Closing the Control Loop on Boiler Operations: Results from a TDLAS Sensor and Smart Process Control Software Combination

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Abstract

The National Energy Technologies Laboratory, NETL, has sponsored two Zolo Technologies-led projects at DTE Belle River Unit 2 and AEP Amos, to demonstrate the reduction of CO_2/MWh via generation efficiency improvements. The DTE boiler is a 650 MW, sub-critical coal fired plant with a 2009 capacity factor of 89%. The AEP boiler is a 1,300 MW, super-critical unit with a capacity factor of 88%.

The objective of the project is to reduce CO_2/MWh through combustion balancing and optimization. The key project tools are plant personnel training, in-furnace measurement of combustion gases, expert engineering services, and software optimization. The technologies and methods developed during this project can be used to provide significant, rapid, and low-cost reductions in CO_2 emissions on the majority of coal-fired boilers across the US. To date, the project has trained plant personnel, installed in-furnace measurement sensors, conducted manual combustion balancing and implemented combustion optimization software.

Performance testing at the DTE plant from July 25 to July 30 shows impressive benefits from the integration of these tools:

Measurement	**Initial**	**Post**	**Change**	**Impact/Year**
Tons of CO2/MWh	1.069	1.043	-2.43%	127,000 Tons of CO_2 reduced
Net Unit Heat Rate (Btu/kWh)	10,393	10,224	-1.63%	$1,700,000 in fuel savings
NOx (lb/MBtu)	0.251	0.201	-20.0%	$731,000 NOx credits, increased availability

These results were obtained with minimal change in boiler CO and LOI and without additional boiler degradation.

At AEP Amos, only manual tuning has taken place so far; however, the benefits are equally impressive: Based on the plant's CO_2 CEMs, the CO_2 intensity, CO_2/MW-h, has been reduced by 1.80%, or 180,000 tons CO_2/year, leading to a yearly fuel savings of $2,100,000. This was accomplished with no increase in stack CO or SO_2 and a net *reduction* in NO_x of approximately 5%. Additional improvements are expected after implementation of the smart process software.

Background

Coal-fired power plants provide approximately 51% of the electricity generated in the United States. In general, the efficiency of the generation process in the United States is poor due to a combination of lack of attention to upgrading infrastructure, a confused and confusing regulatory environment, and simple complacency. In general, plants currently care about only two things: 1) keeping the lights on and 2) whatever the government tells them they have to care about, e.g. emissions. As a result, the primary focus of plant operations is availability. Efficiency is, at best, an afterthought even though coal savings would be significant if efficiency was given greater emphasis.

Climate change, the desire for energy independence, and resource conservation are beginning to change attitudes. However, plants are ill-equipped to operate in an environment in which efficiency and reduced CO_2 emissions are given increased emphasis. Improving combustion efficiency and biomass co-firing can provide nearly immediate and cost-effective CO_2 reduction.

For instance, we have already demonstrated a 2 % efficiency increase at two nominally well-run plants. If that improvement is extrapolated across the United States coal-fired boiler fleet, it would be equivalent to immediately doubling the total amount of CO_2-free electricity generated by wind and solar energy in the United States but at roughly 1/100th the cost of solar PV and 1/25th the cost of wind power. Biomass co-firing also represents a cost-effective means to reduce CO_2. At a coal-fired power plant in Elverlingsen Germany in a joint project with Siemens, we were able to demonstrate a 50% increase in the fraction of biomass co-fired (from 6 to 9%) simply by measuring conditions in the boiler directly and using smart process software to affect modifications in the staging of air and fuel.

Efficiency in the generation process and biomass co-firing will eventually change from an afterthought to a priority and Zolo's sensor technology, particularly integrated with smart process software, is an obvious and extremely cost-effective means to affect the necessary improvements.

Theoretical Section

Figure 1 depicts tradeoffs that must be addressed in boiler operation. Very generally, the air/fuel ratio must be adjusted carefully to optimize efficiency. Too much excess air decreases overall efficiency because it has the unwanted effect of cooling the combustion gasses, and the fans that blow the excess air into the boiler represent a parasitic system loss. (They require more electricity to blow more air). In addition, too much excess air creates additional NO_x. On the other hand, excess air has benefits. If staged and directed properly, it assures low CO emissions and low carbon content in the fly ash. It can provide a slightly oxidizing environment near the boiler walls that helps to prevent wall wastage and down time from boiler tube leaks. Excess air also tends to aid in the control of slagging which can cause significant boiler losses if left unchecked. In general, boilers operate with more excess air than is necessary "to be comfortable". The reason for this caution is shown in Figure 2, which is a 2-d tomogram of the O_2 concentration (and T, CO, and H_2O) in the DTE boiler in its "as found" configuration. The issue is immediately obvious. In order to maintain "comfortable levels" of O_2 near the walls (~2-3%), concentrations of O_2 in the center of the boiler were above 5%. Prior to the installation of the laser-based sensing grid, the operators had no knowledge of the *distribution* of the excess air (or of the fuel, for that matter). In general, we observe that these distributions are highly non-uniform; consequently, an assumption of uniformity and a desire to operate the boiler in a “comfortable” mode leads to extremely inefficient operating conditions.

