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FUEL CONSUMPTION INDEX FOR PROPER MONITORING OF POWER PLANTS - REVISITED

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ABSTRACT

This paper presents an method for heat rate monitoring of power plants which employs a true "systems approach". As an ultimate monitoring parameter, derived from Second Law concepts, it quantifies system losses in terms of fuel consumption by individual components and processes. If electricity is to be produced with the least un-productive fuel consumption, then thermodynamic losses must be understood and minimized. Such understanding cuts across vendor curves, plant design, fuels, Controllable Parameters, etc. This paper demonstrates that thermal losses in a nuclear unit and a trash burner are comparable at a *prime facia* level. The Second Law offers the only foundation for the study of such losses, and affords the bases for a true and ultimate indicator of system performance.

From such foundations, a Fuel Consumption Index (FCI) was developed to indicate specifically what components or processes are thermodynamically responsible for fuel consumption. FCIs tell the performance engineer why fuel is being consumed, quantifying that a portion of fuel which must be consumed to overcome frictional dissipation in the turbine cycle (FCI_{TCycle}), the combustion process (FCI_{Comb}), and so forth; and, indeed, how much fuel is required for the direct generation of electricity (FCI_{Power}). FCIs have been particularly applicable for monitoring power plants using the Input/Loss Method.

FCIs, Δheat rates based on FCIs, and an "applicability indicator" for justifying the use of Reference Bogey Data are all defined. This paper also presents the concept of "dynamic heat rate", based on FCIs, as a parameter by which the power plant operator can gain immediate feedback as to which direction his actions are thermally headed: towards a lower or higher heat rate.

NOMENCLATURE

FCI_j = Fuel Consumption Index for any $j_{\underline{th}}$ component or process, $\Sigma FCI_j = 1000$; unitless.
$\int \partial \widetilde{FCI}_{Power}$ = Dynamic Fuel Consumption Index for Power; unitless.
g = Specific exergy composed of physical, chemical, and thermal contributions; Btu/lbm.
g_{Fuel} = Specific exergy of As-Fired fuel; Btu/lbm.
G_{in} ≡ Total system exergy flow and shaft power inputs; Btu/hr.
ΣG_{Misc} = Miscellaneous exergy flows inlet and outlet from the system: steam-air heater, water losses, etc; Btu/hr.
HBC ≡ Firing Correction (i.e., "energy credit"), Btu/lbm_{AF}.
HHV = Higher heating value, laboratory determined; Btu/lbm_{AF}.
HHVP = As-Fired (wet-base) higher heating value corrected for a constant pressure process, Btu/lbm_{AF}.
hr_j = Differential heat rate associated with any single $j_{\underline{th}}$ component or process; ΔBtu/kWh.
Δhr_j = Difference between two differential heat rates associated with the same $j_{\underline{th}}$ component; ΔΔBtu/kWh.
HR = Unit heat rate (gross, total system); Btu/kWh.
ΔHR = Difference in unit heat rate, commonly termed "unit heat rate deviation"; ΔBtu/kWh.
$\int \partial HR_D$ = Dynamic Heat Rate, ΔBtu/kWh.
I_i = Irreversibility for an $i_{\underline{th}}$ component or process; Btu/hr.
ΔKE/m = Relative specific kinetic energy, assumed zero.
ΔPE/m = Relative specific potential energy, assumed zero.
$m_{Air}g_{Air}$ = Total exergy of moist combustion air inlet; Btu/hr.
m_{AF} = Mass flow rate of As-Fired fuel; lbm/hr.
∂Q = Incremental heat transfer; Btu/hr.
Q_{in} = Heat transfer to the working fluid from boiler; Btu/hr.
Q_{Rej} = Heat transfer from the condenser tube-side to the circulatory water (i.e., local environment); Btu/hr.
SFU_j = Specific Fuel Usage of any $j_{\underline{th}}$ component or process, Δfuel flow per power; Δlbm_{AF} /kWh.
T_{Ref} = Temperature of reference conditions; degree F.
∂W = Incremental shaft power; Btu/hr.
ΣW_{Fan} = Summation of shaft powers supplied to combustion gases and air (generally the FD and ID fans); Btu/hr.
ΣW_{Pump} = Summation of pump shaft powers supplied to the boiler and turbine cycle; Btu/hr.
W_{output} = Gross electrical generation; Btu/hr.
$(1 + \Psi_j)$ = Term used to test applicability of the Reference Bogey Data (if positive, data is applicable); unitless.

Subscripts:

AF As-Fired (wet with mineral matter).
A Actual case being monitored on-line in real-time.
B Bogey (targeted) case, based on Referenced Bogey Data.
i Non-power component or process (subscript i and "non-Power" are used interchangeably for irreversible FCI terms).
j Any component or process: non-power, power or environmental.
n System substance: fuel, combustion gas or working fluid.

INTRODUCTION

This paper discusses the use of an "ultimate" performance monitoring parameter derived from Second Law concepts. A summary of its underlying technology is available; refer to: Boyle, et al, 1990; Meyer, Silvestri & Martin, 1959; and Kotas, 1985. The predecessor to this work was first published in 1991 (Lang & Horn). Similar techniques have also been applied at power plants (Yasni & Carrington, 1987).

The Fuel Consumption Index developed indicates specifically what components or processes are thermodynamically responsible for fuel consumption in a thermal system. It can be used for thermodynamic system design, monitoring, diagnosing problems and economic dispatching. It tells us why fuel is being consumed. For example, it quantifies that a portion of fuel must be consumed to overcome frictional dissipation in the turbine, pressure drops in extraction lines, the combustion process, and how much fuel is required to produce electricity.

Examining the detailed enthalpy differences throughout a system, as opposed to simple summations of heat and power transfers across global boundaries, helps us understand system internals and ways of improvement. In this fashion, enthalpy is the "working variable" for First Law studies and deals with the quantity of energy. Certainly it is useful in this context. However, from a global perspective the First Law measurement of performance, thermal efficiency or heat rate, quantifies only the exchange of energy from boiler to environment ($1 - Q_{Rej}/Q_{in}$). In this context, **the First Law fundamentally relates to the utilization of energy flows**. Although $Q_{in} - Q_{Rej}$ is system power, one is never advised to assess heat rate changes by addressing changes in power production; but classically one addresses such changes through changes in Q_{in} and Q_{Rej} (Salisbury, 1950). Indeed, for many system design situations an increase in efficiency implies lower power (typically Q_{in} is reduced in greater proportion than Q_{Rej}).

The professional life of a thermal performance engineer is not devoted to the management of energy flows, nor to the conservation of fuel *per se*. Our *raison d'être* is the generation of adequate electricity for society using minimum fuel. This two-sided livelihood does not result nor imply the closing of power stations to conserve fuel. Further, the concept of unit heat rate, as the traditional tool of the performance engineer, does not address effective electric generation. For illustration, unit heat rate can be improved, most quickly, by doing those things which reduce power production. The increase of turbine extraction flows, the "creation" of steam consuming cogeneration processes, the use of auxiliary turbines for pump drives, the use of steam for space heating - all improve heat rate (by lowering Q_{Rej}), but say little of electrical generation. Further, as is well established, unit heat rate cannot be used for comparisons between different plant designs. One does not compare a nuclear cycle heat rate to a supercritical fossil-fired heat rate. Such comparisons are needed! For monitoring the major components of power plants (boiler, turbines, feedwater heaters, etc.) the North American industry historically has used differential heat rates - differences as a function of power level relative to some benchmark test, and generally based on vendor assumed sensitivities to efficiency. In practice, it is extremely rare to find a power plant monitoring system whose traditional differential heat rates sum to any reasonable unit heat rate.

In summary, unit heat rate (used for utilization of energy flow) is not intended for improving electrical production nor as an absolute measure. Further, the historical concept of differential heat rates, produced from "Controllable Parameters", can only be thought of as perverse if used to monitor and improve electrical production.

PRINCIPLES

All energy flows do not have the same potential for power production. Studies by Carnot and Gibbs have shown that any material not in equilibrium with its environment has available energy flow, thus the potential for power production. In general, the higher the pressure and temperature, the higher the available energy, or quality of energy, and thus more available power. The direct and immediate measure of this "quality" is exergy (also termed thermodynamic availability). Exergy is the Second Law's "working variable" and deals with the quality of energy. **The Second Law fundamentally relates to the utilization of potential power** associated with a given operating system. It is ideal for assessing the effective creation of electricity using minimum fuel.

While enthalpy relates to the transfer of energy flow within a component; exergy relates to the available energy flow of a fluid relative to its surroundings. As an example, the ability of a steam turbine to produce useful power is not dependent on its boiler's output of energy flow. The boiler could be supplying a great deal of energy to a huge flow of liquid water, and not produce a pound of steam. The ability of the turbine to produce power is dependent on the quality or available energy of the inlet steam provided by the boiler, as well as quantity.

