GETTING THE MOST FROM BOILERS

THE BOILER IS THE MOST CRITICAL COMPONENT OF A POWER PLANT IN TERMS OF OUTAGES. STEPHEN STORM GIVES AN IN-DEPTH LOOK INTO ITS OPTIMISATION.

The reliability and optimisation of pulverised coal-fired and oil-fired boilers often corresponds with the performance of the auxiliary equipment, controls and all of their processes. These include, but are not limited to, combustion control equipment such as the fuel preparation and measurement systems, coal pulverisers, burners, forced draft and induced draft fans, air pre-heaters, air dampers, and processes such as primary air, secondary air, and fuel delivery systems. These produce the 'inputs' to a large utility furnace and it is essential that the systems be validated and proven through periodic instrumentation and system device calibrations.

By doing so, this ensures minimal variability from the design values for the system. By integrating a performance-driven maintenance programme that evaluates the performance of the mechanical

"The fact of the matter is that most forced outages and/or reliability issues with large steam plants are related to the performance and reliability of the boiler."

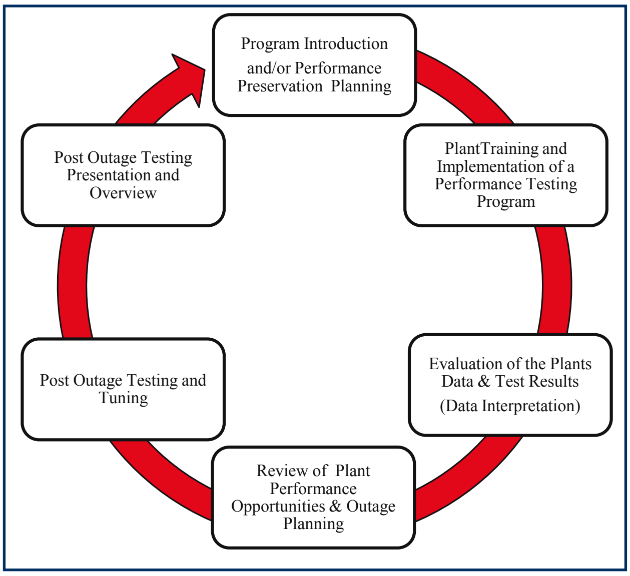


Figure 1: Storm Technologies Inc. (USA) - APPLES, cycle of events

components with actual measurements of their calibration and/or performance, you can indeed manage the system. As the old saying goes, "if you can measure it, you can manage it." With that said, let's take a look at a successful 'performance improvement' and/or 'preservation' programme that is based on industry best practices for boiler tuning and testing methodologies.

Storm Technologies Inc (USA) has been promoting the essentials for combustion for many years and offers a unique approach to optimisation which is a comprehensive, yet a fundamentals-driven effort for obtaining optimum steam generator performance, capacity and reliability.

This approach integrates a five part optimisation programme:

1. Training – helping others understand combustion and boiler performance
2. Testing – measuring performance to evaluate the baseline performance
3. Interpretation and planning – performance driven maintenance
4. Tuning – operational optimisation, fuels flexibility and efficiency
5. Performance preservation – maintaining best possible performance.

This cycle is STORM's Annual Plant Performance Longevity and Evaluation Services (APPLES) approach and is shown in Figure 1.

Optimum combustion and best heat rate operation of a large utility boiler requires a coordinated approach of matching combustion and the performance of the steam cycle. Quite often, you'll find a large number of folks intrigued and interested with the performance measurement, care and cleanliness of steam turbine/generator, while the boiler is often neglected and under-appreciated. The fact of the matter is that most forced outages and/or reliability issues with large steam plants are related to the performance and reliability of the boiler. Given that the cost of fuel to fire the boiler is typically in the magnitude of 80 per cent of the production cost of a typical power station, efficiency of the boiler should be ranked first on the list of important things to do. Just for review, let's take an example of a 500MW unit designed for 1000F/1000F and 2,400 psi throttle pressure.