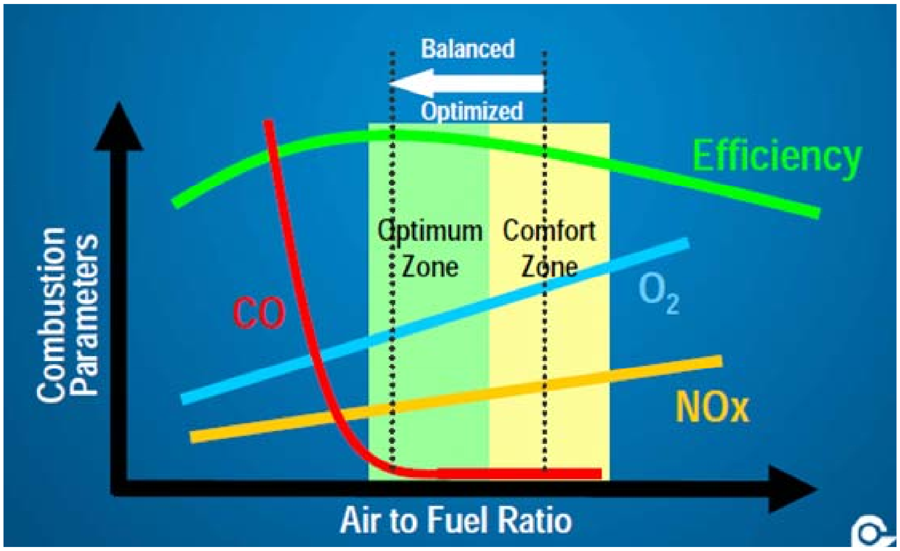


Figure 1: Graphical representation of tradeoffs encountered in boiler operations

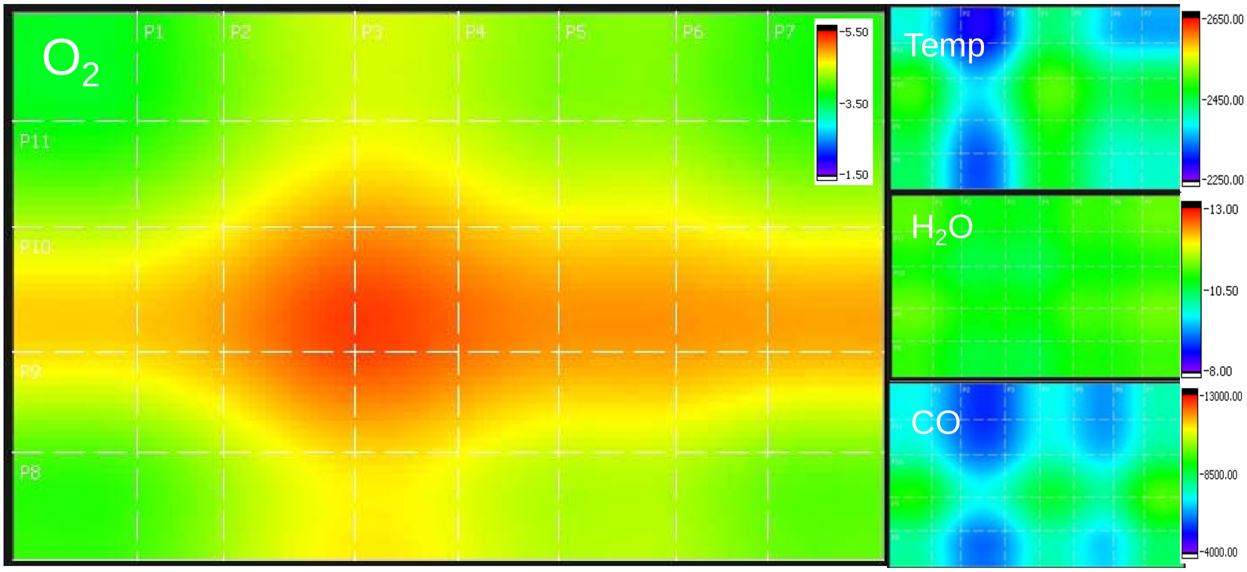


Figure 2: DTE boiler tomography in “as found” condition prior to manual tuning or smart process software implementation. The distribution of combustion species and temperature is extremely non-uniform and this leads to boiler inefficiency.

Experimental

Details of the two installations follow. The two plants are significantly different in terms of their size (650 vs. 1300 MW) and configuration.

The DTE Belle River Station Unit 2

- 612 Net MW (647 Gross MW) sub-critical coal fired plant.
- Firing barge delivered Powder River Basin (PRB) coal.
- B&W opposed wall-fired pulverized-coal. Eight B&W MPS-89 pulverizers.
- Only 7 pulverizers are in use during normal operation.
- Single reheat, tandem compound, four-flow turbine.
- Seven-heater feedwater cycle.
- Two steam driven feedwater pumps.
- Twin single pass surface condensers with four water boxes fed by river water.
- One Dry Electrostatic Precipitator.

