Exergetic Systems presents an

INTRODUCTION TO THE INPUT/LOSS METHOD

What It Does

Exergetic Systems, San Rafael, California, has developed, tested and installed a unique method of monitoring fossil-fired power plants, termed the Input/Loss Method. The method is especially useful when applied to coal-fired units. Input/Loss allows determination of the following parameters in **real-time**:

- **Fuel Chemistry (with water & ash)**
- **Fuel Heating Value**
- **Boiler Efficiency**
- **Fuel Flow**
- **Turbine Cycle Heat Rate**
- **Unit Heat Rate**
- **Effluent Flow Rates**
- **Emission Rates** ($lb_{Effluent}$/million-Btu_{Fuel})
- **Fuel Consumption Indices** (specifies thermodynamic losses and assigns fuel usage to system component)
- **Tube Failure Flow Rate & Location.**

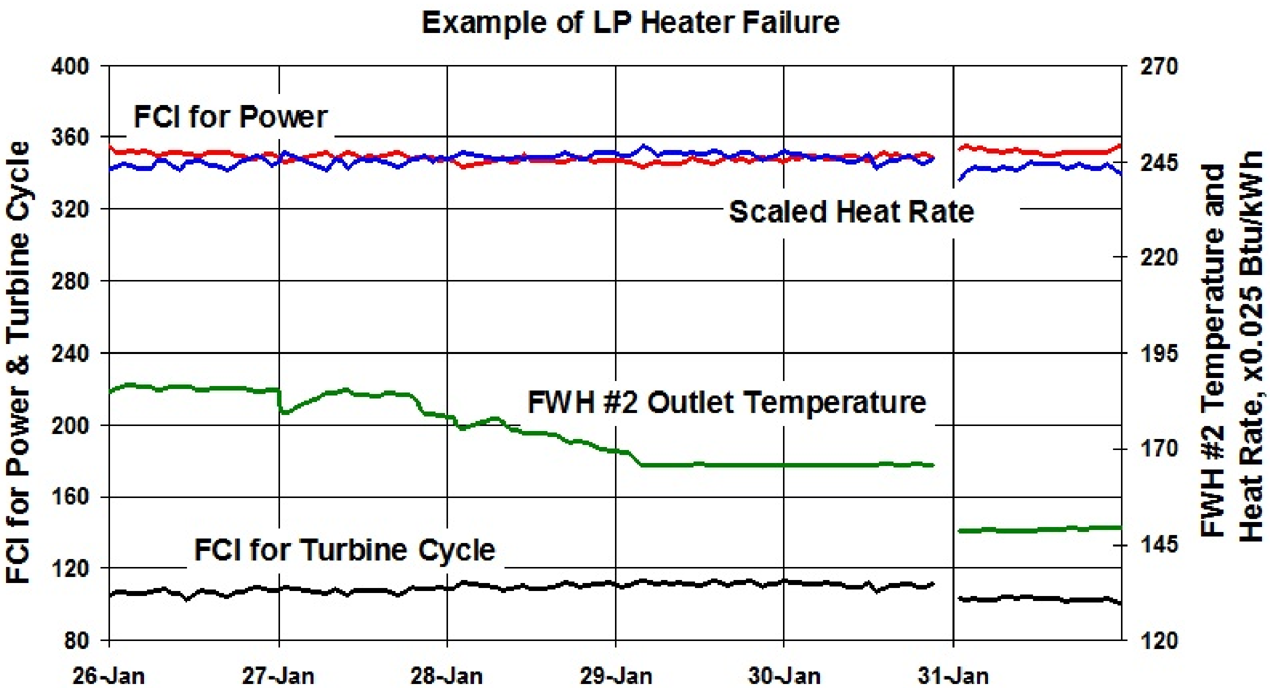
Exergetic Systems' philosophy of monitoring power plants is not to just supply data for displays, but to reduce data via integrated system models, to provide diagnostic information about the power cycle and direction as to how heat rate can be recovered. Any monitoring system can display data from plant instrumentation. The Input/Loss Method provides information. With this philosophy, Exergetic Systems has concentrated on what it does best - power plant thermodynamics. Functionally, a single personal computer, the **Calculational Engine**, executes the Input/Loss Method. The Calculational Engine *per se* is designed for an engineer's consumption; it produces a ≈continuous stream of performance information and engineering reports. Operator displays are then presented through the DCS (via its data highway, historian and graphics packages).

The Calculational Engine identifies heat rate degradations within the system with each Engine "revolution", selected by the engineer, but typically once every 3 minutes - operating on 5, 15 or 30 minute running averages (a one-hour straight average is also available used for reduction of test data).

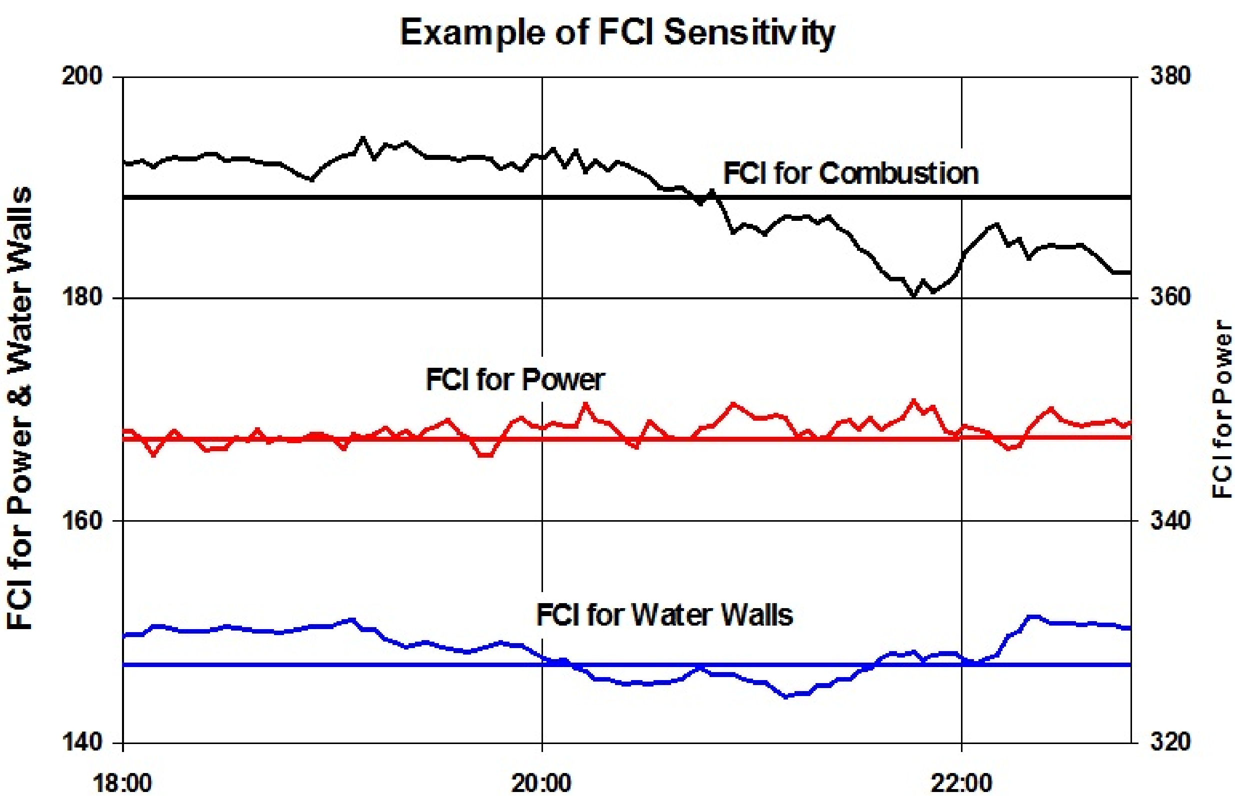
Input/Loss explains fuel usage through its Fuel Consumption Indices. Fuel is consumed to produce electricity and to over-come component and process losses; understanding this division of fuel usage is key for improving heat rate - the consumption of less fuel for every kilowatt produced. The system is expandable: from a base of high accuracy boiler efficiency; to Second Law analyses; to complete **fuel chemistry (with fuel water and ash), As-Fired heating value, coal flow and unit heat rate**; all on-line. Calculations are based on either higher heating value (gross calorific), or lowering heating value (net calorific); with either Btu or SI units. This Method allows full integration of emissions monitoring with thermal performance. Indeed, for the first time, accurate emission flows are obtained, fully consistent with system efficiency.

