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

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ABSTRACT

The Input/Loss Method is a unique process which allows for complete thermal understanding of a power plant through explicit determinations of fuel chemistry including fuel water and mineral matter, fuel heating (calorific) value, As-Fired fuel flow, effluent flow, boiler efficiency and system heat rate. Input consists of routine plant data and any parameter which effects system stoichiometrics, including: Stack CO₂, Boiler or Stack O₂, and, generally, Stack H₂O. It is intended for on-line monitoring of coal-fired systems; effluent flow is not measured, plant indicated fuel flow is typically used only for comparison to the computed.

The base technology of the Input/Loss Method was documented in companion ASME papers: Parts I, II and III (IJPGC 1998-Pwr-33, IJPGC 1999-Pwr-34 and IJPGC 2000-15079/CD). The Input/Loss Method is protected by US and foreign patents (1994-2004).

This Part IV presents details of the Method's ability to correct any data which effects system stoichiometrics, data obtained either by direct measurements or by assumptions, using multi-dimensional minimization techniques. This is termed the Error Analysis feature of the Input/Loss Method. Addressing errors in combustion effluent measurements is of critical importance for any practical on-line monitoring of a coal-fired unit in which fuel chemistry is being computed. It is based, in part, on an "L Factor" which has been proven to be remarkably constant for a given source of coal; and, indeed, even constant for entire Ranks. The Error Analysis feature assures that every computed fuel chemistry is the most applicable for a given set of system stoichiometrics and effluents.

In addition, this paper presents comparisons of computed heating values to grab samples obtained from train deliveries. Such comparisons would not be possible without the Error Analysis.

NOMENCLATURE

Stoichiometric Terms:

a = Moles of combustion O₂ input to the system.
 $a\beta$ = O₂ entering with air leakage associated with the system's air pre-heater; moles/base.
 A_{Act} = Concentration of O₂ in combustion air local to

(and entering) the system; molar ratio.

b_A = Moisture in the entering combustion air; moles/base.
 $b_A\beta$ = Moisture entering with air pre-heater leakage; moles/base.
 b_Z = Water/steam in-leakage from working fluid; moles/base.
 b_{PLS} = Fraction of Pure Limestone (CaCO₃) required for zero CaO effluent production; moles/base.
 d_{Act} = Total effluent CO₂ at the system's boundary; moles/base.
 d_{theor} = Effluent CO₂ based on theoretical combustion; moles/base.
 g = Effluent oxygen at the system's boundary; moles/base.
 G_{Act} = Total effluent oxygen at the system's boundary ($g + a\beta$).
 j = Effluent water without moist air leakage; moles/base.
 J_{Act} = Total effluent water ($j + b_A\beta$); moles/base.
 J_{theor} = Effluent H₂O based on theoretical combustion; moles/base.
 n_i = Molar quantities of combustion dry gas products at system boundary without air leakage specifically those products associated with the following quantities: d_{Act} , e_{Act} , f , g , h , k_{Act} , l , m , p , q , t and u ; moles/base.
 n_{ii} = Molar quantities of non-gas combustion products at system boundary, specifically those products associated with the following quantities: j , $x\alpha_{10}$, σb_{PLS} , $(1.0 - \sigma + \gamma)b_{PLS}$, $x\alpha_{CaCO_3}$ and v ; moles/base.
 N_k = Molecular weight of compound k .
 R_{Act} = Ratio of 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; molar ratio.
 x = Moles of As-fired fuel/base, $\sum n_i = 100$ moles of dry gas product at the Stack is the calc. "base"; moles/base.
 $x_{MAF-theor} \alpha_{MAF-10}$ = Fuel MAF ash based on theoretical combustion; moles/base.
 $x_{MAF-theor} \alpha_{MAF-7}$ = Fuel MAF CO₂; moles/base.
 z = Moles H₂O per effluent CaSO₄ based on laboratory tests.
 α_k = As-Fired (wet-base) fuel constituent k per mole of fuel:
 $\sum \alpha_k = 1.0$, where $k = 0, 1, 2, \dots, 10$ plus fuel CaO.
 β = Air pre-heater Dilution Factor (ratio of air leakage to true combustion air); molar ratio
 $\beta \equiv 100(R_{Act} - 1.0) / [a R_{Act} (1.0 + \phi_{Act})]$
 γ = Molar ratio of excess CaCO₃ to its stoichiometric requirements (e.g., $\gamma = 0.00$ if no CaO is found in

the effluent from injected limestone); molar ratio.

σ = Kronecker function: unity if sulfur is present in the fuel.

ϕ_{Act} = Ratio of non-oxygen gases (N_2 and Ar) to oxygen in the combustion air; molar ratio.

$\phi_{\text{Act}} \equiv (1.0 - A_{\text{Act}}) / A_{\text{Act}}$

ϕ_{Ref} = Reference ratio of non-oxygen gases (nitrogen and argon) to oxygen in the combustion air, taken as 3.7737245.

Multidimensional Minimization Terms:

$F(\vec{x})$ = Objective function, a functional relationship of the independent variables \vec{x} ; unitless.

C_i = Correction factor applied to Choice Operating Parameter i .

HHV_{k3} = Higher heating value as used by the minimization techniques as a System Effect Parameter; Btu/lbm.

J_m = Bessel function of the first kind, of order m .

L_{k1} = L Factor as used by the minimization techniques as a System Effect Parameter; lbm-effluent/million-Btu_{Fuel}.

m_{AF} = Fuel flow, an As-Fired quantity (i.e., wet with water and fuel mineral matter) computed by Input/Loss; lbm_{AF}/hr.

$m_{\text{AF-PLT}}$ = The system's measured fuel flow; lbm_{AF}/hr.

M_L = Dilution factor applied to System Effect Parameter L_{k1} .

M_W = Dilution factor applied to System Effect Parameter m_{AF} .

M_H = Dilution factor applied to System Effect Parameter HHV_{k3} .

S_i = Scaling factor for the independent variable x_i .

s_i = Pre-scaling factor used to adjust S_i ; unitless.

\vec{x} = Vector of independent variables, based on scaled Choice Operating Parameters,

Λ_i = Choice Operating Parameter i ; see the specific parameter.

Λ_{0-i} = Initial Choice Operating Parameter i ; that is, either the raw signal, a guess, or a previously computed value.

λ_j = Defined argument of J_m ; unitless.