AEP John Amos Station Unit 3

- 1300 Gross MW super-critical coal fired plant.
- B&W opposed wall-fired pulverized-coal boiler with 12 B&W MPS-89
- Pulverizers feed 96 burners.
- Single reheat steam turbine with two shafts and two generators with a four-flow LP turbine
- Three Ljungstrom Air Heaters.
- Eight stages of feedwater heating.
- One steam driven feedwater pump.
- Twin single pass surface condensers with four water boxes fed a parabolic cooling tower.
- One flue gas desulphurization system.
- One dry electrostatic precipitator.
- One Selective Catalytic Reduction System (SCR)

Combustion Monitor

The Zolo*BOSS* combustion monitors for these two stations are nominally identical but the configuration as installed on the boilers is slightly different. The Zolo*BOSS* consists of a laser-based combustion sensor designed for the ultra-harsh combustion environment of a coal powered furnace (Figure 3). The Zolo*BOSS* uses tunable diode laser absorption spectroscopy (TDLAS) measurements, wavelength multiplexing capabilities, and tomographic algorithms to generate two-dimensional maps of boiler conditions including temperature, O_2, CO, and H_2O concentrations. CO_2 measurements can be added as an option. Visibility into the combustion zone makes real time balancing of boiler constituents possible.

Figure 3: Zolo*BOSS* system architecture.

The Zolo*BOSS* at Belle River Unit 2 includes a 7x4 grid of laser paths in the combustion zone and three additional laser paths through the superheat pendant region. Front to rear paths are located above each burner column and are supplemented by four left to right paths to enable 2D combustion balancing (Figure 4). The three superheater laser paths provide an early warning of fouling based on temperature level and gradient.

The Zolo*BOSS* at John Amos Unit 3 includes fourteen parallel laser paths (Figure 5) in the combustion zone of the boiler. Front to rear paths are located above each of the 12 burner columns to enable left to right combustion balancing with two additional paths are located nearer the water walls. This configuration was chosen due to the distance required of any transverse paths (> 110 feet) and the general lack of access to the transverse boiler walls.

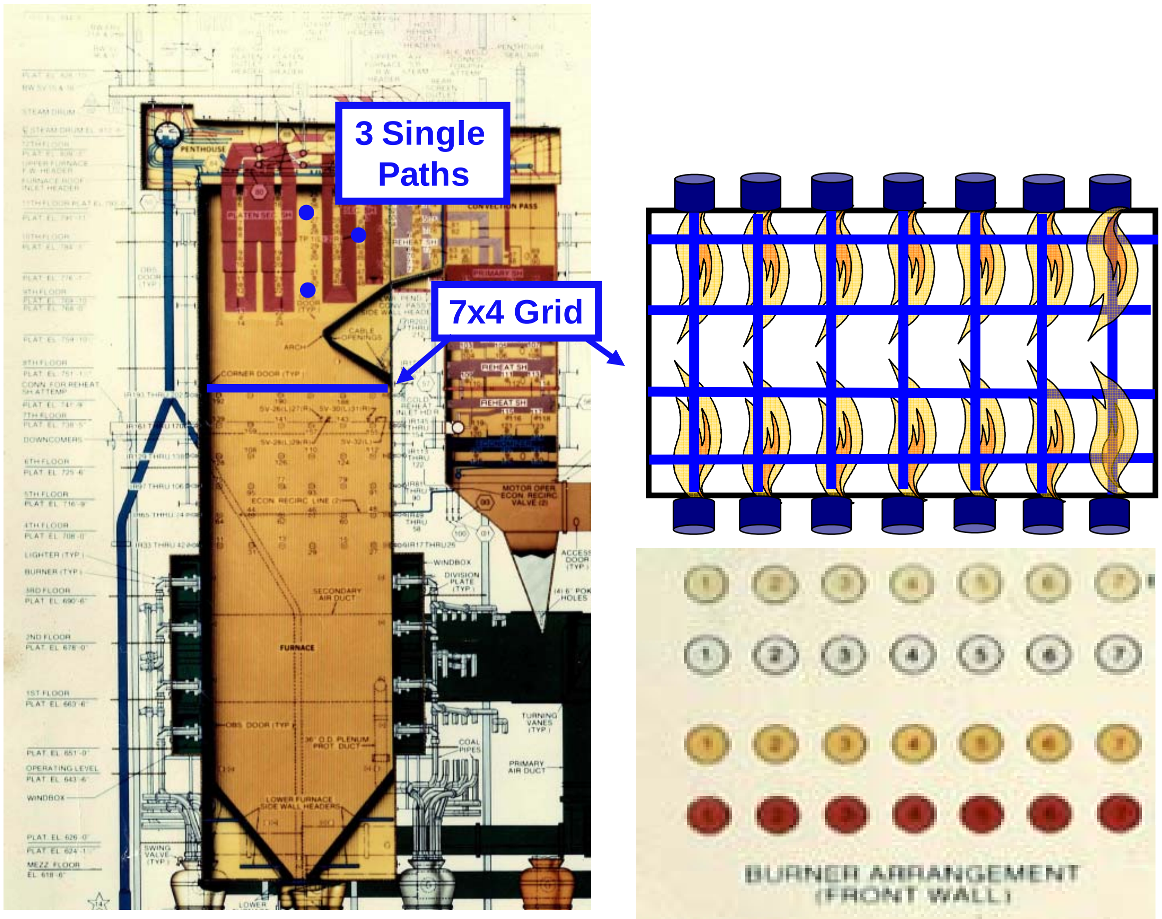


Figure 4: DTE laser path configuration.