The following paragraphs discuss the basic concepts needed for proper system evaluation. They are involved in their engineering execution. However, for fossil-fired units the analysis has been incorporated into a computer program, called EX-FOSS™, which allows the Second Law to be applied quickly and accurately (Lang, 2002). The thermodynamic concepts are equally applicable for nuclear power production, or any thermal system.

Exergy

Exergy is a measure of the available energy of a substance relative to its surroundings. It is a state function, thus the change in specific exergy from one point to another is path independent when considering a closed steady-state system. It is defined by the following:

$$g \equiv (h - h_{Ref}) - T_{Ref}(s - s_{Ref}) + (KE - KE_{Ref})/m + (PE - PE_{Ref})/m \tag{1}$$

EX-FOSS computes the exergy of all inlet and outlet "substances" involved with the total system (fuel, combustion gases and working fluid). Computation of exergies are relative to a reference environment, and since each substance may not be present in the reference environment a thermodynamic path must be provided. The path established internal to EX-FOSS has three steps:

1) The substance under consideration is first brought to the standard state: $P^o = 1$ bar (14.50382 psia) and $T^o = 298.15$ K (77 F).

2) The substance is then transformed chemically to a different, reference specie, which is found (by assumption) in equilibrium with the environment. This is accomplished using ideal chemical reactions at the standard state.

3) The reference specie is taken, via pressure and temperature changes, from the standard state to a reference condition P_{Ref}, T_{Ref}, h_{Ref} and s_{Ref}.

This procedure was chosen to make use of published values of the Heats of Formulation, ΔH^o_f, and the Gibbs Free Energies of Formulation, ΔG^o_f, at standard state conditions. It should be noted that the resultant exergies are independent of the chosen paths. Using this procedure Eq.(1) can be written as the following, for a given substance n:

$$g_n = \Delta g_{std,\,n} + g_{std,\,n} \tag{2}$$

In this equation, Δg_{std} is defined as the exergy change from the initial state to the standard state (step 1), and g_{std} is the exergy of the converted substance at standard state as transformed to the reference specie (steps 2 and 3). Once the environment and reference conditions have been defined, g_{std} is constant and needs to be calculated but once. For Reference species, n-Ref, g_{std} is defined as:

$$g_{std,\,n\text{-}Ref} = (h_{n\text{-}Ref,\,To,\,Po} - h_{n\text{-}Ref,\,T\text{-}Ref,\,P\text{-}Ref}) - T_{Ref}\,(s_{n\text{-}Ref,\,To,\,Po} - s_{n\text{-}Ref,\,T\text{-}Ref,\,P\text{-}Ref}) \tag{3}$$

For the original substance, n, g_{std} is then defined as:

$$g_{std,\,n} = \Sigma g_{std,\,n\text{-}Ref} - \Delta H^o_{c,\,n} + \frac{T_{Ref}}{T^o}[\Delta H^o_{c,\,n} + \Sigma\Delta G^o_{f,\,n}] \tag{4}$$

Eq.(2) is a general equation which calculates the absolute exergy of any substance; it can be shown to identical to Eq.(1) if used for a single species (given $\Delta KE = \Delta PE = 0$). EX-FOSS employs the aforementioned method, resulting in Eq.(4), for it allows calculation of multi-species exergies without resorting to tables of compiled reference conditions; conditions which often vary with every analysis (Kotas, 1985).

The exergy of fuels is calculated using the same method described above with the Gibbs Function of the combustion reaction estimated using a method developed by Ikumi, Lou and Wen (1982). This method is essential for analysis of coal fuels. These authors approach the problem sequentially: 1) estimate the entropy of fuel, 2) calculate the entropy change of the combustion reaction, 3) calculate the free energy of combustion reaction using the Heat of Combustion and the entropy of the reaction, 4) use the Gibbs Function of reaction in Eq.(4) to calculate the exergy of the fuel. Δg_{std} calculations for fuels are made using known, or estimated, specific heats.

"Reference conditions" are defined by the actual conditions existing at the plant and its local environment, and in turn so define the important thermodynamic **reference environment**. EX-FOSS defines this environment in an unique but practical manner, as the conditions which would exist if the actual environment was allowed to reach thermodynamic equilibrium with the thermal system (Gaggioli, 1990). This is established by performing mass and energy balances of the air and water entering the system (without fuel firing, $m_{AF} = 0.0$), and then assuming the resultant mixed thermodynamic state is that at which the air and cooling water are in equilibrium with the system's working fluid. In other words: leave the power plant "as-is", just turn-off the flow of fuel. Typical results from this analysis yield a reference temperature approximately equal to the inlet cooling water temperature, for plants using once-through cooling from river/lake/ocean water; or approximately equal to the air wet bulb temperature, for plants using cooling towers.

The maximum power (i.e., potential) which could be produced or consumed by the working fluid in any process is measured by its associated change in exergy flow. The net change is given by:

$$\Delta G \equiv \int m dg = \Sigma m g_{outlet} - \Sigma m g_{inlet} \tag{5}$$

Therefore, exergy audits permit performance engineers to quickly determine the degree (termed effectiveness) components are consuming or producing actual versus potential power. An important concept is that total exergy flows are destroyed when viewing an in- situ system interfaced with its environment. In other words, in the process of power production the exergy bound in the fuel must eventually be returned to the environment, manifested through system losses and electricity. However, since exergy is a thermodynamic property, within the confines of a closed, steady-state system, the summation of all exergy changes must be zero (e.g., working fluid in a turbine cycle). These subtleties are important: the rate of exergy destruction, and concomitant creation of either thermodynamic losses (i.e., irreversibilities) or shaft power, when viewed from a systems standpoint, allows qualitative assessment as to where in the system the fuel's exergy is dissipated.

<u>Irreversibility</u>

Irreversibility is the unrecoverable thermodynamic loss associated with any process, the "loss of potential power" from the system. Irreversibility is defined, for a process or system, by the following:

$$I = \int(1 - T_{Ref}/T)\,\partial Q - \int\partial W - \int m dg \tag{6}$$

Eq.(6) is a simple accounting of potential power losses from a process. The $\int(1 - T_{Ref}/T)\partial Q$ term is the Carnot conversion of energy flow to power, via the motive ∂Q heat transfer, a negative term if <u>from</u> the process. The Carnot conversion can be thought of as the equivalent of the exergy resultant from heat transferred from the process directly to the environment. For EX-FOSS heat exchangers use of the L_β term, of ASME PTC 4.1, invokes such transfer. The $\int\partial W$ and $\int m dg$ terms represent the difference between actual shaft power (produced or supplied), and the actual exergy change of the process (potential power supplied or produced to the fluid), thus a net lost of potential power. The sign of $\int\partial W$ is positive if power is produced. For example, if a turbine produces $+0.3980\times10^9$ Btu/hr shaft power, from a -0.5044×10^9 Btu/hr decrease in steam exergy, assuming no heat transfer, from Eq.(6) the irreversibility is $0.1064\times10^9 = 0.0 - 0.3980\times10^9 - (-0.5044\times10^9)$; the positive difference between actual and potential powers. The irreversibility listed in EX-FOSS output is a total system concept.

At the system level, irreversibility is the difference between the total exergy and actual power inputs, less actual power output. Professor Y.M. El-Sayed has suggested to the author an index based on a ratio of irreversibility to total fuel energy flow be considered. Progressing this idea, a "Fuel Consumption Index" was developed based on total exergy and actual power inputs to the system (such that unity summations would result).

FUEL CONSUMPTION INDEX

As stated, of the total exergy and power inputs to a system, only irreversibilities and power output will result. This can be expressed by Eq.(8), where the total exergy and power inputs to the system is defined by G_{in}.

$$G_{in} \equiv m_{AF}g_{Fuel} + m_{Air}g_{Air} + \Sigma G_{Misc} + \Sigma W_{Pump} + \Sigma W_{Fan} \qquad (7)$$
$$= \Sigma I_i + W_{output} \qquad (8)$$

Eq.(8) represents a clear statement of the Second Law applied to a power plant. From this concept the Fuel Consumption Index is developed by simply dividing through by G_{in} for individual components or processes and the power production. Note, as developed below, separate accounting of power terms, inputs versus production (W_{output}), is important when implementing these concepts for real-time monitoring.

