RMEL Plant Management Conference
June 14-15, 2012

# ONE MORE TIME: FIRST APPLY THE FUNDAMENTALS!

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## Introduction

Since the Clean Air Act Amendment was passed in 1990, there have been many advancements in clean coal combustion. Most of the advancements have been at the back end; stack clean up devices that were installed to clean the flue gases before discharge to the environment. Some, such as selective catalytic reactors (SCR), flue gas desulfurization systems (FGD) and high efficiency baghouses have been installed at significant capital investment. Other advances in boiler cleaning such as intelligent sootblowing, water lances and water cannons have addressed changes from design fuels to PRB or Illinois Basin Coals for fuel flexibility and competitive generation reasons. The state of the art for boiler controls has advanced with smart transmitters, neural networks and improved boiler control hardware. The frequency of outage overhauls has been changed from two per year, to sometimes as long as five years.

I began my career in the electric power industry in the 1960's and as we have progressed to clean coal combustion and many advancements in producing competitive generation from coal. I have been struck by the common and frequent disregard for the application of the fundamentals as a first step. No matter which topic one may pursue to grow, first the basics need to be applied for the best success. Whether in sports, such as football where young athletes are taught to "block, tackle, run" or in chemistry where we learned to balance equations of chemicals combined to form a compound. It is my intention and my pleasure to present how applying the fundamentals can also improve overall pulverized coal plant operations, maintenance, efficiency, reliability, capacity and environmental compliance.

Here are some fundamentals that are often skipped over, including the 13 Essentials of Optimum combustion and 22 Operations and Maintenance Controllable Heat Rate Variables. For example, the most commonly overlooked fundamentals:

- Make sure the furnace has free oxygen. Many boilers we test do not. This is due to air in leakage downstream of the furnace. Excess oxygen is measured at the economizer exit and usually assumed to be the same at the furnace. The average age of the USA coal fleet is about 40 years. Should we be surprised that air in leakage is a common problem?
- Fuel fineness should be 75% passing 200 mesh on PRB as well as Bituminous coals.
- Fuel and air flows to the burner belt should be balanced.
- Pulverizer performance should be checked periodically and maintenance completed based on mill performance. We call it "Performance Driven Maintenance."
- Combustion airflow's should be measured and controlled. This includes all combustion airflow's; primary airflow, secondary airflow and over-fire airflow path's. These should

be controlled and proportioned over the load range for best performance. Primary flow elements need periodic calibration checks to compare the measured flow by a hand velocity traverse with the indicated flow.

- Understanding of how applying the above can impact efficiency, reliability, capacity, environmental factors and competitive generation.

Competitive generation by coal, when competing today against abundant and inexpensive natural gas means both burning the lowest cost fuels and achieving the best possible efficiency. How do you do this? It takes a well led operations and maintenance team equipped with many tools. My advice is to first, apply the fundamentals!

1. <u>A Primer on Combustion in Large Utility Furnaces</u>

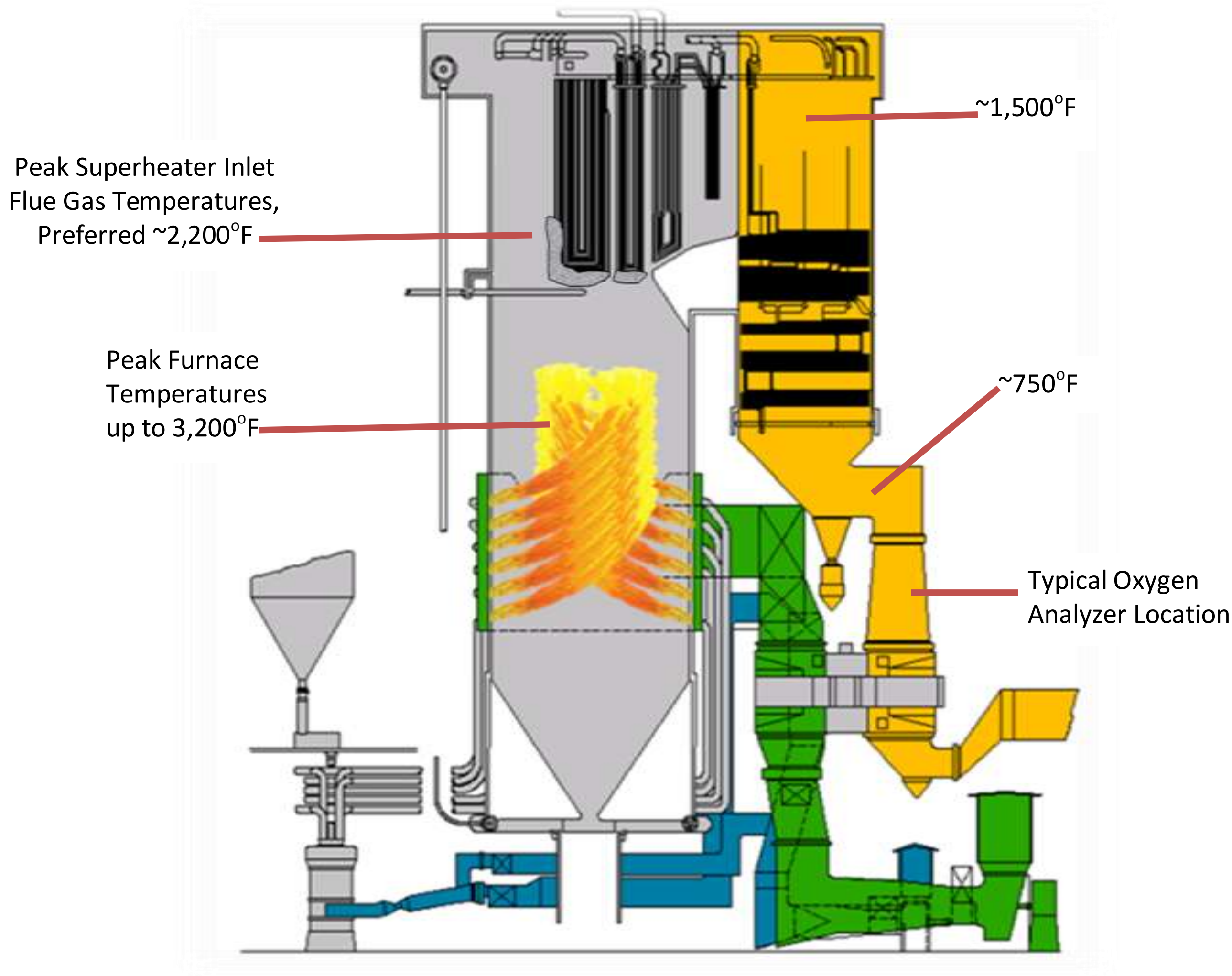



**Figure 1**

Note from Figure 1 that the peak flame temperature in the burner belt will reach in excess of 3,000°F. For a 500MW boiler, the distance from the top burners to the superheater inlet is usually about 55 feet. This provides a very brief residence time to complete combustion. In fact, the time a coal particle enters the furnace at the top burner level, until the products of combustion pass the plane of the apex of the nose arch, is about one or two seconds.

This is the first important step in coal power generation, to release enormous amounts of heat energy in the first second or two that the fuel enters the furnace, complete combustion of that fuel and absorb the heat energy into the water walls. Depending on the fuel, Bituminous, PRB or Lignite, the heat absorbed in the furnace in the first two seconds of combustion is between 35% and 45% of the total heat released by the fuel. The peak flame temperatures for some fuels will exceed 3,200°F. The flue gas temperatures leaving the burner belt therefore are cooled by the time the products of combustion pass the plane of the "nose arch" by about 1,000°F. This is important and although it is basic and most of you know this, it is worthy of review to study the tremendous amount of energy transfer from radiant heat in the furnace in mere seconds. Once this basic fundamental is considered then the importance of the application of the 13 Essentials becomes very clear.