In addition, based on the Engine's complete resolution of system stoichiometrics, methods have been developed to detect tube failures and their location! Indeed, from September 2003 to April 2004 tests at a 600 Mwe coal-fired unit routed temporary heat exchanger drain lines from inlet headers to the combustion space for direct testing of the Tube Failure Model and its ability to locate faulted heat exchangers.

The following is an example of Input/Loss detecting a degraded Turbine Cycle; investigation revealed a broken bellows joint in a Low Pressure feedwater heater extraction line.



The following is an example of a typical coal-fired operation, showing marked improvement in the combustion process with a concomitant increase in FCI for Power (lower heat rate). A higher FCI for Power means less fuel per kilowatt, for any other FCI a higher value means higher losses.



Input/Loss History

The Input/Loss Method developed from the company's significant testing activity starting in 1982. With the objective of understanding a power plant's thermal performance, successive testing projects evolved procedures which **guaranteed** results (i.e., through Calculational Closures). Such guarantees, in part, implied updating the fuel's heating value and computed fuel flow. Early efforts involved adjusting only fuel water, then carbon/hydrogen relationships, then to complete fuel chemistries including fuel mineral matter (ash). Throughout, this mandated employing effluent measurements on-line, totally integrated with system thermodynamics. Required effluents include CO_2, O_2, and effluent moisture. Note that the history of determining fuel chemistry from combustion products is quite old - dating back to at least the 1950s. Several attempts to apply such techniques to power plants have been attempted. What has been missed, accomplished by Input/Loss, is an integration of effluents with a high accuracy boiler efficiency determined independent of any flow rate, an ability to compute heating values from fuel chemistry, a mechanism for understanding system air leakage and several related topics - resulting in a computed fuel flow intrinsically dependent on such parameters. Practically what is accomplished with Input/Loss is an ability to employ Boiler or Stack O_2 with Stack CO_2 measurements, an integration of system air leakage within the stoichiometrics, and concurrently performing Fuel Iterations. Details are provided in the issued Patents.

During more than 30 major testing projects, and hundreds of Steam Generator analyses, the Input/Loss Method was subjected to a series of proof-of-process tests. These involved both coal- and gas-fired units. The critical benchmark testing was primarily done on gas-fired units (given that fuel flow could be measured with accuracy and then compared to the computed). Although developed for coal-fired units, including Powder River Basin and lignite coals, Input/Loss has equal applicability for oil-, gas- or biomass-fired plants. If a unit switches coal types, or from coal to gas, the Input/Loss Method will serve equally well without computational disruptions.

Required Data

Routine Turbine Cycle data is required to develop the energy flow to the working fluid. Routine Steam Generator data is required, without use of fuel or effluent flows, used to compute boiler efficiency. Input/Loss then preforms Fuel Iterations between an assumed fuel chemistry leading to computed effluents (EX-FOSS), and known effluents leading to computed fuel chemistry (HEATRATE). In addition to routine plant instrumentation, Input/Loss requires the following:

- Ambient psychrometrics
- Well-place Boiler O_2 probes in sufficient quantity to assure a representative measurement or multiple Stack O_2 probes
- Stack CO_2 (per in-situ CEMS)
- Stack H_2O
- Multiple Stack Temperatures.

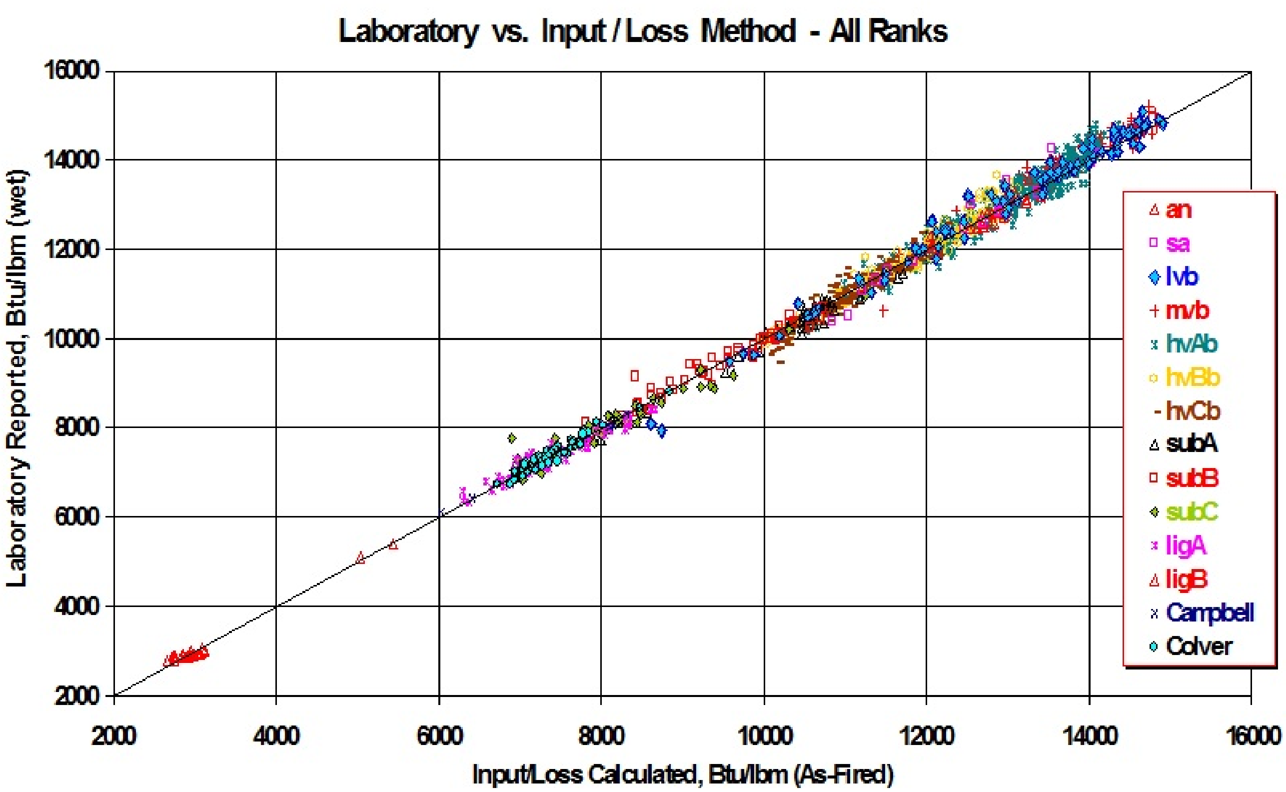
The Engine accepts any combination of on- or off-line Air Pre-Heater leakage input: a ratio of inlet/outlet CO_2 or O_2, either a wet-based or a dry-based ratio - in any combination with the O_2 signal - which can be input as live data. Exergetic Systems has direct experience with a number of manufacturers of moisture probes.

Input/Loss assumes no effluent concentration measurement is accurate; only signal consistency is required. To address this, Exergetic Systems has developed a method to correct any data which might affect system stoichiometrics (termed Choice Operating Parameters, COPs). This method (via the ERR-CALC program) employs several optimization techniques, including multidimensional minimization, random search, neural net techniques, etc. The unique approach taken involves correcting COPs (i.e., effluent measurements) such that certain fuel or system parameters remain constant or as-measured (termed System Effects Parameters, SEPs).