Fuel Consumption Index is a unitless measure of fuel consumed as assigned thermodynamically to those individual components or processes responsible for fuel consumption, given a system's production of power. It quantifies the exergy and power consumption of all components and processes relative to the total exergy and power supplied to the system, by far the predominate term being the fuel's exergy, $m_{AF}g_{Fuel}$. Based on Eq.(8), FCI is defined for non-power components and process (e.g., combustion and mixing) as:

$$FCI_i \equiv 1000 \frac{I_i}{G_{in}} \qquad (9)$$

and for the power production process as:

$$FCI_{Power} \equiv 1000 \frac{W_{output}}{G_{in}} \qquad (10)$$

As used in Eqs.(9) & (10) the terms G_{in}, irreversibility and power all employ units of Btu/hr, thus FCI is unitless. Arbitrarily, the index is multiplied by 1000, thus $\Sigma FCI_j = 1000$ (where j represents all components and processes). Note, by definition, the environment as a "process" can not produce a net $\int(1 - T_{Ref}/T)\partial Q$ nor $\int \partial W$ power, thus $FCI_{Envir} \equiv 0$; more fully discussed below. Some typical values of the FCI include: 402 for direct electrical production (gross power available at the generator terminals), 271 for a fossil combustion process, 202 for boiler heat exchangers, 40 for the main turbines, 29 for the condenser, etc. These imply that 40.2% of the supply exergy is converted to electricity, 27.1% is destroyed via combustion losses, 20.2% is destroyed via boiler heat exchanger losses, etc. Again, one important characteristic of the FCI is that it must sum to 1000, therefore a decrease in the FCI of one component means an increase in the FCI of another component. Thus systems can be compared, universally, relative to their fuel's potential to make power.

For example, if the FCI of direct electrical production decreases from 402 to 395, assuming constant power production, ∂W, and the FCI of the boiler heat exchangers increases from 202 to 209, with no other changes, one can state that more fuel (higher G_{in}) is being used to produce the same power, this being caused by higher losses in the boiler heat exchangers (more of the fuel's exergy is being destroyed in the heat exchangers).

Specific Fuel Usage

Specific Fuel Usage, having units of Δlbm_{Fuel}/kWh, is a measure of the fuel consumed as assigned individual components per kilowatt of electricity produced. It is generically determined from:

$$SFU_j = 3412.1416\ FCI_j\ m_{AF} / (1000\ W_{output}) \qquad (11)$$

Specific Fuel Usage (termed SFU) can be thought of as the additional fuel required to produce a kilowatt of electricity due to the non-ideal transfer of available energy. More simply, SFU_j is the additional fuel consumed by the system due to irreversible losses or power production in a particular component or process. Of course, summation of SFU_j yields the total fuel flow per kilowatt: $3412.1416\ m_{AF}/W_{output}$.

Differential Heat Rates

Differential heat rate, as defined for this work, is determined for individual components and processes consistent with both First and Second Law concepts. It need not be a perverse topic. Differential heat rates, termed hr_j in units of ΔBtu/kWh, are defined from SFU_j. For all i th irreversible components and processes, hr_i follows directly from Eq.(11):

$$hr_j = SFU_j\ (HHVP + HBC) \qquad (12)$$
$$hr_i = 3412.1416\ FCI_i\ m_{AF}(HHVP + HBC)/(1000 W_{output}) \qquad (13)$$

Use of HHVP and HBC terms, versus HHV, is required to maintain the strict definitions of fuel energy flows used throughout Input/Loss Methods, including boiler efficiency computations (see Lang, 2000). Differential heat rates for the power term and a so-called "environmental" term are developed through a similar relationship, substituting Eq.(10) into (14):

$$hr_{Power} + hr_{Envir} = 3412.1416 FCI_{Power}\ m_{AF}\ (HHVP + HBC)/(1000 W_{output}) \qquad (14)$$
$$= 3412.1416\ m_{AF}\ (HHVP + HBC) / G_{in} \qquad (15)$$

$$hr_{Power} \equiv 3412.1416 \qquad (16)$$
$$hr_{Envir} \equiv 3412.1416\ [\ m_{AF}\ (HHVP + HBC)\ -\ G_{in}\ ] / G_{in} \qquad (17)$$

In Eq.(16) the hr_{Power} term is defined by the Btu/kWh conversion factor. This is done for two reasons. First, the conversion factor is indicating that 3412.1416 ΔBtu/hr of exergy consumed (the potential for power) by the process of direct generation, is indeed 1.0 kW of electricity. Second, by so defining hr_{Power}, a mechanism is then provided to the operator, through hr_{Envir} via Eq.(17), which emphasizes the thermodynamic impact the environment plays on the system's supply streams; i.e., the input of exergy flow G_{in} , versus the input of fuel energy flow, m_{AF} (HHVP + HBC).

By defining hr_j terms in Eqs.(13), (16) & (17), the summation of hr_j for all components and processes is the First Law-based definition of unit heat rate, termed *HR*. This is more than a mathematical convenience; $\sum hr_j$ involves inherent consideration of all thermodynamic losses, the power production process and the environmental term, i.e., the entire system. This feature of $\sum hr_j$ is critical if the operator is to receive consistent information.

$$HR \equiv \sum hr_j \tag{18}$$
$$= \sum hr_i + hr_{Power} + hr_{Envir} \tag{19}$$
$$= 3412.1416 \ m_{AF} (HHVP + HBC) / W_{output} \tag{20}$$

System heat rate may also be developed directly from the computed FCI_{Power} term by substituting Eq.(10) for W_{output} and then Eq.(17) for G_{in} into Eq.(20); an important relationship for sensitivity studies. In the resulting Eq.(21), note that hr_{Envir} is typically numerically small, and for the common sensitivity study can be considered constant.

$$HR = (1000 / FCI_{Power}) (3412.1416 + hr_{Envir}) \tag{21}$$

Again, a higher FCI_{Power} implies a lower unit heat rate. It is noteworthy that with these concepts, the operator need not rely on vendor predictions nor the Controllable Parameters method to evaluate a particular component's effects on system heat rate. It allows the operator breakdown of heat rate, component by component, thus allows the monitoring of degraded equipment and the search for improved operation. The Second Law guarantees consistent hr_j values.

To reiterate, classical unit heat rate, employing an Input-Output approach does nothing for the thermodynamic understanding of individual components or processes. **Second Law appraisal of heat rate, through FCI, is based on a rational evaluation of a system's response to fuel consumption. The FCI concept considers the entire system: losses through individual components and processes, and resulting electrical production. The Second Law's FCI approach allows improved unit heat rate through maximization of electrical production - not the trivial minimization of heat rejection.**

Comments on Unit and Turbine Cycle Heat Rates

Using the Fuel Consumption Index requires no redefinition of unit heat rate, but clearly a rethinking in terms of differential heat rates. As discussed, the summation of differential heat rates, $\sum hr_j$, determined through FCIs, indeed results in the classical definition.

The following sections discuss the interpretation of FCIs associated with a boiler/turbine cycle system. As will be seen, there are computed FCIs associated with miscellaneous turbine cycle components, electrical power production, and the boiler's heat exchangers. Although one would think the industry's definition of turbine cycle heat rate would intertwine with the FCI concept, the summation of these terms **do not** result in turbine cycle heat rate. It is common practice to speak of differential heat rates associated with turbine cycle components as computed by PEPSE, THERM, EX-SITE or other such simulation programs. These differential heat rates describe effects of changes in boundary conditions, individual component performances, etc. For example, if hot reheat temperature is degraded by 10 ΔF, the computed turbine cycle heat rate is said to be effected by ≈10 ΔBtu/kWh; the unit heat rate is said to be effected by $\approx 10/\eta_{Boiler}$ ΔBtu/kWh (typically assuming the boiler's efficiency is constant). Such studies give no consideration of **why** the reheater's temperature is degraded; and without the **why**, the result is coarse. The degradation could be caused by any one or more of the following: degraded heat transfer on the gas side; increases in environmental losses (boiler casing); lower ambient temperatures; lower fuel heating value; lower fuel flow; improved flue gas heat transfer upstream of the reheater; changes in gas flows via baffling in the convective gas path (if used); and/or degraded heat transfer on the working fluid side of the reheater. It is possible that many of these operational conditions might not impact combustion efficiency, or the ratio of useful energy supplied to fuel flow might be constant - thus the assumption of $\approx 10/\eta_{Boiler}$ for Δheat rate, in the conventional sense, might be valid! However, the point is that all of these situations affect system losses and thus fuel usage for a given power production. The tracking of losses, through FCIs, adds needed sensitivity and addresses the problem directly.

If the system is operating in a boiler-follow-turbine scenario, the boiler will intrinsically adjust to changes in generation demands, fuel quality, the environment, sooted heat transfer and/or degraded machinery. Differential heat rates can not be assessed in isolation; however this is indeed the modality for most on-line monitoring systems. Such common on-line calculations typically examine Controllable Parameters. For the turbine cycle, Controllable Parameters typically include throttle pressure, throttle temperature, reheat temperature and condenser pressure. For the boiler, Controllable Parameters include stack temperature and excess air. From a thermodynamicist's viewpoint turbine cycle differential heat rates or boiler Δefficiencies computed for these parameters, in isolation, have no value. An FCI_j can not be assigned to a Controllable Parameter; not to the hot reheat temperature for example, but to the reheater as it interacts with combustion gases, with the working fluid, delivering energy flow to turbines.