Quantities Related to System Terms:

AF = Air/Fuel ratio; mass ratio.

BBTC = Energy flow to the working fluid, derived directly from the combustion process; Btu/hr.

HBC \equiv Firing Correction; Btu/lbm_{AF}.

HHVP = As-Fired higher heating value, based on HHV_{AF} ($k3 = AF$) and used in system evaluations as corrected for a constant pressure process; Btu/lbm_{AF}.

HR = System heat rate (HHV-based); Btu/kWh.

m_{LS} = The system's "indicated limestone flow"; lbm/hour.

W_{output} = Gross power generated from a power plant; kWe.

η_B = Boiler efficiency (HHV-based); unitless.

Subscripts and Abbreviations:

Act = Actual value determined from the operating thermal system.

AF = As-Fired fuel at the thermodynamic boundary.

Dry = Dry chemical base (i.e., free of water).

MAF = Moisture-Ash-Free chemical base.

Ref = Reference value.

PLS = Pure limestone, CaCO_3 .

theor = Conditions associated with theoretical combustion.

INTRODUCTION

Use of any method, other than Input/Loss, which determines fossil fuel chemistry from effluent concentrations must have assurance that the measurements are both consistent and accurate. Although the Input/Loss Method must rely on consistent measurements, they need not be accurate. Indeed, Input/Loss assumes that no instrument's signal is accurate (including CEMS data), and especially when considering the combined and complex effects of multiple system parameters which might effect system stoichiometrics. Of course the effluents CO_2 , O_2 and H_2O directly impact system stoichiometrics, and thus computed fuel chemistry; but system stoichiometrics may, indeed, also be effected by:

P Air pre-heater leakage if using boiler-side O_2 in combination with Stack CO_2 ;

P Concentration of O_2 in the combustion air;

P CO_2 generated from limestone injection;

P CO_2 generated from the fuel's mineral matter;

P Water in-leakage into the combustion space (via soot blowing, atomizing steam, tube leaks, etc.); and

P Limestone flow rate (affecting CO_2 production).

Generically, any parameter which effects system stoichiometrics, and thus computed fuel chemistry, is termed a "Choice Operating Parameter" (COP). This work demonstrates that COPs can be corrected using multidimensional minimization techniques including artificial neural-networks, by minimizing differences between a so-called "System Effect Parameter" (SEP) and its associated reference value. A SEP is simply any parameter of the thermal system or its fuel which can directly impact the determination of system heat rate. For example, SEPs could include an L Factor as it is effected by fuel chemistry (Lang, 1999), fuel heating value, fuel flow, etc. Note that fuel heating value and fuel flow are used only for those special cases where their values may be relied on as consistent, or accurate given special fuels testing, etc. The point is that an SEP is so selected such that a change in any COP, as impacting a SEP, will thus impact a computed system heat rate. COPs and SEPs definitions are important, they are used throughout this work.

What is key to this work is that COPs are corrected for inaccuracies and then used in deterministic models to compute fuel chemistry, fuel heating value, etc., thus guaranteeing consistent system mass and energy balances. COPs are corrected by minimizing error in SEPs. COPs are the independent variables in an objective function, which when the objective function is minimized (driven to zero), drives SEPs to their reference values by correcting COPs.

The idea of correcting COPs for later use in deterministic models is non-trivial, it speaks to the use (and mis-use) of non-deterministic models. Non-deterministic models such as artificial neural-networks (ANN) are used to bypass system thermodynamics. It speaks to a bright line drawn between the process of correcting COPs (using any means possible including ANN) and subsequent use of corrected COPs in explicit thermodynamic modeling.

A US patent by Alouani, *et al.*, (US 6,192,352) well defines

differences between an ANN approach to monitoring complex systems such as power plants, and the deterministic approach advocated here. The patent presents a quotation by a L.A. Zadch:

“... as the complexity of a system increases, our ability to make precise and yet significant statements about its behavior diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics.”

Zadch’s comments crystalize methodological differences. One purpose of this paper is to thwart blind use of ANN technologies and their attempt to circumvent thermodynamics - to demonstrate that they are not needed. Using the Input/Loss Method, properly engineered and attention paid, in which differences between calculated SEPs and their corresponding reference values are minimized by correcting COPs, one can achieve both precision and significance in the understanding of power plants. **Contrary to the views of those advocating ANN technologies, the concept of corrected COPs (effluents) feeding explicit thermodynamics allows for both precision and significance where Input/Loss is installed.**

Having set the philosophy, developing a mechanism to actually correct COPs involved addressing some very serious technical problems. These problems are bound intrinsically with the nature of fossil-fired system stoichiometrics and effluent measurement technologies, they principally include:

- 1) the incredible sensitivity effluent CO₂ concentration has on computed fuel chemistry, as it effects system-wide carbon balancing;
- 2) the interrelationship between a CO₂ signal, measured wet, and effluent H₂O;
- 3) the obvious interrelationship between effluent CO₂ and concomitant O₂, system air leakage, etc.; and, most importantly,
- 4) all such effects have a classical “shallow valley” response between independent (COPs) and dependent variables (SEPs).

What is meant by a shallow valley response is that any given change in a COP, large or small, could have a trivial effect on the objective function and computed SEPs, even through that change is both real and appropriate to the physical system and has appropriately described stoichiometric inter-relationships. This paper presents solutions to such problems; such solutions evolved from having experimented with over 1000 different forms of objective functions.

THERMODYNAMIC CONSERVATIONS AND COMBUSTION STOICHIOMETRICS

This section, for the record, presents a typical combustion equation to illustrate how corrected COPs directly impact system mass and energy balances. Although details for the fuel chemistry

computations are described in the Part I paper, the following shows how a complete mass balance is possible given resolved system stoichiometrics, all based on corrected COPs.

Conservation of the thermal system’s mass flows, combustion gases and working fluid, is dependent on consistency of the combustion stoichiometrics, given a reasonably steady system; refer to TABLE 1. Given the computed quantities HHVP, HBC and η_B , and with measured working fluid energy flow, BBTC, fuel flow is then computed based on the classical boiler efficiency equation, Eq.(63). Considered key to such conservations is the Input/Loss computed boiler efficiency, Eq.(62). It is at odds, in its details, with all steam generator efficiency standards; refer to the Part III paper for a detailed description (Lang, 2000), and to a supplement white paper critiquing steam generator efficiency standards (Lang, 2004a).