One of these SEPs is the the L-Factor, L_{Fuel} . To develop L_{Fuel} for a given fuel Input/Loss requires a history of ultimate analyses of the specific fuel. Such data is also analyzed for Moisture-Ash-Free (MAF) hydrogen vs. carbon molar relationships. Once established no further updates to the process are required. The system requires no periodic "tweaking". Note that L_{Fuel} is not EPA's F-Factor (believed erroneously computed if using EPA procedures).

As part of Exergetic Systems' benchmark testing program, 1200 ultimate coal analyses involving 12 Ranks and speciality coals from over 400 mines, were process through Input/Loss. This work demonstrated standard deviations in L_{Fuel} can be <0.10% for certain Ranks (for example, L_{Fuel} for Low Volatile Bituminous coal is 792.82 $lbm_{Dry\text{-}Effluent}$/million-$Btu_{Fuel}$ **±0.049%**). Even for some of the poorest lignites, standard deviations in L_{Fuel} have been found at **±0.275%**. Experience has established other SEPs, found quit useful for correcting COPs data. For further details see the Part IV paper available from www.ExergeticSystems.com.

Using these 1200 chemistries with Input/Loss Methods - with imposed errors on effluent concentrations - resulted in proof-of-process comparisons; see the following figure as based on correcting COPs using the SEP L_{Fuel}. This plot does not demonstrate Input/Loss accuracy *per se*, but only the validity of generic Input/Loss Methods. For a studied fuel, reasonably behaved, errors in heating value are typically ± 0.50%.



Tube Failure Detection

Input/Loss has an ability to rapidly detect tube failures and their location within the Steam Generator, without direct instrumentation. By "location" implies the heat exchanger in which a tube has failed, and thus leaking to the combustion space; e.g., a tube failure in the Economizer, Reheater, etc. Rapid detection reduces damage, minimizes degraded heat rate, and minimizes repair time, thus **saving million of dollars**. Tube failures are detected through use of system stoichiometrics, in combination with an ability to correct effluent data through use of optimization procedures. A Stack H_2O instrument is not required, nor is its presence a panacea. The location of the failure within a Steam Generator is determined through use of energy balances and iterative techniques - made possible only because of the integration between effluents and boiler efficiency. Further, the model also indicates how the stoichiometric mechanism of a tube failure has been identified.

Effluent water concentration (at the Stack) may consist of many sources: water formed from the combustion of hydrocarbons; free water born by the fuel; moisture carried by combustion air including air leakage; heat exchanger tube leaks; water added at the point of combustion (e.g., steam used to atomize fuel); pollutant control processes resulting in the in-flow of water; and soot blowing. All such sources of water are addressed by Input/Loss Methods through system stoichiometrics or direct measurements and integrated through a high accuracy boiler efficiency ... in combination with an ability to correct COP parameters through ERR-CALC procedures.

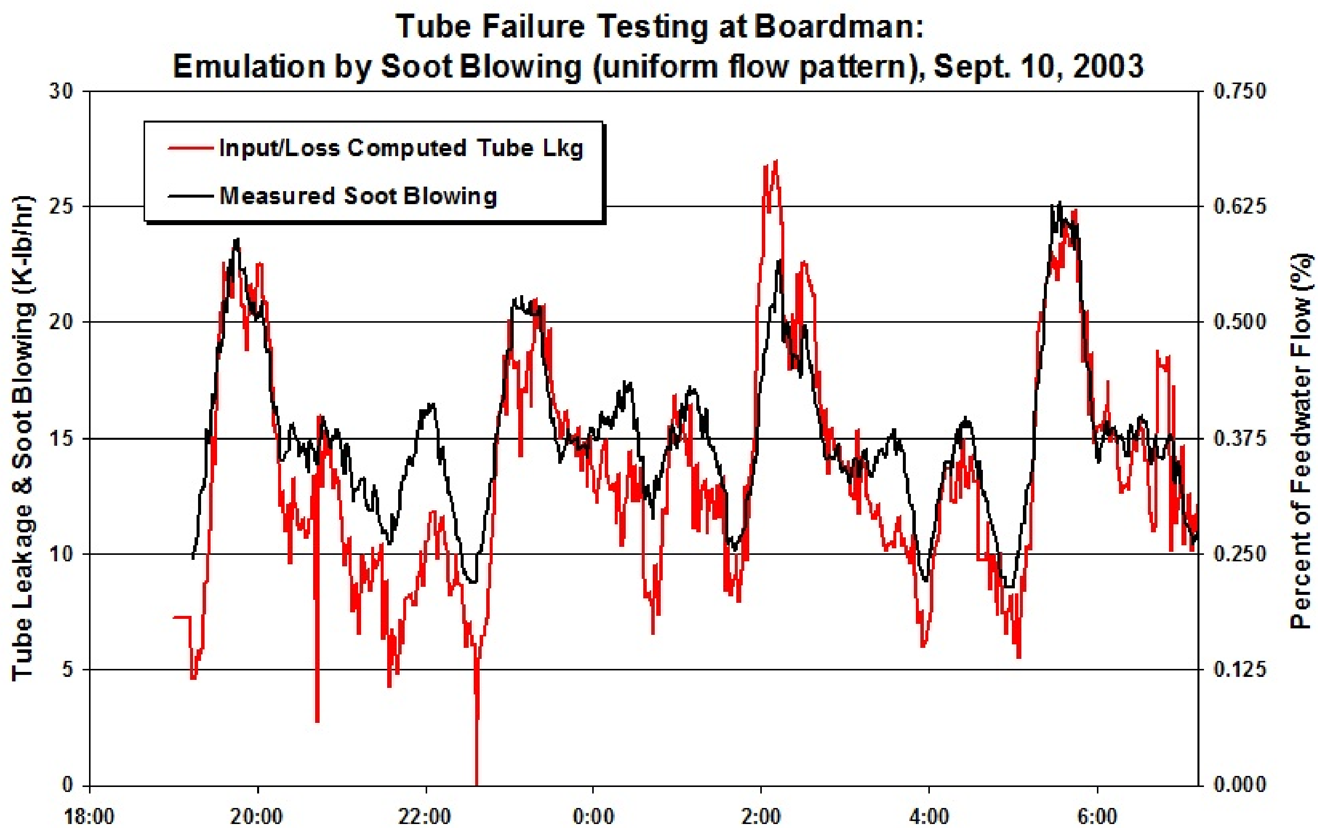
To date (April 2004), the Tube Failure Model has successfully identified a number of tube failures at several installations. Indeed, its initial success at Portland General Electric's Boardman unit has lead to an aggressive testing program running from September 2003 through March 2004. This effort routed blow-down lines from the inlet heaters of all major heat exchangers to the combustion space. The blow-down flows were individually metered. Thus through selected blow-downs, proof-of-process testing demonstrated the predictability of the Tube Failure Model. In addition to this direct injection, testing involves emulating tube leakage using soot blowing steam: by simply declaring soot blowing flow to be an unknown and allowing the Engine to compute a "tube leakage", then comparing results.

