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PRACTICAL EXPERIENCE WITH THE INPUT/LOSS METHOD AS APPLIED TO A CFB POWER PLANT

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ABSTRACT

In late 1995 the Input/Loss Method was installed for on-line monitoring of an independent power producer located in Colver, PA. Colver is a 115 MWe Circulating Fluidized Bed (CFB) steam generator burning poor quality coal, having typically ±20% variation in As-Fired heating value, **providing considerable difficulties to operating staff.**

The Input/Loss Method provides a complete thermal understanding of a power plant through explicit determinations of fuel flow, emission flows, fuel chemistry, fuel heating value and thermal efficiency. Direct measurements of fuel or emission flows are not made. In addition, the Method employs a Fuel Consumption Index (FCI) technology to alert the operator as to which components/processes within the system higher irreversible losses - in terms of higher fuel consumptions for a given power level - thus where improved heat rate can be found. The Method also uses a Sulfur Function Optimizer (SFO) parameter which assists the operator in minimizing the use of limestone, while just meeting regulatory SO_2 effluents

This paper discusses a number of actual operational situations, taken over the past four years, which were resolved with the help of the Input/Loss Method. For example: the usefulness of the SFO parameter, tracking FCI for key processes, comparisons of grab fuel samples to Input/Loss predictions, plant-evaluated economics, etc. Problems with required effluent (CEMS) instrumentation, experience with a CEMS error analysis procedure, stoichiometric assumptions, air leakage assumptions, etc. are discussed. PAPER-57c.doc

NOMENCLATURE

k_{fuel} = Moles of SO_2 created from fuel sulfur, before reaction with limestone, moles SO_2/100 moles dry gas.
l = Moles of SO_3 per 100 moles dry gas.
γ = Molar ratio of excess $CaCO_3$ to stoichiometric $CaCO_3$ (e.g., γ = 0.0 if no effluent CaO, internally computed).
HR_{Bogey} = Unit heat rate for the targeted or "Bogey" performance, generally established through input-output testing, Btu/kWh.
HR_{Actual} = Unit heat rate for the "Actual" performance in real-time.
hr_j = Incremental heat rate of a j<u>th</u> component or process, for example the "power" process, a reheater component, etc., ΔBtu/kWh.
m_{AF} = As-Fired Fuel Mass Flow Rate, lbm_{AF}/hr.
m_{Air} = Flow rate of moisture combustion air, lbm_{Air}/hr.
$m_{LS\text{-}pred}$ = Predicted limestone mass flow, lbm/hr.
$m_{LS\text{-}Actual}$ = Actual (indicated) limestone mass flow, lbm/hr.
SFO = Sulfur Function Optimizer, defined by Eq.(12), its min. will both reduce limestone flow and effluent SO_2, --.
FCI_j = Fuel Consumption Index for a j<u>th</u> component or process (note: $\sum FCI_j + FCI_{Power} = 1000$), --.
FCI_{Power} = Fuel Consumption Index for the system's direct power generation process (i.e., the creation of electricity), --.
g = Specific exergy composed of physical, chemical, and thermal contributions, Btu/lbm.
g_{Fuel} = Specific exergy of as-fired fuel, Btu/lbm.

G_{in} = $m_{AF}g_{Fuel} + m_{Air}g_{Air} + \Sigma G_{Misc} + \Sigma W_{Pump} + \Sigma W_{Fan}$, Btu/hr.

ΣG_{Misc} = Summation of miscellaneous exergy flows inlet and outlet from the system, such as a steam-air heater, system water losses, water makeup, etc., Btu/hr.

I_j = Irreversible loss associated with a non-power component or process, Btu/hr.

b_{PLS} = Molar fraction of pure limestone [$CaCO_3$] required for zero CaO production, per 100 moles of dry gas product.

b_{PLS*} = Fuel produced SO_2 less Regulated SO_2, molar fraction of pure limestone [$CaCO_3$] required for perfect regulation of SO_2 emissions.

W_{output} = Gross power generation, Btu/hr.

W_{Fan} = Shaft power input to system from combustion air fans, Btu/hr.

W_{pump} = Shaft power input to system from working fluid pumps, Btu/hr.

SUBSCRIPTS:

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

INTRODUCTION

When installed at the Colver Power Project, the Input/Loss Method was intended to provide a complete thermal understanding of the system through explicit determinations of fuel and effluent flows, fuel chemistry, fuel heating value and thermal efficiency. Direct measurements of fuel or effluent flows are not made. In addition, the Method employs a Fuel Consumption Index (FCI) technology to alert the operator as to which components/processes within the system have higher irreversible losses - in terms of higher fuel consumptions for a given power level - thus where improved heat rate can be found. In addition, the Method uses a Sulfur Function Optimizer (SFO) parameter that assists the operator in minimizing the use of limestone, while just meeting regulatory SO_2 effluents. The Method is designed for on-line monitoring and, using these tools, continuous improvement of unit heat rate. Its installation at the Colver facility is significantly important for the enhancement of CFB boilers using high ash fuel and/or with uncertain heat contents (e.g., trash or bio-mass burners). This is especially true for the US export of CFB boilers, in many cases, whose only practical fuel is high ash, low calorific coal.

For a given power production, fuel energy can not be conserved unless it is continually and accurately metered. For coal-fired units metering of fuel flow to the accuracy required for performance monitoring has been rarely attained, to say nothing of changing heating values. Traditionally, if a power plant has a ± 10% error in flow, its coal metering would be considered acceptable, but worthless for performance monitoring.

The method developed at Exergetic Systems, termed the Input/Loss Method (Lang, 1994-99, 1999b & 1999c) determines coal flow and As-Fired heating value based on turbine cycle energy flows, boiler performance through iterative techniques, routine emission measurements, and assumptions or indicated Air/Fuel ratio & effluent water measurements. In general, unit heat rate at coal-fired plants can be routinely monitored within ± 1.1% standard deviation using Input/Loss. This statement is based on assumptions of measuring feedwater flow within ± 1.0% accuracy, being able to properly characterize the moisture-ash-free (MAF) fuel, and whose As-Fired fuel has reasonably behaved fuel ash and fuel water characteristics - producing a standard deviation in fuel heating value of less than ± 0.5% (Lang, 1999b). The Colver MAF fuel is well characterized (Lang, 1998), however its As-Fired ash varies by ± 19% and its water by ± 40%! Colver's feedwater flow measurement error is believed to be less than ± 1.0%. Given these circumstances, and numerous sensitivity analyses on the fuel, Colver's on-line unit heat rate is believed to be known within ± 1.6% standard deviation.

As important as accurate As-Fired heating value and fuel flow are, thus unit heat rate, their determinations are also integrally coupled with computed Fuel Consumption Indices, FCI. FCIs quantify true thermodynamic losses throughout the system (Lang and Horn, 1991). With FCIs, knowledge as to where in the system improvement can be had is revealed to the plant operator.

The Input/Loss Method reflects an integrated approach as one can not rationally understand the system if the principle effluent concentrations are missing any more than ignoring a feedwater flow or gross power measurement. The result is instantaneous gross unit heat rate, and the identification of where in the system unusual thermal losses are occurring.

HARDWARE AND THE CALCULATIONAL ENGINE

The on-line monitoring system at Colver consists of several workstations, interfaced to a Bailey Infi-90 data acquisition and control system. These workstations, through FIX32 data management software (from Intellution, Boston, MA), feed data to Exergetic Systems' **Calculational Engine**. This Engine, a single personal computer, continually computes software embodying the Input/Loss Method. The over-all system is called the "Monitoring and Performance Station" (MAPS). The principal Engine software includes:

- EX-FOSS, for analysis of fossil-fired steam generator including determination of fuel flow, system mass & energy balances and Fuel Consumption Indices;
- FUEL, for determining composite fuels (given up to five coals, oils or gaseous fuels);
- HEATRATE, for determination of As-Fired fuel chemistry (including fuel water and ash) and heating value Lang, 1999c);
- EX-SITE-under-Excel, for analysis of turbine cycles using Excel macros for detailed modeling; and,
- ERR-CALC, for determining correction factors in instrumentation signals (Lang, 1999b).

The EX-FOSS, FUEL & HEATRATE software are integrally coupled through executive software, these are the principle for Input/Loss; EX-SITE-under-Excel is optionally coupled for on-line operation. ERR-CALC can be called periodically or integrally coupled to analyze instrumentation signals essentially continually. All software can be used for off-line, "what-if", studies. The Engine is provided averaged plant data every 15 minutes; computes within minutes; providing the plant workstations with consistent thermodynamic information. The Colver Engine has 90 MHz speed which is adequate for 15 minute averaged data (Exergetic Systems is currently recommending a 450 MHz computer, especially if ERR-CALC is placed on-line). FIX32 software, from Intellution Inc., Boston, MA, provides for historical data trending and alarms. Microsoft SQL Server is used to maintain an extensive archival database.