Eq.(19-corr) nomenclature is unique in that brackets are used for clarity: for example, the expression “ $\alpha_{10}[\text{Ash}]$ ” means the fuel moles of ash, algebraically simply α_{10} ; the expression “ $d_{\text{Act}}[\text{CO}_2]$ ” means the effluent moles of CO₂, algebraically simply d_{Act} . The stoichiometric base of Eq.(19-corr) is 100 moles of dry Stack gas.

$$\begin{aligned} & \times [\alpha_0[\text{C}_{\text{YR}}\text{H}_{\text{ZR}}] + \alpha_1[\text{N}_2] + \alpha_2[\text{H}_2\text{O}] + \alpha_{3\text{-corr}}[\text{O}_2] + \alpha_{4\text{-corr}}[\text{C}] \\ & + \alpha_5[\text{H}_2] + \alpha_6[\text{S}] + \alpha_7[\text{CO}_2] + \alpha_8[\text{CO}] + \alpha_9[\text{H}_2\text{S}] \\ & + \{ \alpha_{10} - \alpha_{\text{CaO}} \} [\text{Ash}] + \alpha_{\text{CaCO}_3} [\text{CaCO}_3]]_{\text{As-Fired Fuel}} \\ & + [(1.0 + \beta)(a[\text{O}_2] + a\phi_{\text{Act}}[\text{N}_2] + b_{\text{A}}[\text{H}_2\text{O}])]_{\text{Air}} \\ & + b_z[\text{H}_2\text{O}]_{\text{In-Leakage}} + [(1.0 + \gamma)b_{\text{PLS}}[\text{CaCO}_3]]_{\text{As-Fired PLS}} \\ & = d_{\text{Act}}[\text{CO}_2] + g[\text{O}_2] + h[\text{N}_2] + j[\text{H}_2\text{O}] + k_{\text{Act}}[\text{SO}_2] \\ & + [e_{\text{Act}}[\text{CO}] + f[\text{H}_2] + l[\text{SO}_3] + m[\text{NO}] + p[\text{N}_2\text{O}] \\ & + q[\text{NO}_2] + t[\text{C}_{\text{YP1}}\text{H}_{\text{ZP1}}] + u[\text{C}_{\text{YP2}}\text{H}_{\text{ZP2}}]]_{\text{Minor Components}} \\ & + \sigma b_{\text{PLS}}[\text{CaSO}_4 \cdot z\text{H}_2\text{O}] + x\alpha_{10}[\text{ash}] + v[\text{C}_{\text{Refuse}}] \\ & + [\{ (1.0 - \sigma + \gamma)b_{\text{PLS}} + x\alpha_{\text{CaCO}_3} \} [\text{CaO}]]_{\text{Excess PLS}} \\ & + [\beta(a[\text{O}_2] + a\phi_{\text{Act}}[\text{N}_2] + b_{\text{A}}[\text{H}_2\text{O}])]_{\text{Air Leakage}} \quad (19\text{-corr}) \end{aligned}$$

TABLE 1 presents the principal terms associated with a fossil-fired thermal system. If inlet and outlet mass flows disagree by more than 0.2%, errors are considered significant. Note well that the defined Dilution Factor, β , and the Leakage Factor, R_{Act} , are key variables which address stoichiometric interrelationships. R_{Act} allows Boiler O₂ ($R_{\text{Act}}g$) to be used as a COP at the same time as Stack CO₂ (d_{Act}) and Stack H₂O ($j + \beta b_{\text{A}}$); or Stack CO₂ and Stack O₂ ($g + \beta a$) to be used as COPs at the same time as Boiler H₂O ($R_{\text{Act}}j$). The terms $\alpha_{3\text{-corr}}$ and $\alpha_{4\text{-corr}}$ are fuel oxygen and carbon fractions corrected for CO₂ producing mineral matter found as CaO within the fuel ash, thus $(\alpha_{10} - \alpha_{\text{CaO}})$.

**TABLE 1:
Mass Balance Based on System Stoichiometrics**

Fuel Flow Rate (m_{AF})	= BBTC / [η_B (HHVP + HBC)]
Combustion Dry Air	= $m_{\text{AF}} (1.0 + \beta)(a + a\phi_{\text{Act}}) N_{\text{Air}} / (xN_{\text{AF}})$
Combustion Air Moisture	= $m_{\text{AF}} (1.0 + \beta) b_{\text{A}} N_{\text{H}_2\text{O}} / (xN_{\text{AF}})$
Water In-Leakage	= $m_{\text{AF}} b_z N_{\text{H}_2\text{O}} / (xN_{\text{AF}})$
Pure LimeStone (PLS)	= $\frac{m_{\text{AF}} (1.0 + \gamma) b_{\text{PLS}} N_{\text{CaCO}_3}}{\sum \text{INLET MASS FLOWS}}$

$$\begin{aligned}
\text{Dry Gas as Boiler Effluent} &= m_{AF} 100 N_{\text{Gas}} / (R_{\text{Act}} x N_{AF}) \\
\text{Dry Air Leakage} &= m_{AF} \beta (a + a \phi_{\text{Act}}) N_{\text{Air}} / (x N_{AF}) \\
\text{Combustion Moisture plus Air Leakage} & \\
\text{Moisture at Boundary} &= m_{AF} (j_{\text{Act}} + \beta b_A) N_{\text{H}_2\text{O}} / (x N_{AF}) \\
\text{Calcium Sulfate from PLS} &= m_{AF} \sigma b_{\text{PLS}} N_{\text{CaSO}_4 \cdot \text{zH}_2\text{O}} / (x N_{AF}) \\
\text{Calcium Oxide from PLS} &= m_{AF} (1.0 - \sigma + \gamma) b_{\text{PLS}} N_{\text{CaO}} / (x N_{AF}) \\
\text{Calcium Oxide from} & \\
\text{Carbonates in Fuel} &= m_{AF} x \alpha_{\text{CaCO}_3} N_{\text{CaO}} / (x N_{AF}) \\
\text{Carbon in Ash} &= m_{AF} v N_C / (x N_{AF}) \\
\text{Ash Flow (Bottom, Fly)} &= \frac{m_{AF} \alpha_{10} N_{\text{Ash}} / N_{AF}}{\sum \text{OUTLET MASS FLOWS}}
\end{aligned}$$