Results from the Boardman testing are spectacular, meeting all original objectives:

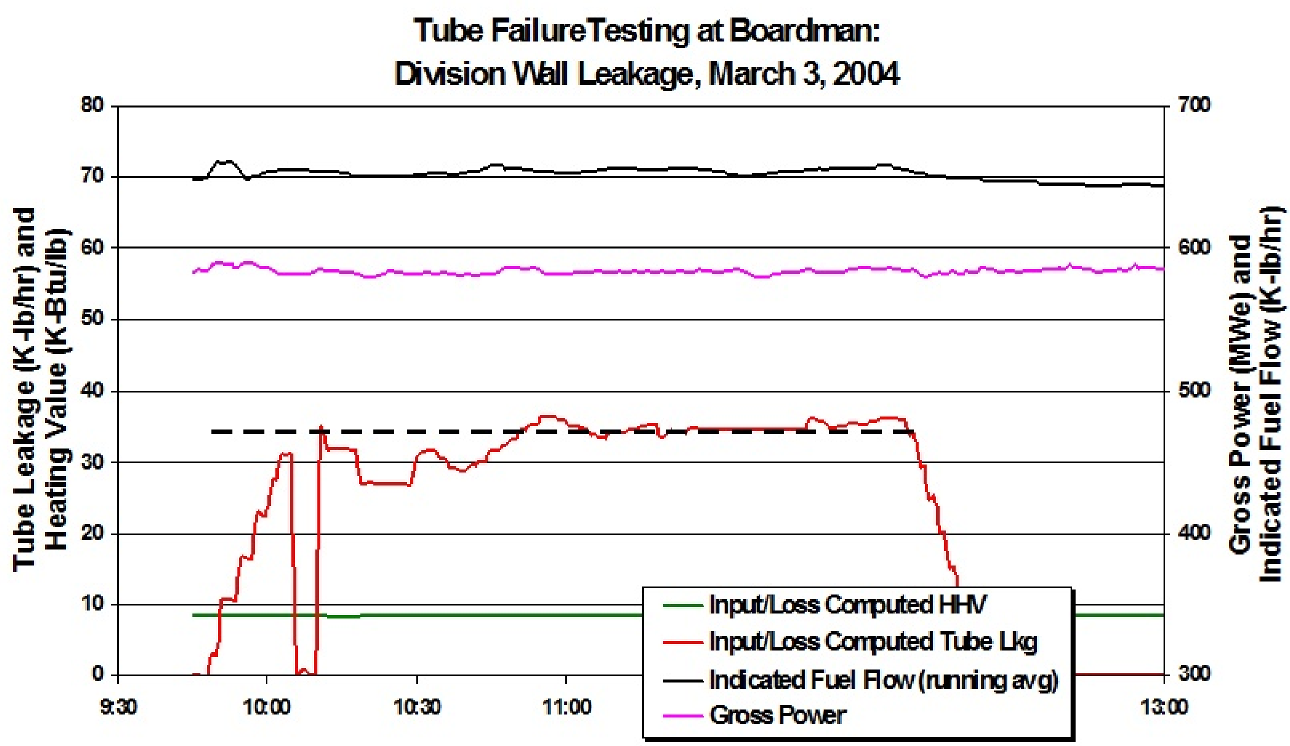
- Detection sensitivity is demonstrated at the ±2,000 lbm/hr level (0.05% of feedwater flow).
- Leak locations were successfully predicted in all five heat exchangers tested.
- The thermal impact of tube leakage is a function of leakage location; as demonstrated by test, and assuming a 40,000 lbm/hr leakage, effects include: 1.0% $\Delta\eta_B$ in boiler efficiency at the Economizer, varying to 0.5% at the Reheater. Before this testing such losses were unknown to the industry ... as tube leakage was under-appreciated.

Comparisons to soot blowing flow are presented below as are the results from a direct injection. Bear in mind that a 2,000 lb/hr resolved tube leak is only 0.05% of feedwater flow at Boardman, this is well within typical data chatter associated with feedwater flow metering. However, Input/Loss system stoichiometrics are sufficiently sensitive to allow for such detection even at these low levels.

See the paper "Detection of Tube Leaks and Their Location Using Input/Loss Methods" for more details. In 2005 this paper won the American Society of Mechanical Engineers (ASME) Prime Movers Committee Award. This award recognizes outstanding contributions to the literature of thermal electric station practice; it was established in 1954.



Tube Failure Testing at Boardman:
Emulation by Soot Blowing (uniform flow pattern), Sept. 10, 2003
Input/Loss Computed Tube Lkg
Measured Soot Blowing
Tube Leakage & Soot Blowing (K-lb/hr)
Percent of Feedwater Flow (%)
30
25
20
15
10
5
0
0.750
0.625
0.500
0.375
0.250
0.125
0.000
18:00
20:00
22:00
0:00
2:00
4:00
6:00



Tube Failure Testing at Boardman:
Division Wall Leakage, March 3, 2004
Tube Leakage (K-lb/hr) and Heating Value (K-Btu/lb)
Gross Power (MWe) and Indicated Fuel Flow (K-lb/hr)
80
70
60
50
40
30
20
10
0
700
600
500
400
300
9:30
10:00
10:30
11:00
13:00
Input/Loss Computed HHV
Input/Loss Computed Tube Lkg
Indicated Fuel Flow (running avg)
Gross Power

Testing for Real-Time Heating Values

Direct testing of computed heating values is, at best, a difficult task when burning coal; and especially if burning a highly variable coal such as from the Powder River Basin (PRB) or lignite. Although such testing work continues, Exergetic Systems believes that secondary indications of computed heating value serve equally well. These indications are trends in the plant's fuel flow and/or combustion air flow. Industrial experience with emission flows would indicate the measurements are biased, and unreliable even for trending. However, at every installation of Input/Loss, engineers quickly develop "sanity checks" as to monitoring performance, and generally based on trended flow rates. The bases for such sanity checks stems from Input/Loss' computational consistency.

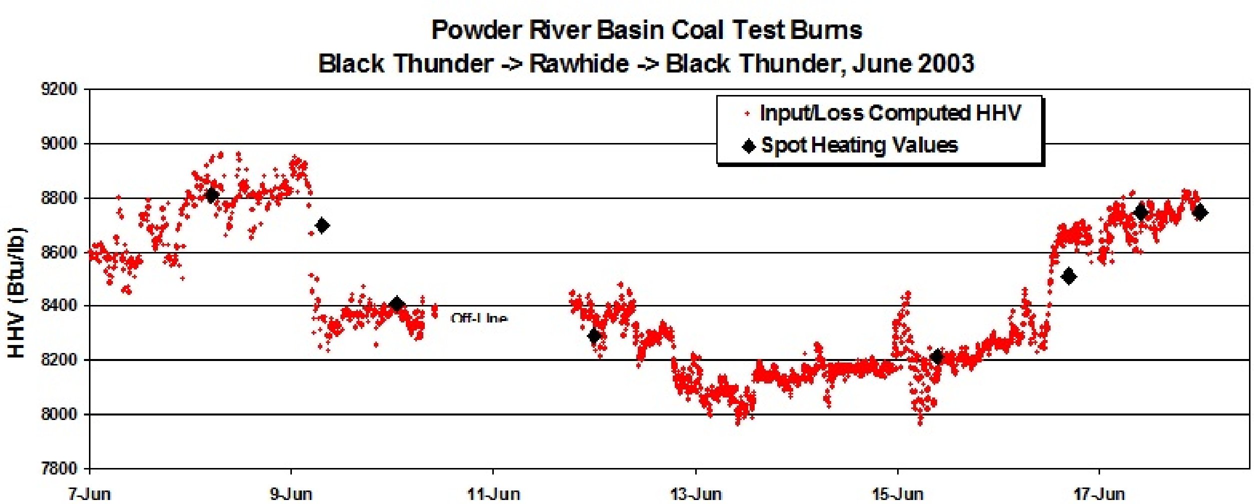
The governing equation for the Input/Loss Method is its computation of fuel flow based on the energy flow to the working fluid, computed boiler efficiency and heating value, and the fuel's Firing Correction. With a computed fuel flow all system mas flows are then determined: combustion air flow, Air Pre-Heater leakage flows, emission flows, etc. All are directly and consistently related. This governing equation is non-forgiving: an error in computed heating value is only compounded by a concomitant error in boiler efficiency, and thus will appear in all mass flows.

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

where:

m_{AF} = Mass flow of As-Fired fuel (i.e., wet with water and ash), lbm_{AF}/hour.
BBTC = Energy flow to the working fluid from combustion gases, Btu/hr.
$\eta_{B\text{-}HHV}$ = Boiler efficiency (HHV-based), unitless.
HHVP = As-Fired higher heating value, Btu/lbm_{AF}.
HBC = Firing Correction term, Btu/lbm_{AF}.