The key to the Engine software lies with its implementation of the Input/Loss Method and resultant Fuel Consumption Indices. In addition, the system provides the operator with a Sulfur Function Optimizer (SFO) parameter which minimizes limestone flow for a given SO_2 effluent.

The Input/Loss Method is based on a system-oriented view of the power plant. Basic understanding of boiler thermal performance is had from computer simulation of the boiler using internally updated fuel chemistries, effluents concentrations, indicated Air/Fuel ratio and energy flow to the working fluid. Consistency is mandated through application of the error analysis routine, ERR-CALC, based on Multidimensional Minimization techniques (Lang, 1999b). As a system solution, Input/Loss procedures lead to boiler mass flow balances for fuel, combustion air, leakage's and effluents, without reversion to direct measurement of fuel or effluent flows. In summary, thermodynamic understanding is had for the entire system; with such understanding determination of all mass flows becomes intrinsic.

FUEL CONSUMPTION INDEX

Details of the Fuel Consumption Index, a Second Law concept, are reported in the literature. Briefly note, in the context of this paper, that the real importance of the Input/Loss Method to FCIs lies with its determination of fuel chemistry and fuel flow. These quantities allow for complete mass and energy balances around the system. Given such resolutions, calculational procedures then produce Fuel Consumption Indices (FCI) and associated differences (ΔFCI) (Lang & Horn, 1991). Use of ΔFCIs allows the performance engineer to immediately identify which component or process within the system is consuming more, or less, fuel relative to a "Bogey" (targeted) consumption at a given power level.

Since 1991, the FCI concept has been applied to 16 power plants in the US and abroad. The following two paragraphs discuss the classical First Law approach to power plant monitoring, following by exergy analysis leading to the FCI concept.

Enthalpy is used in energy balances to analyze the flow of energy through a system's components. Examining the detailed energy flows through components within a system, as opposed to simple summations of heat and power transfers across global boundaries helps us understand the system and ways of improvement relative to design or some target operation. 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 system performance, thermal efficiency, quantifies only the exchange of energy from boiler to the environment ($1 - Q_{rej}/Q_{in}$), indeed **First Law analysis fundamentally relates to the utilization of energy flows**. Although ($Q_{in} - Q_{rej}$) is of course system power, one is never advised to assess power plant 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}). Baring Salisbury's early, robust and most excellent techniques with differential heat rate; First Law methods as now practiced force the performance engineer to use vendor curves, non-integrated design parameters and "rules of thumb" for identification of degraded components. Current practice is termed "controllable parameters".

If electricity is to be produced with the minimum of unproductive consumption of fuel - then fundamental thermodynamic losses must be understood on a system basis. Such understanding cuts across vendor curves, plant design, fuels, etc. Thermal losses in a nuclear unit are comparable at a *prime facia* level to losses associated with a CFB system. They are what we must minimize in the production of electricity, no manner the method of that production. Second Law methods offer the only foundation for the study of such losses. As established by Carnot and Gibbs (1873), all energy flows do not have the same potential for power production; any material not in equilibrium with its environment has an available energy flow, thus the potential for power production. In general, the higher the pressure and temperature, the higher this potential. The direct and immediate measure of this potential is termed "exergy". Exergy is the Second Law's "working variable" and deals with the quality of energy, that is, its potential to produce or consume shaft power. **Second Law analysis fundamentally relates to the utilization of potential power** associated with a given operating system. Second Law methods force the engineer to maximize the potential (and realizable) shaft power associated with a thermal system. Through determination of changes in true component and process losses, direct measure of changes in why more or less fuel is being burned (at a given power level). It is ideal for assessing the effective creation of electricity using minimum fuel.

Of the total exergy and shaft power inputs to a system, only irreversibilities and power output will result. This is a performance engineer's definition of the Second Law. This is expressed by Eq.(2), where the total exergy and power input to the system is defined by G_{in}.

$$G_{in} \equiv m_{AF}g_{Fuel} + m_{Air}g_{Air} + \Sigma G_{Misc} + \Sigma W_{Pump} + \Sigma W_{Fan} \qquad (1)$$

$$G_{in} = \Sigma I_i + W_{output} \qquad (2)$$

Eq.(2) 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, processes and the power production. Separate accounting of power input terms versus production (W_{output}) is obviously important.

The 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 total exergy, $m_{AF}g_{Fuel}$. Based on Eq.(2), FCI is defined for non-power components (e.g., processes such as combustion, reheater, superheater, etc.) as:

$$FCI_j = 1000 \frac{I_j}{G_{in}} \qquad (3)$$

and for the power production process as:

$$FCI_{Power} = 1000 \frac{W_{output}}{G_{in}} \qquad (4)$$

ΔFCIs and ΔHeat Rates are defined by the following for a given component or process, j. The literature presents details as to the straight forward conversion of FCI_j to hr_j (Lang & Horn, 1991).

$$\Delta FCI_j = [FCI_j]_{Bogey} - [FCI_j]_{Actual} \qquad (5)$$

for a given W_{output}; intended for on-line monitoring by plant operators, target less actual for each component and process.

$$\Delta hr_j = [hr_j]_{Actual} - [hr_j]_{Bogey} \qquad (6)$$

for a given W_{output}; intended for on-line monitoring by plant operators, actual less target for each component and process.

$$\Delta HR_j \equiv \Sigma \Delta hr_j \qquad (7)$$

$$\Delta HR = HR_{Actual} - HR_{Bogey} \qquad (8)$$

for a given W_{output}; this is the classical definition of the difference in unit heat rate: actual less target for the total system. Note that an improved unit heat rate ($\Delta HR < 0$) is proportional and of the same sign as ΔI_j.

For computational over-checks the following important identities are continuously reviewed:

$$\Sigma FCI_j = 1000.0 \qquad (9)$$

$$\Sigma \Delta FCI_j = 0.0 \qquad (10)$$

Further, these techniques guarantee that the summation of incremental heat rates, $\Sigma[hr_j]_{Actual}$ computed on-line, must equal the classical definition of unit heat rate.

Techniques have also been developed to determine whether or not the bogey data associated with ΔFCI_j and Δhr_j is indeed applicable to the monitored system. Basically, an "applicability parameter" is computed, which if positive guarantees that a given component differential heat rate, Δhr_j, will vary (with the same sign for a given power) as changes in irreversibility $[I_{j\text{-}Actual} - I_{j\text{-}Bogey}]$. **This is critically important.** Simply stated, for a given jth component or process, lower losses should always imply lower differential heat rate. And in like manner for the system: a given unit heat rate deviation, ΔHR, will vary (with the same sign for a given power) as$[\Sigma I_{j\text{-}Actual} - \Sigma I_{j\text{-}Bogey}]$, provided the data is "applicable" as numerically determined. It is believed that this is the first time an on-line monitoring system can internally confirm the usefulness of its benchmark database.

SULFUR FUNCTION OPTIMIZER

Limestone is commonly injected into fluidized bed boilers to control sulfur emissions, as done at Colver. The Sulfur Function Optimizer (SFO) parameter was developed for the Colver plant to assist in minimizing the consumption of limestone. Limestone costs per pound at Colver exceeds that of its coal fuel.

EX-FOSS allows for limestone injection with applicable gas re-circulation. Though EX-FOSS stoichiometric balances, and relying on indicated limestone flow rate, the SFO parameter is computed. Making operational adjustments to minimize the SFO parameter will minimize both SO_2 effluent and excess limestone. When using EX-FOSS on-line, through the Engine, the SFO parameter can be minimized by the boiler operator to thus minimize actual limestone flows in achieving closer control of SO_2 effluent. SFO is defined by the following:

$$\mathrm{SFO} = \frac{\text{(net } SO_2 \text{ \& } SO_3 \text{ stack emissions) plus (excess limestone)}}{\text{(sulfur in fuel) plus (limestone supplied)}} \tag{11}$$

or, in terms referenced in earlier papers (Lang, 1998):

$$\mathrm{SFO} = \frac{k_{Fuel} + \ell - b_{PLS}(1.0 - \gamma)}{k_{Fuel} + \ell + b_{PLS}(1.0 + \gamma)} \tag{12}$$

Concomitant with the SFO, the Engine produces a recommended, and optimized, limestone flow:

$$m_{LS\text{-}pred} = m_{LS\text{-}Actual} b_{PLS*} / b_{PLS} \tag{13}$$

This limestone flow is based on the indication of plant limestone feed, assumed not accurate but consistent; thus leading the operator to corrective action.