2. Reviewing the Short Life of a Pulverized Coal Particle

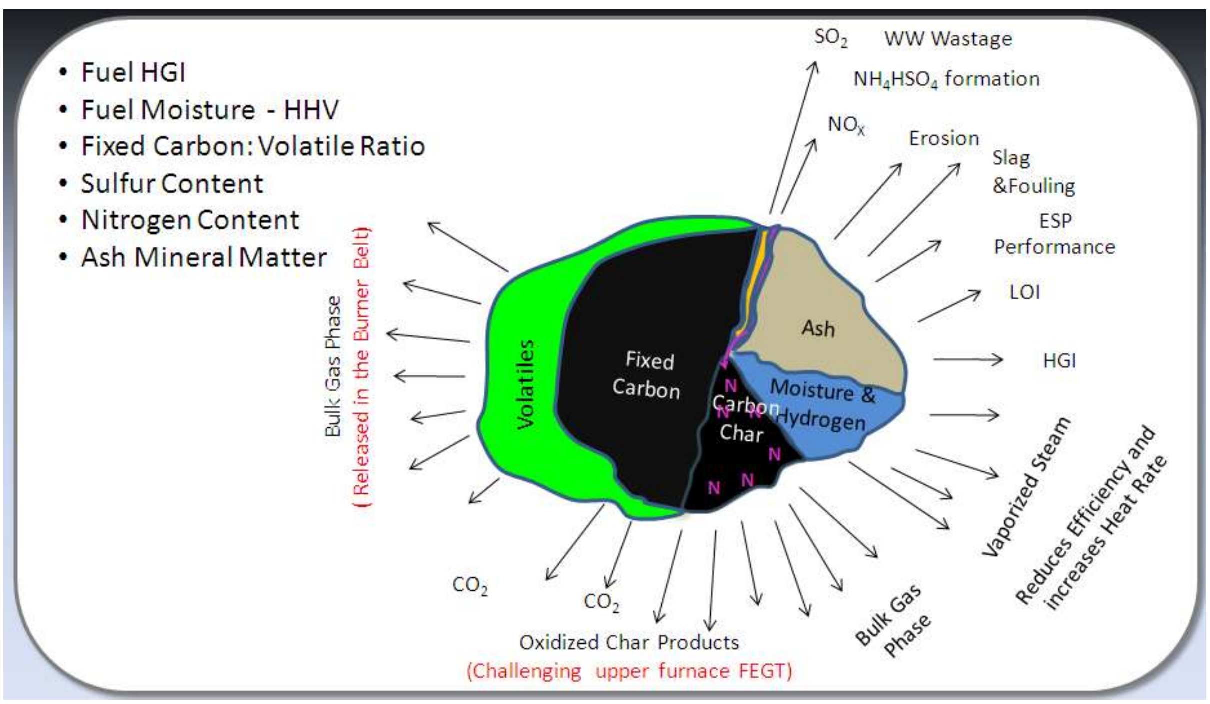



**Figure 2**

Let's think about the short life of a pulverized coal particle. Within a particle of coal are the usable combustible products quantified by a "proximate analysis" as volatile matter and fixed carbon. These are the reasons why we use coal in the first place. Dense chemical energy that creates the heat for our magnificent and massive external combustion heat engines, aka a coal fueled power plant. Along with the usable carbon and hydrogen, come other pesky constituents of moisture, ash and sulfur. These can be handled quite well with today's clean coal technologies, advances in sootblowing technology, FGD and modern coal pulverizers. So can the nitrogen in the coal. Most of the oxides of nitrogen formed in a pulverized coal boiler originate from the nearly trace amounts of nitrogen in the raw coal, between 0.5% as in some PRB fuels to above 1.4% in some Bituminous fuels. Even though the fuel bound nitrogen is minor amounts, this fuel bound nitrogen is believed to be the source of up to 75% of the furnace produced oxides of nitrogen.

**Solution**: apply effective low $NO_X$ burners, SCR or SNCR and the $NO_X$ can be minimized. That is, if the furnace inputs are optimized such as the fuel and air balance, proper proportions of OFA, fuel fineness, etc. Also coming along, unwanted with the combustible constituents of coal, is the ash which is inert to power generation but is important for slagging and fouling. Very minor constituents of the coal ash that receive a lot of attention and need to be dealt with to protect the environment, are arsenic, mercury and other trace metals. These also can be handled with today's advanced clean combustion technologies. It is beyond the scope of our time together to discuss these. Suffice it to say getting the furnace inputs right is important in the clean coal combustion process. This my friends is why for several decades I have focused on helping coal plant operations and maintenance teams to first apply the fundamentals to optimize the furnace inputs.

3. Burner Belt Basics

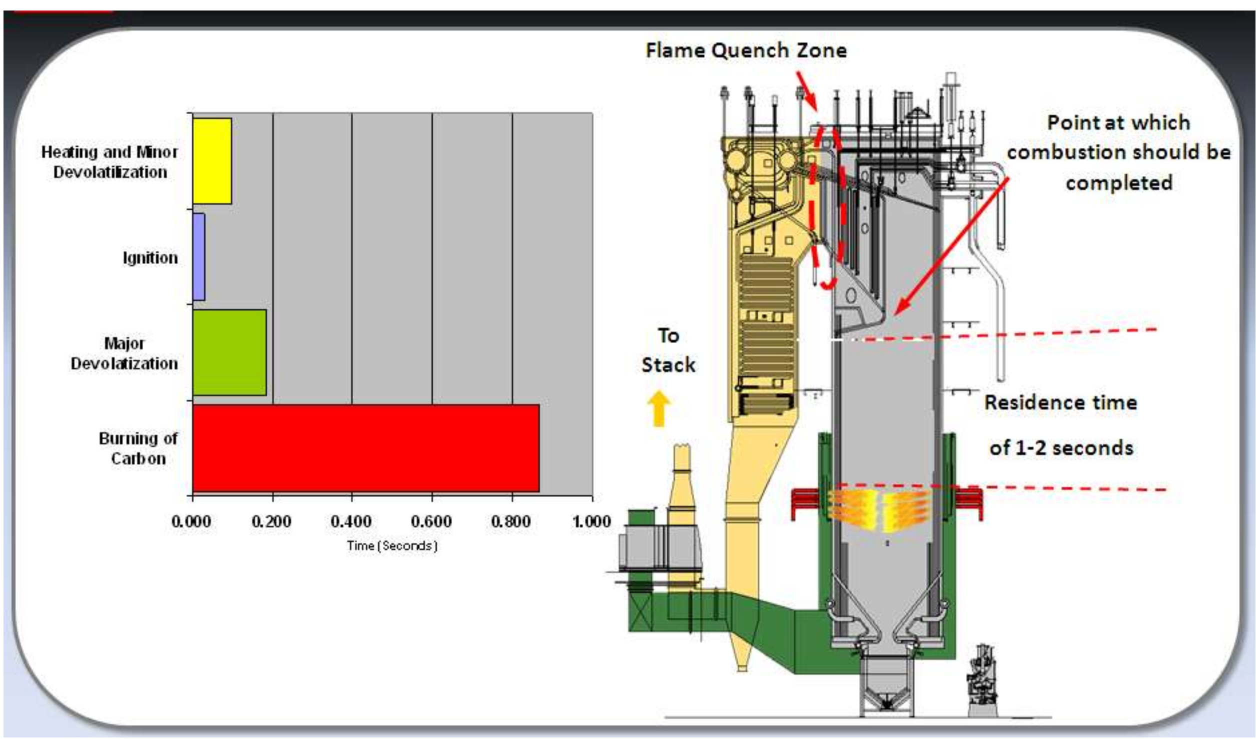



**Figure 3**

Residence time is short whether a 1960's vintage pulverized coal boiler or a modern furnace designed after the Clean Air Act Amendment of 1990. For a pre-CAAA boiler design, the residence time may be only one second. If a new boiler, it may be two seconds. Most of the precious time needed for combustion is to burn out the elemental carbon char. This is after the volatiles are released in the first two tenths of a second from the time a coal particle enters the furnace.

4. <u>So, what about low NOx burners? How do they figure in to furnace performance?</u>

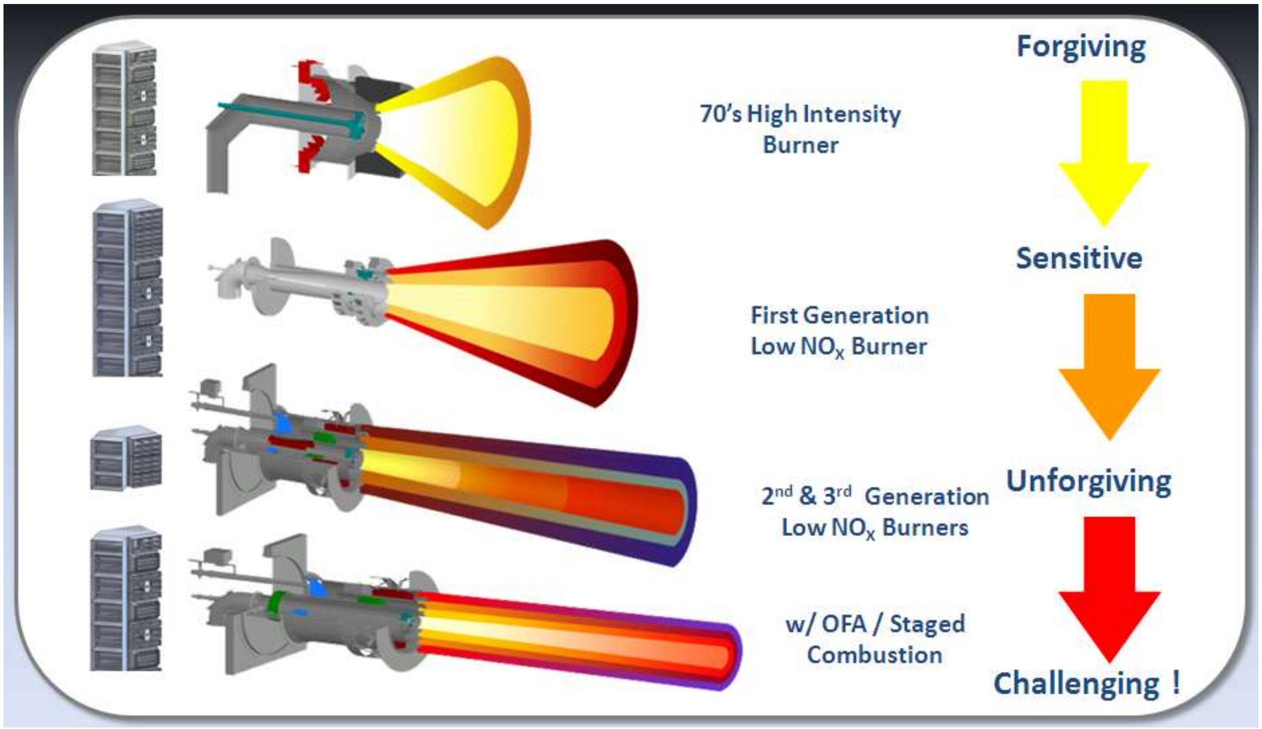



**Figure 4**

We should remain mindful that nearly everything that has been accomplished to reduce the furnace $NO_X$ production has been to slow down the combustion intensity. Stated another way, the newer design low $NO_X$ burners deliberately separate the air and fuel to stage combustion and release the fuel bound nitrogen in a fuel rich environment. Combustion is deliberately delayed so that complete combustion can be completed "later" in the furnace. Some low $NO_X$ burner suppliers claim that the "peak" flame temperatures may not exceed the thermal $NO_X$ threshold of about 2,800°F. A less intense flame is a longer burning flame. To reduce flame intensity, overfire air is usually applied. Often all of the excess air is supplied through overfire air ports separated from the burner belt. Thus, if the economizer exit is 20% excess air (or a stoichiometry of 1.2) and there is zero air in leakage from the furnace to the oxygen analyzers, then the burner belt would be at a stoichiometry of 1.0 if the burners are perfectly balanced with fuel and air.