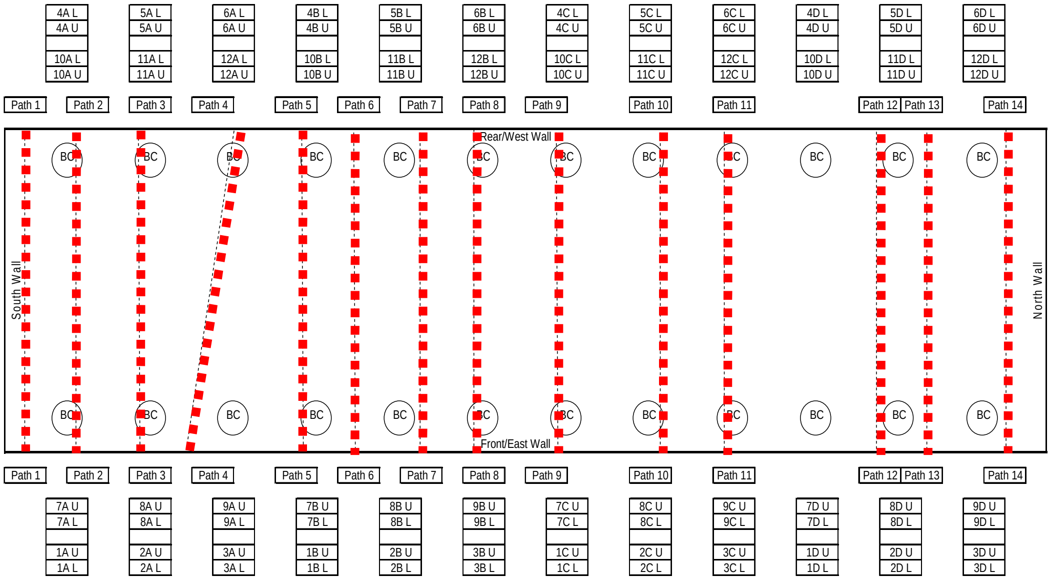


Figure 5: Laser path layout at AEP Amos Plant.

Software Optimizer

The software optimizers used in the project were chosen by the respective plants. The NeuCo system "Combustion'Opt" chosen by DTE Belle River optimizes fuel and air mixing to improve efficiency and reduce emissions. Efficiency improvements are sustained by continuously evaluating control variables and manipulating boiler setpoints. Optimization is provided by neural network and model predictive control technologies that produce real-time closed-loop combustion optimization.

The Emerson Smart Process system chosen by AEP Amos uses advanced analytics and artificial intelligence algorithms to achieve combustion balance and minimize emissions. Optimization with the Emerson system will commence in the next stage of the project.

Training

Training at both plants consisted of:

- CO_2/MWh reduction awareness
- Zolo*BOSS* operation and maintenance
- Combustion'Opt boiler optimization system
- Live balancing exercise using Zolo*BOSS* tomography

Results

The focus of the manual tuning exercise at DTE was to balance combustion and reduce excess air to realize efficiency gains. Balancing combustion ensures that O_2 depletion zones and temperature hot spots are minimized. O_2 depletion zones and hot spots increase the propensity for boiler slagging which is a critical issue for the plant. Hot spots also tend to generate the majority of NO_x. Reduction of excess air results in lower fuel consumption (due to less auxiliary power and dry gas losses) and thus decreased heat rate and CO_2/MWh.

Balancing Combustion

Prior to the installation of the Zolo*BOSS*, balancing efforts were limited to observing point measurements available from the O_2 probes in the economizer. Downstream O_2 probes offer only a partial view of the combustion process and require an increased excess air set point for margin to prevent slagging and increased CO. It is industry practice to operate with excess air beyond the requirements of ideal combustion because of possible imbalances in the boiler. High levels of excess air decrease unit efficiency, increase NOx, and require more fuel to deliver the same amount of power to the grid. The efforts in this project utilized the Zolo*BOSS* combustion monitor to balance combustion in a manner that was not previously available, so that excess air could be balanced and then safely reduced.

Figure 6 shows the tomography that resulted after a round of manual tuning on the DTE boiler. Compared to the "as found" data of Figure 2, the overall level of excess air is reduced and is generally more uniform. Even the lowest levels of excess air (~2.5%) are sufficient to insure "comfortable" boiler operation since the actual concentration is continuously monitored in real time over the entire boiler cross section.