INPUT/LOSS EXAMPLES

The following examples are listed in no particular order. All were obtained from the Colver's MAPS system and the Calculational Engine.

Example: Air Pre-Heater Leakage

Figure 1 illustrates a decline in unit performance over time using monthly averaged values. FCI_{Power} and FCI_{Boiler} both decrease significantly while $FCI_{Combustion}$ increases during the time frame of October 98. This decrease in performance corresponds to the discovery of air in-leakage from the Air Pre-Heater (APH) showing increased losses throughout the system. The APH leakage was verified using a portable O_2 instrument to record and compare stack and boiler O_2 readings. The ratio of O_2 across the APH serves as an air leakage correction factor (an Ex-Foss input) to account for air leakage in the Engine's calculations. Refer to the use of the β, ϕ_{Act} & R_{Act} parameters, discussed in previous papers (Lang, 1998 & 1999b), which allow any mix of air pre-heater leakages, local combustion oxygen concentration, and measurement points on either side of the air pre-heater.

Example: Steam Coil Air Heater Effects on FCI

Figure 2 illustrates the affects of placing the primary and secondary Steam Coil Air Heaters in service. The FCIs for the primary and secondary SCAHs both increase as their supplied steam flow increases resulting in higher fuel consumption for the same power. Also note, the Combustion and Stack FCIs show increased losses. This demonstrates how all the FCIs are interrelated - a systems analysis - and thus improvements in one component or system must be offset by losses in another.

Example: Use of the EX-FOSS Limestone Model

Referring back to Figure 1 an increase in the SFO parameter also contributed to the observed decline in unit performance during the time frame October 98 through March 99. FCI_{Power} and $FCI_{Combustor}$ both show increased losses during the same time frame caused by the increase in limestone flow used to control Sulfur emissions. A substantial increase in fuel sulfur (1.9% - 2.3%) was noted during this time frame. Note well, fuel sulfur increases from 1.8 to 2.2% are not sufficient from a combustion view-point, however the concomitant increase in limestone flow has dramatic effects on CFB combustion. The SFO parameter is also shown in Figure 2.

Example: Alternative Fuel (used tire burning)

In August 1998 Colver conducted a test burn using Tire Derived Fuel (TDF) to supplement the facility's normal coal fuel (waste coal from sub-bituminous mining). Figures 5 and 6 show the thermal performance data before, during and after the test burn of TDF. One interesting observation indicates that while the Boiler FCI show increased losses, the Power and Combustion FCIs show improved performance. Again, all ΔFCI_j must sum to zero, Eq.(10). The FCI concept, because any G_{in} to a thermal system will always result in either irreversible losses and power output (i.e., conservation of the Second Law), thus $\sum \Delta FCI_j = 0.0$ and thus forced definition of where in the system higher losses occur. Again the interrelationship between FCIs is demonstrated.

Example: Typical Startup and FCI Interrelationships

Figure 5 illustrates common interrelationships between the FCI terms of Power, Combustion, Boiler, Turbine, Superheater and Stack Losses associated with a unit startup. Results indicate a reduction in $FCI_{Combustion}$ (lower losses, indicating less fuel is required to produce the same power); this is off-set by increasing $FCI_{Turbine\text{-}Cycle}$ and $FCI_{Superheater}$ (lower heat exchanger effectiveness); FCI_{Stack} initially increases then drops when additional fans are bought on-line; FCI_{Power} is relatively constant. Again, since $\sum FCI_j = 1000.0$, all FCIs must balance one another.

Example: Higher Fuel Flow for Combustion Process

Figure 6 illustrates well behaved relationships between Fuel Consumption Indices for Power, Combustion and "Boiler" (a macro heat exchanger descriptive of the ecomonizer outlet to the superheater inlet). Again, this transient is a classical example of more fuel being consumed to produce the same power (lower

FCI_{Power}), caused by a degraded combustion process. As seen, the situation was corrected essentially immediately.

Example: Higher Fuel Flow for Superheater Losses

Figure 7 illustrates another example of FCI sensitivity: a declining FCI_{Power} (always bad => more fuel producing the same power), caused by increases in $FCI_{Superheater}$ and $FCI_{Combustion}$ (both having higher irreversible losses). Corrections were not accomplished in a rapid manner.

Example: Lower Fuel Flow for Combustion Process

Figure 8 illustrates again that the principle Fuel Consumption Indices responded well: FCI_{Power} has increased (always good, less fuel is needed to produce the same power); however $FCI_{Superheater}$ and FCI_{Boiler} have slightly increased (having higher irreversible losses); and all are off-set by declining FCI_{Stack} and $FCI_{Combustion}$ (having lower irreversible losses). This is due in part to an increase fuel HHV with a decrease in fuel flow changing the solids inventory in the boiler and thus affecting unit performance.

Example: Heat Released by Combustion

Figure 9 represents an excellent example of why the term "Heat Released from Combustion" (ERC = HPR - HRX, in Btu/lbm; see previous works), or its corresponding total energy flow (Btu/hr), should be closely monitored by Colver operators. Observed is decreasing feedwater and fuel flows - nominally causing higher irreversible losses - but also influenced by higher stack CO_2 causing a step change in the predicted heating value, thus higher ERC. Indeed this is a complex situation, but the record appears to be reasonable.

Example: Higher Fuel Flow for Combustion Process

Figure 10 is another example of declining FCI_{Power} (bad) caused by increasing $FCI_{Combustion}$. This is an example of how rapidly sulfur emissions can change due changing fuel chemistry. During this period the operator is having trouble controlling sulfur emissions. The SFO and ΔLimestone Flow show the operator's difficulties. As sulfur emissions increase more limestone is called for; as the limestone reacts with the sulfur, emission levels drop resulting in excess limestone flow to the boiler. When fuel sulfur values are this high (2.5%) the amount of limestone needed to maintain emissions can exceed the capacity its handling system. The operator then has no other option but to reduce load to maintain emissions compliance. The effects of these sulfur and limestone transients are easily seen in the power and combustion FCIs.

COMMENTS AND CRITICISMS

Three criticisms are offered, two related to the practical implementation of Input/Loss, and one addressing training: 1) the need to electronically segregate the Calculational Engine from the unit's data acquisition system; 2) establishing adequate computational throughput by selection of what is to be simulated; and 3) operator training in use of the FCI concept. Addressing these issues has subtleties which are important to any on-line system.

Electronically segregating the Calculational Engine (running the Input/Loss software), and the plant's data acquisition has proven to be important such that the personnel maintaining Engine software are separate from data manager-types. Exergetic Systems has learned this lesson through hard experience. For one installation a total integration of engineering calculations and data management was attempted - an "organic" system. At Colver a too close connection is still present. For example, heat flows to the turbine cycle are computed under FIX32, these properly should be performed within the Engine. For a more recent installation a revised spreadsheet-based interface (based on Microsoft's Excel) has been developed and implemented. This interface provides columns for "plant" data, or at the engineer's option, reference data; the Engine choosing which column to process based on off- or on-line commands. If data acquisition is off-line the Engine does nothing, nothing is displayed. This allows use of any data manager software; it clarifies where problems exist; it is thought to be superior over the current Colver installation.

Adequate computer power relative to simulation options is not obvious. This criticism extends to what is to be simulated by the on-line system. One of the authors (Lang) is not unaware of turbine cycle simulators. He now believes that simulating turbine cycles on-line is a mistake. These computations are generally not robust, for MAPS consumes 80% of Engine time; and provides little data to the performance engineer over any (15 minute) on-line cycle time. The Second Law analysis computed by EX-FOSS includes "Miscellaneous Turbine Cycles" losses, generally a small fraction of the total losses (i.e., frictional dissipation and pressure drop effects – it does not include the reheater, electrical production, etc.). The proper progression would first identify a degraded turbine cycle through the turbine cycle FCI, and then turn to detailed turbine cycle simulators used off-line with current boundary conditions. It is believed to be more appropriate to save the computing time and reduce computer faults, and replace the computational processing with error analysis (i.e., ERR-CALC). Colver continues to employ a turbine cycle simulator.

Training of any power plant operator should be a continuing process. Training Colver operators in the proper interpretation of FCI information, and acting on it, was initially difficult. One method used was to compare limestone costs between shifts (noting annual differences of up to $1 million). Another was to compare the stability of the CFB combustion process between shifts, noting affects on Combustion FCI. The authors were concern that FCIs would not be as "acceptable" to operators as their equivalent in heat rate terms. Over time this was not the case, operators are now using FCIs and ΔFCIs directly given that it is easier to interpret, given $\sum\Delta FCI_j = 0.0$, than incremental heat rates, Δhr. An "engineer's video" of how to use the FCI concept was produced, without success.