Given a unit load capability of 500MW, a capacity factor of 90 per cent, together with a fuel cost of US$3.00/MMBtu and a normal heat rate of 10,000Btu/kWh, the approximate fuel cost per year can be calculated as follows:

Total heat input = (500,000kW)(8,000 hours/year)(10,000Btu/kW)
Total heat input = 4 x 10^{13} Total Btu's/year
Total annual fuel cost at US$$3/mBtu = Total Btu input/1,000,000 x US$3.00/mBtu = total annual fuel cost at US$3/mBtu = US$120m.

It's not unusual to have the boiler and turbine meet design efficiency while the unit efficiency may be 5-7 per cent lower than design. With that said, this stealth penalty may be greater than US$7m/year

Table 1: Stealth heat rate losses (typical)

Typical stealth losses (O&M variables)	Potential for improvement	
Air in leakage reduction	50.4K/cal	200Btu/kWh
Reducing air heater leakage	12.6K/cal	50Btu/kWh
Primary airflow optimisation	12.6K/cal	50Btu/kWh
Pulveriser optimisation – improved fuel line balance, reduced coal rejects through the pyrite hoppers	25.2K/cal	100Btu/kWh
Reduced carbon in ash	12.6K/cal	50Btu/kWh
Reduction of de-superheating spray water flows	12.6K/cal	50Btu/kWh
Total:	**12.6K/cal**	**500Btu/kWh**

based on the previous example of the 500MW unit. Variables such as steam temperatures and de-superheating spray flows to the super-heater and re-heater of the boiler will not impact 'boiler efficiency,' but the steam conditions can have a huge impact on the overall plant heat rate. The variables that negatively impact heat rate should be considered as 'stealth losses'. An example of very common losses that Storm Technologies Inc has identified throughout the industry can be seen in Table 1.

Stealth heat rate factors

As previously illustrated, factors such as de-superheating spray water flows, non-optimum steam temperatures at low loads, air in-leakage, air heater leakage, high tempering airflows, unbalanced fuel lines, poor fuel balance, non-optimised secondary and over-fire air flows are all known to induce elevated heat rates. We refer to these variables as stealth heat rate factors.

Increased heat rate correlates with lower overall cycle efficiency and increased emissions. Therefore, these factors should be evaluated and optimised using a comprehensive approach to identify problematic areas in need of attention. A qualified test contractor should be hired to measure the 'inputs' to a steam generator to evaluate variances in the design performance and/or decreased efficiency. Storm Technologies 'claim to fame' is not only measuring the losses associated with non-optimum combustion and operations, but also correcting the root cause of the deviation through 'results-driven' maintenance.

Developing a test protocol

On a typical pulverised coal-fired unit, implementation of a testing programme should encompass at least seven areas for measurement, calibration and optimisation (these are shown in Table 2, together with the main provisions required). It should be noted that on a oil-fired unit, items 3-7 are equally as important. Most of the provisions required prior to implementation of the testing programme, are installations of testing ports during an outages.