To summarize, the following important quantities are computed with assurance that these quantities are base on thermodynamic conservations.

$$\eta_B = [(-\text{HPR}_{\text{Act}} + \text{HRX}_{\text{Act}}) / (\text{HHVP} + \text{HBC})] \eta_A \quad (62)$$

$$m_{AF} = \text{BBTC} / [\eta_B (\text{HHVP} + \text{HBC})] \quad (63)$$

$$\text{HR} = m_{AF} (\text{HHVP} + \text{HBC}) / W_{\text{output}} \quad (64)$$

$$= \text{BBTC} / (\eta_B W_{\text{output}}) \quad (65)$$

MINIMIZATION TECHNIQUES

Five multidimensional minimization techniques are available to the Input/Loss user. All techniques seek to minimize the numerical value of an objective function. These techniques include: Broyden-Fletcher-Goldfarb-Shanno (BFGS), generic Conjugate Gradient, Newton-Raphson, Simulated Annealing algorithms, and artificial neural-networks (ANN). These techniques, and, notably, their combinations, are designed to address all situations of bias in COPs. All of these techniques, except Simulated Annealing and ANN, employ derivatives of the objective function with respect to the independent variable. These techniques require input of initial estimates of COPs (Λ_{0-i}), found by guess or by-golly. The BFGS, generic Conjugate Gradient and Newton-Raphson techniques employ unconstrained searches towards optima. Simulated Annealing and ANN employs random, pattern recognition and constrained searches in which the COPs are numerically bounded by lower and upper limits. The Simulated Annealing technique will always find an optimum.

In solving the shallow valley response problem it was found that the Bessel function of the first kind was ideally suited when configured with an appropriate argument and scaling. The Bessel function emulates the sensitivity that important COPs have on both SEPs and on the descriptive thermal system in general. The Bessel function of the first kind of order zero (J_0) has a relatively flat (shallow) functionality as its argument approaches zero. Apart from this, the function offers non-linearity which is advantageous in converging out-lying arguments. Of great importance is that the derivative of J_0 is a Bessel function of the first kind of order one (J_1), having a high degree of sensitivity as its argument approaches zero. This derivative relationship addresses a significant number of shallow valley problems presented by the COPs associated with

fossil combustion. Another technique addressing the shallow valley problem and involving use of the Bessel function is the formulation of its argument, termed λ_j , [i.e., $J_0(\lambda_j)$]; these arguments are described below, defined by Eqs.(2A), (2B) and (2C).

The objective function, F , is a function of independent variables \vec{x} , or $F(\vec{x})$, which when driven to zero yields corrected COPs and optimized SEPs. SEPs include three general types and their associated reference values: the L Factor (L_{k1}); the As-Fired fuel flow (m_{AF}); and the higher heating value (HHV_{k3}). The higher heating value is chosen as either: an As-Fired value, HHV_{AF} ; a Dry value, HHV_{Dry} ; and/or a MAF value, HHV_{MAF} . For most situations use of the L_{Fuel} L Factor, defined by Eq.(72), is preferred; others are available. The power plant engineer may select from any one or more or all of these System Effect Parameters, whose differences with respect to reference values are minimized by altering a selection of COPs. SEPs are chosen such that they reflect influences on system heat rate through COPs, and, at the same time, reflect inter-dependencies between COPs. Literally, any variable in Eqs.(64) or (65) would apply, or, indeed, the COPs on which they are dependent. For example: changes in the concentration of effluent CO_2 (a COP defined as Λ_{1S} or Λ_{1B}), effects computed fuel chemistry, also effects computed heating value, also effects computed boiler efficiency, all of which effect system heat rate; but a change in CO_2 may be caused by a change in the concentration of effluent H_2O (the COP Λ_{2S} or Λ_{2B}), or a change in the concentration of fuel ash (via the COP Λ_3), whose changes may also effect fuel flow and fuel chemistry.

The following summarizes the objective functionalities demonstrating the aforementioned principles:

$$\begin{aligned}
F(\vec{x}) &= \sum_{i \in I} f[S_i, J_0(\lambda_L), J_0(\lambda_W), J_0(\lambda_H)] \\
\lambda_L &= f[L_{k1}, L_{k1-\text{Ref}}, M_L] \\
\lambda_W &= f[m_{AF}, m_{AF-\text{PLT}}, M_W] \\
\lambda_H &= f[\text{HHV}_{k3}, \text{HHV}_{k3-\text{Ref}}, M_H] .
\end{aligned}$$

The symbol $\sum_{i \in I}$ is defined following Eq.(3). Note that as $F(\vec{x})$ is minimized the quantities $\vec{\lambda}$ are updated in turn ($\Lambda_i = x_i/S_i$), thus allowing SEPs to be computed leading directly to the computation of λ_L , λ_W and λ_H . SEPs have the following important inter-relationships: computed fuel chemistry is dependent on several or all COPs, $\vec{\lambda}$; computed heating values (HHV and HHVP) are dependent on fuel chemistry, thus $\vec{\lambda}$; and boiler efficiency (η_B) determined using the Input/Loss Method is dependent directly on Λ_i effluents, is also dependent on fuel chemistry, and is also dependent on heating value, thus $\vec{\lambda}$. Working fluid energy flow and Firing Correction terms (BBTC and HBC) are dependent on routine operating parameters. Summary functionalities include:

$$\begin{aligned}
x_i &\equiv S_i \Lambda_i \\
L_{k1} &= f[\text{fuel chemistry}(\vec{\lambda}), \text{HHV}(\vec{\lambda})] \\
m_{AF} &= f[\text{BBTC}, \eta_{B-\text{HHV}}(\vec{\lambda}), \text{HHVP}(\vec{\lambda}), \text{HBC}] \\
\text{HHV}_{k3} &= f[\text{fuel chemistry}(\vec{\lambda})].
\end{aligned}$$

SYSTEM EFFECT PARAMETERS

As discussed, System Effect Parameters include three general types and their associated reference values: the L Factor (L_{k1}); the