SUMMARY

The work of refining Input/Loss Methods, training operators and the interpretation of results, is a continuing task at the Colver power plant. The problems of controlling a CFB boiler, minimizing limestone injection, modeling a wildly varying fuel, etc. are tasks which require full cooperation between vendor and plant staff. The authors believe that the Input/Loss Method has shown good promise in tracking and improving heat rate at the Colver facility.

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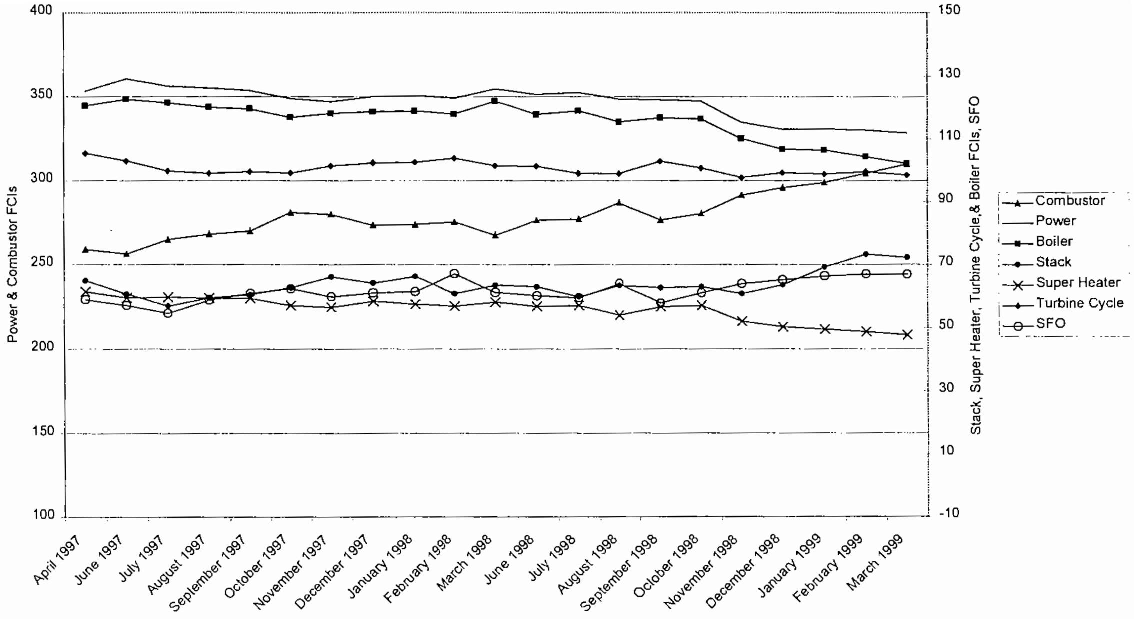