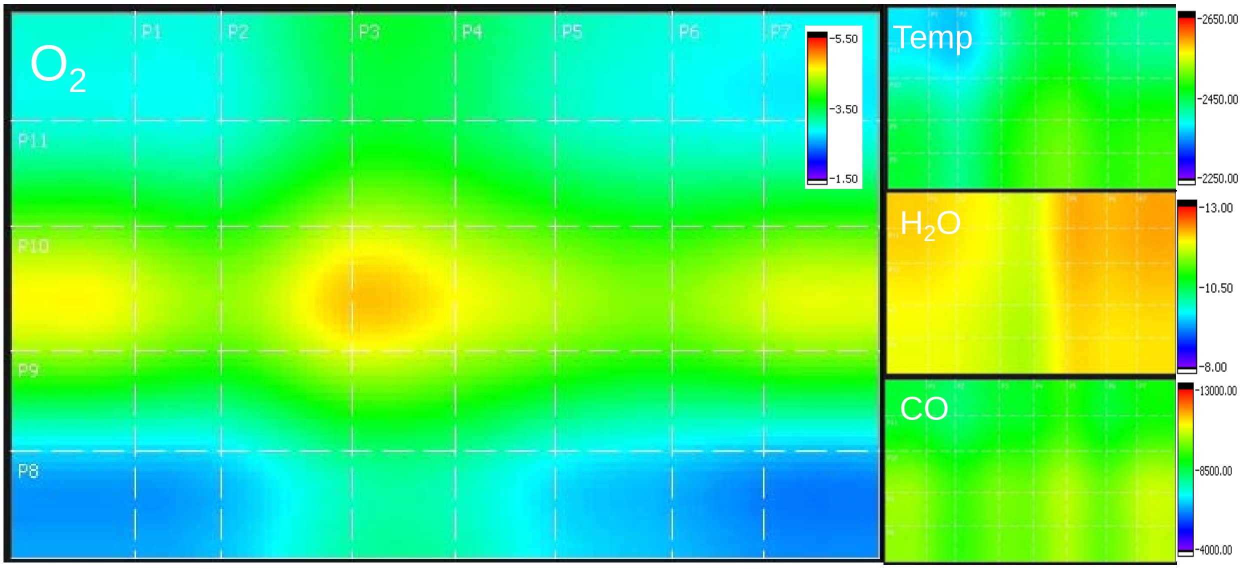


Figure 6: Tomography of DTE boiler after manual tuning.

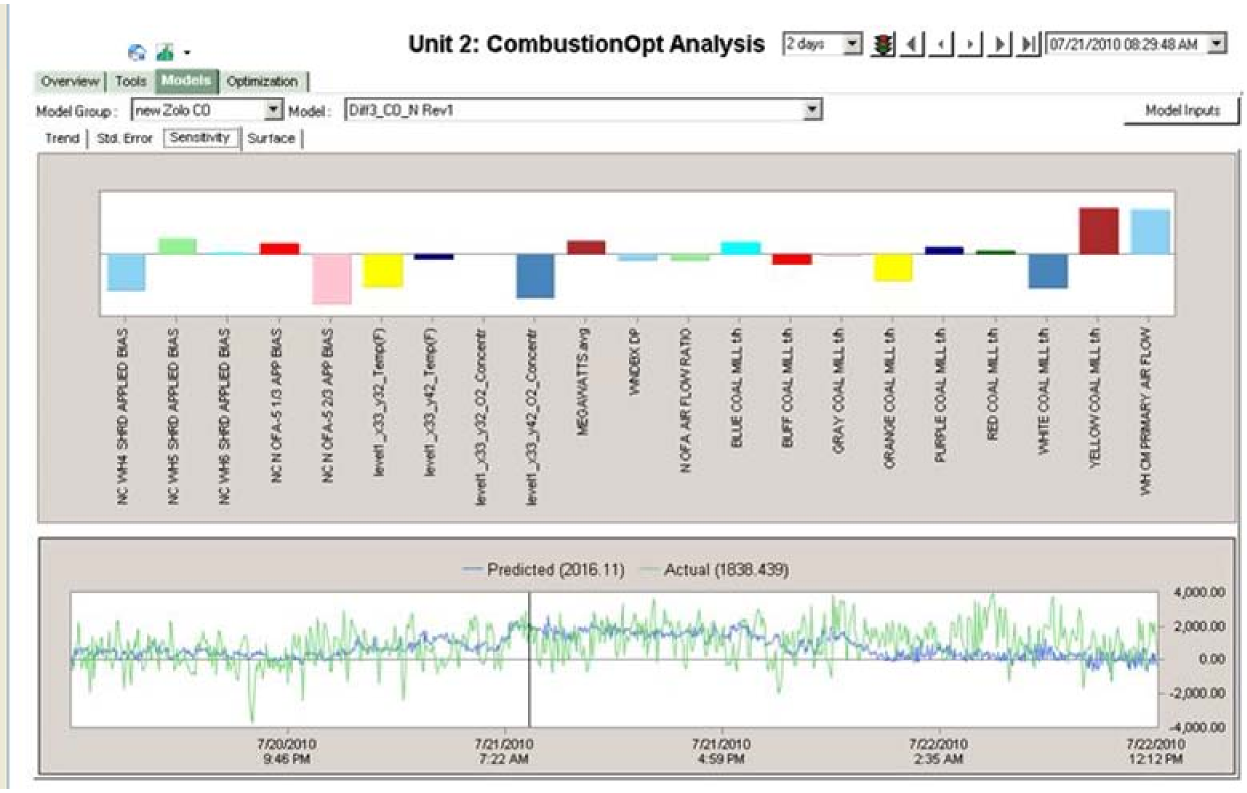
Optimizer Tuning

The introduction of an optimizer with an *in-situ* combustion monitor has two advantages:

1. Fuel and air flows are optimized 24/7.
2. The optimizer continually learns and adapts to changing furnace inputs.

Prior to observing sustained efficiency improvements, it must first be shown that the optimizer can balance combustion and control excess O_2 to improve efficiency. This is demonstrated using the same performance testing that was conducted for the baseline and manual tests. If the optimizer is able to improve efficiency during the performance test it is reasonable to assume it can maintain efficiency improvements during standard unit operation.