What happens when some burners are fuel rich as shown below? The products of combustion can remain actively burning until they reach the superheater. This "secondary combustion" can elevate the furnace exit gas temperature by as much as 800 to 1,000°F above optimum.

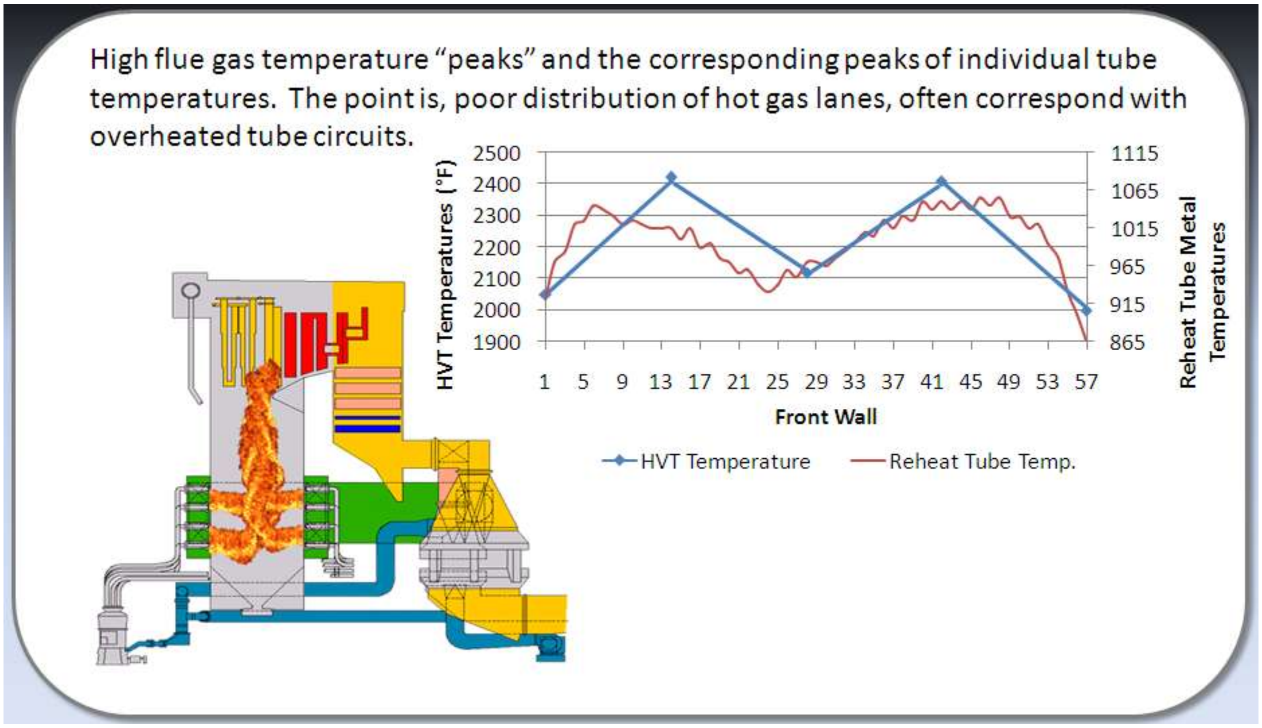



**Figure 5**

Depicted here is a 360MW wall fired boiler tested just after completion of a major overhaul. The graphic shows flames carrying over into the superheater and the blue line on the graph shows measured peak temperatures at the superheater inlet of ~2,400°F. This is mild flame carry over but when coal ash with a softening temperature of 2,100°F is supplied to this boiler it will require continuous long retractable sootblower operation.

The point of Figure 5 is that this data was taken after a major outage with very close attention applied to all 13 Essentials, including the use of calibrated flow nozzles to measure and control primary airflows, flow nozzles to measure and control secondary airflows to a compartmentalized windbox, burner mechanical tolerances were precise within ±¼" of design and fuel fineness was greater than 75% passing 200 mesh. Even with all of this, the furnace exit gas temperature "peaks" were ~2,400°F.

Notice that the approximate "average" HVT temperature is indicated from the five points of measurement to be about 2,200°F. An ideal FEGT, but the individual points show the fallacy of using "bulk" flue gas temperature or other methods to ascertain the average or bulk gas temperature. It is the individual peak temperatures that cause slagging problems.

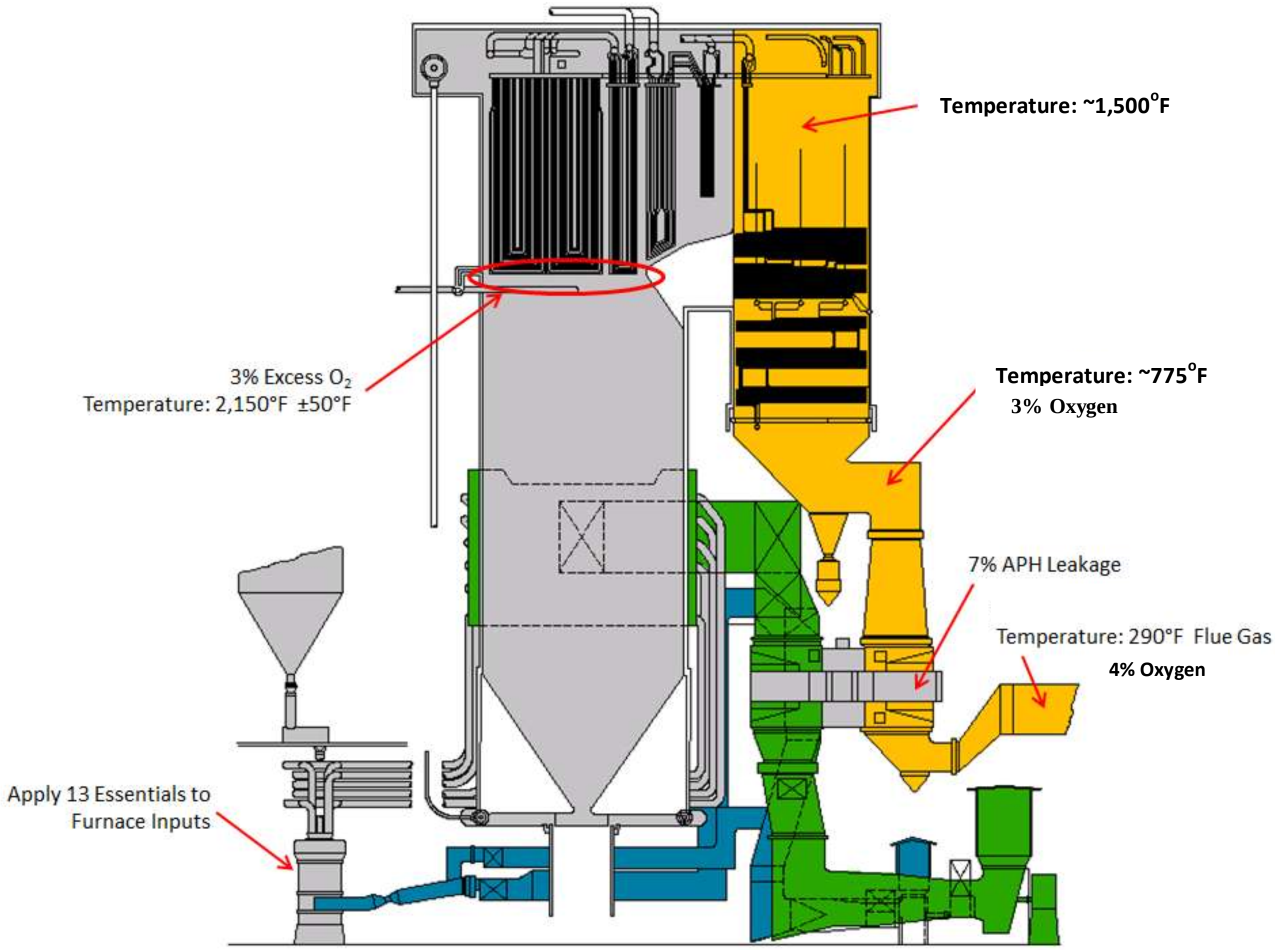



**Figure 6**

Figure 6 shows the overview of temperatures, tuning and flue gas oxygen levels that would be considered optimum for many typical pulverized coal units. It is difficult to approach "perfection" when tuning a furnace for the lowest $NO_X$ and using varied fuel sources. Figure 6 shows the ideal temperatures and flue gas excess oxygen levels that are worthy goals. A quick check of the quantities of air in-leakage can be determined by checking the $CO_2$ or $O_2$ in the stack by the CEM's. If it is 10-13% excess oxygen, then a lot of tramp air is being moved by the ID fans.