Figure 1
Historical FCI Plot

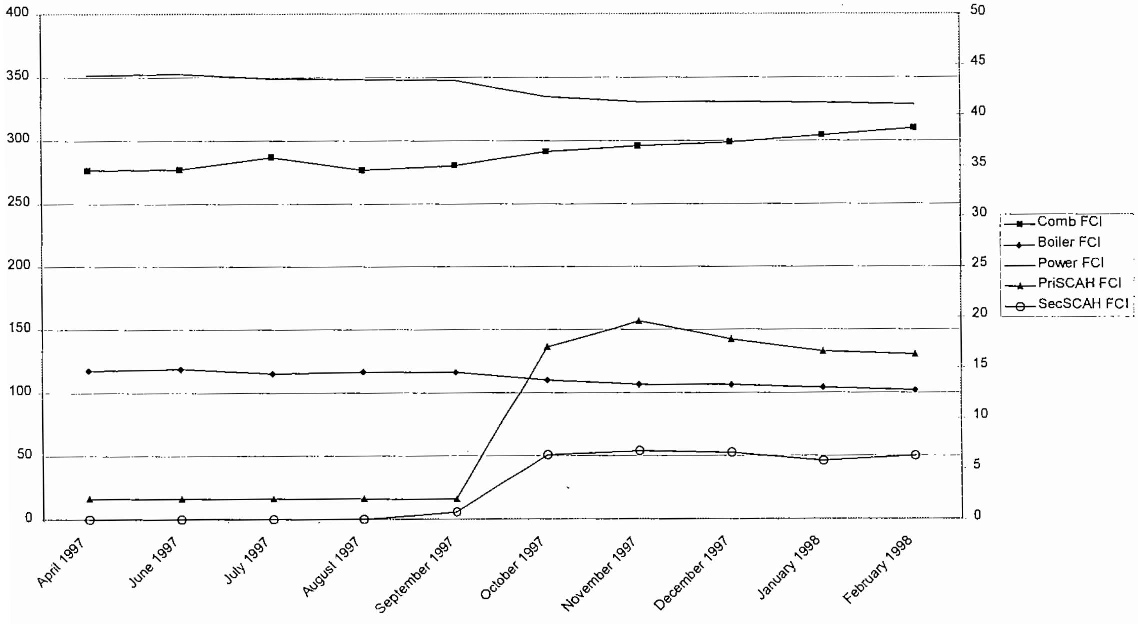


Figure 2
Steam Coil Air Heater FCIs

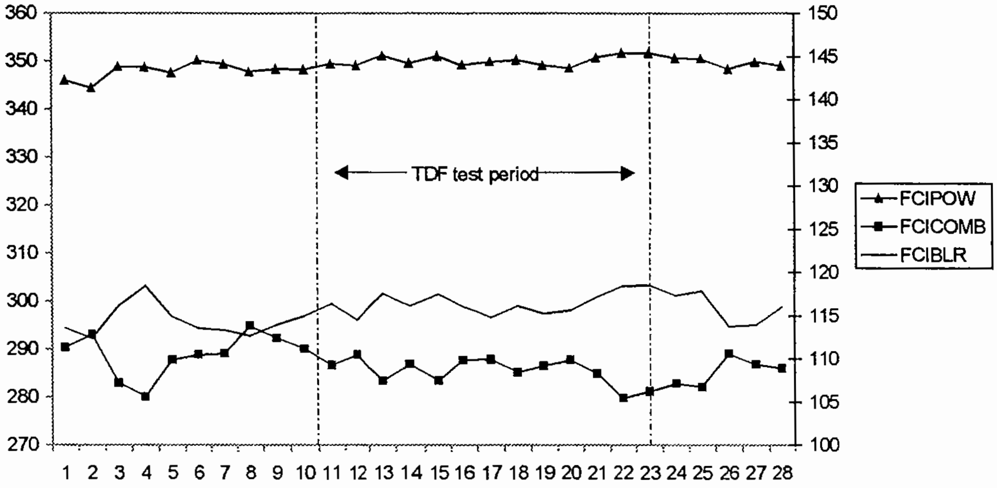


Figure 3
TDF FCI Results

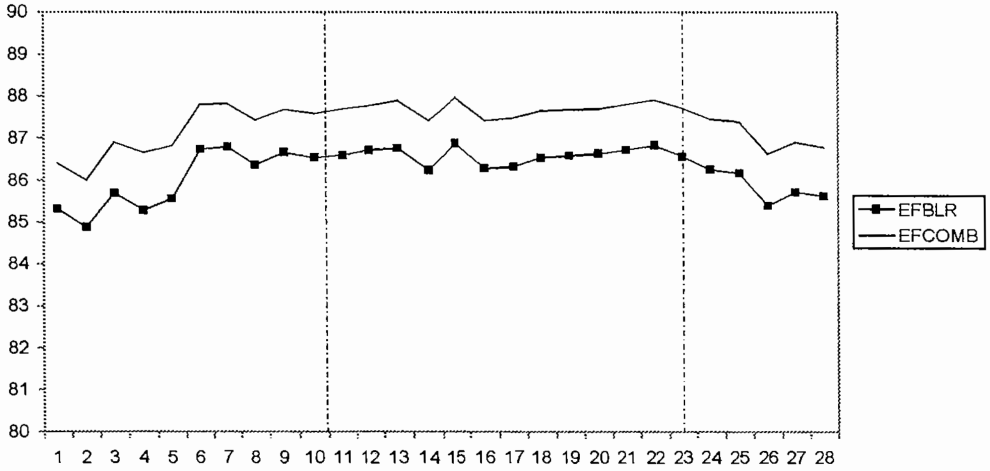
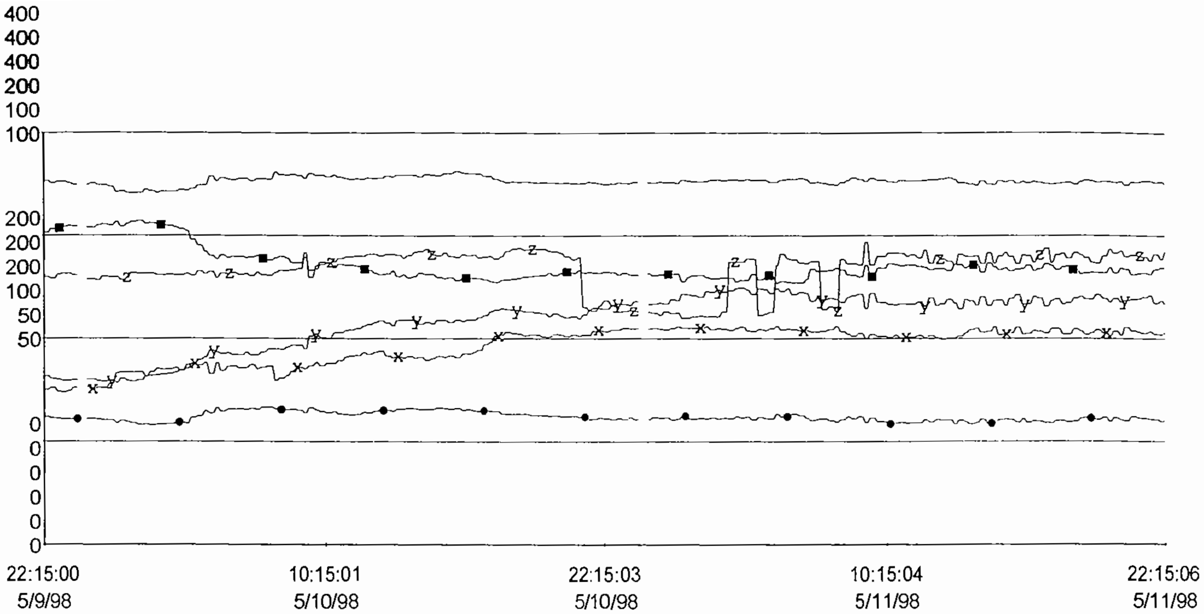
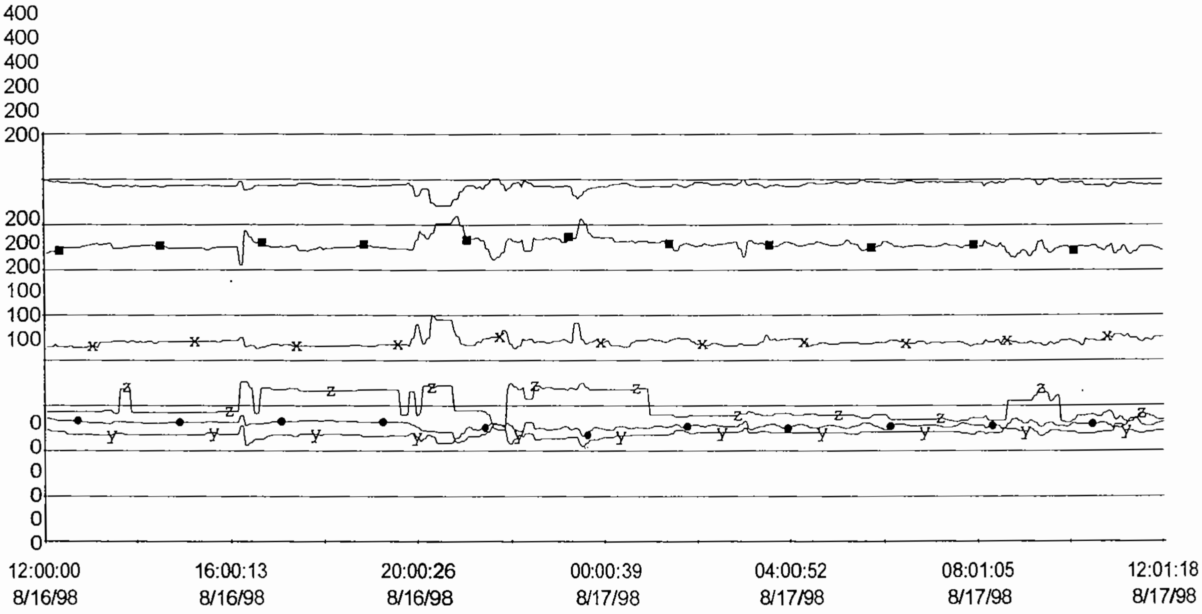


Figure 4
TDF Calculated Boiler and Combustion Efficiencies



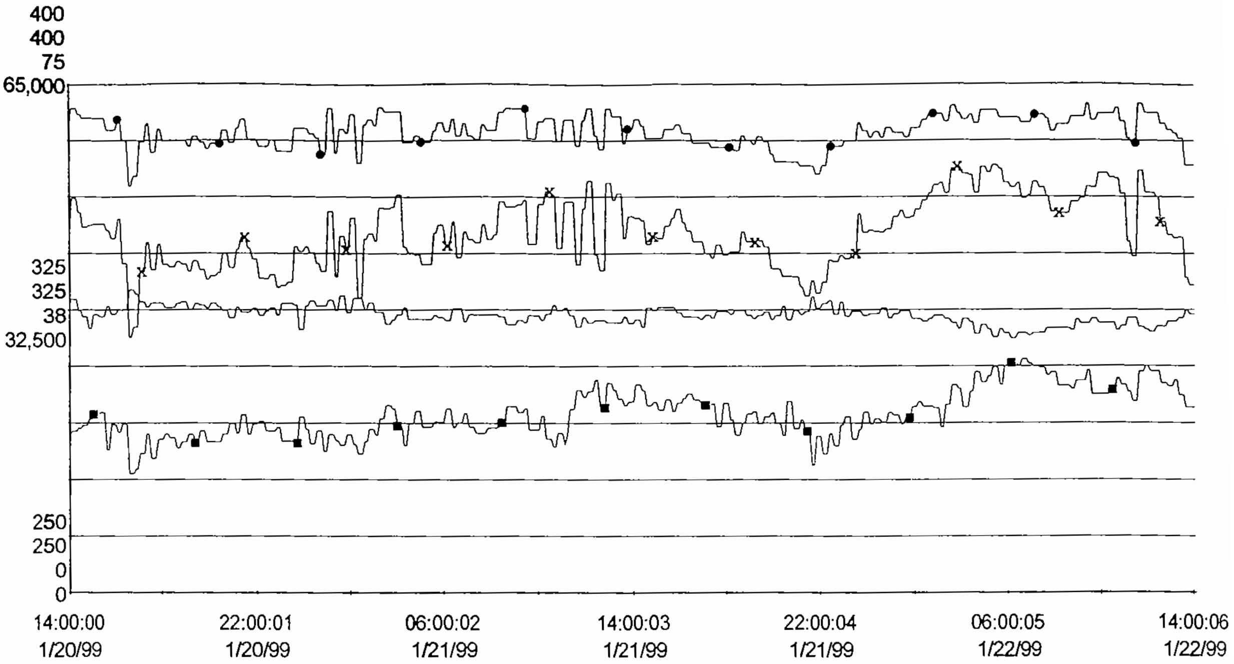
——	MAPS:FCIPOW	FCIPOW	351
—■—	MAPS:FCICOMB	FCICOMB	264
—●—	MAPS:FCIBLR	FCIBLR	123
—x—	MAPS:FCITG	FCITG	104
—y—	MAPS:FCISUPR	FCISUPR	57
—z—	MAPS:FCISTAC	FCISTAC	58