Work at DTE showed that an optimizer is most effective when a plant engineer constrains the solution space in which the optimizer searches. At DTE, the goal of the optimizer is to maintain optimal combustion tuning in a continuous fashion. The plant engineer used Zolo*BOSS* data to focus shroud and fuel bias changes to sections of the boiler that were imbalanced. For example, if a boiler imbalance was observed in the north-west corner, the optimizer was constrained to address the imbalance by adjusting the column of burners directly underneath the imbalance. The constraints reduced the search space for balanced combustion from forty burners and fourteen over-fire air (OFA) ports to three burners and one OFA port. This decreased the optimization search space and allowed for rapid balancing of the combustion zone. The software performs a series of parametric experiments within limits defined by the operators to develop relationships between combustion parameters measured by the Zolo*BOSS* and the various actuators that are available to the plant operators. As mentioned above, the number of actuators is too large to attempt a complete parametric analysis so an attempt is made to choose which actuators are likely to have the most effect at a given position in the boiler and limit the parametric analysis to this set of actuators. For a wall-fired boiler such as the DTE Unit, sufficient *a priori* knowledge is available to make this choice accurately. (For a T-fired unit, the relationships may not be so straightforward due to the overall swirl in the flow.) The results of one such parametric analysis are shown in Figure 7 where the software is testing the importance of various parameters on the CO concentration in one section of the boiler. The bar graphs show either a positive or negative influence on CO concentration for each parameter. At the bottom of Figure 7 is a time history of the CO concentration in one particular section of the boiler. The green curve is the CO concentration as measured by the Zolo*BOSS* whereas the blue curve is the software-predicted concentration after the software has learned the effect of each of the parameters. The close correspondence of the measurements and the model indicates that the CO concentration is deterministic based on the parameter set utilized and that the model has "learned well."


Unit 2: CombustionOpt Analysis

2 days

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Model Group: new Zolo CO

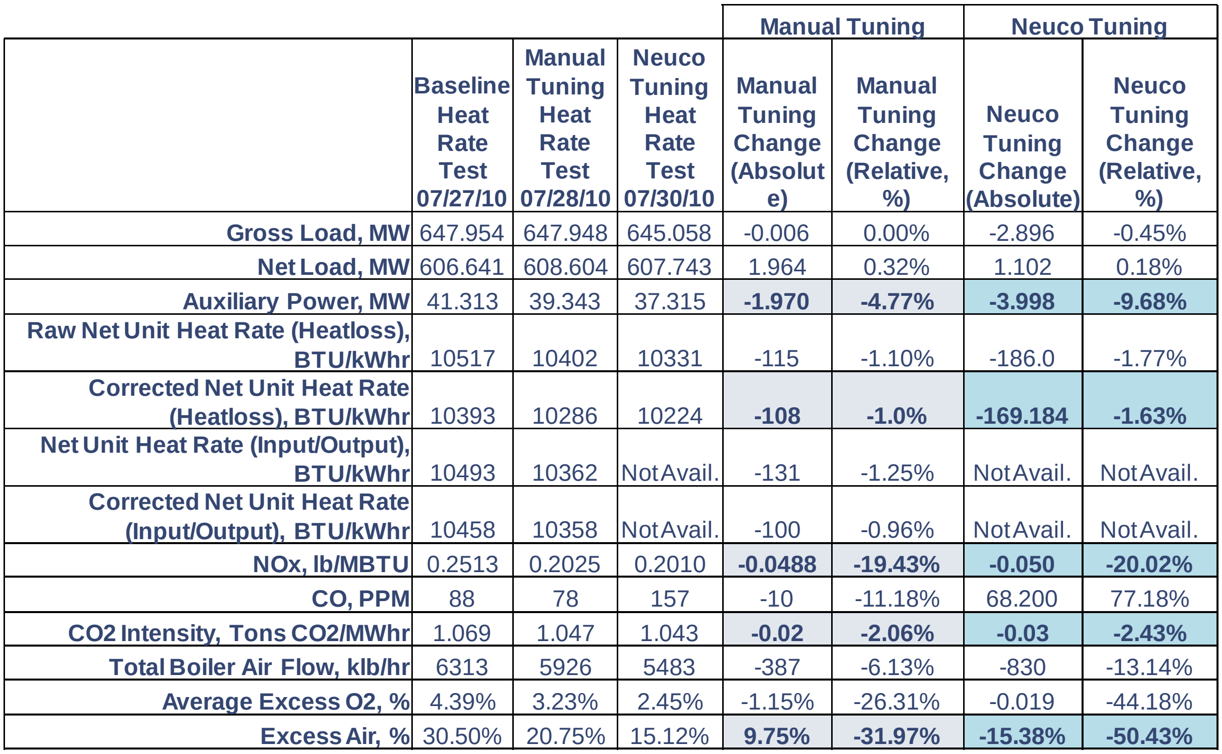
Model: Diff3_CO_N Rev1

Figure 7: Example data from software parametric learning process.