5. <u>Applying the 13 Essentials</u>

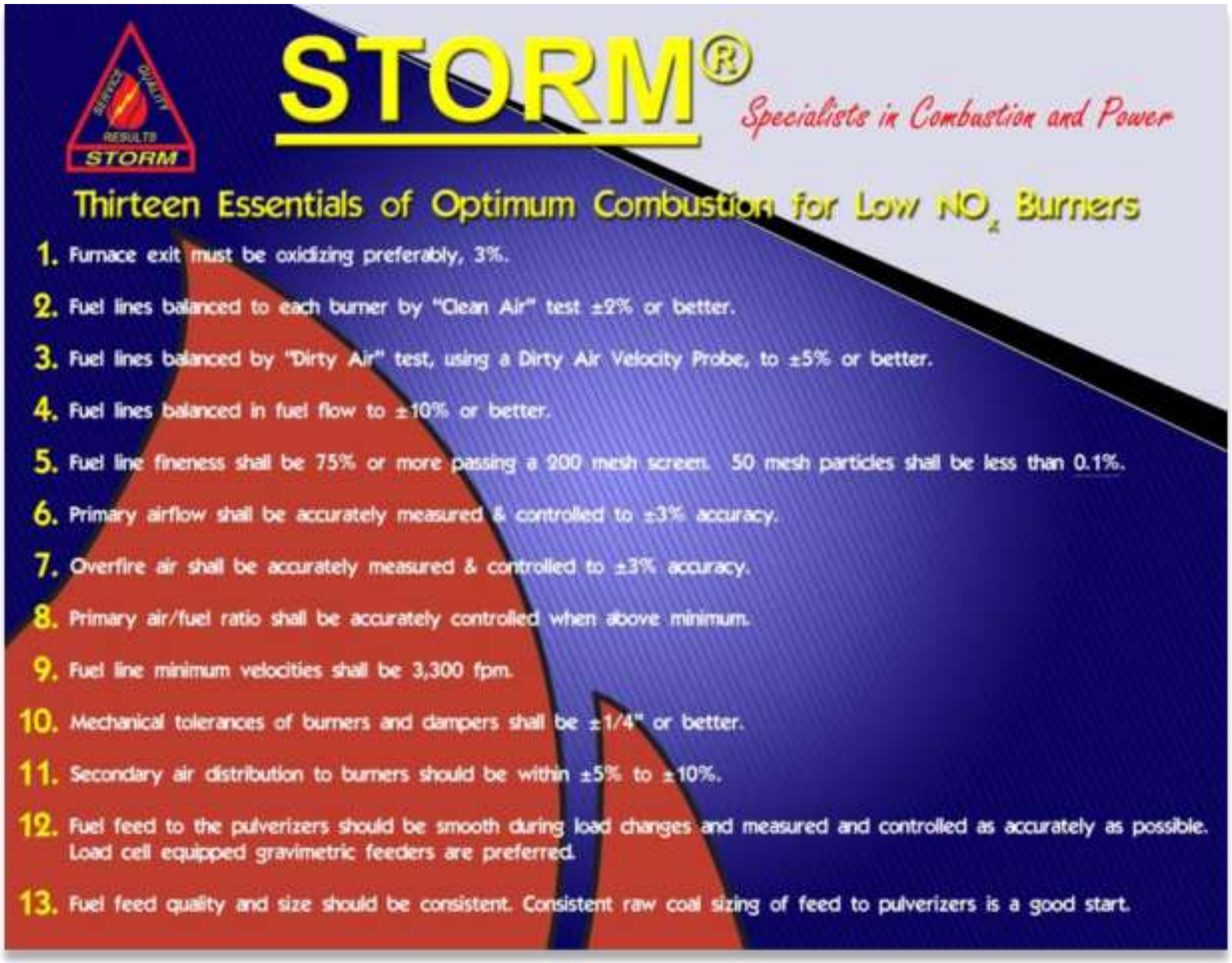



**Figure 7**

The reason furnace exit oxygen is at the top of the list is for a reason! If there is insufficient oxygen to complete combustion, then no matter how good the fuel and air are balanced, fuel fineness achieved, etc. unacceptable combustion will be experienced! These fundamentals have stood the test of time and began as the 10 pre-requisites of optimum combustion in the 1980's. Over time, we added several based on experiences since the Clean Air Act Amendment became law.

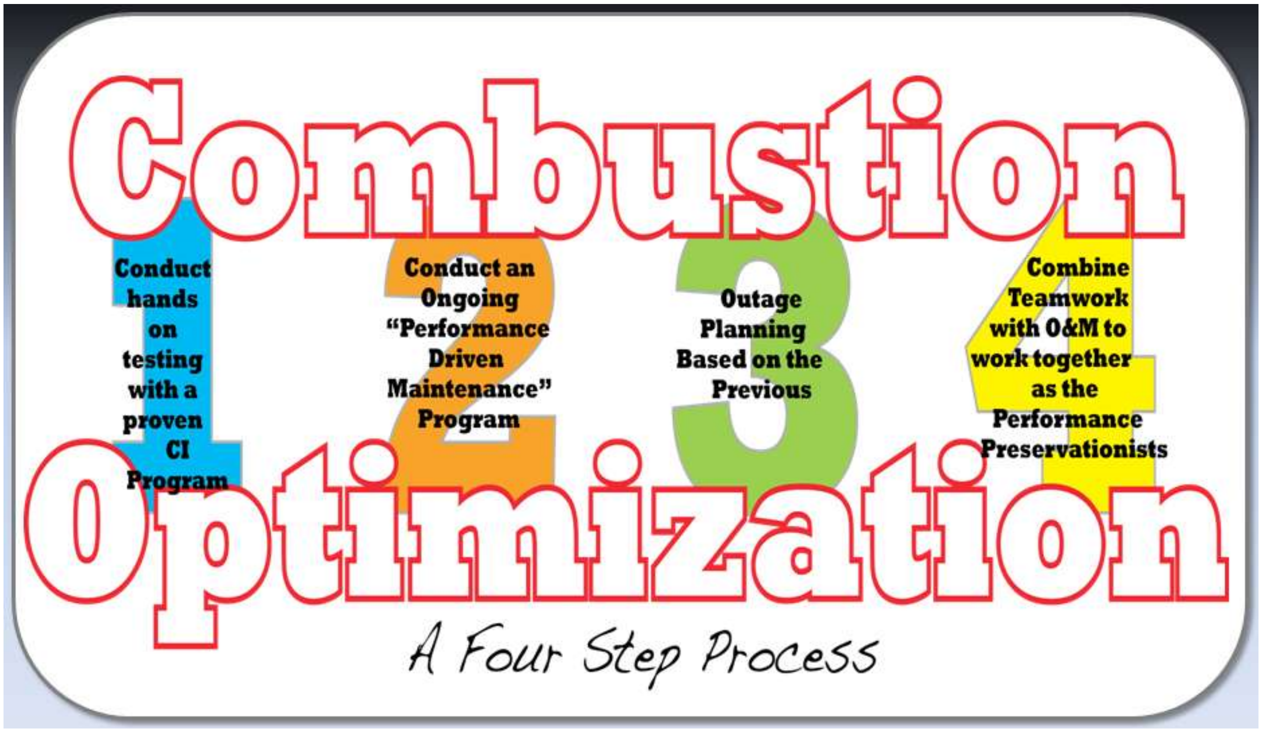



**Figure 8**

First we recommend a comprehensive evaluation. This is to formulate a bench mark or baseline and to identify opportunities. Quantifying the furnace excess oxygen levels, stratifications of combustion products, fuel fineness, fuel balance, etc. when the furnace inputs are quantified. The actual results of the combustion process are measured, and then corrective action can be planned. This is basically a four step process to test-tune-review data and apply corrective action with the operations and maintenance team.

The key to optimization, in our experience, is to apply performance driven maintenance. The following will describe our approach to combustion optimization of pulverized coal fueled large utility boilers.