Figure 5
Start Up FCI Interrelationships



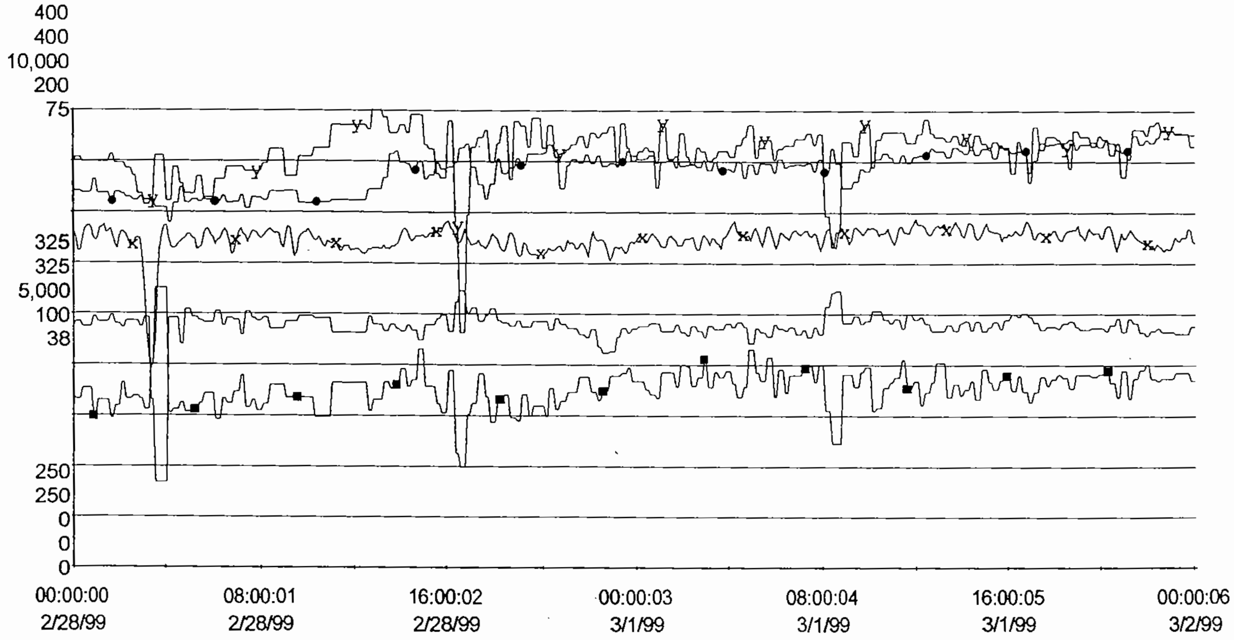
——	MAPS:FCIPOW.F_CV	Power Fuel Consumption Index	347
—■—	MAPS:FCICOMB.F_CV	Combustion Fuel Consumption Index	297
—●—	MAPS:FCIBLR.F_CV	Boiler Fuel Consumption Index	109
—x—	MAPS:FCITG.F_CV	Turbine Generator Fuel Consumption	98
—y—	MAPS:FCISUPR.F_CV	Superheater Fuel Consumption Index	51
—z—	MAPS:FCISTAC.F_CV	Stack Fuel Combustion Index	74

Figure 6
Degraded Combustion Process



———	MAPS:FCIPOW.F_CV	Power Fuel Consumption Index	329
—■—	MAPS:FCICOMB.F_CV	Combustion Fuel Consumption Index	306
—●—	MAPS:SFOACT.F_CV	Sulphur Function Optimizer, %	68
—x—	MAPS:WWLSPR.F_CV	Mass Flow of Targeted Limestone	48,053

Figure 7
Limestone and Fuel Sulfur
Degrade Combustion



———	MAPS:FCIPOW.F_CV	Power Fuel Consumption Index	328
—■—	MAPS:FCICOMB.F_CV	Combustion Fuel Consumption Index	311
—●—	MAPS:PREDHHV.F_CV	Predicted dry HHV	8,991
—x—	MAPS:JAFI104_34.F_CV	Total Coal Flow Rate	143
—y—	MAPS:SFOACT.F_CV	Sulphur Function Optimizer, %	67