The results of the manual and software optimizations are shown in Figure 8. In all categories except NO_x reduction, the software optimizer does significantly better than manual tuning alone, in most cases by a factor of ~2. This is not particularly surprising when one fully appreciates the complexity of the tuning space. It is not possible for a person to optimize combustion with so many parameters affecting the outcome. Even without considering secondary effects (one parameter changing the nature of the relationship between two other parameters), the space is much too complex for a human to explore. And, in fact, we have severely limited, albeit in an intelligent way, the space that the software optimizer is allowed to explore. A more full optimization will take place in the future.

AEP Amos Results

The project at AEP Amos is several months behind the DTE project; consequently, only a manual optimization has been completed. However, the results are very encouraging as can be seen from the tomography shown in Figure 9. Excess air has been substantially reduced and the combustion is more uniform. What may not so obvious is the flame intensity is higher in the measurement zone as can be seen in the higher CO levels and temperature. It is likely that optimization has stretched out the flame front allowing the low NO_x burners and overfire air to operate more closely to the intended design. Figure 10 shows the quantified results. The heat rate for the unit has (so far) been reduced by 0.88%. The NO_x has been reduced by 5% and the CO_2 intensity in CO_2/MW-hr has been reduced by 1.88%. In a boiler of this size (1300 MW), these modest initial manual tuning results will save AEP $2,100,000 annually. We expect even larger savings as a result of the software optimization which is now under way.



				Manual Tuning		Neuco Tuning	
	Baseline Heat Rate Test 07/27/10	**Manual Tuning Heat Rate Test 07/28/10**	**Neuco Tuning Heat Rate Test 07/30/10**	**Manual Tuning Change (Absolute)**	**Manual Tuning Change (Relative, %)**	**Neuco Tuning Change (Absolute)**	**Neuco Tuning Change (Relative, %)**
Gross Load, MW	647.954	647.948	645.058	-0.006	0.00%	-2.896	-0.45%
Net Load, MW	606.641	608.604	607.743	1.964	0.32%	1.102	0.18%
Auxiliary Power, MW	41.313	39.343	37.315	**-1.970**	**-4.77%**	**-3.998**	**-9.68%**
Raw Net Unit Heat Rate (Heatloss), BTU/kWhr	10517	10402	10331	-115	-1.10%	-186.0	-1.77%
Corrected Net Unit Heat Rate (Heatloss), BTU/kWhr	10393	10286	10224	**-108**	**-1.0%**	**-169.184**	**-1.63%**
Net Unit Heat Rate (Input/Output), BTU/kWhr	10493	10362	Not Avail.	-131	-1.25%	Not Avail.	Not Avail.
Corrected Net Unit Heat Rate (Input/Output), BTU/kWhr	10458	10358	Not Avail.	-100	-0.96%	Not Avail.	Not Avail.
NOx, lb/MBTU	0.2513	0.2025	0.2010	**-0.0488**	**-19.43%**	**-0.050**	**-20.02%**
CO, PPM	88	78	157	-10	-11.18%	68.200	77.18%
CO2 Intensity, Tons CO2/MWhr	1.069	1.047	1.043	**-0.02**	**-2.06%**	**-0.03**	**-2.43%**
Total Boiler Air Flow, klb/hr	6313	5926	5483	-387	-6.13%	-830	-13.14%
Average Excess O2, %	4.39%	3.23%	2.45%	-1.15%	-26.31%	-0.019	-44.18%
Excess Air, %	30.50%	20.75%	15.12%	**9.75%**	**-31.97%**	**-15.38%**	**-50.43%**

Figure 8: Table comparing results from manual tuning and software optimization at DTE Belle River. In all categories except NO_x reduction, the software optimization does significantly better than manual tuning.