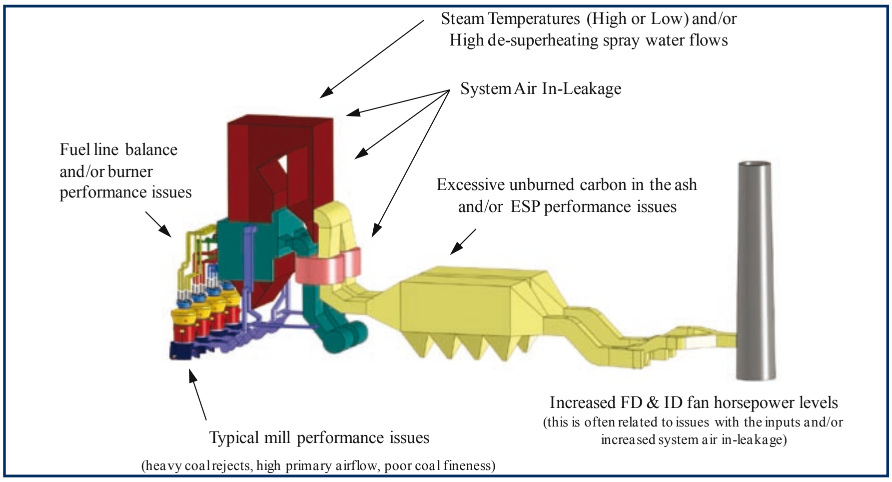
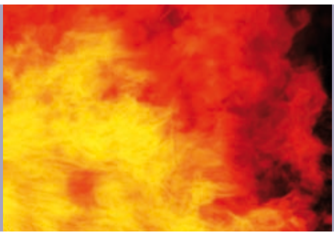


Figure 2: Typical stealth heat rate factors

Table 2: Basic performance parameters and provisions

Item	Description	Outage provisions
1.0	Pulveriser and fuel line performance	
1.1	Clean airflow balance	
1.2	Dirty airflow balance	
1.3	Fuel flow balance	Representative test ports must be
1.4	Air-fuel ratios	installed as a prerequisite to the initial
1.5	Pulverised coal fineness	
2.0	Primary air calibration and control	
3.0	secondary airflow distribution	Accessibility and testing ports are required
4.0	Excess O_2 probe measurement accuracy	Multi-point probes are preferred
5.0	Furnace exit gas temperatures and flue gas measurement	Water and air supply hoses and fittings will need to be prepared, safe test platforms; test ports- bent tube openings with observation/test door assemblies
6.0	Air heater performance; Boiler efficiency and system air-in leakage measurement (boiler stack - exit)	Accessibility and testing ports are required
7.0	In-situ flyash sampling and analyses for sizing and unburned carbon	Accessibility and testing ports are required; multi-point emission sampling systems by Storm Technologies are suggested for ease of testing/daily measurements



Combustion optimisation

Whether a boiler is pulverised coal-fired, oil, or gas, optimisation of the inputs to the furnace is a must. For most of today's large utility boilers, the furnace residence time from the instant fuel enters the furnace, until the point the products of combustion leave the furnace, is in the magnitude of only one second. In addition, for carbon char to completely combust, it must be above 1400°F (760°C) and in an oxidising atmosphere. Finally, all in-furnace solutions to reduce NO_X, deliberately stage combustion (which means separating the air and the fuel and using up furnace residence time by delaying combustion).

These points illustrate the importance of precisely measuring and controlling fuel flow and combustion airflow into the furnace. Modern low NO_X burner retrofits to utility boilers have continued to reduce the flame intensity and delayed the combustion airflow mixing with the fuel. This in turn has progressively reduced furnace forgiveness and the original three phase combustion solution of optimisation of time, temperature and turbulence.

Typically, low NO_X burners operate at stoichiometries of 0.8 to 1.0 by design. Considering that the furnace residence time is fixed by the furnace size. Similar requirements of mixing and distribution apply to oil and gas, however the fuel portion is much easier to uniformly distribute. With solid fuels only a second or two is available to complete the combustion of all the devolatilised coal or 'carbon char' to CO_2. Complete combustion with minimal boiler outlet CO or unburned carbon in ash is the ideal. The precise distribution of fuel and combustion air to the furnace has become more important than back in the 1960s and 1970s when high furnace flame intensities were common and therefore 'furnace forgiveness' with most low NO_X conversions is history.