# Furnace Exit HVT Testing

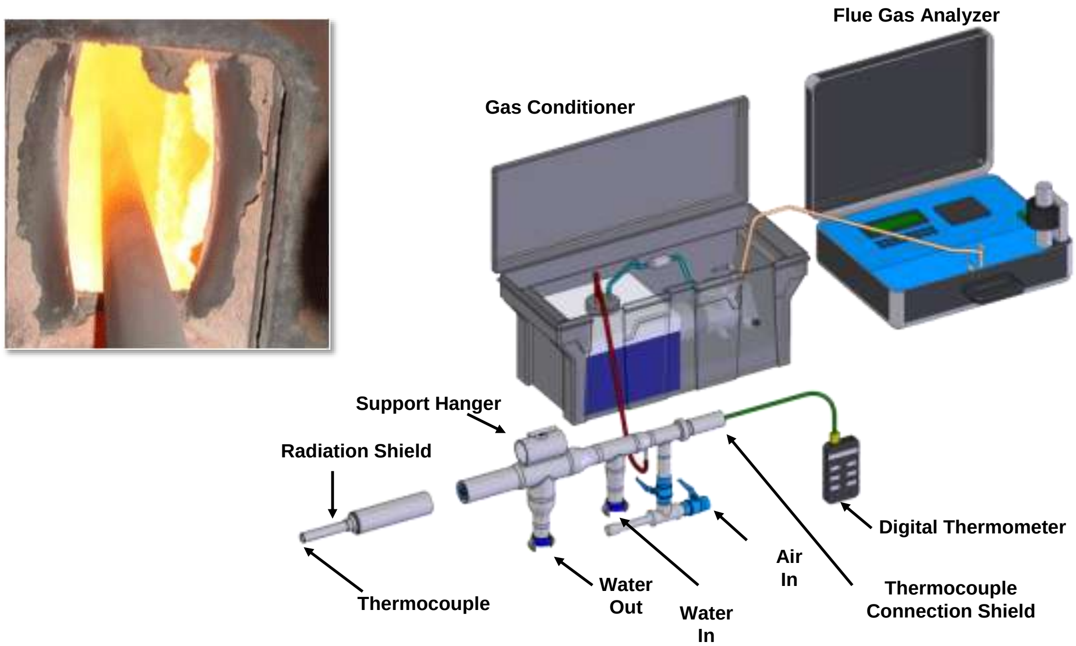
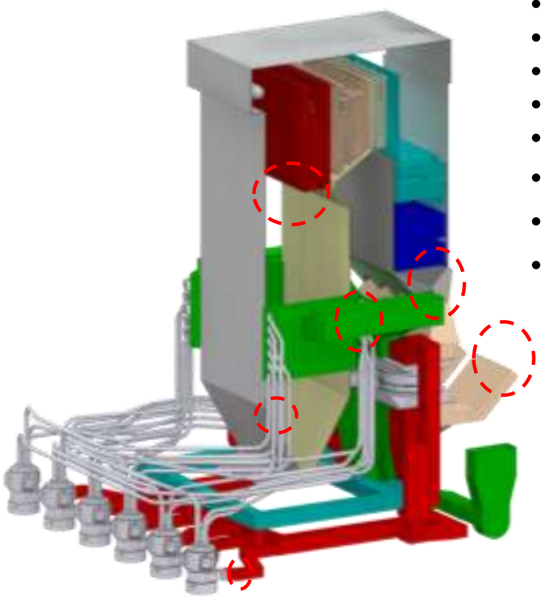



**Figure 9**

Based on our experience, the HVT probe is the most useful test tool to quantify furnace performance. The name of the HVT probe, High Velocity Thermocouple probe, infers that it is useful for measuring the true temperatures at the furnace exit. This is true! It is useful for temperature measurement. However, the real value in using an HVT probe is to use it as a water-cooled flue gas sampling probe to ascertain free oxygen levels and carbon monoxide levels across the furnace. By doing so, fuel rich and air rich lanes of the products of combustion can be identified. Then fuel line balancing or airflow balancing can be tuned, based on the measurement of flue gas constituents at the upper furnace.

The water-cooled HVT probe provides a furnace exit quality of combustion measurement. Once lanes of fuel rich products of combustion are identified, then they can be corrected. Measuring products of combustion just one or two seconds after fuel admission to the furnace, provides an opportunity to measure and quantify the amplitudes of the extreme fuel rich and air rich zones of the burner belt.

# Comprehensive Evaluation



- Gross Turbine Cycle Heat Rate (GTCHR)
- Fuel Line Performance Measurements
- Mill Inlet Primary Airflow Calibrations
- Total Secondary Airflow Measurement & Calibration
- Furnace Exit Gas Temperature & Flue Gas Constituents
- Economizer Outlet Flue Gas Measurements
- ID Fan Discharge / Stack Inlet Flue Gas Measurements
- “Stealth Loss” Evaluation

**Figure 10**

The success of the Storm approach has been rooted in being cognizant of as many measurable factors as possible. For example, at one time reducing flyash carbon content (loss on ignition) was thought to be simply a pulverizer fineness issue. That is not reality today with low $NO_X$ combustion. High carbon in ash content can also be present, even with outstanding fuel fineness. It is all of the furnace inputs that need to be optimized and on a comprehensive basis. The 13 Essentials cover nearly all of the factors that affect furnace performance. The usefulness of applying the 13 Essentials is that different test techniques and instrumentation are used to measure airflows, flue gas chemistry, ash carbon content and fuel fineness. Therefore, by measuring the furnace inputs and products of combustion, a more complete diagnosis of the root causes of slagging, high CO, high LOI or other factors can be ascertained.

# Typical STORM Burner Testing & Tuning Locations

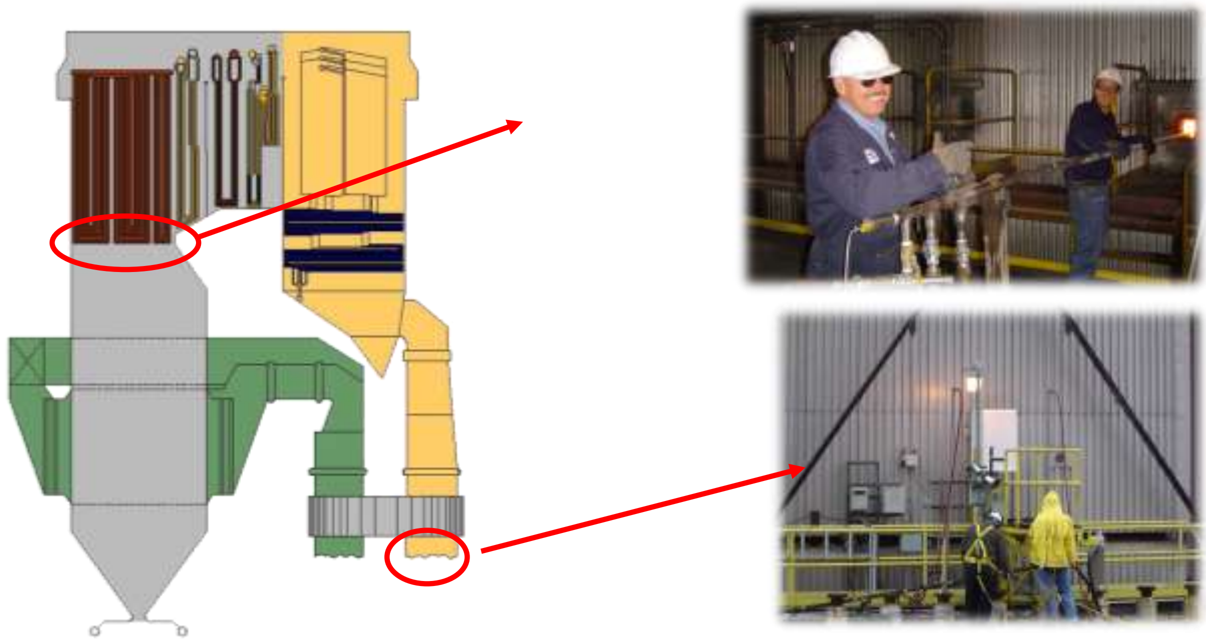


**Figure 11**

Traditional acceptance testing by the ASME performance test codes focuses on the flue gas analyses and temperatures at the airheater inlet and outlet flue gas ducts. From that and the fuel ultimate analysis, the heat losses can be determined on a percentage of efficiency loss per pound of as fired fuel. This assumes that the flue gas constituents at the economizer exit are the same as the furnace exit based on zero air in-leakage. As the coal fleet has aged, air in leakage of the boiler setting is no longer zero. Therefore, the Storm focus for combustion optimization begins at the furnace exit. The furnace exit is the point at which that combustion should be completed. Therefore, the use of water-cooled probes to measure and verify complete combustion before the products of combustion enters the superheater.

# Clean Air Testing

**Figure 12**

The Storm approach is to concentrate on getting the inputs to the furnace right. Therefore, fuel line balance is an important pre-requisite. A needed first step in balancing the fuel flows. Balancing the system resistance of all of the fuel pipes is the first step in fuel line balancing. Fuel pipes have varied lengths and varied numbers of bends. Therefore, orifices are used to balance the system resistance of the short pipes and the longer pipes with more bends and more equivalent length.

# DIRTY AIRFLOW TESTING

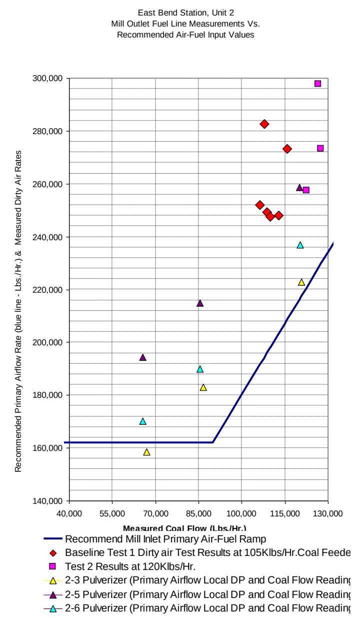



**Figure 13**

Measurement of the flowing coal air mixture is done with a "dirty air probe" because the fuel is about 1,000 times more dense than the transport air and is a solid. The flow of the fuel air mixture may not exactly follow clean air balance. Measurement of the flowing mixture is done for three reasons: 1) determine the actual in service air/fuel ratios, 2) ascertain the "balance", and 3)use the measured velocity to set the isokinetic coal sampling rate to sample the fuel flow and extract representative fineness samples.

# Isokinetic Coal Sampling

**Figure 14**

Obtaining truly representative coal fineness samples remains a challenge. The best time-proven, and proven to be successful, tool that Storm has used to sample fuel fineness is the Storm Isokinetic Coal Sampler. This device obtains representative coal fineness samples for complete sieve analysis which is a very important step in diagnostic testing by itself. Also, fuel flows through each coal pipe are measured so that corrective action of fuel balancing can be applied. For solid fuel combustion optimization, this is at the heart of tuning the burner belt. The old Peter Drucker quote in management comes to mind, “If you can measure it, you can manage it.” This applies to getting the furnace inputs right too!