Periodically, a power plant will conduct test burns of different coals, which affords an opportunity for direct comparisons. Such an example is provide below. Further, Exergetic Systems has proposed to the power industry several new methods of qualifying on-line monitoring systems. These new methods include comparisons to the unit's Energy Compensator, to a computed soot blowing flow, to a computed relative humidity, etc. (refer to the white paper "Notes on Benchmarking On-Line Monitoring Systems").



Patents

The Input/Loss Method, representing certain processes which can lead to improvements in the thermal efficiency of systems burning fossil fuels through system thermodynamics and emissions monitoring, is protected by United States, European, Canadian and Australian patents. Additional patents are pending. The following partial list of Input/Loss Patents, and associated technologies, are available for licensing, please inquire. There are several additional Patents concerning improved Regenerative Rankine cycles, efficient operation of pollution reduction processes, etc., please inquire. Copies can be had from Exergetic Systems, or from www.USPTO.gov.

- "Method for Fuel Flow Determination and Improving Thermal Efficiency in a Fossil-Fired Power Plant":
  United States Patent No. 5,367,470, November 22, 1994.

- "Methods and Systems for Improving Thermal Efficiency, Determining Effluent Flows and for Determining Fuel Mass Flow Rates of a Fossil Fuel Fired System":
  United States Patent No. 5,790,420, August 4, 1998.

- "Input/Loss Method for Determining Fuel Flow, Chemistry, Heating Value and Performance of a Fossil-Fired System":
  United States Patent No. 6,522,994, February 18, 2003;
  Australian Patent No. 762,836, October 23, 2003;
  Canadian Patent No. 2,325,929, June 8, 2004.

- "L Factor Method for Determining Heat Rate of a Fossil Fired System Based on Effluent Flow":
  United States Patent No. 6,560,563, May 6, 2003.

- "Input/Loss Method for Determining Boiler Efficiency of a Fossil-Fired System":
  United States Patent No. 6,584,429, June 24, 2003.

- "F Factor Method for Determining Heat Rate and Emission Rates of a Fossil-Fired System":
  United States Patent No. 6,691,054, February 10, 2004.

- “Method for Correcting Combustion Effluent Data When Used for Input/Loss Performance Monitoring of a Power Plant”:
  United States Patent No. 6,714,877, March 30, 2004.

- "Method for Detecting Heat Exchanger Tube Failures When Using Input/Loss Performance Monitoring of a Power Plant":
  United States Patent No. 6,745,152, June 1, 2004.

- "Method for Detecting Heat Exchanger Tube Failures and Their Location When Using Input/Loss Performance Monitoring of a Power Plant":
  United States Patent No. 6,651,035, November 18, 2003;
  European Patent No. 1,502,188, July 25, 2007;
  Great Britain Patent No. 1,502,188, July 25, 2007;
  Republic of Ireland Patent No. 1,502,188, July 25, 2007;
  Canadian Patent No. 2,479,238, February 16, 2010.

- "Method for Remote On-Line Advisory Diagnostics and Dynamic Heat Rate When Used for Input/Loss Performance Monitoring of a Power Plant":
  United States Patent No. 6,799,146, September 28, 2004.

- "Method to Synchronize Data When Used for Input/Loss Performance Monitoring of a Power Plant":
  United States Patent No. 6,810,358, October 6, 2004.

- "Method for Improving the Control of Power Plants When Using Input/Loss Performance Monitoring":
  United States Patent No. 6,868,368, March 15, 2005.

- "Method and Apparatus for Analyzing Coal Containing Carbon Dioxide Producing Mineral Matter as Effecting Input/Loss Performance Monitoring of a Power Plant":
  United States Patent No. 6,873,933, March 29, 2005.

- "Method for Detecting Heat Exchanger Tube Failures and Their Location When Using Input/Loss Performance Monitoring of a Recovery Boiler":
  United States Patent No. 7,039,555, May 2, 2006.

- "Input/Loss Method Using the Genetics of Fossil Fuels for Determining Fuel Chemistry, Calorific Value and Performance of a Fossil-Fired Power Plant":
  United States Patent No. 7,328,132, February 5, 2008.

- "Input/Loss Method and Apparatus Using the Genetics of Fossil Fuels for Determining Fuel Chemistry, Calorific Value and Performance of a Fossil-Fired Power Plant":
  Australian Patent No. 2006-201203, October 9, 2008;
  European Patent No. 1,835,228, July 7, 2010;
  Great Britain Patent No. 1,835,228, July 7, 2010;
  Republic of Ireland Patent No. 1,835,228, July 7, 2010;
  German Patent No. 1,835,228, July 7, 2010;
  Swiss Patent No. 1,835,228, July 7, 2010.

- "Apparatus for the Determination and Evaluation of Coal Chemistry Based on the Genetics of Fossil Fuels":
  United States Patent No. 7,809,526, October 5, 2010.

Engine Software

Exergetic Systems supplies the following existing software components for its Calculational Engine, brief descriptions of the principle software follow:

- EX-FOSS (Steam Generator simulator)
- FUEL (fuel chemistry management, prep for EX-FOSS)
- HEATRATE (fuel chemistry and heating value calculations)
- ERR-CALC (error analysis of any parameter effecting system stoichiometrics)
- SIP (Excel interface for input and output)
- ESI_Lib (Excel DLL Add-Ins for SIP support, thermodynamic properties, etc.)
- EX-FLOW (reduction of flow meter data)

EX-FOSS is a performance monitoring (executable) program for fossil-fired boilers which provides a high level of computation and diagnostic capability. Such capability includes heat transfer modeling, soot blowing recommendations, stack acid & moisture dew points, excess air recommendations, the input of hot- or cold-side Air Pre-Heater effluent data, variance analysis, etc. EX-FOSS also calculates an innovative Second Law performance parameters: the Fuel Consumption Indices (FCIs) and Component Heat Rates. These parameters aid in directly locating the source(s) of performance degradation. EX-FOSS requires specification of fuel chemistry, routine boiler data and Boiler or Stack O_2; it computes all effluents.

FUEL is a service (executable) routine for EX-FOSS, which combines up to five fuels (of any type, molar or weight fractions), to form a composite fuel. FUEL alters EX-FOSS input files.

HEATRATE is an (executable) routine designed to operate in an iterative fashion with EX-FOSS and FUEL, together forming Input/Loss “Fuel Iterations”. HEATRATE calculations include the determination of fuel chemistry and heating values based on effluents. HEATRATE computations also resolve the location of a heat exchanger having tube leakage.

ERR-CALC is a sophisticated program operating Multi-Dimensional Minimization techniques on SEPs such as L_{Fuel} and others (depending on their consistency, such as plant "indicated" fuel flow, reference heating values, etc.). The only output from ERR-CALC are correction factors to COPs (any parameter which might effect system stoichiometrics).

DCS Interfaces

Exergetic Systems assumes complete responsibility for developing appropriate Latching Software; i.e., communication software between the DCS data highway and SIP. Currently Exergetic Systems has Latching Software with the following data managers, many having seen years of Engine experience:

- PI from OSIsoft, Inc.
- RTX from Real Time eXecutives, Inc.
- Ovation from Emerson Electric (i.e., Westinghouse Process & Control)
- @aGlance from Axeda Systems Inc.
- ModBus protocol from Modicom Inc. (for Engine output only)
- OPC protocol from IBM and Emerson Electric
- Profibus DP
- DeviceNET from Allen-Bradley
- ASCII protocol in serial format.

Engines are typically commissioned with between 60 and 120 acquisitioned data points. It employs 1 minute averaged data. The great majority of these points are commonly monitored by the DCS. Polling this data for updates typically occurs multiple times every minute, the Engine then forms the selected running average. Output is updated, typically consisting of 100 to 200 points (user defined). Calculations are based on 5, 15 or 30 minute running averages; a 60 minute average is also available.