As-Fired fuel flow (m_{AF}); and the higher heating value (HHV_{k3}). The most important of these, by far, is the L Factor as is used routinely for most situations. The higher heating value may be employed when the thermal system is operating under controlled conditions (e.g., under a testing program) in which its fuel is well characterized. The L Factor is important in reducing the impact of the shallow valley response problem found with fossil-fired systems. An important reason for this is that L'_{Fuel} has been demonstrated to have remarkably small standard deviations for a given Rank of coal (typically $\pm 0.05\%$). To address the influences fuel water and fuel ash have on the L Factor, the numerator of the L'_{Fuel} term contains the quantities J_{theor} and $(x_{MAF-theor} \alpha_{MAF-10})$, its denominator contains the As-Fired term $(x_{theor} N_{Fuel} HHV)$. The L_{Water} and L_{Ash} terms have also been employed, as has an L_{CO2} term. The various forms of the L Factors (L_{k1}) are defined by the following.

$$L_{Fuel} = 10^6 [100 N_{Dry-Gas}] / (N_{Dry-Fuel} HHV_{Dry}) \quad (71)$$

$$L'_{Fuel} = 10^6 [x_{Dry-theor} N_{Dry-Fuel} + a_{Dry-theor} (1.0 + \phi_{Ref}) N_{Air} - J_{theor} N_{H2O} - x_{MAF-theor} \alpha_{MAF-10} N_{Ash} - x_{MAF-theor} \alpha_{MAF-7} N_{CO2}] / (x_{theor} N_{Fuel} HHV) \quad (72)$$

$$L_{Water} = J_{theor} N_{H2O} / (x_{Dry-theor} N_{Dry-Fuel} HHV_{Dry}) \quad (73)$$

$$L_{Ash} = [x_{MAF-theor} \alpha_{MAF-10} N_{Ash} + x_{MAF-theor} \alpha_{MAF-7} N_{CO2}] / (x_{Dry-theor} N_{Dry-Fuel} HHV_{Dry}) \quad (74)$$

$$L_{CO2} = d_{theor} N_{CO2} / (x_{Dry-theor} N_{Dry-Fuel} HHV_{Dry}) \quad (75)$$

where the identities:

$$x_{MAF-theor} N_{MAF-Fuel} HHV_{MAF} = x_{Dry-theor} N_{Dry-Fuel} HHV_{Dry} = x_{theor} N_{Fuel} HHV_{AF}$$

have proven useful. The SEPs L_{Water} , and the combined ($L_{Water} + L_{Ash}$), although all are a function of $\bar{\Lambda}$ through fuel chemistry, are intended to be used to optimize only the COP for effluent water (Λ_{2S} or Λ_{2B}) as it effects fuel water. The SEPs L_{Ash} and the combined ($L_{Water} + L_{Ash}$), although all are a function of $\bar{\Lambda}$ through fuel chemistry, are intended to be used to optimize only the COP for Air/Fuel ratio (Λ_3) as such ratio effects fuel ash (see Part I). These SEPs are unique in that they are designed for selective use, illustrating that SEPs may be formed specific to a selected COP, provided that the overall process reflects the influence on system heat rate. Their use has proved valuable for fuels having low or predictable fuel water and fuel ash contents. However, the universal L Factor, L'_{Fuel} , has proven very successful for optimizing all COPs ($\bar{\Lambda}$), including fuel water and fuel ash.

Along with the L Factor, the power plant engineer may also choose, in any combination, the plant's indicated fuel flow, the As-Fired heating value, the Dry heating value and/or the MAF heating value as System Effect Parameters. Although the engineer has complete flexibility, with this flexibility must apply common engineering judgement. For example, optimizing effluent water against HHV_{MAF} or HHV_{Dry} (heating values without water) would make little sense given the lack of connectivity.

Selecting the system's indicated fuel flow, m_{AF-PLT} , is at odds with traditional thought and the author's previous statements, since inaccuracies in a measured flow of a bulk fuel, such as coal, may be

appreciable. However, in developing Input/Loss, observations at several power plants revealed that coal flow measurements may be consistent, not necessarily accurate, reflecting changes in any number of quantities which may impact system heat rate. The minimization techniques may be used to minimize the difference between a computed fuel flow (m_{AF} of Eq.(63) and TABLE 1) and the system's indicated fuel flow, m_{AF-PLT} , through optimized COPs. Thus, Input/Loss allows use of the system's indicated fuel flow to aid in the determination of computed fuel chemistry and fuel heating value! It must be used with caution. For many situations use of the system's indicated fuel flow should be accompanied with the L'_{Fuel} factor of Eq.(72), to assist with stability and reasonableness of solution. To further enhance stability and reasonableness of solution the power plant engineer may option to limit the range of fuel concentrations. The engineer may also limit the numerical range of each selected COP when using Simulated Annealing or ANN. Further, to address the likelihood that m_{AF-PLT} is in error, both a Dilution Factor (M_W) and off-set (Δm_{AF}) have been applied to the relationship between m_{AF} and m_{AF-PLT} ; see Eq.(2B).

In summary, the process involving the minimization of differences in System Effect Parameters, by correcting Choice Operating Parameters, results in correction factors, C_i . These correction factors are based on the ratio of the converged COP (Λ_{F-i}), to its initial value (Λ_{0-i}).

$$C_i = \Lambda_{F-i} / \Lambda_{0-i} \quad (1)$$

COMPUTER MECHANICS

The structure used to implement the Error Analysis feature of Input/Loss involves use of a single personal computer, operating first an ERR-CALC program which produces correction factors to COPs, followed by Fuel Iterations. ERR-CALC contains all relevant methods discussed in this paper, its only output are the corrections factors of Eq.(1). Corrected COPs ($C_i \Lambda_{0,i}$) are then input to the Fuel Iterations for resolution of fuel chemistry, heating value, fuel flow, associated mass balances of TABLE 1, etc. Fuel Iterations are performed using three programs: FUEL which prepares fuel data for EX-FOSS, the steam generator simulator EX-FOSS (Lang, 2004b), and the HEATRATE program. EX-FOSS is a major software tool in which fuel chemistry, heating value, etc. are input, combustion effluents are then computed. HEATRATE is the reverse: input includes corrected COPs from which fuel chemistry and heating value are computed. This process iterates until convergence is reached with fuel moles (x), fuel water fraction and heating value.

FORMULATIONS AND OBJECTIVE FUNCTION

The following paragraphs discuss the more important multidimensional minimization techniques as recommended for correcting COPs.

The BFGS technique represents a second generation of multidimensional minimization techniques. As such, it is considered one of the most robust of techniques for a well conditioned problem. The particular BFGS technique employed by the Input/Loss Method

has a superior reputation for convergence (Shanno, 1976). The BFGS technique is the preferred method for use on a continuous bases after the problem has been properly conditioned with scaling factors, and selections of COPs and SEPs have been established appropriate to the system. These input parameters are also applicable to the generic Conjugate Gradient technique.