# Combustion Airflow Distribution & Control

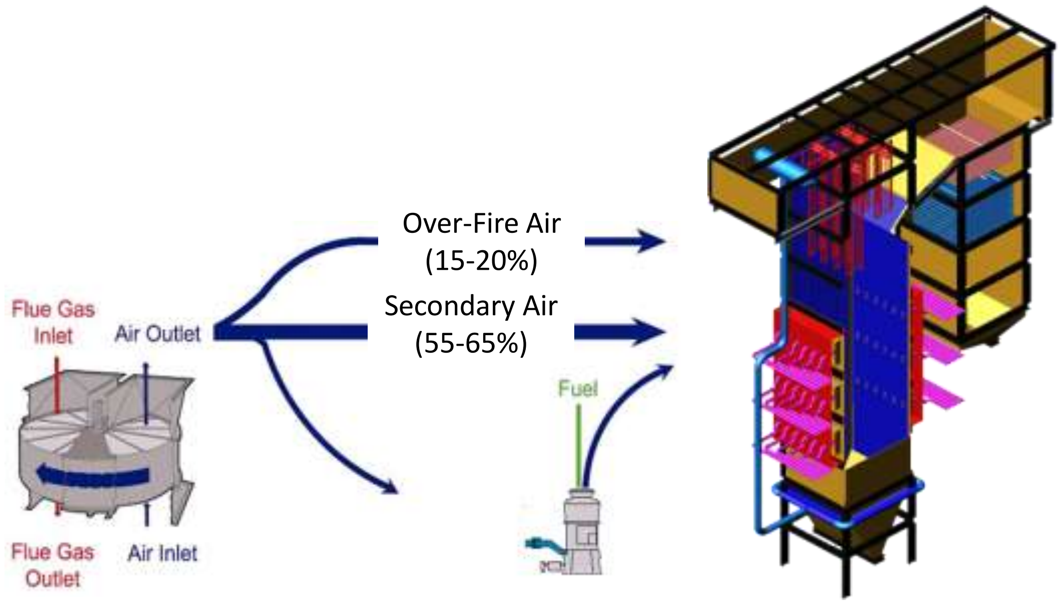



**Figure 15**

The typical airflow proportioning of large utility boilers is shown on this figure. It is important for fuel flow optimization and measuring. Fuel balancing is the first step to balancing the furnace inputs. So is it important to measure and control combustion airflows! Extremely and vitally important for combustion airflows is the accurate and optimum proportioning of airflows for fuel transport (primary air), secondary air and overfire air. Most modern large utility boilers use over fire air as part of the in furnace $NO_X$ reduction. Often overfire airflows are either not accurately measured or have no measurement devices at all, relying on damper position or the assumed flows of the original design.

For load response as well as combustion optimization, our experience favors the use of flow nozzles or venturis as robust power plant quality primary elements. Controls tuning to measure and control the optimum proportions of airflows over the load range are a must have for best load response and day to day efficient and reliable operation.

# Flue Gas Measurements (Typical Imbalances)

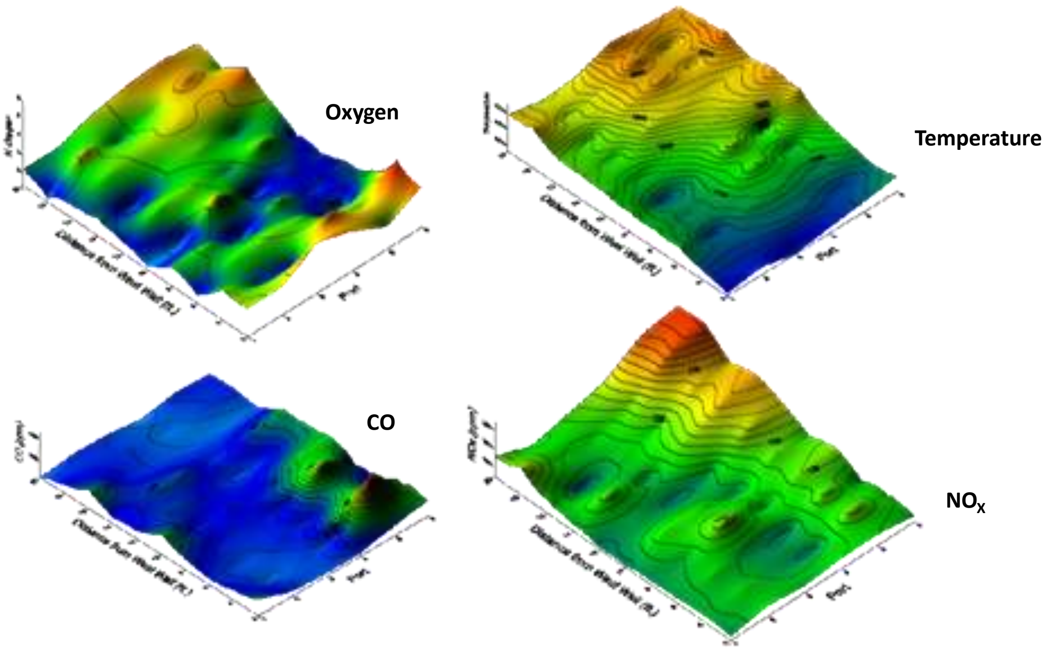
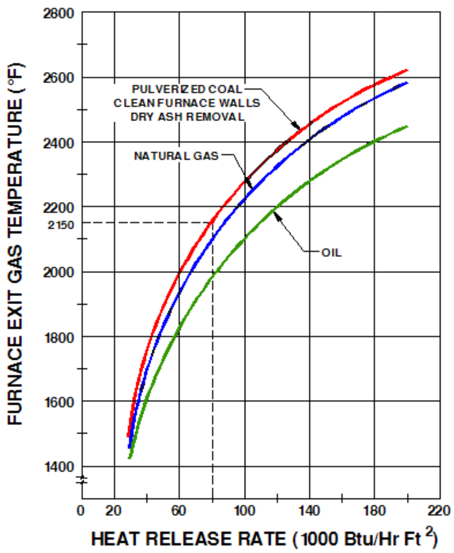



**Figure 16**

It is not the average temperatures or average flue gas excess oxygen that causes slagging, hot tubes, or zones of localized reducing atmosphere. The furnace exit stratifications, when measured and mapped, can be very helpful in applying burner belt corrections.

Note that the use of 3 dimensional plots as shown in Figure 16 are a more advanced method of describing upper furnace temperatures and flue gas chemistry. Figure 16 is from data in the last couple of years. Figure 5 is from data about 20 years ago. Of course to obtain data such as shown in Figure 16, more test points are required.

High furnace exit gas temperatures can contribute to overheated metals, such as these superheater alignment castings that only lasted 1 year due to greater than 2,500°F. furnace exit gas temperatures.




Note: This is FEGT with Optimized Combustion

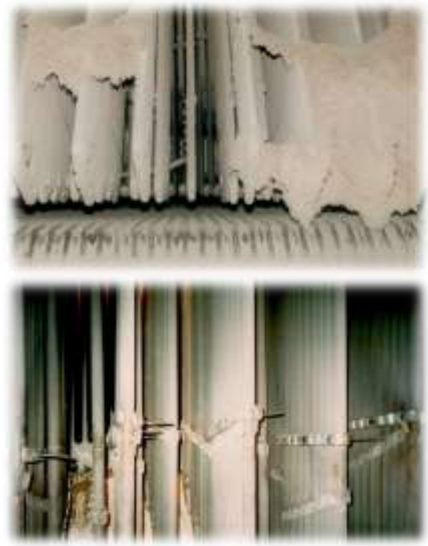


**Figure 17**

The FEGT (furnace exit gas temperature) should be in the range of 1,900°F to 2,200°F on all of the large utility boiler furnaces that we are aware of. Rarely do I use the terms "always" or "never" – but the furnace exit gas temperatures should always be in the range of 2,250°F. Never should the furnace exit gas temperature be above about 2,450°F at a single point. If the flue gases are above that, it is almost always because of secondary combustion due to poor furnace performance, stratified fuel and air streams, high primary airflows or insufficient excess air. Of course, the waterwall deslaggers must be functional to create normal furnace waterwall tube ash deposit levels.

Normal furnace ash deposition is often referred to as being "commercially clean." Maintenance of the furnace cleaning devices of course is important; whether short retracting wall de-slaggers, water assist de-slaggers or water cannons. Being mindful that the first 1,000°F in flame temperature reduction occurs in the furnace and that upwards of 35% of the total boiler heat absorption is done by radiant heat transfer in the furnace. This highlights both the need for combustion optimization, as well as for effective boiler cleaning.