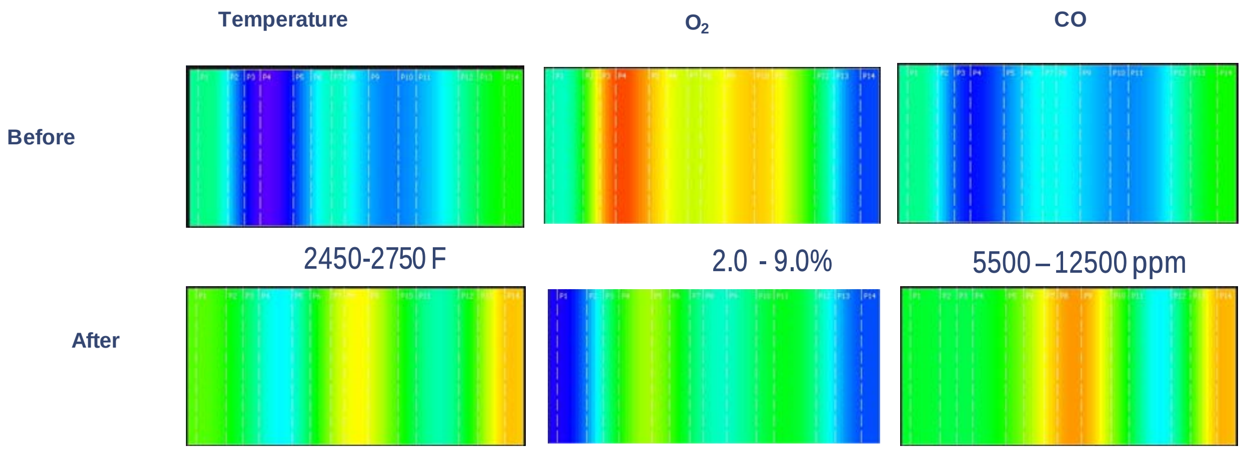
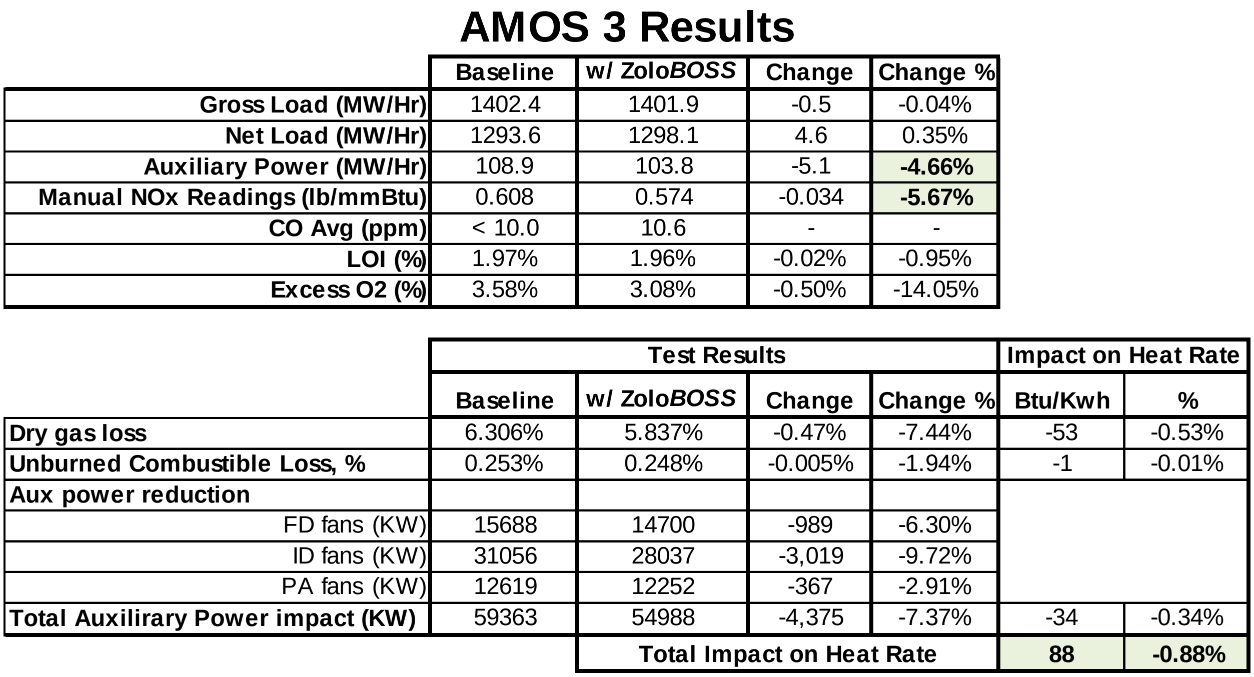


Figure 9: Tomography before and after manual tuning at AEP Amos plant. Reduction of excess air is obvious.



AMOS 3 Results

	Baseline	w/ Zolo*BOSS*	Change	Change %
Gross Load (MW/Hr)	1402.4	1401.9	-0.5	-0.04%
Net Load (MW/Hr)	1293.6	1298.1	4.6	0.35%
Auxiliary Power (MW/Hr)	108.9	103.8	-5.1	**-4.66%**
Manual NOx Readings (lb/mmBtu)	0.608	0.574	-0.034	**-5.67%**
CO Avg (ppm)	< 10.0	10.6	-	-
LOI (%)	1.97%	1.96%	-0.02%	-0.95%
Excess O2 (%)	3.58%	3.08%	-0.50%	-14.05%

	Test Results				Impact on Heat Rate	
	Baseline	w/ Zolo*BOSS*	Change	Change %	Btu/Kwh	%
Dry gas loss	6.306%	5.837%	-0.47%	-7.44%	-53	-0.53%
Unburned Combustible Loss, %	0.253%	0.248%	-0.005%	-1.94%	-1	-0.01%
Aux power reduction						
FD fans (KW)	15688	14700	-989	-6.30%		
ID fans (KW)	31056	28037	-3,019	-9.72%		
PA fans (KW)	12619	12252	-367	-2.91%		
Total Auxilirary Power impact (KW)	59363	54988	-4,375	-7.37%	-34	-0.34%
		Total Impact on Heat Rate			**88**	**-0.88%**

Figure 10: Results of the manual tuning effort at AEP Amos.

Summary

Initial results from a two coal-fired power plant study to demonstrate a reduction in CO_2/MW-hr through combustion optimization using TDLAS-based combustion zone tomography coupled with software optimization indicate a ~2% improvement leading to a $2.1 million/year savings on coal costs at one plant and a $2.4 million/year savings at the other plant. Implementing this technology across the U.S. fleet of power plants would reduce CO_2 by 44,000,000 tons per year saving a total of $800,000,000 in coal costs. If implemented, this CO_2 reduction represents more CO_2-free energy than all of the currently installed solar and wind power in the United States at a fraction of the cost. (1/100th the cost of large scale solar PV and 1/25th the cost of large scale wind installations).