The Newton-Raphson method is one of the oldest and simplest multidimensional minimization techniques. This method requires the objective function's compounded vector gradient, resulting in a Jacobian determinant. Generally it will yield a very efficient means of convergence but requires reasonable initial COPs (Λ_{0-i}); however, without such reasonableness it may fail wildly.

The Simulated Annealing procedure (Goffe, 1994), because it employs a global, constrained methodology, is the preferred method for initial study of a new Input/Loss installation. It may also be used to assist in the selection of which COPs are best for a particular thermal system. This procedure simulates the annealing process of metal, requiring the controlled reduction of a pseudo-temperature to achieve a desired result (i.e., achieving a minimum potential energy of the metal's structure when slowly cooled, thus the minimizing of an objective function). This is a brute force approach involving random search; gradients are not used. As similar to Simulated Annealing, ANN technology is used to recognize patterns in COPs which result in a minimized objective function.

For Simulated Annealing and ANN, typically between 1000 to 3000 iterations within ERR-CALC are required for convergence. To address the problem of long computing times, Input/Loss duplicates within the ERR-CALC program only those calculations from the EX-FOSS and HEATRATE programs which effect SEPs, and to therefore compute SEPs within ERR-CALC (which are then repeated within the Fuel Iterations, but with corrected COPs). This results in a considerable reduction in computing time required to evaluate repeated objective function calculations involving system stoichiometrics. Specifically, these duplicated calculations include HEATRATE stoichiometrics, L Factor calculations, heating value calculations, and an approximation of the effects changing stoichiometrics and changing heating value has on boiler efficiency and thus the effects on computed fuel flow. In summary, these duplicated calculations determine affects on the SEPs (L_{k1} , m_{AF} , and HHV_{k3}) of a given set of COPs ($\vec{\Lambda}$).

The objective function developed after considerable effort is given by the following. Again, the SEPs (L_{k1} , m_{AF} and HHV_{k3}), are functions of a set of independent variables (scaled Λ_i).

$$\lambda_L = [(L_{k1} - L_{k1-Ref}) / L_{k1-Ref}]^{M_L} \quad (2A)$$

$$\lambda_W = [(m_{AF} - m_{AF-PLT} - \Delta m_{AF}) / (m_{AF-PLT} + \Delta m_{AF})]^{M_W} \quad (2B)$$

$$\lambda_H = [(HHV_{k3} - HHV_{k3-Ref}) / HHV_{k3-Ref}]^{M_H} \quad (2C)$$

$$F(\vec{x}) = \sum_{i \in I} \{ S_i [1.0 - J_0(\lambda_L)] + S_i [1.0 - J_0(\lambda_W)] + S_i [1.0 - J_0(\lambda_H)] \} \quad (3)$$

In Eq.(3) and as used elsewhere, the symbol $\sum_{i \in I}$ indicates a summation on the index i, where i variables are contained in the set

I defined as the elements of $\vec{\Lambda}$. For example, assume the user has chosen the following: Λ_{1S} is to be optimized to minimize the error in L'_{Fuel} and HHV_{MAF} , Λ_{2S} is optimized for L'_{Fuel} and m_{AF} ($M_W = 1.40$), Λ_4 is optimized for L'_{Fuel} , and Λ_{7B} is optimized for L'_{Fuel} . Therefore: $\vec{\Lambda} = (\Lambda_{1S}, \Lambda_{2S}, \Lambda_4, \Lambda_{7B})$, $I = \{\Lambda_{1S}, \Lambda_{2S}, \Lambda_4, \Lambda_{7B}\}$, thus $\vec{x} = (x_1, x_2, x_3, x_4)$; $x_1 = S_1 \Lambda_{1S}$; $x_2 = S_2 \Lambda_{2S}$; $x_3 = S_3 \Lambda_4$; $x_4 = S_4 \Lambda_{7B}$; where Eq.(3) for this example then becomes:

$$F(\vec{x}) = S_1 \{ [1.0 - J_0(\lambda_L)] + [1.0 - J_0(\lambda_H)] \} + S_2 \{ [1.0 - J_0(\lambda_L)] + [1.0 - J_0(\lambda_W)] \} + S_3 [1.0 - J_0(\lambda_L)] + S_4 [1.0 - J_0(\lambda_L)]$$

COPs may be chosen by the power plant engineer from any combination or all of the following:

$$\Lambda_{1S} = d_{Act}; \quad \text{Stack CO}_2 \text{ (w/air leakage effects)} \quad (11S)$$

$$\Lambda_{1B} = d_{Act} R_{Act}; \quad \text{Boiler CO}_2 \text{ (w/o air leakage effects)} \quad (11B)$$

$$\Lambda_{2S} = J_{Act} \equiv j + b_A \beta; \quad \text{Stack H}_2\text{O (with moisture from air pre-heater leakage)} \quad (12S)$$

$$\Lambda_{2B} = j R_{Act}; \quad \text{Boiler H}_2\text{O (w/o air leakage effects)} \quad (12B)$$

$$\Lambda_3 = AF; \quad \text{Air/Fuel ratio} \quad (13)$$

$$\Lambda_4 = R_{Act}; \quad \text{Air pre-heater Leakage Factor} \quad (14)$$

$$\Lambda_5 = A_{Act}; \quad \text{Concentration of O}_2 \text{ in the combustion air} \quad (15)$$

$$\Lambda_6 = m_{LS}; \quad \text{System's indicated limestone flow} \quad (16)$$

$$\Lambda_{7S} = G_{Act} \equiv g + a \beta; \quad \text{Stack O}_2 \text{ (with air pre-heater leakage)} \quad (17S)$$

$$\Lambda_{7B} = g R_{Act}; \quad \text{Boiler O}_2 \text{ (w/o air pre-heater leakage)} \quad (17B)$$

$$\Lambda_8 = m_T; \quad \text{Tube leakage mass flow} \quad (18)$$

The selection of one or more of the Choice Operating Parameters must depend on common understanding of power plant stoichiometrics and associated relationships to physical equipment.