# AIR IN-LEAKAGE AND X-RATIO

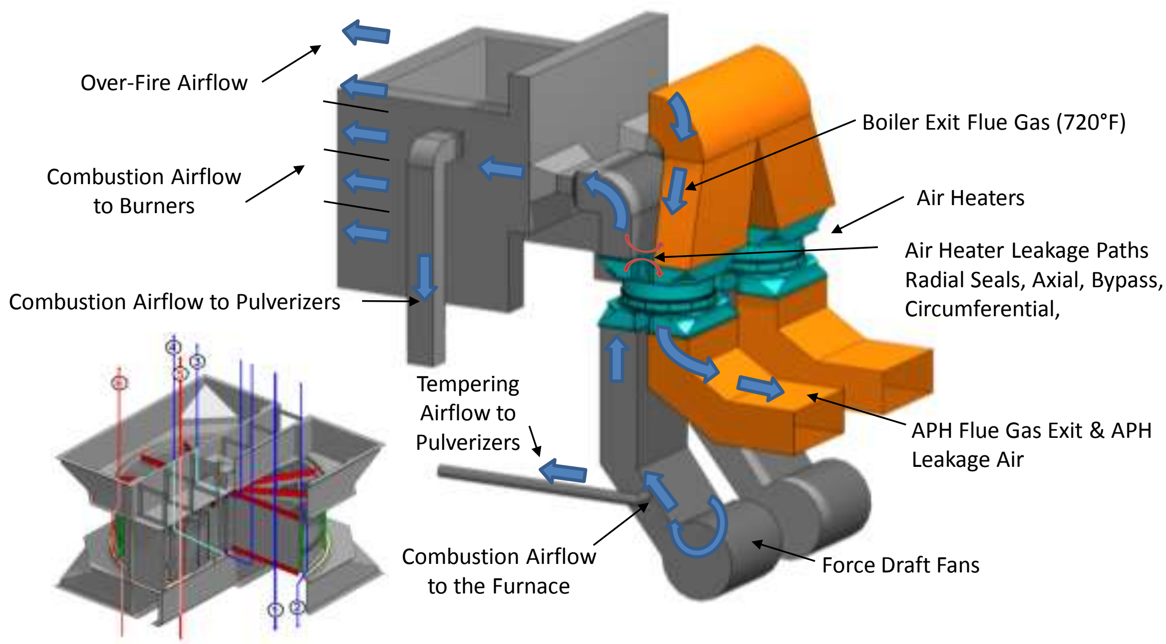



**Figure 18**

For most large utility boilers (95% or more) the air heater is the last heat trap of the boiler. Most utility boilers use regenerative airheaters. Over 90% of the combustion air that enters the furnace should pass through the airheater. The small amount of tempering air and seal air to the pulverizers are the only combustion airflow that should bypass the airheater. The X-ratio is basically the ratio of the mass flow of air to the mass flow of flue gas flow through the airheater. This is sometimes called the heat capacity ratio (or X-ratio) which is equivalent to:

$$\text{X Ratio} = \frac{\text{Mass flow of air x average Cp heat of air}}{\text{Mass flow of flue gas x average Cp heat of flue gas}}$$

Therefore, bypassing of air around the airheater, such as tempering air, ash hopper seals in leakage of failed expansion joints at the economizer exit will allow air to flow into the flue gas stream but not pass through the air side of the regenerative air heater (Ljungstrom or Rothemuhle). This unfavorable X-ratio creates a controllable heat loss. In some old pulverized coal fueled boilers, the air in-leakage has created a stealth heat loss that is in the range of 200-300 Btu's/kwh.

# (3) Part Fly ash Sieve/LOI Analysis

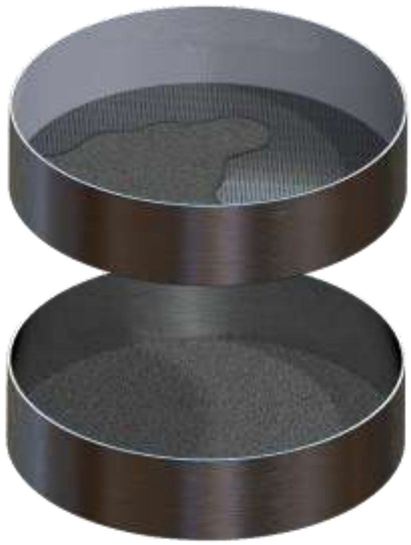



**Figure 19**

The 3-part flyash sieve analysis is one of the most cost effective and useful tests done in combustion analysis of pulverized coal units. First, a representative flyash sample is taken. A 50 gram sample is sieved through a 200 mesh sieve. Most of the ash should pass the 200 mesh sieve because ideally the coal was greater than 75% passing a 200 mesh sieve upon admission to the furnace. The three part loss on ignition or carbon analysis is done on 1) the original representative flyash sample, 2) the ash remaining on the 200 mesh sieve, and 3) the ash passing the 200 mesh sieve.

The benefit of the 3-part analysis of flyash LOI is that is serves as a referee to identify opportunities for improvement of the pulverizer fineness or other problems, such as insufficient furnace oxygen, poor mixing, etc. For example, if the ash remaining or the 200 mesh sieve is large particles and say 50% LOI then this is clearly a pulverizer performance issue. However, if 80% of the ash passes the 200 mesh sieve, and the fine particles are 15% LOI, then these fine ash particle with high LOI cannot be corrected by increasing mill fineness. The high LOI in the fines is a result of poor combustion air and fuel mixing in the furnace.

## Draft Loss & System Air In-leakage Measurement

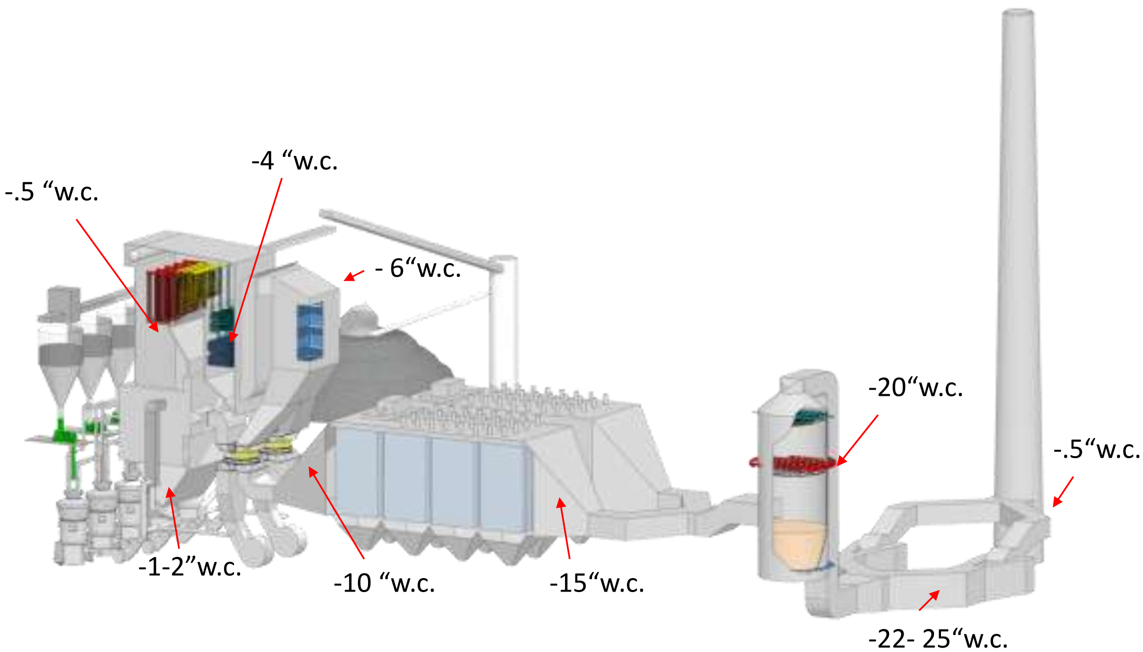



**Figure 20**

Taking into account, all pressure drops is worthwhile. Pinpointing high draft losses at the superheater, economizer, SCR or airheater can be revealing of other problems such as slagging, fouling, ammonium bisulfate fouling or other. It is a good baseline check; especially worthwhile with SCR's, baghouses and FGD scrubbers, because the parasitic power of large ID fans is significant. Also as fouling progresses so do the high negative pressures increase even further. Thus when expansion joints fail, enormous amounts of ambient air ingress can be the result. It is good to test periodically.

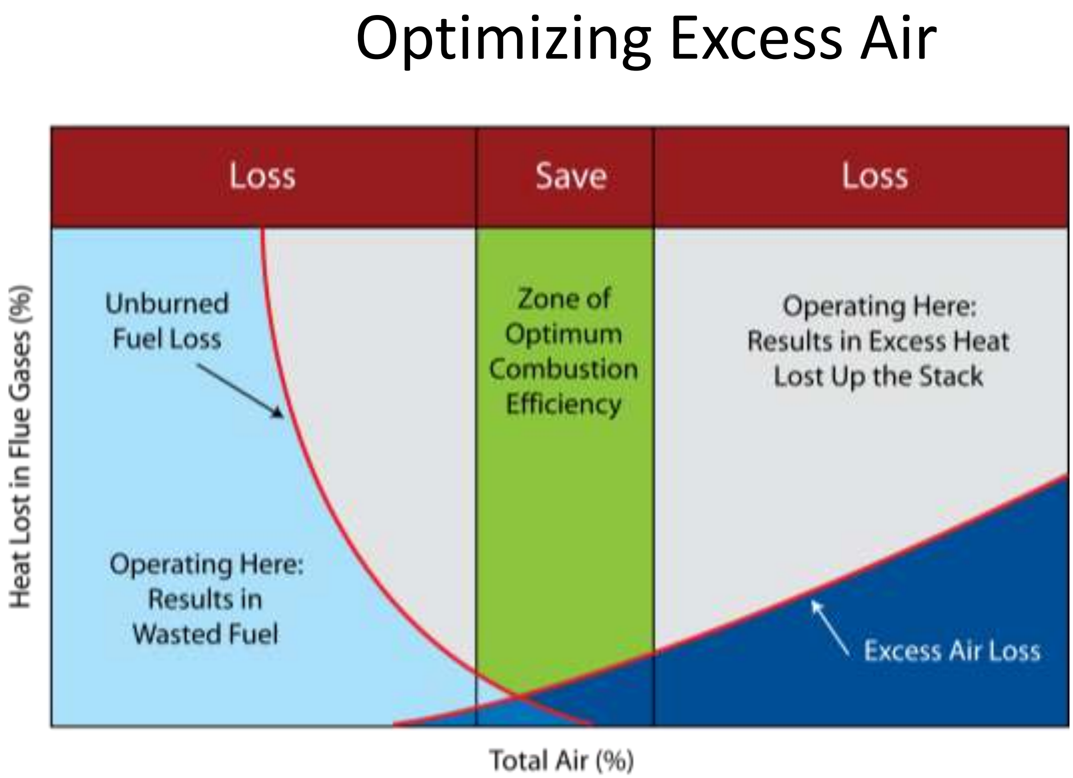



**Figure 21**

Most operators know they can reduce boiler $NO_X$ by reducing excess air. However, if combustion is not complete at the furnace exit then airflow reductions cannot be done legitimately. Reducing the excess air with an already low level will increase the CO, flyash carbon content and flame carry over into the superheater. Therefore, one other benefit of combustion air and fuel balancing is to legitimately reduce stack losses and the quantity of the products of combustion to the backend pollution control equipment. Also, reductions in the total airflows will reduce the fan auxiliary power as well as stack heat losses.