INTERPRETATION OF RESULTS

This is a tedious section, but necessary for thermodynamic teaching when FCIs are applied at a power plant ... either read this section, or simply watch FCIs, and especially Dynamic FCIs, respond to operator actions!

However, if using ΔFCI_j, Δhr_j and ΔHR values, differences relative to bogeys (targeted values), this section does present a parameter which can be used to judge the applicability of Reference Bogey Data. This parameter is termed $(1 + \Psi_j)$. It is important as a sanity check to assure that ΔFCI_j, Δhr_j and ΔHR values are valid for a given situation being monitored (i.e., the interaction of combustion gases with working fluid and plant configuration).

Appendix A presents detailed calculational procedures for applying ΔFCI_j, Δhr_j and ΔHR quantities at a power plant. Appendix B offers brief comments on applying FCI_j, hr_j and HR quantities.

Summary of EX-FOSS Outputs

Table 1 is a Second Law output page produced by EX-FOSS for a 680 MWe system firing 12,400 Btu/lbm coal. The indicated modeling in Table 1 is not particularly unique, it includes the following components: ID Fan, FD Fan, Steam-Air heat exchanger (STM-AIR), Air Pre-Heater, Economizer, Primary Superheater, Reheater, Reheat sprays, Final Superheater, Secondary Superheater, superheater sprays and a "Boiler" representing water walls. This unit has a split convective gas path, thus the non-zero mixing loss. The relative gas flow split is generally input based on reasonable downstream temperature ratios.

The form of the computer output is independent of modeling (given a current limit of 12 regions). Within the output, note that "Exergy In Fuel" is the exergy of the fuel immediately before combustion, "Exergy In Air" is the exergy of the combustion air (not necessarily the total air into the system), and "Total Exergy Out" is the exergy out of the combustion process (the exergy of the flue gases at the actual flame temperature, before interfacing with the first heat exchanger). The "Stack Loss" term is listed near the bottom and is simply the exergy of the flue gases (stack side, without air pre-heater leakage) exiting the system; air leakage is accounted in the air pre-heater component. FCI_{Power}, termed "Elec. Power" in the output, is based solely on the actual gross power produced at the generator terminals. The "Misc. TG Cycle" term describes all miscellaneous losses within the turbine cycle proper, excluding gas/water heat exchangers and the actual gross electrical production. "Misc. TG Cycle" typically includes: turbine shaft losses, throttle value losses, frictional dissipation in feedwater heaters, condenser losses, etc. The heat rate term for "Misc. TG Cycle" must not be confused with a vendor's turbine cycle heat rate. The "Sys. Totals" terms include summations of the various columns, except for effectiveness which is gross power divided by G_{in}.

Much can be written, and studied, concerning the Second Law balance presented by EX-FOSS (Table 1). However, the following points summarize the highlights and a few calculational over-checks which are possible:

- The total exergy and shaft power input to the system, termed G_{in}, is defined by Eq.(7). The fuel's exergy is listed under "Exergy in Fuel". The air's exergy is listed either as the input to the first air component, or (if no air component is modeled) is listed under the "Exergy in Air" (reflecting ambient conditions). The pumping power is listed by an asterisk (*), next to the "Elec. Power" row. The air's FD fan power is listed by an asterisk, next to the fan component. The ΣG_{Misc} term accounts for miscellaneous exergy flows into the system, for example exergy supplied to a steam air heater.

- Although FCI_{Power} is evaluated using Eq.(10), the differential heat rate for direct electrical production, hr_{Power} listed as "Elec. Power", is constant as discussed.

- The differential heat rate which can be charged directly to the environment, hr_{Envir}, is defined by Eq.(17). Note that any irreversibility term associated with the environment is, by definition, zero, thus $FCI_{Envir} \equiv 0$. From Eq.(17), if G_{in} exceeds the energy flow of the fuel, hr_{Envir} will be negative. hr_{Envir} relates to the exergy associated with fuel and combustion air, and with bring unique combustion products to equilibrium in the environment. The example of Table 1 indicates a hr_{Envir} which is 1.4% of unit heat rate, which is typical (if not high). The $[m_{AF}(HHVP + HBC) - G_{in}]$ term of Eq.(17) relates to the absolute contribution the environment plays on the system via firing fuel. Of interest to a thermodynamicist is that: if pure graphite is burned with theoretical O_2 at 77F (no excess air, and $g_{Air} = 0$); and $\Sigma G_{Misc} = \Sigma W_{Pump} = \Sigma W_{Fan} = HBC = 0$; and a "thought" environment consists only of CO_2 at 77F... then g_{Fuel} = HHVP and hr_{Envir} would be identically zero. Using hr_{Envir} the engineer can assess the direct impact a fuel and its firing correction has on the environment.

- The total unit heat rate, *HR*, determined from Second Law principles, will always equal the classical definition: energy flow supplied by power production, or, $m_{AF}(HHVP + HBC)/W_{output}$.

- Boiler effectiveness (listed next to the "+" symbol in the "Stack Loss" row) times turbine cycle effectiveness (listed in the "Elec. Power" row) will equal total system effectiveness. FCI_{Power} divided by 10, should always equal the plant's effectiveness in per cent.

- The combustion's irreversibility is the summation of "Exergy in Fuel", "Exergy in Air" and "Total Exergy Out".

- The "Mixing Loss" is the summation of irreversible losses associated with mixing gases and/or the irreversible loss of recirculating gas through the combustor.

Summary of ΔFCIs and ΔHeat Rates

This section discusses details associated with defining and interpreting ΔFCI_j and Δhr_j values. In these formulations "A" is used to indicate the actual (monitored) condition, "B" is used for the bogey (targeted) condition. $[FCI_i]_B$ and $[FCI_{Power}]_B$ values, with the $[m_{AF}(HHVP + HBC)]_B$ term, are based on linear interpolation of Reference Bogey Data; such interpolation is denoted by braces {...}. Note well, all ΔFCI_j and Δhr_j values are interpreted at the same (and actual) power, W_{output}.

$$[FCI_i]_A = 1000\ I_{i\text{-}A}/G_{in\text{-}A} \quad \textit{versus} \quad [FCI_i]_B = \{1000\ I_{i\text{-}B}/G_{in\text{-}B}\} \tag{22A\&B}$$

$$[FCI_{Power}]_A = 1000\ W_{output}/G_{in\text{-}A} \quad \textit{versus} \quad [FCI_{Power}]_B = \{1000\ W_{output}/G_{in\text{-}B}\} \tag{22C\&D}$$

$$[FCI_{Envir}]_A \equiv [FCI_{Envir}]_B \equiv 0 \tag{22E\&F}$$

$$[\Delta hr_i]_A = 3.4121416\ [FCI_i]_A\ [m_{AF}(HHVP{+}HBC)]_A/W_{output} \quad \textit{versus} \quad [\Delta hr_i]_B = \{3.4121416\ [FCI_i]_B\ [m_{AF}(HHVP{+}HBC)]_B/W_{output}\} \tag{23A\&B}$$

$$[hr_{Power}]_A \equiv [hr_{Power}]_B \equiv 3412.1416 \text{ Btu/kWh} \tag{23C\&D}$$

$$[\Delta hr_{Envir}]_A = 3412.1416\{[m_{AF}(HHVP{+}HBC)]_A - G_{in\text{-}A}\}/G_{in\text{-}A} \quad \textit{versus} \quad [\Delta hr_{Envir}]_B = \{3412.1416\{[m_{AF}(HHVP{+}HBC)]_B - G_{in\text{-}B}\}/G_{in\text{-}B}\} \tag{23E\&F}$$

$$HR_A \equiv [\Sigma hr_j]_A;\ @\ W_{output} \quad \textit{versus} \quad HR_B \equiv [\Sigma hr_j]_B;\ @\ W_{output} \tag{24A\&B}$$

From these relationships the following differences are developed. Note that the subscript j denotes all non-power, power and environmental terms.

$$\Delta FCI_j = [FCI_j]_B - [FCI_j]_A;\ @\ W_{output}; \tag{25}$$
intended for on-line monitoring by plant operators, target less actual for each component and process.

$$\Sigma\Delta FCI_j = 0; \tag{26}$$
used as a computational over-check.

$$\Delta hr_j = [hr_j]_A - [hr_j]_B;\ @\ W_{output}; \tag{27}$$
for on-line monitoring by plant operators, actual less target for each component and process.