The use of the exponents M_L , M_W and M_H in Eqs.(2A), (2B) & (2C), termed Dilution Factors, allows a dilution or dampening of the functionality between reference SEPs and the selected COPs ($\vec{\Lambda}$). Dilution Factors allow the numerical processes to recognize that reference SEPs may themselves have bias, applicable when multiple SEPs are employed (e.g., L Factor in combination with fuel flow). Examples of such bias include: error in establishing the reference L Factor; the reference heating value having been determined incorrectly, analyzed incorrectly in the laboratory and/or having intrinsic uncertainties; the indicated fuel flow having serious instrumentation error; etc. Although engineering judgement and a valid database may be reasonably anticipated and applied in the cases of reference L Factors and reference heating values, such judgement and a valid database are rare in the case of the plant's indicated fuel flow. Dilution Factors M_L (influencing L_{k1-Ref}) and M_H (influencing HHV_{k3-Ref}) may be assumed to be unity for most situations. However, for coal-fired plants, it is likely that indicated fuel flow will always have some bias; thus Δm_{AF} and M_W (both influencing m_{AF-PLT}) should be determined based on sensitivity studies. Specifically, M_W may be adjusted until Input/Loss computed total effluent flow reasonably agrees and/or tracks the measured,

computed combustion air flow agrees and/or tracks the measured, computed fuel flow agrees and/or tracks the indicated fuel flow, and similar system-wide comparisons.

Note that a standardized A_{Act} term, the concentration of O_2 in the combustion air local to and entering the system, has been defined by the Nation Aeronautics and Space Administration (NASA) at sea level as 20.9480%. However, as employed herein, the value of A_{Act} (as COP Λ_5) may be influenced by: altitude of the system; local atmospheric inversions or other weather patterns which may result in starving the local environment for oxygen given a consumption by combustion and not being replenished; and/or combustion gases leaking directly into the combustion air stream. A_{Act} leads directly to a determination of the ϕ_{Act} term appearing in all combustion equations. In common text books ϕ_{Act} is assumed to be constant at 3.76; if using the NASA standard $\phi_{Act} = \phi_{Ref}$ is 3.7737254. Input/Loss assumes ϕ_{Act} is a variable, dependent on A_{Act} , to be determined by the power plant engineer based on circumstances local to the thermal system and the physical system.

To address inter-dependencies of COPs, Input/Loss combustion stoichiometrics incorporate the R_{Act} term (COP Λ_4), and the A_{Act} term. Input/Loss stoichiometrics also incorporates the ϕ_{Act} term as derived solely from A_{Act} , and the β term derived from both ϕ_{Act} and R_{Act} . Air pre-heater leakage dilutes all exiting combustion effluents with moist air from the local environment, thus all important effluents, CO_2 , H_2O and O_2 used for system stoichiometric are effected and thus have inter-dependencies. Many times a power plant's more precise effluent measurements, especially O_2 , may be found at the air pre-heater's inlet (economizer outlet or "Boiler"), and not at the air heater outlet; thus requiring the use of the R_{Act} term. Although most environmental regulations require effluent measurements at the system's boundary, translation between the air heater inlet and outlet measurements is many times essential. The R_{Act} term allows for such translation and thus establishes inter-dependencies among COPs. Effluents comprising COPs may be used either upstream or downstream of the air pre-heater, and in any mix. Effluent measurements upstream of the air pre-heater (Boiler) would employ terms, for example, of $d_{Act}R_{Act}$, jR_{Act} and gR_{Act} (COPs Λ_{1B} , Λ_{2B} and Λ_{7B}). Effluents downstream of the air pre-heater, typically at the exit of the system (Stack), would employ terms d_{Act} , J_{Act} and G_{Act} (COPs Λ_{1S} , Λ_{2S} and Λ_{7S}). Sorbent injection into the combustion process, such as limestone (COP Λ_6) as used to control sulfur emissions, may create additional effluent CO_2 , and/or could decrease the effluent H_2O if the sulfate product is matrixed with water, $CaSO_4 \cdot zH_2O$. In summary, use of these terms addresses four features which specifically force inter-dependency of the COPs: 1) the ability to address air pre-heater leakage through application of the Leakage Factor R_{Act} and the ϕ_{Act} term used to determine the Dilution Factor, β ; 2) the ability to describe effluent concentrations on either side of the air pre-heater and in any mix, through application of R_{Act} ; 3) the ability to address injected sorbents, such as limestone which effects effluent CO_2 , commonly used in fluidized bed combustors; and 4) the use of a variable ϕ_{Act} term based on variable O_2 concentration in the system's local combustion air (A_{Act}).

METHOD OPTIONS

Method Options allow the power plant engineer to choose from individual, or collections, of multidimensional minimization techniques which are suitable for any one of the many operational situations found at a power plant or steam generator. Method Options control the numerical procedures used by the ERR-CALC program; and, as such, only apply when ERR-CALC is executed. Eight Method Options are available, the more popular are discussed in TABLE 2.

**TABLE 2:
Method Options**

Method Option	Suggested Usage
BFGS (Option M1)	For routine analysis BFGS is the most robust of techniques, requiring the least trouble in set-up and it affords rapid computing times.
Simulated Annealing (Option M4)	For scoping a new installation in which the accuracy of the instrumentation is unknown. Requires the longest of computing times.
BFGS with Sim. Ann. (Option M5)	For situations in which BFGS fails to properly converge, procedures automatically default to Simulated Annealing.
Sim. Ann. for Scaling (Option M7)	For periodic computing pre-scaling and scaling factors which may be applied to any other minimization technique.

SYSTEM OPTIONS

System Options control the HEATRATE program as to how fuel chemistry is computed (e.g., fixed or variable MAF chemistry). Three System Options are available as presented in TABLE 3: Fixed MAF Chemistry (Option S1); complete As-Fired fuel chemistry (Option S2); and As-Fired fuel chemistry but with constant MAF fuel ash (Option S3).

System Option S3 allows the MAF molar fuel ash to be computed as a function of MAF heating value (HHV_{MAF}), which has been found to have a wide applicability:

$$\alpha_{MAF-10} = K_{41} + 10^{-4} K_{42} HHV_{MAF} + 10^{-8} K_{43} (HHV_{MAF})^2 \quad (30)$$

In general, the constants K_{42} and K_{43} are zero, thus setting α_{MAF-10} equal to the constant K_{41} . For some lignite coals, the constants K_{42} and K_{43} have been found to be non-zero. These constants may be based on historical ultimate analyses of the fuel. System Option S3 is recommended only if MAF fuel ash has been determined to be either essentially constant or predictable. System Options S2 or S3 are most commonly employed; S2 being commonly recommended.

