument vendors should recognize that since repeatability of calibrations on modern instruments is attainable within $\pm 0.1\%$, then all thermodynamic property affects rising to this level should be considered. As examples: water's C_p and Δh_{fg} values are functions of temperature, i.e., since many bombs are automated to run at a given T_{cal} , accurate properties at T_{cal} should be applied. Although benzoic acid's Heat of Combustion is not sensitive to temperature, the poorer quality coals can be sensitive (at $\pm 0.3\%$ and higher) given high fuel and/or product water. Higher Rank coals having low water contents have sensitivities less than that of benzoic acid. Further, no correction for constant pressure should be made or reported for a determined HHV; ASTM D5865 procedures require HHV to be reported at constant volume, the as-tested.
- ❑ It is suggested that the National Institute of Standards and Technology (NIST) determine high accuracy temperature effects on Heats of Combustion of coal, at least for the lower Ranks, including a standardized lignite B. Such studies would inform labs as to sensitivities, establish guidelines and enhance awareness for accurate work. Also, NIST should consider a substitute for benzoic acid having greater temperature sensitivity (again, perhaps some hydrocarbon fuel with standardized amounts of water emulating several Ranks).
- ❑ Calorimeter preparation of coals should reasonably emulate the As-Fired particle size. ASTM D2013 calls for reducing to #60

US Standard sieve (250 μm). However, coal pulverizers may grind to a #50 (297 μm) mesh, #100 (149 μm) or #200 (74 μm). Also, heating of coal samples before testing must consider effects on vaporization of volatiles.

SUMMARY

This work demonstrates an improved approach to the determination of boiler efficiency; when thermodynamically accurate, consistent system mass/energy balances are then guaranteed. From such consistencies, fuel flow and effluent flow are determined with greater accuracy than obtained from direct measurements.

NOTES and ERRATA

The following both explains and corrects several items associated with this and previously published works (both Input/Loss and industrial methods):