$\Delta HR \equiv HR_A - HR_B$; @ W_{output}; the classical definition definition of the difference in unit heat rate, actual less target for the total system. (28A)

$$\Delta HR = \Sigma \Delta hr_j \tag{28B}$$

Note that the sign conventions used for Δhr_j and ΔHR were chosen such that an improved unit heat rate ($\Delta HR < 0$), follows the same sign of ΔFCI_{Power} and $[\Sigma I_{i\text{-}A} - \Sigma I_{i\text{-}B}]$ given reduced losses.

When ΔFCI_{Power} is negative, it follows from Eqs.(25) and (22C&D) that $G_{in\text{-}B} > G_{in\text{-}A}$, therefore the system is producing the same power with a lower $G_{in\text{-}A}$ actually consumed (i.e., lower fuel energy flow). System losses, $\Sigma I_{i\text{-}A}$, must therefore be less than the bogey, as is obvious by rewriting Eq.(8):

$$W_{output} = G_{in\text{-}B} - \Sigma I_{i\text{-}B} = G_{in\text{-}A} - \Sigma I_{i\text{-}A} \tag{29}$$

where, if $G_{in\text{-}B} > G_{in\text{-}A}$ given a constant W_{output}: $\Sigma I_{i\text{-}A} < \Sigma I_{i\text{-}B}$. Thus when ΔFCI_{Power} is negative, $[\Sigma I_{i\text{-}A} - \Sigma I_{i\text{-}B}]$ is always negative (i.e., lower losses, actual less target). Although mathematically obvious, the concept that exergy & power supplied and a system's irreversible losses, must both be lower than the bogey's (given a negative ΔFCI_{Power}), has significant importance when monitoring power plants. When ΔFCI_{Power} is negative the system's performance is always improved relative to the bogey. No operational actions are necessary, other than perhaps to drive ΔFCI_{Power} further negative.

When ΔFCI_{Power} is positive, more fuel is being consumed to overcome higher irreversible losses. In addition to Eq.(29), this can be seen most easily by substituting Eq.(8) into Eqs.(22C&D) for G_{in}, and then into Eq.(25):

$$\Delta FCI_{Power} = \frac{1000\, W_{output}}{\Sigma I_{i\text{-}B} + W_{output}} - \frac{1000\, W_{output}}{\Sigma I_{i\text{-}A} + W_{output}} \tag{30}$$

Thus when ΔFCI_{Power} is positive, $[\Sigma I_{i\text{-}A} - \Sigma I_{i\text{-}B}]$ is positive (i.e., higher losses); a situation always requiring corrective action. Remedial action can be addressed by studying the highest negative non-power terms, ΔFCI_i, and thus investigating why degradations are present. Of course at least one negative non-power term will always offset the positive ΔFCI_{Power}, given $\Sigma \Delta FCI_j = 0$.

When a $\Delta FCI_{non\text{-}Power}$ term is negative for a specific ith component or process, higher losses per exergy supply ($I_{i\text{-}A}/G_{in\text{-}A}$) is present relative to the bogey standard, see Eqs.(22A&B) & (25). Such a higher ratio implies a degraded condition in which corrective action is required. Corrective action should be taken without reservation if ΔFCI_{Power} is positive; i.e., one or more negative ΔFCI_i (bad) are opposing a positive ΔFCI_{Power} (bad). However, if ΔFCI_{Power} is minor, and the ΔFCI_i being examined is just off-setting another positive ΔFCI, then corrective action should be taken with a system's view. Clear understanding of system effects can be found by examining in detail the ith component or process, through differences in corresponding differential heat rates (Δhr_j), and through the $(1 + \Psi_i)$ parameter described below.

When a $\Delta FCI_{non\text{-}Power}$ term is positive for a specific ith component or process, lower losses per exergy supply ($I_{i\text{-}A}/G_{in\text{-}A}$) are present compared to the bogey. In general no corrective action should be taken. A positive ΔFCI_i (good) will always off-set either one or more negative ΔFCI_i (bad) and/or a negative ΔFCI_{Power} (good).

Applicability Parameter

These paragraphs discuss the applicability parameter, $(1 + \Psi)$, used to justify the use of a set of Reference Bogey Data for a given monitoring situation. This parameter applies only to ΔFCI_j, Δhr_j and ΔHR calculations.

Component heat rate differences, Δhr_i, will vary (with the same sign) as $[I_{i\text{-}A} - I_{i\text{-}B}]$, provided the Reference Bogey Data is "applicable" to the situation being monitored. To test for the applicability of the Reference Bogey Data, the following develops a relationship between Δhr_i and ΔI_i. Substituting Eqs.(22A&B) into Eqs.(23A&B) for FCI_i and then into Eq.(27):

$$\Delta hr_i = (3412.1416/W_{output}) \{ I_{i\text{-}A}\, [m_{AF}(HHVP + HBC)]_A/G_{in\text{-}A} - I_{i\text{-}B}\, [m_{AF}(HHVP + HBC)]_B/G_{in\text{-}B} \} \tag{31}$$

In simplifying Eq.(31), Eq.(17) for hr_{Envir} is rewritten for the actual and bogey values:

$$[m_{AF}(HHVP + HBC)]_A/G_{in\text{-}A} = 1 + hr_{Envir\text{-}A}/3412.1416 \tag{32A}$$
$$[m_{AF}(HHVP + HBC)]_B/G_{in\text{-}B} = 1 + hr_{Envir\text{-}B}/3412.1416 \tag{32B}$$

By substituting Eqs.(32A&B) into Eq.(31), and use of Eqs.(22A-D), an expression can be developed for Δhr_i dependent only on FCI, hr_{Envir}, power and irreversibility terms:

$$\Delta hr_i = \frac{3412.1416}{W_{output}} [I_{i\text{-}A} - I_{i\text{-}B}] (1 + \Psi_i) \tag{33}$$

where Ψ_i is developed as follows, in terms amenable for on-line monitoring since all terms would have been computed. The term ε is a small value to prevent division by zero given $FCI_i = 0.0$.

$$\Psi_i \equiv \frac{(hr_{Envir\text{-}A} FCI_{Power\text{-}B} FCI_{i\text{-}A} - hr_{Envir\text{-}B} FCI_{Power\text{-}A} FCI_{i\text{-}B})}{3412.1416\,(FCI_{Power\text{-}B} FCI_{i\text{-}A} - FCI_{Power\text{-}A} FCI_{i\text{-}B}) + \varepsilon} \tag{34}$$

It is obvious from Eq.(33) that as long as $(1 + \Psi_i)$ is positive, the sign of ΔI_i will determine the sign of Δhr_i. Thus, for a given ith component or process, lower losses will always imply lower differential heat rate for the actual.

By definition the Δhr_{Power} term is zero. The Δhr_{Envir} term can be evaluated simply as ($hr_{Envir\text{-}A} - hr_{Envir\text{-}B}$), and could bear either sign. However, since $[FCI_{Envir}]_A \equiv [FCI_{Envir}]_B \equiv 0.0$, Δhr_{Envir} "applicability" has no meaning, other than to indicate relative differences between fuel energy flows and $G_{in\text{-}A}$ & $G_{in\text{-}B}$. Thus the terms Ψ_{Envir} and Ψ_{Power} are procedural and assumed zero.

Thus given $(1 + \Psi_i) > 0$, the Reference Bogey Data is said to be applicable to the monitored situation for an individual component or process. An additional "reasonableness" criteria would have: hr_{Envir} < 2% of their respective unit heat rates.

Unit heat rate deviation, ΔHR, will vary (with the same sign) as $[\Sigma I_{i\text{-}A} - \Sigma I_{i\text{-}B}]$, and thus as ΔFCI_{Power}, provided the Reference Bogey Data is applicable to the situation being monitored. Lower irreversible losses, $\Sigma I_{i\text{-}A} < \Sigma I_{i\text{-}B}$, imply improved (lower) unit heat rate. When considering the same electrical generation for the actual and bogey, then differences in unit heat rate relative to a bogey will be entirely due to non-power effects in the system (i.e., ΔI, G_{in} and Δhr_{Envir}). A decrease in system irreversible losses, $\Sigma I_{i\text{-}A}$, must imply a decrease in $G_{in\text{-}A}$; which *approximately* implies a decrease in fuel energy flow, $\Delta[m_{AF}(HHVP + HBC)]_A$ for a constant W_{output}, thus $\Delta HR < 0$ (good). On the other hand, if $\Delta FCI_{Power} \approx 0$ for the same W_{output}, then from Eq.(30) $\Sigma I_{i\text{-}A} \approx \Sigma I_{i\text{-}B}$ and the actual and bogey unit heat rates will be *approximately* the same, $\Delta HR \approx 0$. *Approximately* has been used with emphasis because of the subtleties of the hr_{Envir} term as appears in Eqs.(34) & (36). In a similar manner as developed above, unit heat rate deviation can be expressed by the following:

$$\Delta HR = \frac{3412.1416}{W_{output}} (\Sigma I_{i\text{-}A} - \Sigma I_{i\text{-}B}) (1 + \Psi_{System}) \qquad (35)$$

where Ψ_{System} is developed as follows:

$$\Psi_{System} \equiv \frac{(hr_{Envir\text{-}A} FCI_{Power\text{-}B} - hr_{Envir\text{-}B} FCI_{Power\text{-}A})}{3412.1416\,(FCI_{Power\text{-}B} - FCI_{Power\text{-}A}) + \varepsilon} \qquad (36)$$

Again, as long as $(1 + \Psi_{System})$ is positive, and the hr_{Envir} terms are less than 2% of their respective unit heat rates, the Reference Bogey Data is said to be applicable to the monitored situation for the total system (unit). Note, whereas individual components or processes could legitimately indicate a negative $(1 + \Psi_i)$ given wildly varying operations; system affects must always indicate a positive $(1 + \Psi_{System})$ for valid relevance.