Modern systems are often equipped with intelligent software-based systems. However, it is still extremely important to ensure the essentials or validations of the 'inputs' are periodically evaluated and proven. For example, once the properties of the 'as fired' fuel are known, through basic chemistry you can determine how much additional oxygen is required to convert all of the hydrogen into water and the carbon into CO_2. As the fuel properties vary, airflow requirements also change slightly. As an example, increased levels of carbon and hydrogen bound in the fuel require more oxygen to convert those quantities. Considering this, it is of paramount importance that total airflow is sufficient and apportioned properly for staged and controlled combustion. Non-optimum measurement of the combustion airflow will likely lead to fuel rich or lean environments within the furnace, impacting on emissions. Operations with excessively high primary airflow will reduce residence time within a coal mill and also the amount of residence in the furnace for carbon burn-out. Because of this, it is also extremely important to measure the velocity of the pulverised coal departing a coal nozzle such that tuning of the primary and secondary airflow ratios together with distribution can be optimised.

All too often the combustion airflow delivered to a furnace is not measured and validated and therefore the most important function of 'staged' or controlled combustion is overlooked. Within the USA, the importance of stoichiometry control with high-sulphur coals has become a serious matter as non-optimum

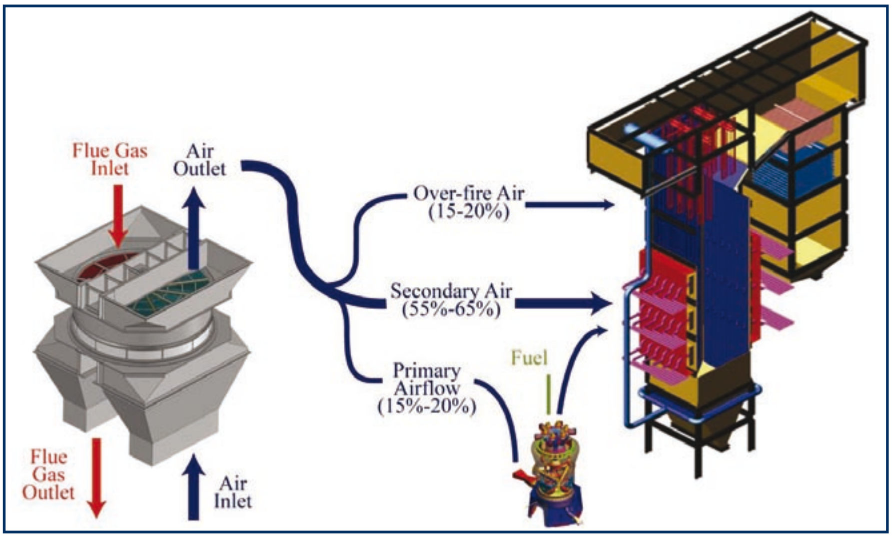


Figure 3: Typical combustion airflow paths on a pulverised coal-fired unit

measurement of the stoichiometric firing ratios can indeed result in severe water wall wastage, increased slagging and the associated reliability factors.

Throughout the USA and abroad, it is my experience that most often, actual airflow measurement and control is often neglected and the 'assumed' excess air at the furnace exit is determined by the accuracy and/or representation of the boiler exit O_2 probes. However, too often the O_2 probes are found non-representative of the actual measurements when a representative grid of flue gas samples is collected.

Theoretically, excess oxygen can be an indicator of combustion airflow. However, experience has shown that older units with high tramp air infiltration upstream of the O_2 probes corrupts the ability to accurately determine the true amount of excess air in the unit (as tramp air in-leakage falsely represents excess air). Because of the importance of stoichiometry control and balancing of the combustion airflow, it's important to periodically measure combustion airflow as well as conduct periodic system air in-leakage tests.

Figure 4 shows how an example of an acceptable measurement where the measured values follow the theoretical air calculations. This demonstrates the importance of accurate airflow measurement and control on a mass flow basis. Non-feedback, percentage-based control systems are often vague and leave room for errors based on predetermined ranges and values.