- 1a) An August 20, 2000 revision to the original paper corrected an error in computing the HHV temperature sensitivities for High Volatile-A Bituminous (hvAb) and Sub-Bituminous C (subC) coals. To thoroughly study such sensitivities Table 4 was then prepared for all coal Ranks, including the sensitivity of $\text{HPR}_{\text{ideal}}$. Although conservation of $\text{HPR}_{\text{ideal}}$ and HRX_{cal} terms was originally discussed, this revision emphasized the $\text{HPR}_{\text{ideal}}$ term. Of importance, $\text{HPR}_{\text{ideal}}$ allows unity efficiency, via Eq.(3B), at any Firing Correction given $\sum \text{Losses} = 0.0$. Interestingly, this implies that water in the combustion air is not a credit/debt to the process *per se* - it only becomes a system loss when evaluated at the boundary when $T_{\text{stack}} \neq T_{\text{cal}}$.
- 1b) A October 6, 2000 revision incorporated numerous reader comments, hopefully offering more clarity, without change in the formulations.
- 1c) A January 6, 2003 revision corrected heating value conversions: constant volume vs pressure, and HHV vs LHV; Eqs.(22B) & (38) thru (42) were altered. Reader comments were addressed.
- 1d) A March 4, 2009 revision corrected the use of the ID and gas circulatory fan powers, reversing the sign affecting HNSL; see Eq.(12) and the paper: "Errors in Boiler Efficiency Standards", ASME 2009 Power Conference, POWER2009-81221.
- 2) The sign convention associated with the HPR & HRX terms follows the assumed convention of a positive numerical heating value, thus the non-conventional sense of HPR & HRX in Eq.(2B). In prior works the senses of HPR & HRX terms was reversed for simplicity of presentation, a mis-communication (the EX-FOSS program reverses these signs for its output report). Typical values include the following: $[- \text{HPR}_{\text{Act-HHV}} + \text{HRX}_{\text{Act-HHV}}] = [- (-7664) + (-1064)]$, Btu/lbm. The sign of sensible heat terms, $\int dh$, follows this difference: $[- \text{HPR}_{\text{Act}} - \int dh_{\text{Products}}]$; and: $[+ \text{HRX}_{\text{Act}} + \int dh_{\text{Reactants}}]$. Heats of Formation, ΔH_f^0 , are always negative quantities.
- 3) In ASTM procedures, the bomb calorimeter's temperature rise is multiplied by the weight of heated water, having an assumed heat capacity of 1.000 Cal/gm-C. There is no requirement to conduct the burn at 20C (68F), but rather to be "within 2 to 3 ΔC of the temperature of the room" (thus the assumption that C_p values are \approx constant). However, at 14.6959 psia & 68F $C_p = 1.00026$, at 77F $C_p = 0.99897$ Cal/gm-C; or 0.13%, or 17 $\Delta\text{Btu/lbm}$ regards a 13,000 Btu/lbm coal [this exceeds the calibration repeatability of modern calorimeters]. Several questions thus arise. If a given fuel's heating value varies only slightly with temperature - why worry about T_{cal} ? Why worry about temperature affects on ΔH_f^0 ?
 - a) For reporting consistency, heating value determinations should be conducted at the established calorimetric temperature (either codified or by custom). Present ASTM codes specify that heating values are referenced to 68F for solid & liquid fuels, and 60F for gaseous fuels. For solid and liquid fuels ASTM codes fail to specify detailing procedures required to achieve a certain T_{cal} .
 - b) Heating value dependency on T_{cal} aside ... computing $\Delta H_f^0 = f(T)$, and HBC from a T_{cal} base produces demonstrable $\Delta\eta_B$ differences of 0.2 to more than 0.4% in boiler efficiency. As Heats of Formation and HBC effect both combustion products and reactants, they must be used consistently throughout the evaluations - at a fixed reference temperature, the only thermodynamically logical choice being an applicable T_{cal} .
- 4) Caution should be used when assigning units to the ΔH_f^0 and enthalpy terms used herein; both Btu/lbm and Btu/lb-mole are used up to Eq.(19), thereafter Btu/lbm is consistency used.
- 5) Before the current version, EX-FOSS used $T_{\text{cal}} = 77\text{F}$ for all fuels. However, recognizing inconsistency with calorimetric temperature, a hodge-podge of corrections was made in earlier versions. T_{cal} is now an input. As part of the Input/Loss confirmatory testing program, key fuel flow comparisons were made in 1994; see Part I, Table 3. Re-analysis of this data with the current EX-FOSS (Ver.2.7, Mod.52) resulted in average differences between calculated and measured increasing from 0.13% to 0.19% $\Delta\eta_B$.
- 6) The use of the term "boiler absorption efficiency" of Eq.(11) and elsewhere has been pointed out as inconsistent with vendor use (i.e., the rate of boiler heat absorption). The term developed by recognizing via Eqs.(9) & (14) that: $\eta_A = \text{BBTC} / [\eta_{\text{C-HHV}} m_{\text{AF}}(\text{HHVP} + \text{HBC})]$, thus relating the "efficiency" of energy take-up by the working fluid from the combustion process.
- 7) It can be argue that a boiler efficiency obtained in any manner (gross, net, "fuel" or guess) could be used to obtain fuel flow provided η_B is multiplied by an appropriately "adjusted" heating value term. However, the objective of this work - in counterpoint to ASME PTCs - is to assure consistency between fuel flow, boiler efficiency, unit heat rate and effluent flow. This is accomplished through HPR_{Act} , HRX_{Act} and HBC. As an example of such consistency, combinations of Eqs.(10), (16) and the stoichiometric terms afforded from Eq.(19) results in the following expression for wet effluent mass flow,

illustrating the inter-dependency with unit heat rate, η_{C-HHV} , APH leakage, etc.:

$$m_{\text{Effluent}} = \frac{[N_{\text{Dry-Gas}} + (j_{\text{Act}} + \beta b_A)N_{\text{H}_2\text{O}}] HR_{\text{HHV}} \eta_{C-HHV} \text{Power}}{xN_{\text{AF}} [-HPR_{\text{Act}} + HRX_{\text{Act}}]}$$

- 8) From Eq.(14), (15) or (30) it is obvious that the ratio $[BBTC/m_{\text{AF}}]$ must be computationally constant: $BBTC/m_{\text{AF}} = \eta_{B-HHV}(\text{HHVP} + \text{HBC})$. Also, from Eq.(13B) and considering HNSL and HBC are the same for either HHV- or LHV-based calculations, the following are considered important identities.

$$\eta_{B-HHV}(\text{HHVP} + \text{HBC}) \equiv \eta_{B-LHV}(\text{LHVP} + \text{HBC}) - HPR_{\text{Act-HHV}} + HRX_{\text{Act-HHV}} \equiv -HPR_{\text{Act-LHV}} + HRX_{\text{Act-LHV}}$$