Figure 8
Changes in Fuel HHV

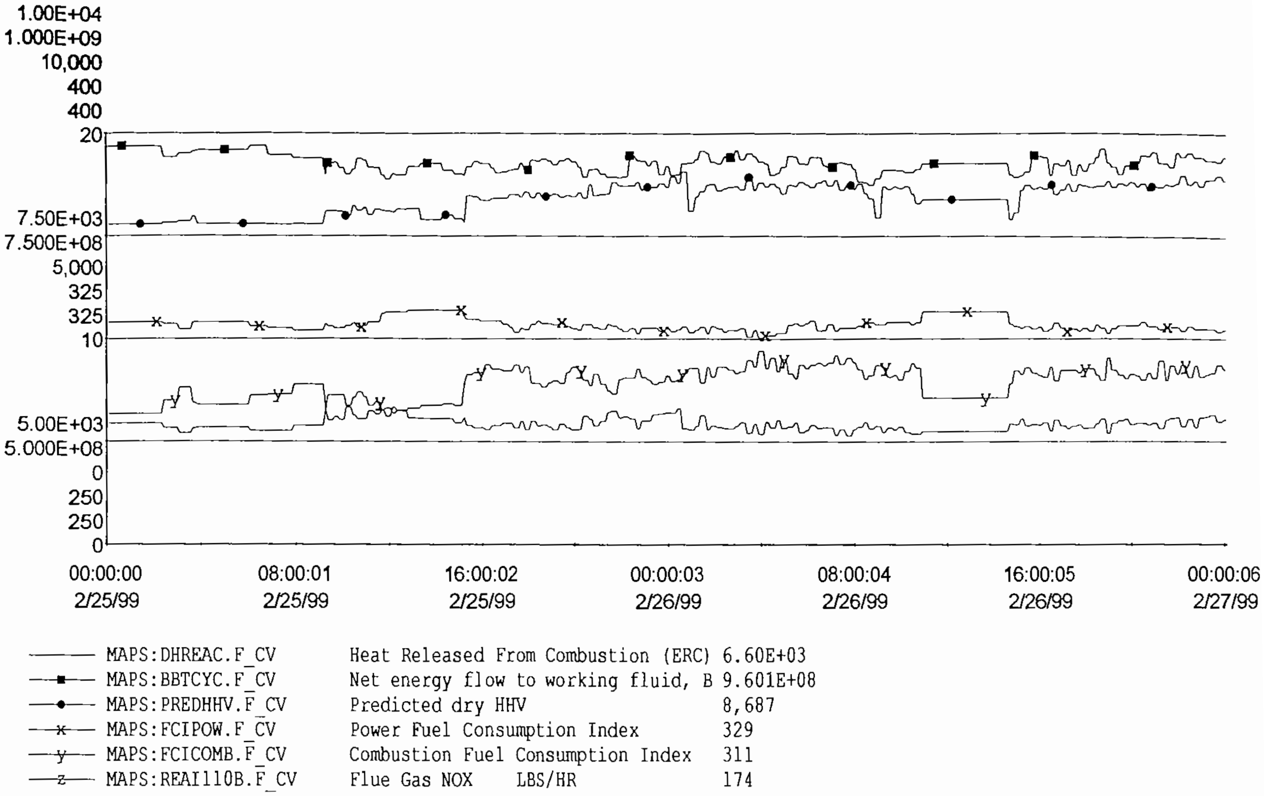


Figure 9
Heat Released from Combustion

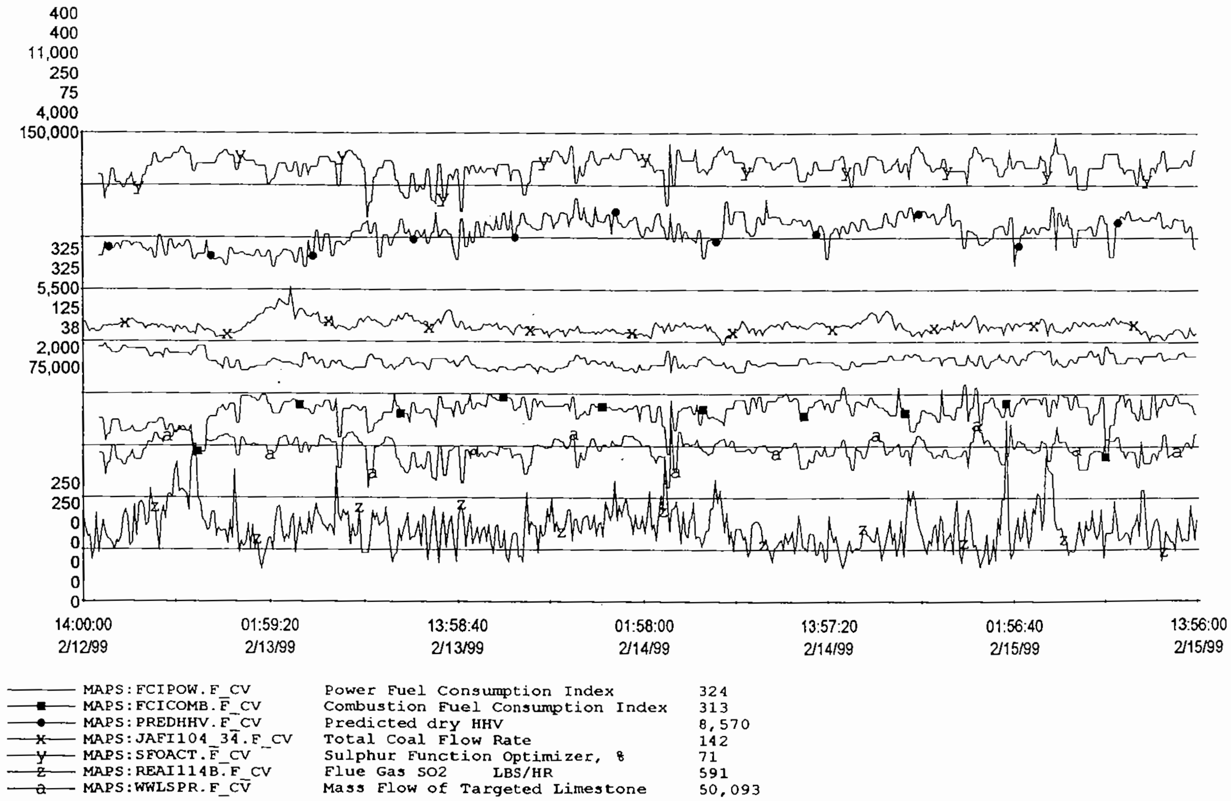
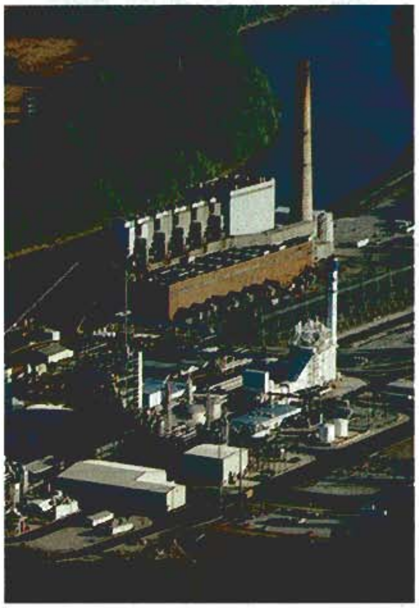


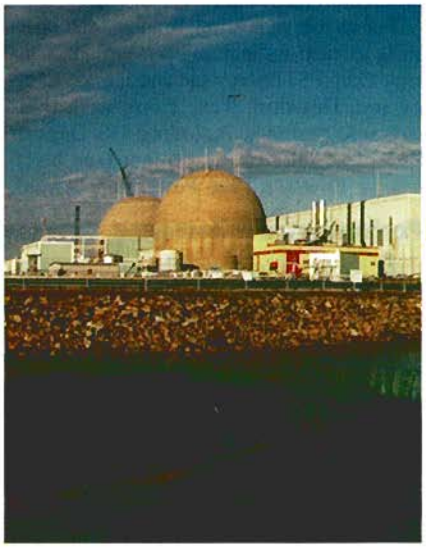
Figure 10
Fuel Chemistry Changes

The 1996 Powerplant Award

Five plants honored

These diverse facilities represent leadership in the application of fresh ideas, advanced technologies, and equipment designs, plus creative business and plant-management techniques to optimize among energy efficiency, competitive economics, and environmental impact. The 1996 Powerplant Awards will be formally conferred during a special ceremony to be held in December at Power-Gen Americas, in Orlando, Fla. For details, fax Joanne Sohn at 212-627-3811.





Cinergy Corp/PSI Energy Inc Wabash River station

For demonstrating a powerplant for the next millennium by repowering a 1950s-vintage steam turbine/generator with an advanced integrated coal gasification/combined cycle

Virginia Power North Anna nuclear plant

For dramatically reversing course and becoming the lowest-production-cost nuclear plant in the US, and leading the industry's performance turnaround

Florida Power & Light Co Martin station

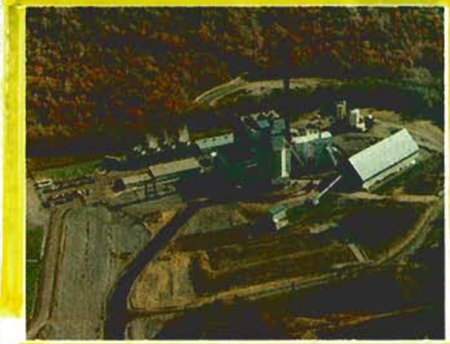
For pioneering advanced combined-cycle technology and realizing its promise through an aggressive, empowered O&M team

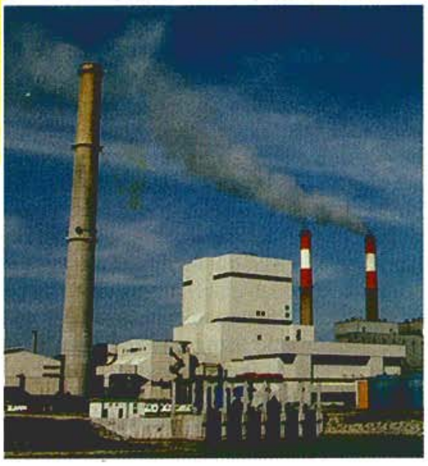
Interpower/Ahlcon Partners LP Colver power project

For assiduously learning from its neighbors, as well as extending the technology of waste-coal-fired circulating fluidized-bed boilers in several important areas

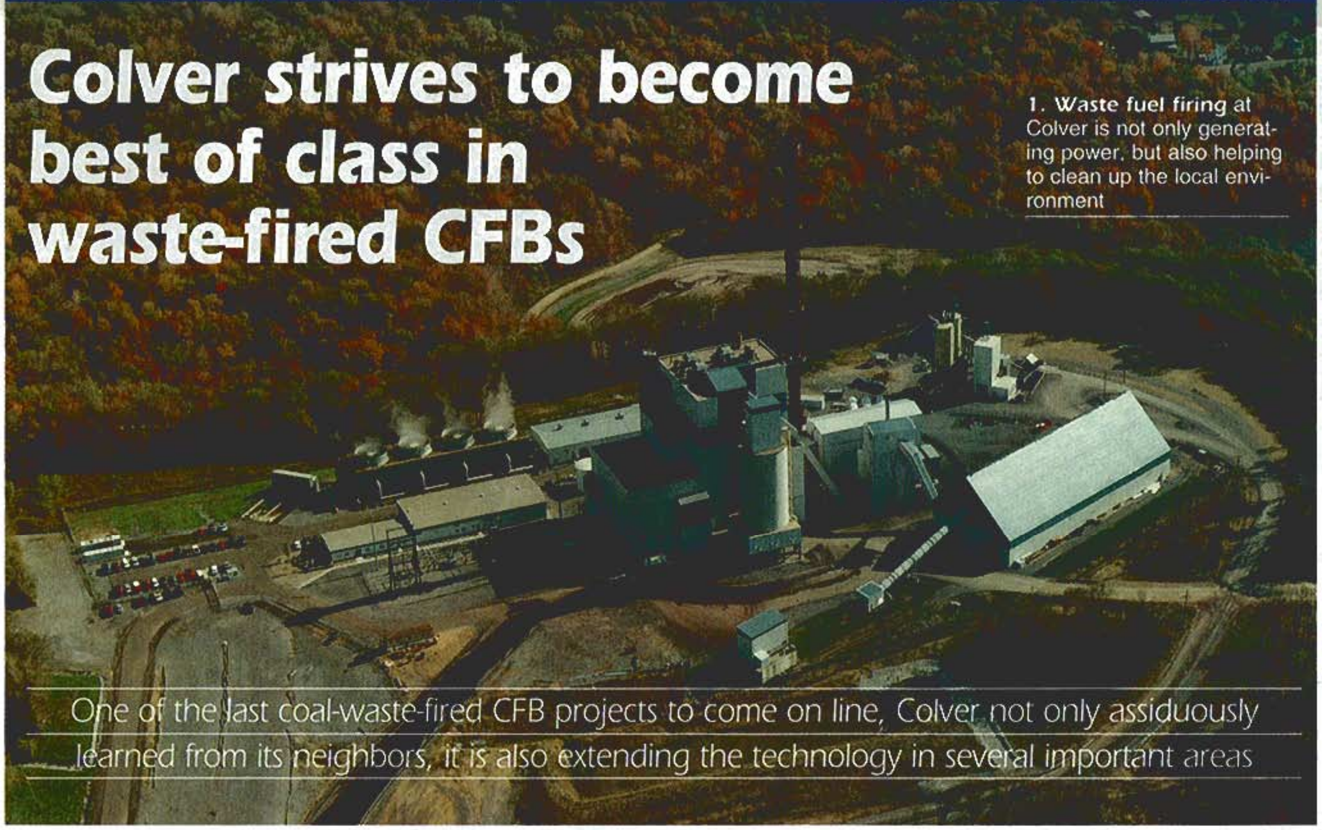
Associated Electric Cooperative Inc Thomas Hill/New Madrid stations

For successfully implementing what was perhaps the most ambitious conversion to Powder River Basin coal, both for environmental compliance and competitive positioning





Colver strives to become best of class in waste-fired CFBs



1. Waste fuel firing at Colver is not only generating power, but also helping to clean up the local environment

One of the last coal-waste-fired CFB projects to come on line, Colver not only assiduously learned from its neighbors, it is also extending the technology in several important areas

It began with an ambitious agenda for the Colver Power Project: Generate cost-effective power with the first coal-waste-fired circulating fluidized-bed (CFB) boiler to operate at 2400 psig while solving several existing environmental and economic challenges in the western Pennsylvania area where the project is located.