If $(1 + \Psi_{System})$ is negative, or the Δhr_{Envir} term is significant, one must question the applicability of the Reference Bogey Data. Most likely, the cause was preparing Input-Output tests which were atypical: perhaps using fuel having greatly different heating values than that being monitored, or system configurations or operations not used during monitoring. Given such situations, although the methods will continue to produce consistent results using FCI_j, hr_j and HR values, the relevance to bogey data (ΔFCI_j, Δhr_j and ΔHR) can not be supported. Corrective actions could involve re-testing to establish more relevant Reference Bogey Data, or double interpolation of Reference Bogey Data sets (e.g., $[FCI_j]_B$ and $[m_{AF}(HHVP+HBC)]_B$) versus load and fuel heating value.

At the component level the power plant operator is afforded ΔFCI_i and Δhr_i terms with relevance over-checks. At the system level, as a minimum, the operator has direct indication that recommended actions based on ΔFCI_{Power} and ΔHR are indeed valid and relevant to the Reference Bogey Data.

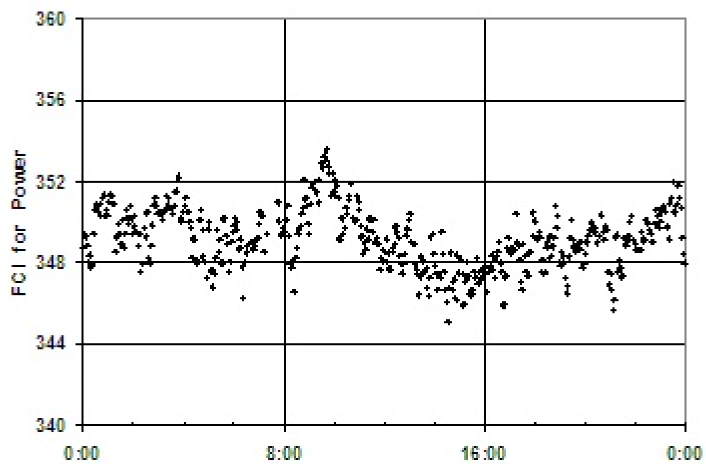
DYNAMIC HEAT RATE

Even through reliable system heat rate and consistent differential heat rates are obtainable by applying FCI techniques, experience has shown that with some coal-fired units, especially those firing blends of coals and which load follow, that data scatter can mask clear interpretation of results. This has lead to confusion as to the actions operators are taking in the short term - are such actions improving or degrading heat rate? However, through proper integration and presentation techniques, lucid time sensitive heat rates may be developed. This is achieved through Dynamic FCIs and Dynamic Heat Rates.

Dynamic Heat Rate is defined as a time weighted unit heat rate based on appropriate quadrature of monitored values. It is presented to the operator in a selectively integrated manner when its slope, $\partial HR/\partial t$, indicates an improved heat rate. Although the numerical magnitude of Dynamic Heat Rate is arbitrary, the rules applied for selective integration are chosen such that Dynamic Heat Rate is linearly related to actual improvements. The method presented employs FCI_{Power} values to develop Dynamic Heat Rates, but the general technique can apply to any HR determination.

Typical data scatter can be observed in Figure 1 showing 24 hours of data obtained once every 3 minutes. This data was obtained from a 585 MWe plant burning several, and highly variable, Powder River Basin coals. Although general trends are evident in Figure 1, minute-by-minute decisions based on "micro-trends" is impossible to ascertain. Large coal-fired units have natural system periodicities typically from 15 to 90 minutes. Although 15 minutes is typical of working fluid transient time through the system, pulverizer oscillatory reaction to variable coals tends to dominate both the combustion's and the working fluid's hydraulic responses. Periodicity, if present, must be determined unique to the system being monitored.

Figure 1: Typical FCI Data Scatter for Coal-Firing



First, to develop smoothed information, FCI_{Power} values are time weighted, denoted as $\widetilde{\widetilde{FCI}}_{Power}$.

$$\widetilde{\widetilde{FCI}}_{Power,\,k} = \textstyle\sum_{k=\,n,\,n-1,n-2,\,\ldots\,n+1-M/2} \xi_k \; FCI_{Power,\,k} \qquad (37)$$

Time weighted heat rate may be developed directly using Eq.(37), or otherwise determined via Eq.(38B). The weighting function ξ_k is defined by Eq.(39).

$$\widetilde{\widetilde{HR}}_k = (3.4121416\text{x}10^6 + 1000\, hr_{Envir}) / \widetilde{\widetilde{FCI}}_{Power,\,k} \qquad (38A)$$

$$\widetilde{\widetilde{HR}}_k = \textstyle\sum_{k=\,n,\,n-1,n-2,\,\ldots\,n+1-M/2} \xi_k \, HR_k \qquad (38B)$$

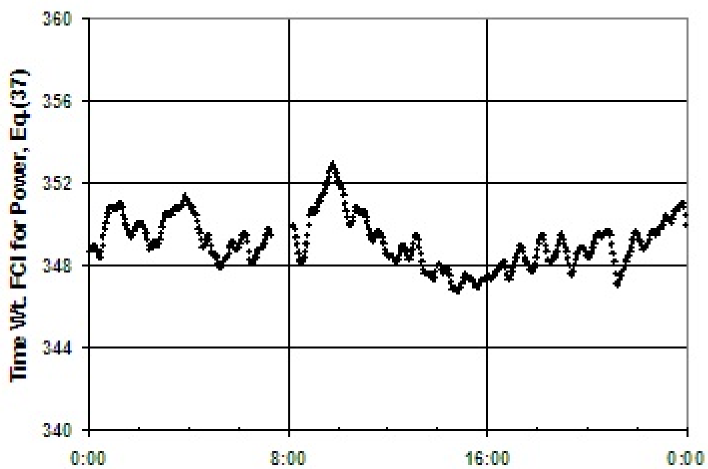
The variable ξ_k, used in Eqs.(37) and (38B), is important as it defines a time weighting function:

$$\xi_k = cos\,[\pi(n-k)/M] \,/ \textstyle\sum cos\,[\pi(n-k)/M] \qquad (39)$$

In these relationships: k is the evaluated time steps; n, is the current time step number, the most recently monitored evaluation; and M is the periodicity of the system in time steps. As presented, the time step size is uniform (data reported every 3 minutes), it need not be uniform. For example: if M = 5 (for a 15 minute periodicity at 3 min/report), and n=238, then: k = 238, 237, 236, 235, 234; yielding: ξ_k = 0.27346, 0.26007, 0.22123, 0.16074, 0.08450. The weighting function may take numerous forms; however, Eq.(39), biasing several of the most current data points, is preferred. Results of applying Eq.(37) on the data of Figure 1 is observed in Figure 2. The periodicity was determined from Figure 2 itself, making adjustments after applying Eq.(37). As the data of Figure 1 was recorded every 3 minutes, given the periodicity being observed at 48 minutes (evident during the last 8 hours), M was determined at 16.

Information present in Figure 2 may itself be useful to system operators. However, as a second step, $\widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},k}$ values are then selectively integrated when its slope is positive; the result $\int \partial\widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power}}$ being termed Dynamic FCI for power (analogous to Dynamic Heat Rate). $\widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},k}$ can be converted to system heat rate using Eq.(38A), selectively integrated producing Dynamic Heat Rate, termed $\int \partial HR_{\mathrm{D}}$.