Engine Hardware

The Calculational Engine, operating the Input/Loss Method, consists of one personal computer, operating under the latest Microsoft operating system. Note that the Engine's software is flexible; it does not require a hyper-fast computer. One revolution of the Engine (resolving fuel chemistry and heating value) typically requires from 20 to 60 seconds using a 1000 MHz computer. However, pronounced changes in effluent data, use of the Tube Failure Model, and/or complex error analysis could impose upwards of 120 second run times. An assumed 3 minutes/revolution frequency is suggested to account for all variations in plant parameters, data acquisition collection, options and SIP (Excel) computational overhead. Monitoring is limited to one computer (Engine) per Unit. The Engine will not operate properly if loaded with any but Engine software and the base operating system. This is indeed an "Engine", its sole function is repetitive computations for a single Unit. Also, communications hardware is required for high speed modem or internet link.

Reports and Displays

It is easy to generate operations and management reports automatically given the Excel-based SIP. Such reports can contain current or historical values. SIP contains ≈2000 output values any of which can be selected. In addition, the following reports are available at each Engine revolution:

- EX-FOSS generates a 12 page standardized "Steam Generator Performance Report";
- EX-FOSS generates an "EPA Emissions Report" for all effluents;
- HEATRATE generates a single page summary of the resolved fuel heating value, fuel flows, unit heat rate and other summary data;
- HEATRATE generates a single page summary of results from the Tube Failure Model: flow rate, failure mechanism and location of the failed tube;
- Generated logs of Warning & Error Messages, and system diagnostic logs; and
- SIP employs 14 spreadsheets, many of which summarize thermal performance information, including differential heat rates and associated savings/costs.
- Up to 40 user defined computations are afforded under SIP whose results are automatically placed in the output array.

The Calculational Engine is intended for an engineer's tending - its purpose is to feed information to the DCS for routine operator display. The following displays are suggested, and typically employed by Input/Loss users; note that all such data is also immediately available to the performance engineer via the Calculational Engine's main display and through SIP. There are routinely 18 FCIs available.

- **Power Plant System**

  Fuel Consumption Indices (FCI) versus time (the most popular format):

Power	Economizer	Reheater
Boiler to Drum	Drum to Final SH	Turbine Cycle

  Economics of Components (based on FCIs and fuel cost)
  HP & IP Turbine efficiencies
  Gross and Net Heat Rates

- **Steam Generator**

  Boiler Efficiency versus time Tube Failures & Location
  Soot Blowing recommendations System Air Leakage

- **Engine Operation**

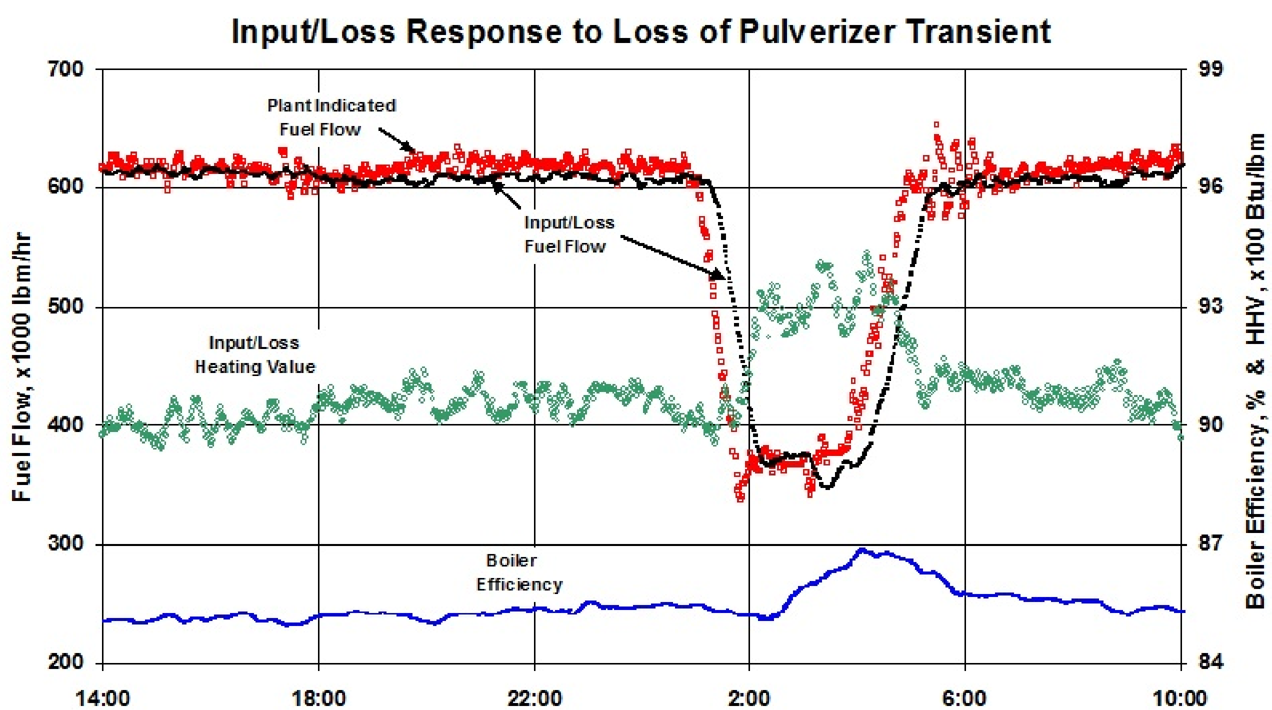
  Input/Loss computed fuel flow versus plant indicated fuel flow.
  Warning messages and numerical convergences
  CO_2 and H_2O correction factors versus time.

“What If” Studies

Classical "What If" studies are simply implemented since the performance engineer has access to all performance computer programs resident in the Calculational Engine and their input files. Exergetic Systems' application programs can be installed on non-Engine computers for off-line analyses. In addition, options are provided which allow the engineer to choose between the use of either the current data (the last averaged data to be down-loaded to the Calculational Engine), or to enter data through a routine's normal input channels. Further, SIP software allows up to 12 "References Cases" to be employed which could represent annual I/O test results, etc.

“What If” questions can only be answered if the on-line monitoring, indeed, is accurately tracking the system. The following plot presents Input/Loss results when monitoring a unique transient associated with a 660 MWe coal-fired unit. This unit was running a mix of low and high energy coals feeding seven mills. Six mills had low-energy 8,100 to 8,500 Btu/lbm Powder River Basin coal with 30% moisture, the seventh mill had 11,000 to12,500 Btu/lbm coal having less than 10% moisture. A low-energy mill was tripped off-line resulting (correctly) in an increase in the computed heating value of the composite fuel (again, based on the selected COPs, optimizing only against a L_{Fuel} SEP). The Engine’s computed fuel flow and the plant’s “indicated” fuel flow are presented showing excellent agreement; boiler efficiency and computed composite heating value are also presented. Full load was re-established by bring a new mill on-line containing a mix of low- and high-energy coal, thus the slightly higher composite heating value starting at 05:30.

Further study of the figure shows a “lag” and then “lead” between the value of computed and plant’s indicated coal flows. The Engine, after solving for fuel chemistry and heating value, computes fuel flow based on heat input to the working fluid, ΣQ. Such transient differences between calculated and indicated coal flows represents effects of the working fluid’s stored energy. During a load decrease, the computed fuel flow is greater than the plant’s indicated since the ΣQ term “sees” effects from the stored energy in the Deaerator and condenser. Conversely during the return to full power, the calculated fuel flow is less than the indicated, caused by an incrementally higher flow actually being added to re-establish stored energies required of the higher load. Although the presentation employs an expanded heating value scale, it also demonstrates the volatile nature of mixing coals. Such information is valuable, allowing for consistent decisions and “What Ifs”.