**TABLE 3:
System Options**

System Options	Suggested Use
Fixed MAF Chemistry (Option S1)	Moisture-Ash-Free fuel chemistry is held constant, while fuel water is computed based on the assumption or measurement made for Stack moisture, fuel ash is computed based on the Air/Fuel ratio or its assumption. S1 is intended for a system with poor instrumentation.
As-Fired Fuel Chemistry (Option S2)	As-Fired fuel chemistry is iterated until consistent with the selected Choice Operating Parameters as based on measurements or assumptions. MAF fuel ash is a computed function of the plant's indicated Air/Fuel ratio. Option S2 is the most universal, making no simplifying assumptions but may be prone to inconsistent COP data.
As-Fired Fuel Chemistry with Constant Fuel Ash (Option S3)	This option is the same as Option S2, except that MAF fuel ash is held constant or computed as a function of MAF heating value (HHV_{MAF}). Option S3 has applicability in all cases where the fuel ash is a relatively small fraction of the fuel, or as otherwise may be held essentially constant or is predictable via Eq.(30).

**TABLE 4:
Analysis Options**

Analysis Options	Suggested Use
Fuel Iterations Without Min. Techniques (Option A2)	This option bypasses the ERR-CALC program and uses established correction factors in computing fuel chemistry and heating value. For example, correction factors could be computed once/day using A4, at other times monitoring with A2.
Fuel Iterations With Min. Techniques (Option A4)	This option invokes the principal calculations discussed in this paper, i.e., resolving correction factors. Given reasonably consistent instrumentation, this option is intended to be used periodically.
Special Limits Study (Option A5)	This option establishes lower and upper numerical bounds for COPs as applicable to Simulated Annealing or ANN by repeatedly varying COPs until errors are encountered. Such bounds are also frequently established by the experienced plant engineer.
Force Cycle (Option A6)	This option allows a pre-determined set of Method and System Options, and even other Analysis Options to be invoked based on a defined criteria. Such criteria may be a computational error, a faulted COP signal, low thermal loads and so-forth; it includes <u>not</u> executing (a calculational "cut-out").

ANALYSIS OPTIONS

Analysis Options control the mechanics of computing techniques used by the ERR-CALC program and the Fuel Iterations process. When engaged, Analysis Options become most important to assure a smooth running Input/Loss. Six samples of the more important Analysis Options are presented in TABLE 4. In general, these options control when the Error Analysis feature and/or the Fuel Iterations are to be applied; these options also provide Δ_i limit calculations used for Simulated Annealing, and facilitate selection of which Method Option is to be used given failure or non-convergence of an initial Method Option.

RESULTS AND CONCLUSIONS

A number of papers and presentations are available which illustrate the direct application of these techniques; see the Part II paper, (Deihl, 1999), (Rodgers & Lang, 2002) and (Rodgers, 2004). In addition, there have been several dramatic demonstrations of Input/Loss' ability to detect tube failures (demonstrating COP Λ_g); see (Lang, 2004c). At several installations, Input/Loss heating value predictions were compared to grab samples. FIG. 1 presents results of test burns at a 700 MWe unit involving Powder River Basin coal; its agreement with spot heating values is typical.

The power plant engineer has a wide variety of choices through which differences between System Effect Parameters and their reference values may be minimized by correcting Choice Operating Parameters. For any given situation found at a thermal system burning fossil fuel, the power plant engineer may exercise the various Method, System and Analysis Options to achieve consistent system stoichiometrics and thermodynamic conservations. To further illustrate such flexibility TABLE 5 presents typical applications. In TABLE 5, the second column denotes the selection of COPs and SEPs: for example, " $\Delta_{1S} \min L'_{Fuel}$ " means that Choice Operating Parameter Δ_{1S} is selected to minimize the error in System Effect Parameter L'_{Fuel} of Eq.(72).

The application of techniques discussed in this paper allows the practical integration of power plant effluents with thermal performance. Installations of Input/Loss have, indeed, resulted in improved heat rate - but only where the plant owner has incentive to monitor and improve thermal efficiency. Given such incentive, Input/Loss performs the most unique computations associated with coal-fired power plants: the on-line prediction of fuel chemistry, heating value, fuel flow and heat rate through integration of effluents with explicit thermodynamics.

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TABLE 5:
Examples of Applications to Different Thermal Systems

The Thermal System	Optimizations	Method, System & Analysis Options
Lignite fuel (high ash and water), high Air/Fuel ratio, with ≈constant MAF fuel chemistry, all instruments having questionable accuracy.	$\Lambda_{1S} \min L'_{Fuel}$ $\Lambda_{2S} \min L'_{Fuel}$ $\Lambda_{7S} \min L'_{Fuel}$	Run M6, S1 and A4 continuously.
Initial debug of a new installation: coal with high water, low and constant ash, multiple O ₂ instruments are used at the Boiler, constant air leakage assumed.	$\Lambda_{1S} \min L'_{Fuel}$ $\Lambda_{2S} \min L'_{Fuel}$ $\Lambda_{7B} \min L'_{Fuel}$	Run M7, S3 and A5 once, followed by a continuous M7, S3 and A3.
Routine monitoring of coal with high water, with low and constant ash, multiple Boiler O ₂ instruments are used having ≈high accuracy.	$\Lambda_{1S} \min L'_{Fuel}$ $\Lambda_{2S} \min L'_{Fuel}$	Run M5, S1 and A4 once every 30 minutes, with A2 and A6 at all other times.
Moderate energy coal having variable ash, low fuel water, ≈constant MAF heating value, variable ambient humidity, tubular air pre-heater (no leakage), CO ₂ & O ₂ are measured at the Boiler for close control, no Stack H ₂ O instrument.	$\Lambda_{1B} \min HHV_{MAF}$ $\Lambda_{1B} \min L'_{Fuel}$ $\Lambda_{2B} \min L'_{Fuel}$ $\Lambda_3 \min L'_{Fuel}$ $\Lambda_{7B} \min L'_{Fuel}$	Run M1 (or M4), S2 and A4 once every 15 minutes, with A2 at all other times.

FIGURE 1:
Test Burns of Powder River Basin Coal
(Black Thunder → Rawhide → Black Thunder, June 2003)