Figure 2: Application of Time Weighting to FCI Data

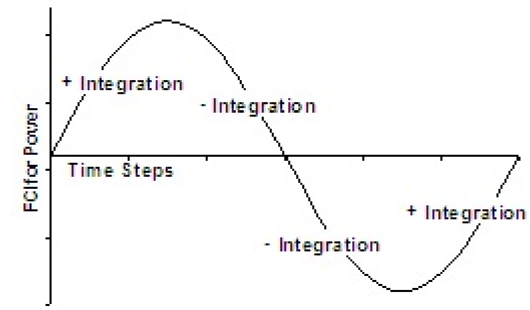


As clearly observed in the last 8 hours of Figure 2, and , of course, present in Figure1, the system has an oscillatory behavior, common in coal-fired systems. These are addressed by developing $\int \partial\widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power}}$ and $\int \partial HR_{\mathrm{D}}$ terms based on parallel integrations, bearing in mind the natural periodicity of the system. Eqs.(40) and (41) define $\int \partial\widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power}}$ and $\int \partial HR_{\mathrm{D}}$.

Given an oscillatory behavior, the integration considers off-setting quadrants (where N = M/4), the first quadrant adding to heat rate improvement given a slope indicating an improved heat rate, the second detracting given a degrading heat rate, the third detracting, and the fourth adding.

The rules for selective integration include: 1) that an improved heat rate is observed at the current evaluation (n versus n-1); 2) that the first quadrant's integration is greater than the fourth, thus an improved heat rate over one cycle; and 3) that the total cycle evaluation is an improvement. Use of Eq.(41) on the data of Figure 2, employing Eq.(38A) for converting to $\widetilde{\widetilde{HR}}_k$, results in Figure 3.

The quantities S_F and S_H are arbitrary, constant scaling factors, established by convenience for presentation. For Eq.(40), S_F = 0.3333 is recommended; for Eq.(41), and as used in Fig.3, S_H = 1.00 is recommended. In Eqs.(40) and (41), for example, the symbol $\sum_{k1}$ represents the corresponding summation on k1, the second line of Eq.(41): $\sum_{k1= m,\, m-1, m-2,\, \ldots\, m-N+1} (\widetilde{\widetilde{HR}}_{k1-1} - \widetilde{\widetilde{HR}}_{k1})$.



$$
\begin{aligned}
\int \partial\widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power}} = 0.5\, S_F \textstyle\sum_{m= n,\, n-1, n-2, \ldots}
& \Big[\textstyle\sum_{k1= m,\, m-1, m-2,\, \ldots\, m-N+1} (\widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},\, k1} - \widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},\, k1-1}) \\
& - \textstyle\sum_{k2= m-N,\, m-N-1,\, \ldots\, m-2N+1} (\widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},\, k2} - \widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},\, k2-1}) \\
& - \textstyle\sum_{k3= m-2N,\, m-2N-1,\, \ldots\, m-3N+1} (\widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},\, k3} - \widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},\, k3-1}) \\
& + \textstyle\sum_{k4= m-3N,\, m-3N-1,\, \ldots\, m-4N+1} (\widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},\, k4} - \widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},\, k4-1}) \Big];
\end{aligned}
$$

conditions for summing on m:

$$
\begin{aligned}
&1)\ \widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},k1} > \widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},k1-1} \\
&2)\ \textstyle\sum_{k1} > \sum_{k4} \\
&3)\ \textstyle\sum_{k1} - \sum_{k2} - \sum_{k3} + \sum_{k4} > 0 \qquad (40)
\end{aligned}
$$

$$
\begin{aligned}
\int \partial HR_{\mathrm{D}} = 0.5\, S_H \textstyle\sum_{m= n,\, n-1, n-2, \ldots}
& \Big[\textstyle\sum_{k1= m,\, m-1, m-2,\, \ldots\, m-N+1} (\widetilde{\widetilde{HR}}_{k1-1} - \widetilde{\widetilde{HR}}_{k1}) \\
& - \textstyle\sum_{k2= m-N,\, m-N-1,\, \ldots\, m-2N+1} (\widetilde{\widetilde{HR}}_{k2-1} - \widetilde{\widetilde{HR}}_{k2}) \\
& - \textstyle\sum_{k3= m-2N,\, m-2N-1,\, \ldots\, m-3N+1} (\widetilde{\widetilde{HR}}_{k3-1} - \widetilde{\widetilde{HR}}_{k3}) \\
& + \textstyle\sum_{k4= m-3N,\, m-2N-1,\, \ldots\, m-4N+1} (\widetilde{\widetilde{HR}}_{k4-1} - \widetilde{\widetilde{HR}}_{k4}) \Big];
\end{aligned}
$$

conditions for summing on m:

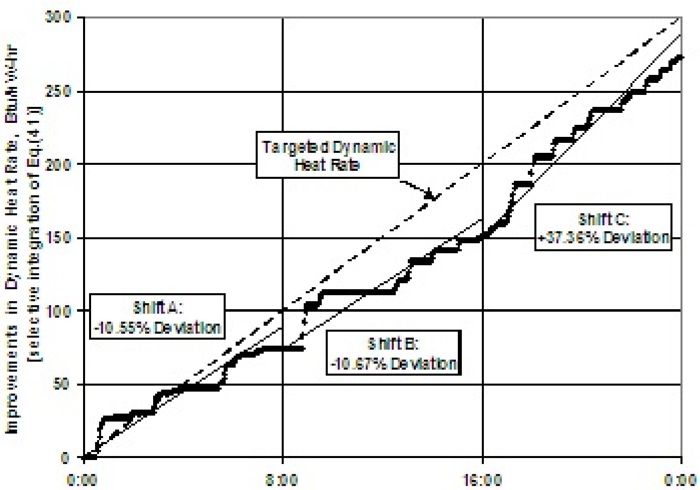
$$
\begin{aligned}
&1)\ \widetilde{\widetilde{HR}}_{k1} < \widetilde{\widetilde{HR}}_{k1-1} \\
&2)\ \textstyle\sum_{k1} > \sum_{k4} \\
&3)\ \textstyle\sum_{k1} - \sum_{k2} - \sum_{k3} + \sum_{k4} > 0 \qquad (41)
\end{aligned}
$$

Note that selective integration results in time weighting only the net improvements from one complete oscillation to the next. Further, simple averaged functions could be applied directly to each integrated quadrant, assuming ξ_k = 1.00 and $\widetilde{\widetilde{\widetilde{\mathrm{FCI}}}}_{\mathrm{Power},k} = \mathrm{FCI}_{\mathrm{Power},k}$.

An additional communication may present trends to the system operator as pre-determined anticipated improvements in Dynamic Heat Rates versus time. It has been found that each operator has unique adjustment characteristics and reactions to system controls which may effect heat rate. Thus, information from Eq.(41) is compared, one work shift versus another, creating competition for the highest improvements in Dynamic Heat Rate. Figure 3 over-plots such anticipated slopes, comparing to those achieved. As can be seen, Shift A and Shift B fall short of the target (even with the system being off-line from 07:20 to 08:11); while Shift C (the recognized "A" team) beat the target by over 37%. Such dramatic differences are not uncommon. The deviations indicated in Figure 3 are determined based on the work shift's starting point and the average improvement as the shift progresses; deviations being based on the actual average slope at any given time compared to the targeted slope.

The targets chosen for Dynamic Heat Rate improvements must be uniquely established for a given system and its fuel, and based on the selective integration employed, and associated rules. Experience has shown that if employing the selective integration of Eq.(41), with S_H = 1.00, that 300 ΔBtu/kWh per day has been found to be reasonable when firing Powder River Basin coals.

Figure 3: Example of Improvements in Dynamic Heat Rate



CONCLUSIONS

Fuel Consumption Indices offer the only logical method for determining differential heat rates associated with components and processes. They quantify system losses in terms of fuel consumption, offering a true "systems approach". Differential heat rates based on FCIs will always sum to gross unit heat rate. When coupled with Input/Loss Methods of determining fuel chemistry and heating value on-line, the smoothed Dynamic Heat Rate, teaches the operator whether his/her actions are improving or degrading unit heat rate.

ACKNOWLEDGMENTS

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APPENDIX A: PROCEDURES FOR USING ΔFCI_j

These procedures only apply if using differences relative to Reference Bogey Data: ΔFCI_j, Δhr_j and ΔHR. They have been checked-out at several power plants employing FCI monitoring:

1) The procedure begins with data from Input-Output tests, or some set of reference (bogey) heat balances. Three load points are recommended. Up to three tests can be analyzed automatically by EX-FOSS to form an unique set of heat transfer correlations, thus offering both convenience and consistency while on-line. For all such tests, the acquired boiler and turbine cycle data sets **must be internally consistent**. These sets are the Reference Bogey Data.

2) If the Input-Output tests are greatly atypical, then appropriate corrections of the Reference Bogey Data sets should be made. This might include corrections to throttle conditions, condenser pressure & reheat temperature. If the unit uses highly variable fuel, heating value (and fuel chemistry) sensitivity studies are recommended; e.g., three fuels, one actual, two outlyers each of these at three loads. Bivariate linear interpolation would then be employed.