Turbine Cycle Monitoring Tools

A Turbine Cycle performance parameter was developed by Exergetic Systems for on-line monitoring. It is not a panacea, but simply another tool which can be used as an "index" for judging the thermal health of a Turbine Cycle. This parameter is called the "L^2 Factor", which stands for Low pressure turbine / Leakage monitoring (not to be confused with the fuel parameter L_{Fuel}). The only plant data required to determine L^2 are LP turbine inlet pressure and gross power. Calculations are performed under SIP. A technical paper descriptive of the L^2 Factor is available.

Exergetic Systems has long used LP bowl pressure as a validity check of steam path flow balance of the HP and IP turbines when analyzing performance test data. If seal flows, leakages, feedwater flow, extraction flows, etc. have been property accounted, then the measured LP bowl pressure can be accurately predicted using flow passing ability of the LP inlet (assuming no erosion or deposits of the nozzles). This, combined with the fundamental relationship between power and flow, resulted in development of the L^2 Factor ($\equiv$ LP Bowl Pressure/Gross Power)^2. Numerous evaluations have showed the parameter to be essentially constant over the upper load range. Given this insensitivity to power, the parameter is monitored with time and thus used to sense changes in thermal performance over the common load range. Any change in the numerical value of L^2 acts as an alarm bell; the Cycle's thermal health has changed!!

Another tool for Turbine Cycle monitoring, proven to be most useful hour-by-hour is a system of surface-mounted thermocouples placed on all condenser penetrations. T/C outputs are routed to the data highway and to operator's displays; they are alarmed at ≈superheated steam temperatures or by experience. This system, not involving Input/Loss, provides an obvious vehicle to identify where in the Turbine Cycle unusual leakages are occurring; it has proven to be especially useful during startup.

Another tool for Turbine Cycle monitoring is the EX-SITE$_{Batch}$ program. Although technically apart from the Engine, it can be used off-line for simulation and detailed study of the Turbine Cycle. Proper use of EX-SITE$_{Batch}$ (or, indeed, of any Turbine Cycle simulator) is explained in a technical paper available on request. However, its use is not advised unless the station has an abundance of idle engineers. If used at all, it should be used at least once per month, properly benchmarked. Note that over 85% of thermodynamic irreversible losses derive from the combustion process and associated heat exchangers. When Turbine Cycles are viewed as devoid of combustion gas/working fluid heat exchangers and the process of power generation, then its "Miscellaneous Turbine Cycle" FCI - computed by EX-FOSS - is rarely over 120 (or 12%). Simulating hundreds of components as with EX-SITE$_{Batch}$ is an unnecessary monitoring burden; and even when run off-line, is typically an unwarranted waste of time if not properly benchmarked.

Fuel Consumption Index

This section extracts the salient points from the technical paper on the Fuel Consumption Index concept; the full paper is available at www.ExergeticSystems.com .

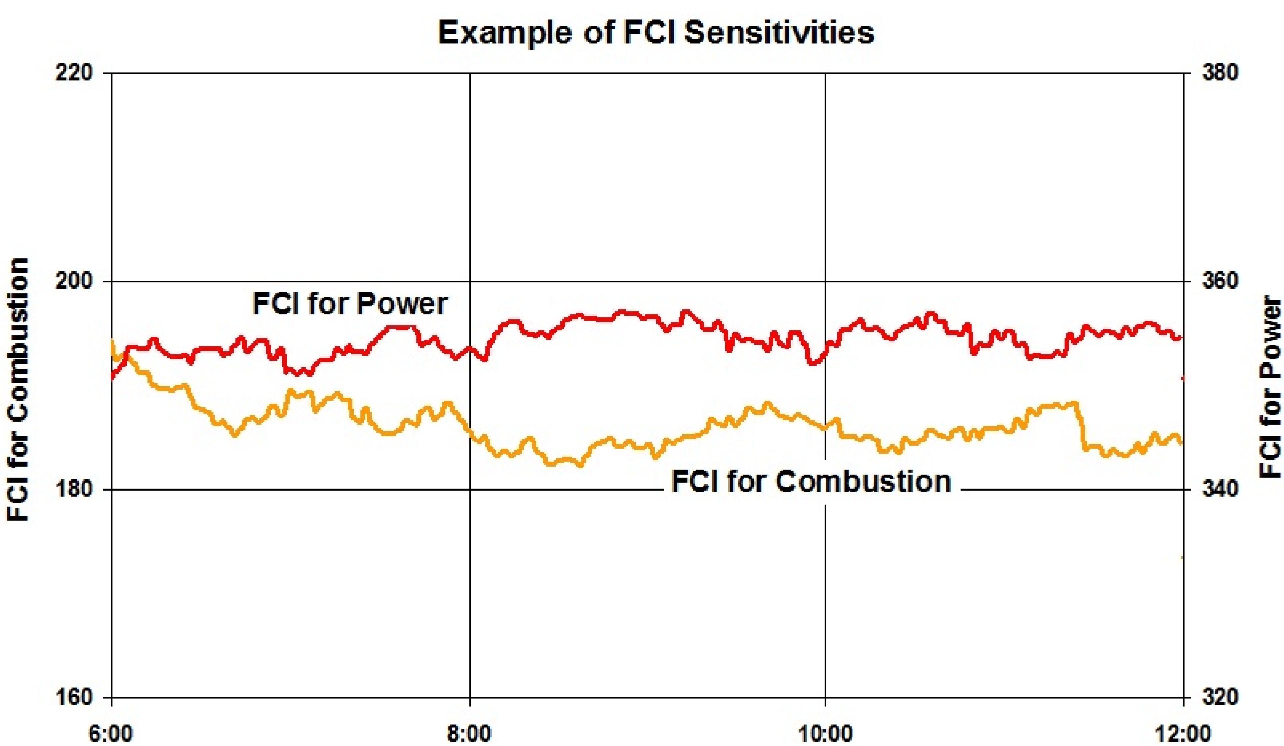
The professional life of a thermal performance engineer is not devoted to the management of energy flows, nor to the conservation of fuel *per se*. Our *raison d'être* is the generation of adequate electricity for society using minimum fuel. This two-sided livelihood does not result nor imply the closing of power stations to conserve fuel. 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 (lower condenser heat rejection, Q_{Rej}), but say little of electrical generation. In summary, unit heat rate as measuring the **utilization of fuel energy flow** (fuel supplied versus Q_{Rej}) is not suited for improving electrical production.

If electricity is to be produced with the minimum of unproductive consumption of fuel - then thermodynamic irreversible losses must be understood on a system bases. Such understanding cuts across vendor curves, plant design, fuels, etc. Thermal losses in a nuclear unit are comparable at a *prima facie* level to losses associated with any thermal system. They are what we must minimize to achieve effective production of electricity, no manner the method of that production. The Second Law offers the only foundation for the study of such losses, through its exergy concept.

Differing energy flows have differing potentials for power production, the direct and immediate measure of this potential for power is exergy: $(h - h_{Ref}) - T_{Ref} (s - s_{Ref})$. Exergy is the Second Law's "working variable" and deals with the quality of an energy flow, a concept which relates to the **utilization of potential power** associated with a given operating system: a system's potential power can only result in losses and actual power (therefore, minimize the losses and power must increase for the given system). The Fuel Consumption Index (FCI) used by Input/Loss is simply a ratio of irreversible losses to this potential power, or a ratio of actual power to potential power.

FCI tells us why fuel is being consumed. It tells us specifically what components and processes are thermodynamically responsible for fuel consumption given either their direct creation of electricity (FCI for Power) or their contributions to irreversible losses (e.g., FCI for Combustion). FCIs sum to 1000 for the entire system, thus one must only maximize the FCI for Power, minimize all other FCIs (losses). When the FCI for Power goes down, it will always be off-set by a higher irreversible loss FCI - indicating the location of the degradation.