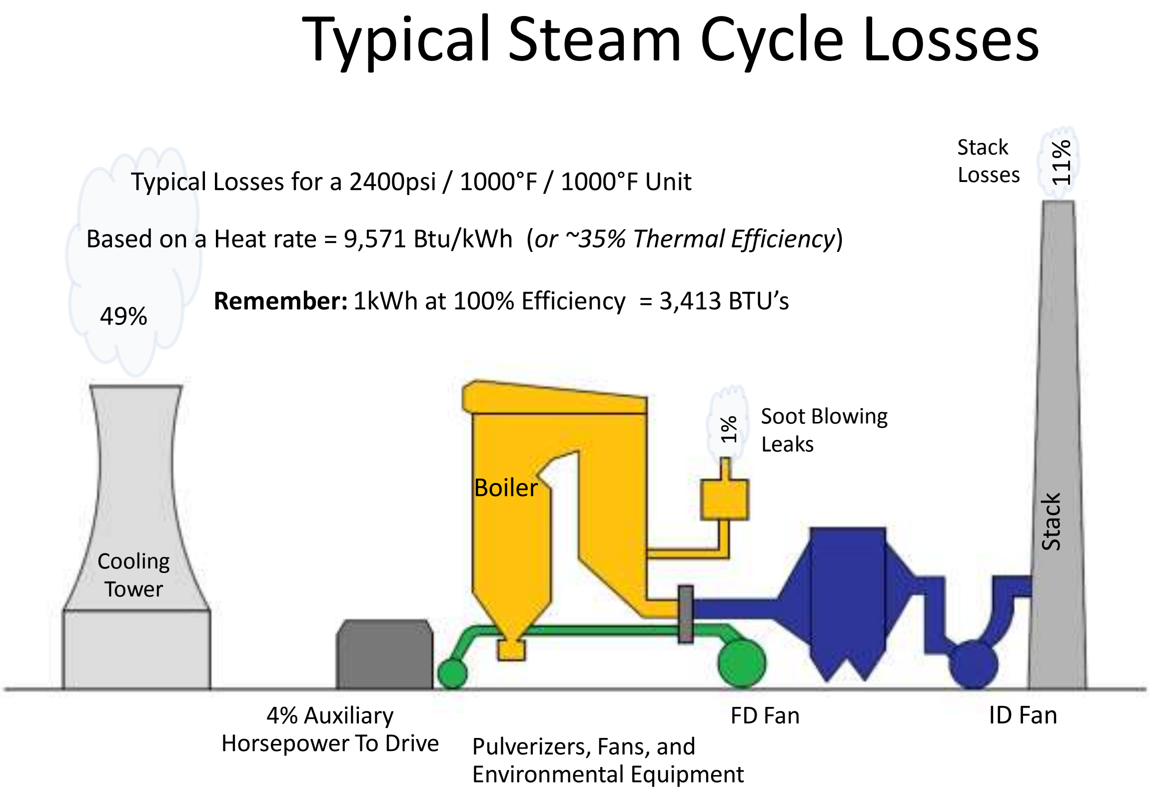



**Figure 22**

Treating a coal fueled power plant on a comprehensive basis is important for achieving optimum heat rate. For example, both design boiler efficiency and design steam turbine efficiency can be measured and achieved, yet the heat rate can be several hundred Btu's away from optimum. What are some of the "stealth losses"? Here are some common examples:

- Tramp air in leakage
- High pulverizer tempering airflow
- High reheater spray water flows
- High draft losses with resultant increased auxiliary power
- High bottom ash carbon content
- Unmeasured combustion airflows


SERVICE QUALITY
RESULTS
STORM
STORM®
Specialists in Combustion and Power
22 Heat Rate Variables
1. Flyash Loss On Ignition (LOI)
2. Bottom ash carbon content
3. Boiler and ductwork air in-leakage
4. More precise primary airflow measurement and control, by reducing tempering air
5. Reducing pulverizer air in-leakage on suction fired mills
6. Pulverizer throat size and geometry optimization to reduce coal rejects and compliment operation at lower primary airflows
7. Secondary airflow measurement and control for more precise control of furnace stoichiometry, especially important for low $NO_x$ operation
8. Reduction of extremely high upper furnace exit (FEGT) peak temperatures, which contribute to "Popcorn Ash" carryover to the SCR's and ApH's, High spray water flows, Boiler slagging and fouling, and high draft losses due to fouling. The high draft losses cause increased in-leakage, increased fan auxiliary power wastage and increased associated losses with the high spray water flows
9. High de-superheating spray water flow to the superheater
10. High de-superheating spray water flow to the reheater
11. High air heater leakage (note: Ljungstrom regenerative airheaters should and can be less than 9% leakage)
12. Auxiliary power consumption/optimization i.e., fan clearances, duct leakage, primary air system optimization, etc
13. Superheater outlet temperature
14. Reheater outlet temperature
15. Airheater outlet temperature
16. Airheater exit gas temperature, corrected to a "no leakage" basis, and brought to the optimum level
17. Burner "inputs" tuning for lowest possible excess oxygen at the boiler outlet and satisfactory $NO_x$ and LOI. Applying the "Thirteen Essentials"
18. Boiler exit (economizer exit) gas temperatures ideally between 650°F to 750°F, with zero air in-leakage (no dilution!)
19. Cycle losses due to valve leak through – i.e. spray water valves, reheater drains to the condenser, superheater and re-heater drains and vents, and especially any low point drains to the condenser or to the hot well
20. "Soot blowing" Optimization – or smart soot blowing based on excellence in power plant operation. (Remember, soot blowing medium is a heat rate cost, whether compressed air or steam)
21. Feed water heater level controls and steam cycle attention to detail
22. Steam purity and the costly impact of turbine deposits on heat rate and capacity

**Figure 23**

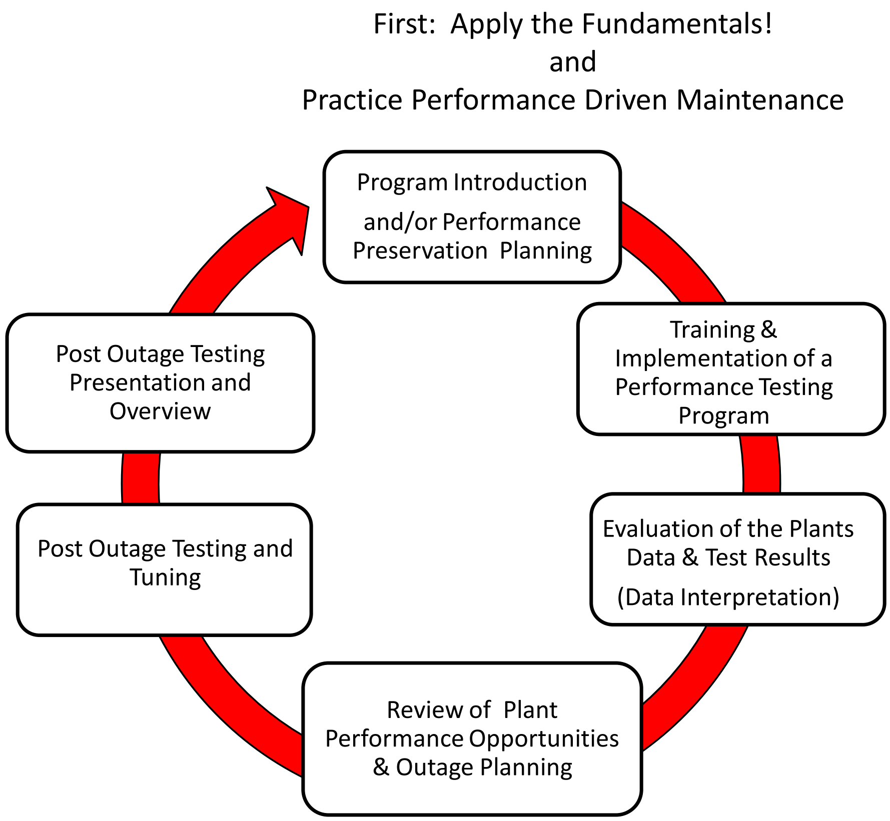



Figure 24

# Thank You! Any Questions?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