3) Using the Bogey Data Sets as input to EX-FOSS, the following Reference Bogey Data (subscript "B-Ref") are tabulated for each simulated load from EX-FOSS output:

- Gross generation, MWe (recorded from EX-FOSS's *Filename.OUT* file Index 0255, or Steam Generator Report page 1B);

- Reference bogey Fuel Consumption Indices, $[FCI_j]_{B\text{-}Ref}$ (from the *Filename.OUT* file Indices hx38, 0183 thru 0188 and 0261, or Steam Generator Report pages 6A and 6B); and
- Reference bogey fuel energy flow, $[m_{AF}(HHVP+HBC)]_{B\text{-}Ref}$ (from the *Filename.OUT* file Index 1453, or Steam Generator Report page 2B).

Arrange these data as a function of the as-tested gross power, for later interpolation. Note that EX-FOSS computes an encompassing "Misc. TG Cycle" FCI_i for all turbine-generator (TG) cycle components not interfaced with combustion gases. If additional detail is required, either PEPSE, THERM or EX-SITE can be used to obtain energy balances, leading to FCI_j data for individual TG cycle components (those not interfaced with combustion gases). However, for the great majority of applications, only use of EX-FOSS is needed and its "Misc. TG Cycle" term (typically a minor value). Indeed, it is this author's view that turbine cycle simulators have no place in on-line monitoring systems. The traditional simulators employ large and complex software, they are prone to fault, and are input with large amounts of data for very little return.

4) Monitor the actual plant conditions (subscript "A"), on-line, recording gross power W_{output} and $[FCI_j]_A$ & $[m_{AF}(HHVP+HBC)]_A$ from EX-FOSS. Of course all data must be produced using the same modeling and data reduction methods as used to establish the Reference Bogey Data.

5) Interpolate within the Reference Bogey Data $[FCI_j]_{B\text{-}Ref}$ and $[m_{AF}(HHVP+HBC)]_{B\text{-}Ref}$, using the actual monitored power, to determine $[FCI_j]_B$ and $[m_{AF}(HHVP+HBC)]_B$, the bogey values at W_{output}. It is critical to employ linear interpolation such that for any monitored load $\Sigma[FCI_j]_B$ = 1000. Of course for the actual, $\Sigma[FCI_j]_A$ = 1000, given it is EX-FOSS computed (as are $[hr_j]_A$ and HR_A).

6) Calculate ΔFCI_j and Δhr_j for each modeled component and process via Eqs.(25) & (27). Calculate ΔHR; see Eqs.(24B) & (28B). Calculate the $(1 + \Psi_i)$ and $(1 + \Psi_{System})$ parameters which indicate the applicability of using the Reference Bogey Data; see Eqs.(34) and (36).

7) When displaying results, two techniques have been implemented over the years, these include the following:

- bar charts of ΔFCI_j and Δhr_j, the most popular;
- visual presentation of the power plant in which colored areas (keyed to ΔFCI_j) are used to indicate its thermal condition.

When displaying ΔFCI_j and Δhr_j results to plant operators, it has been found that simple color schemes (green => good, red => bad), imposed on bar graphs (or on the visual plant), representing numerical values, provides for the best communication.

$\Delta FCI_{Power} < 0$, a green value ($G_{in\text{-}A} < G_{in\text{-}B}$ for the same W_{output}, therefore less fuel consumed), otherwise red given $\Delta FCI_{Power} > 0$;

$\Delta FCI_{non\text{-}Power} > 0$, a green value (lower relative losses), otherwise red given $\Delta FCI_{non\text{-}Power} < 0$;

$\Delta hr_{non\text{-}Power} < 0$, a green value (actual < bogey), otherwise red given $\Delta hr_{non\text{-}Power} > 0$;

$(1 + \Psi_i) > 0$, a green mark thus the Reference Bogey Data is said applicable for determining Δhr_i;

$(1 + \Psi_{System}) > 0$, a green mark thus the Reference Bogey Data is said applicable for unit heat rate deviation, ΔHR.

8) Thoroughly train power plant operators in the proper interpretation of ΔFCI_j and Δhr_j using in-plant examples.

APPENDIX B: COMMENTS ON USING FCI_j

The following comments relate to power plant use of FCI_j, hr_j and HR computed values (without bogeys). Simply stated, over many years of use, it has been observed that power plant operators - almost universally - prefer simple time plots of FCI_j.

When the technique was originally developed, great concern was had over convincing plant operators that the nebulous "Second Law" was the only thing to use. Thus emphasis was placed on training in exergy balances, the formation of FCI_j, the use of hr_j terms, etc. However, experience has clearly suggested such concern had no bases. Typically, operators even with limited understanding of the underlying theory of FCIs, **view nothing else**. They typically do not review hr_j, HR, nor the differences in ΔFCI_j, etc. Again, the advantage is that ΣFCI_j = 1000, and that cause-affects (balance between power and losses) are readily observed. Little interpretation is required; they are simply not hung-up on "heat rate" per se.

Examples of typical FCI time plots, used by operators, are available from Deihl & Lang (1999), and Rodgers & Lang (2002).

Table 1:
Typical EX-FOSS Second Law Output
from its Steam Generator Report
(a 680 MWe unit firing 12,400 Btu/lbm coal)

S E C O N D   L A W   A N A L Y S I S — Page 6A of 6B

ID of Heat Exchanger (Type)		Working Fluid Exergy Btu/hr	Flue Gas Exergy Btu/hr	IRR Btu/hr	EFFECT PCent	Rel. IRR PCent	HHV Heat Rate Btu/kWh	Fuel Consumption Index
IDFan	In:	8082986.7*	400228826	4857096.	39.91	.1204	6.904	.76510
	Out:	N/A	-403454717					
FDFan	In:	12934478.@	9972977.2*	8095022.	94.15	.2007	11.51	1.2751
	Out:	-14812433.@	N/A					
STM-AH	In:	14812433.@	.00000000#	.000000	.0000	.000	.000	.0000
	Out:	-14812433.@	.000000000#					
AIR-PH	In:	14812433.@	776305134	58922509	83.84	1.461	83.75	9.2816
	Out:	-320451306@	-411743751					
Econom	In:	484425273	.12766E10	.11163E9	77.69	2.768	158.7	17.585
	Out:	-873100746	-776305134					
PrimSH	In:	.18223E10	.18495E10	.13605E9	76.25	3.373	193.4	21.431
	Out:	-.22592E10	-.12766E10					
Combustion:				.79261E9	87.24	19.65	1127.	124.85

Exergy In Fuel: .61997E10
Exergy In Air: 12934478.
Total Exergy Out: -.5420E10

Ref. Fuel Data:
Internal Calcs
Ref. State:
Pres = 14.70000
Temp = 64.06220
Enth = 32.19533

Legend:
IRR = Irreversibility; EFFECT = Effectiveness; @ = Air;
* = Shaft Power; # = Working Fluid; + = Boiler Effect.

S E C O N D   L A W   A N A L Y S I S — Page 6B of 6B

ID of Heat Exchanger (Type)		Working Fluid Exergy Btu/hr	Flue Gas Exergy Btu/hr	IRR Btu/hr	EFFECT PCent	Rel. IRR PCent	HHV Heat Rate Btu/kWh	Fuel Consumption Index
Reheat	In:	.19947E10	.25821E10	.23066E9	68.51	5.719	327.9	36.335
	Out:	-.24966E10	-.18495E10					
RSpray	In:	.00000000	.25821E10	.0000001	.0000	.0000	.0000	.00000
	Out:	.000000000	-.25821E10					
FSecSH	In:	.24501E10	.30114E10	.13605E9	68.31	3.373	193.4	21.432
	Out:	-.27434E10	-.25821E10					
PSecSH	In:	.22590E10	.33136E10	.11109E9	63.24	2.754	157.9	17.500
	Out:	-.24501E10	-.30114E10					
SSpray	In:	20351384.	.36292E10	.13956E9	55.77	3.460	198.4	21.985
	Out:	-196367001	-.33136E10					
Boiler	In:	873100746	.54200E10	.84158E9	53.01	20.86	1196.	132.57
	Out:	-.18223E10	-.36292E10					
Mixing Loss:		N/A	N/A	.31094E9	N/A	7.709	442.0	48.981
Stack Loss:		N/A	403454717	.40345E9	46.27+	10.00	573.5	63.553
Environment:		N/A	N/A	.0000000	N/A	.0000	-122.	.00000
Elec Power:		-.2314E10	125665762*	N/A	78.81	N/A	3412.	364.63
Misc TG Cycle:		N/A	.29371E10#	.74801E9	N/A	18.54	1063.	117.83
Sys Totals:		-.5559E10	.92739E10	.4033E10	36.46	100.0	**9023.**	**1000.0**