In the following example FCI for Power has improved through operator action by reducing irreversible losses associated with the combustion process. Such computations would not be possible without understanding fuel chemistry, heating value, fuel flow, combustion gas flows, etc. - all afforded, on-line, by Input/Loss. Such feedback to the operator is vital, and uniquely provided by Input/Loss.



User Comments

Given years of benchmark experience - and an ability to self-calibrate the using soot blowing flow and/or ambient relative humidity - there is no thermodynamic reason why Input/Loss can not accurately monitor a coal-fired power plant. However, in addition to thermodynamics, a successful installation will also rely on properly maintained instrumentation and plant involvement. To this end the following user comments are noteworthy.

Mohave: 96% reliability for 10 years.
"The reliability of Exergetic Systems' on-line Calculational Engine at Mohave exceeded 96% with minimal software maintenance. This outstanding reliability was achieved over a ten year period [1987-1997]. As I remember, debug took approximately 3 months."

Charles L. Roberts, former Manager Performance Engineering,
Mohave Generating Station, Southern California Edison.
Presently with C. Roberts Enterprises, Inc., (928) 775-8145. May 10, 2004.

Colver: 90% reliability for 5 years.
"The Input/Loss Method was installed at the Colver Power Project in early 1996 shortly after the station went into commercial operation. As the station Performance Engineer for 5 years (1996-2001) I would estimate the Input/Loss reliability at over 90%. Even in the face of several loss of instrumentation challenges (stack moisture, stack CO, stack CO_2) the Calculation Engine continued to provide reliable performance data. The flexibility of the Calculation Engine to handle these challenges is a testament to its robust design. Key parameters monitored include: Power FCI, Combustion FCI, Sulfur Function Optimizer "SFO" (developed specifically for the Colver Power Project), and calculated fuel chemistry (heating value, % moisture) since Colver's fuel quality varied significantly."

Brad Deihl, former Engineering Supervisor,
A/C Power - Colver Operations.
Presently Senior Engineer with Exelon Corp., (717) 456-3623. May 25, 2004.

Boardman: 94% reliability for 3 years.
"The Boardman plant analyzed 2002 data and came to the conclusion the Exergetic Systems [Calculational] Engine had a reliability of 94.4%. However, in 2003 and 2004 the reliability has appeared to have matched or bettered that for 2002."

Dave Rodgers, Plant Engineer,
Boardman Coal Plant, Portland General Electric, (541) 481-1226. May 12, 2004.

Nebraska City: 95% reliability.
"We currently use the [Calculational] Heat Rate Engine for trending key parameters, such as, combustion efficiency and miscellaneous turbine cycle. I frequently check the fuel heating value and the Power FCI. The engine is very robust with flexibility in analyzing plant thermodynamics. It provides credible data at least 95% of the time. We take into account daily calibrations of stack CO_2 instruments [Hold Model is activated], which cause small disturbance in engine output only during the calibration period."

Bruce Stanley, Senior Production Operations Engineer,
Nebraska City Unit 1, Omaha Public Power District, (402) 514-8109.
May 14, 2004.

Lough Ree and West Offaly Power Plants: 99% reliability.
"I thought I would comment on the reliability of the Calculational Engines operating your Input/Loss Method at our Lough Ree and West Offaly Power Plants. By examining the Engine system logs (ESI_Run_Configuration.ini) at the West Offaly unit, I see that we are demonstrating over 99% reliability; i.e. "Total Failed Runs" versus "Total Runs". As you know the Lough Ree unit is in outage. Data aside, I must say that after our instrumentation problems have been fixed earlier this year, the Engines haved been extremely sound. Thank you for your efforts. I look forward to our planned testing at West Offaly in two weeks."

Tom Canning
Manager, Test & Efficiency
Power Generation
Electricity Supply Board
Dublin, Republic of Ireland
+353-87-298-9836. April 30, 2007.

Company Experience

Exergetic Systems is a consulting firm dedicated to quality, highly controlled engineering using innovative approaches. The company has learned how to monitor power plants through testing and analyses! It has completed over 36 detailed thermal performance evaluations of power plant systems - both Steam Generator and Turbine Cycle - including testing and analysis, leading to recommendations for heat rate improvement. The company has tested and analyzed conventional fossil-fired, nuclear, combustion turbines, fluidized bed combustors and geothermal units.

The company has supplied Calculational Engines to a wide variety of power plants, for example:

- Mohave Generating Station, Units 1 & 2 (operated by Southern California Edison) burning a coal slurry with highly variable fuel water;
- Colver Power Plant, a fluidized bed combustor with injected limestone, Colver, Pennsylvania (winning the US 1996 **Powerplant of the Year** award, in part due to its use of Exergetic Systems' Input/Loss Method);
- Amynteon Steam Electric Station, Unts 1 & 2 (Public Power Corporation, Greece), 300 MWe units burning lignite-B;
- Lough Ree & West Offaly Power Plants (Electricity Supply Board, Ireland), fluidized bed units burning Irish peat;
- Boardman Coal Plant (Portland General Electric), a 610 MWe unit burning Powder River Basin coal (two of its engineers won ASME’s 2005 **Prime Movers Committee Award** for confirmatory testing of Input/Loss’ Tube Failure Model);
- Ag. Dimitrios Steam Electric Station, Units 1 -5 (Public Power Corporation, Greece), the largest station in Greece with five ≈300 MWe units burning lignite-B;
- Lavrion Steam Electric Station, Units 1 & 2 (Public Power Corporation, Greece), burning oil and natural gas;
- etc.

As of 2010 a total of twenty Calculational Engines have been installed.

Partial List of Clients

A/C Power Colver Operations
Alabama Power Company
American Electric Power Co.
Arizona Public Service Company
Arkansas Power and Light Co.
Baltimore Gas and Electric Co.
Basin Electric Power Coop.
Big Rivers Electric Corporation
Central Illinois Light Company
Columbus Southern Power Company
Consolidated Edison Company
Conn. Yankee Atomic Power
Consumer's Power Company
Cooperative Power Association
Dayton Power & Light Company
Detroit Edison Company
El Paso Electric Company
Electricity Supply Board (Ireland)
Encor-America, Inc.
Enron of North America
First Energy
Florida Power Corporation
Impell Corporation
Iowa Electric Light & Power
Iowa Public Service Company
Iowa Southern Utilities Co.
Jacksonville Electric Auth.
Kansas City Power & Light Co.
Kansas Gas & Electric Company
Kansas Power & Light Company
L.A. Dept. Water & Power
Minnesota Power Company
Mississippi Power Company
Montana Power Company
National Aeronautics and Space Administration (NASA)
Northeast Utilities Service
Ohio Edison Company

Oklahoma Gas & Electric Co.
Omaha Public Power District
Pacific Gas and Electric Co.
Pacific Power and Light Co.
Penn. Electric (PENELEC)
Portland General Electric Co.
Public Service Co. of Colorado
Public Service Co. of Indiana
Public Service Co. of Oklahoma
Public Power Corporation (Greece)
Quabbin Industries
Riley Stoker Corporation
Rochester Gas & Electric Corp.
Rocketdyne Division of Rockwell International, Inc.
Rosemount Controls, Inc.
Sacramento Municipal Utility District
Salt River Project
San Diego Gas & Electric Co.
Santee Cooper (South Carolina Public Service Authority)
Savannah Electric & Power Co.
Scientific Systems Services
South Carolina Gas and Electric Company
Southern California Edison Co.
Southwest Public Service Co.
TransAlta Utilities Corp. (Canada)
Tennessee Valley Authority

Contact Information

Matt L. Reinhardt
Vice President Marketing
voice: **636-209-1011**
fax: 636-887-0070
e-mail: Reinhardt@ExergeticSystems.com

Fred D. Lang, P.E.
President
voice: **415-455-0100**
fax: 415-455-0215
e-mail: Lang@ExergeticSystems.com

Exergetic Systems, Inc.
12 San Marino Drive
San Rafael, California, USA 94901

For technical papers and general information on Exergetic Systems visit:
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