- 9) If only considering reject losses, and since: $\text{HHVP}_{\text{Sup}} \equiv (1 - WF_{\text{Rej}})\text{HHVP}_{\text{AF}} + WF_{\text{Rej}}\text{HHVP}_{\text{Rej}}$, the numerator of Eq.(13C) then becomes:

$$\text{HHVP}_{\text{Sup}} + \text{HBC} - WF_{\text{Rej}}\text{HHVP}_{\text{Rej}} = \text{HHVP}_{\text{AF}} + \text{HBC} - WF_{\text{Rej}}\text{HHVP}_{\text{AF}};$$

where HHVP_{Sup} represents the “supplied” heating value of the fuel; and where the true As-Fired HHVP_{AF} is corrected (as needed) for reduced fuel ash. For LHV calculations the correction for rejected fuel $\Delta H_{\text{corr-LHV}}$ as determined by Eq.(22C), follows directly from differences in As-Fired and “supplied” heating values:

$$\begin{aligned} \text{LHVP}_{\text{Sup}} + \text{HBC} - [WF_{\text{Rej}}\text{HHVP}_{\text{Rej}}] \\ &= \text{LHVP}_{\text{Sup}} + \text{HBC} - [\text{HHVP}_{\text{Sup}} - (1.0 - WF_{\text{Rej}})\text{HHVP}_{\text{AF}}] \\ &= \text{LHVP}_{\text{AF}} + \text{HBC} - WF_{\text{Rej}}\text{HHVP}_{\text{AF}} \\ &\quad + \{(\text{HHVP}_{\text{AF}} - \text{LHVP}_{\text{AF}}) - (\text{HHVP}_{\text{Sup}} - \text{LHVP}_{\text{Sup}})\} \\ &= \text{LHVP}_{\text{AF}} + \text{HBC} - WF_{\text{Rej}}\text{HHVP}_{\text{AF}} + \{\Delta H_{\text{corr-LHV}}\}. \end{aligned}$$

- 10) The following substitution could be used in Eq.(32) for the water terms, but at reduced clarity:

$$\Delta H_{f-\text{Cal/vap}}^0 = \Delta H_{f-\text{Cal/liq}}^0 + \Delta h_{f\text{-Cal}}$$

- 11) Most modern bomb calorimeters use benzoic acid powder for calibration testing. Calibration results, given the known chemistry of benzoic acid, should always be corrected to the established T_{Cal} using the Washburn corrections (and not to an arbitrary T_{RA}). Table 4 is partially based on the following Heat Capacity correlation for coal (in part from Gomez, 1965):

$$\begin{aligned} C_{P/\text{coal}} = 0.189WF_C + 0.874WF_H + 0.215WF_S + 0.360WF_O \\ + 0.419WF_N + C_{P-\text{H}_2\text{O}}WF_{\text{H}_2\text{O}} + C_{P-\text{Ash}}WF_{\text{Ash}}, \text{ Btu/lb-F} \end{aligned}$$

- 12) Heating value conversion from gross to net, when both at constant volume, requires use of the latent heat at constant volume; i.e., the internal energy change $\Delta U_{L/H}$ at T_{Cal} , Eq.(41). Additionally, for a constant volume process in which water formed from fuel hydrogen is reduced to a liquid state, the change in molar gaseous volume is given by the PV work term $\Delta H_{V/P}$ of Eq.(39). $\Delta H_{V/P}$ includes affects from fuel oxygen and nitrogen as they are both chemically bound within the coal matrix, and not diatomic (see Fuchs and Sandhoff, 1942). PTC

4.1, §9.6, as adopted by PTC 4, concerning oxygen is wrong; it assumes that fuel oxygen is in its combined state - which ignores C=O and C-OH binding, and especially errors with fuels having high oxygen contents such as Powder River Basin coals and lignites. To demonstrate consistency, substitute HHV of Eq.(43) into Eq.(37), subtract (38) from the revised (37), and reduce:

$$\begin{aligned} \text{HHVP} &= [\text{LHV} + \Delta U_{L/H}] + \Delta H_{V/P} \\ \text{HHVP} - \text{LHVP} &= \text{LHV} + \Delta U_{L/H} + \Delta H_{V/P} \\ &\quad - \text{LHV} - \Delta H_{V/P} + \Delta PV_{L/H} \\ \text{HHVP} - \text{LHVP} &= \Delta U_{L/H} + \Delta PV_{L/H} \\ \text{LHVP} &= \text{HHVP} - \Delta H_{L/H}; \text{ which is Eq.(44)}. \end{aligned}$$

The following table records typical constant pressure conversions using PTC methods and Eqs.(43) & (44). Caution: although differences appear small for high energy fuels, significant sensitivity is considered to be $\pm 0.10\%$, the same as the repeatability accuracy of modern calorimetric instruments.

As-Tested Heating Value	Corrected by PTC	Corrected by Eq.(43) or (44)	% Diff.
12,410-HHV	12,421.55	12,418.85	+0.002
8,300-HHV	8,308.52	8,304.37	+0.050
2,100-LHV	2,065.42	2,062.31	+0.151

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