With over a year of operating history, Interpower/Ahlcon (A/C) Power Inc, has had good experience with the gob-fired CFB (Fig 1). New jobs have been created for local residents, a dam and reservoir project were completed, and the coal-waste piles are being leveled.

An application of sophisticated performance-monitoring technology testifies to the plant's continuing emphasis on innovation as it prepares for a competitive environment for power sales.

Similar plants are no longer being built, much less planned. Given the changes in the landscape for new independent power projects, it may be years before plants, such as Colver, again find favor with regulators, developers, and investors. Thus, like the last sibling in a brood, Colver

2. Several upgrades and modifications have been made to the fuel handling system

3. All key plant controls are centralized in the main control room and a performance monitoring system has been added

learned much from its sister plants, but is also extending the range for this niche technology. Yet, no matter how many plants of this type are built, burning what amounts to high-grade dirt will never be easy.

For its role in placing what is essentially an environmental blight to productive use, Colver earns POWER's 1996 Powerplant Award.

Meeting expectations

The facility is base-loaded at 102 MW, ±2 MW. Colver's power purchase-agreement requires that the facility be operated in automatic regulation within a 4-MW window. Response rates are periodically tested by the utility. Boiler and turbine tuning have allowed the project to repeatedly achieve the response rate expectations.

The plant has met all operating guarantees and expectations (table). A/C Power-Colver Operations is very satisfied with the performance and operation of the plant, reports Facility Manager Paul Draovitch. While in operation the boiler has been totally reliable; however, problems with the loop-seal expansion joints resulted in lost megawatt-hour production due to the extension of planned outages to repair the joints. Following this failure, the expansion joints were upgraded last fall. The boiler manufacturer, Foster Wheeler Power Systems, Clinton, NJ, has recommended a ceramic-joint design to replace the existing stainless joint. These will be installed in October.

Fuel handling still critical

Lessons learned from previous CFBs were incorporated (POWER, April 1995, p 57) into Colver's design. One area of emphasis was the fuel-handling system (Fig 2), a significant challenge with most CFBs. Even so, some post-design modifications have been required of the system. These include the installation of:

- Heat panels on unloading and transition hoppers to prevent fuel freezing to hopper sides in winter.
- Additional baffles within the crusher/dryer gas ducts, which allow the dryer to achieve design specifications by increasing fuel retention time within the hot gas duct.
- Additional supports, hold-down brackets, and control-logic changes to allow the traveling unloading hopper to remain on its tracks.
- Wetting system to allow crushed fuel fines to be transported by the high-angle transport conveyor.

There are future plans to modify the unloading hopper grating to prevent large, frozen fuel chunks from entering the fuel system.

Operational challenges

Other areas that have presented operational challenges, notes Draovitch, include the crusher-dryer, which had an initial drying capability of 2%. The installation of baffles in conjunction with changes to operating procedures has increased drying percentages to 4 to 6%.

The limestone-feed, rotary-valve clearance and shoe adjustment often requires attention. Slowing down the rotary valves from 16 rpm to 6 rpm has allowed the valve pockets to fill with limestone and minimizes the amount of transport air blowing by the valves.

In the ammonia-injection (selective non-catalytic reduction) NO_x control system, the plant experiences high reagent consumption in winter, low consumption in summer. After rigorous study, no single cause has been identified. Items investigated include ammonia system pressure, fuel-bound nitrogen content, combustor-bed levels, combustor temperatures, cyclone temperatures, boiler O_2, and limestone utilization. Facility personnel are continuing to investigate.

A complete ultrasonic thickness (UT) survey was conducted on the boiler and backpass tubes prior to initial solid-fuel firing. Subsequent UT surveys have shown wear on economizer hanger tubes, certain reheat and superheat tube bends, and economizer tube bends. Shields were installed on the economizer hanger tubes and economizer tube bends. Screens were installed above the reheat and superheat tube bends that showed wear. No abnormal wear patterns were noted in the boiler or anywhere in the unit's refractory.

Performance monitoring

A monitoring and performance system (MAPS) was placed in service in December 1995 to assist operators in optimizing plant performance. MAPS guides the actions of the operator with a real-time display of fuel consumption indices (FCI). The FCI defines specifically which components are responsible for fuel consumption —either in the direct creation of electricity or in the contribution to thermodynamic losses. These parameters can be used for diagnostics and economic dispatching.

Major equipment/service suppliers

CFB boiler	**Foster Wheeler Power Systems,** Clinton, NJ
Monitoring and performance system	**Previs Inc,** Toronto, Ont, Canada; **Exergetic Systems, Inc,** San Rafael, Calif
Crushers/pulverizers	**Pennsylvania Crusher Corp,** Broomall, Pa
Architect/engineer/constructor	**Bechtel Power Corp,** Gaithersburg, Md
Integrated plant controls	**Bailey Controls Co,** Wickliffe, Ohio
Steam turbine/generator	**Mitsubishi Heavy Industries Ltd,** Tokyo, Japan **Westinghouse Electric Corp,** Orlando, Fla
Boiler-feed, other major pumps	**Ingersoll-Dresser Pump Co,** Phillipsburg, NJ
Cooling tower-	**GEA Thermal-Dynamic Towers Inc,** Denver, Colo
Fuel handling equipment	**Stock Equipment Corp,** Chagrin Falls, Ohio
Limestone handling/preparation	**Smoot Co,** Kansas City, Kans; **Fuller Co,** Bethlehem, Pa
Continuous emissions monitoring (CEM) system	**Enviroplan Inc,** Roseland, NJ

With FCI displays, updated in real-time, the operator can observe the impact of his actions component by component and tune the control of each component in an absolute sense, as well as relative to the whole system. System features include:

- Computation of fuel and emissions mass flow rates.
- Instantaneous updates of higher heating value and gross unit heat rate.
- On- and off-line analysis.
- Continuous update of income statement spreadsheets.
- Flexible archival capabilities, including CD-ROM data storage.
- Support for many networked PC workstations and multiple data sources.

A sulfur function optimizer (SFO) parameter was specifically developed for Colver as part of the limestone modeling to reduce both limestone consumption and SO_2 emissions. The model uses the combustion equation modified for limestone conversion to CO_2, calcium sulfate, and calcium oxide. Any form of the sulfate compound, as attached to water, can be addressed, which is important if water is being monitored in the effluent and corrections are being made to the fuel's chemistry.

Ongoing improvements

A redundant fuel-handling-system, progammable logic controller (PLC) was installed in the main control room (Fig 3). The original plant design required that fuel-handling equipment be operated from a fuel-handling control area external to the main control room. A/C Power believes one person can handle all the plant controls and would recommend to future projects that all controls be centralized.

A plant-wide vacuum system was installed that not only improves overall plant cleanliness, it also saves megawatts. Operators can easily clean plugged fuel chutes with the system, minimizing or eliminating the loss of fuel feed to the boiler.

Other completed capital projects include:

- Automation of the steam-jet air ejector regulator, boiler feed-pump discharge stop valves, boiler mainstream stop valve, and boiler-blowdown tank quench valve.
- Installation of redundant loop-seal blower.
- Installation of crusher hydraulic door opener.

Managing warranties

InterPower/Ahlcon Partners LP, Pittsburgh, Pa, jointly developed and managed a warranty program with A/C Power. The plant engineer has effectively managed to completion over 100 warranty items. Based on the success of this program, A/C Power concludes that a properly managed warranty program can eliminate long-term problems, as well as provide substantial cost saving to the project. **Cate Jones**