As noted and previously illustrated, the measurement of combustion airflow and distribution is critical. However, it

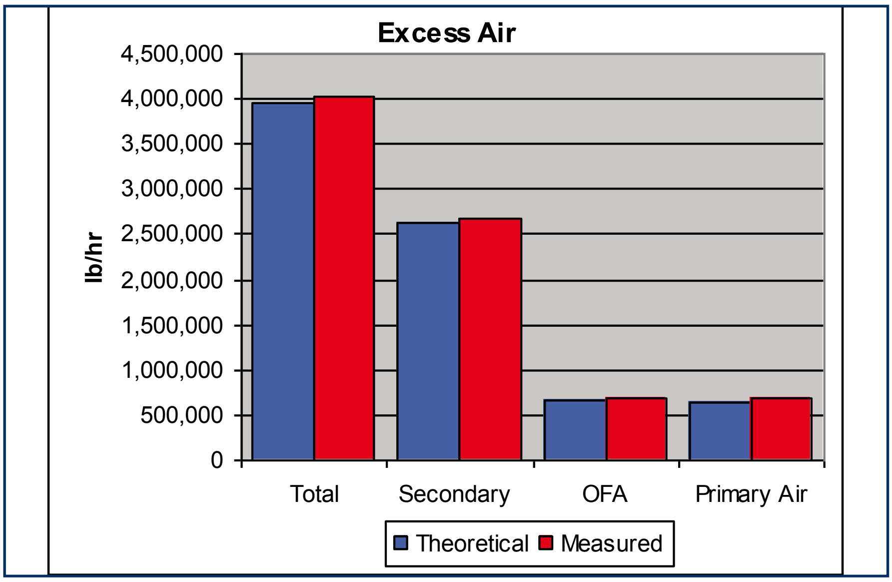


Figure 4: Example of acceptable theoretically calculated and measured airflow, at 15 per cent excess air.

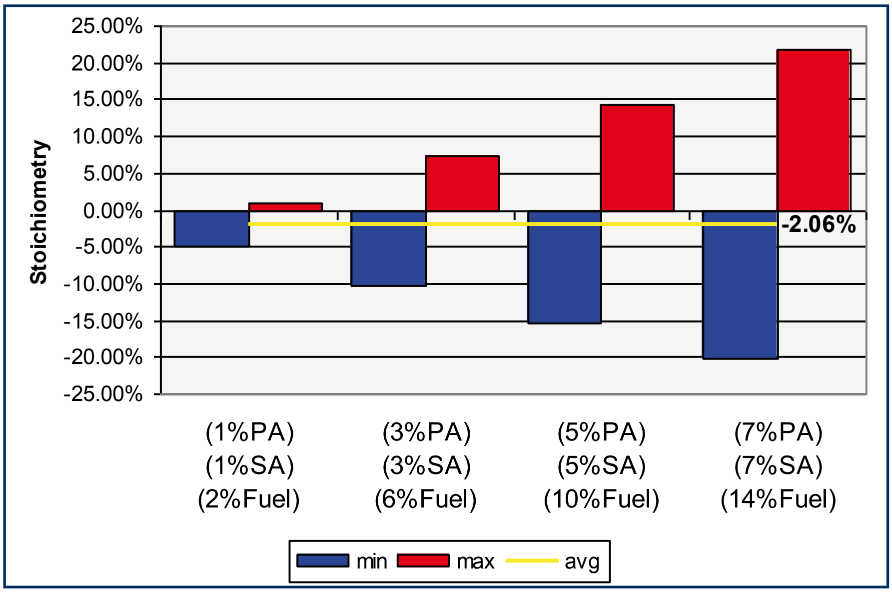


Figure 5: Burner stoichiometry compared to varying fuel and air imbalances on a pulverised coal-fired unit.

is also pertinent that each air flow path distributed to the burners is uniform. Staged combustion and control of stoichiometric firing ratios is important, but average stoichiometry doesn't really matter if the unit is air-rich on one side and fuel-rich on the other. Optimum combustion demands balanced air and fuel flows within acceptable tolerances. Figure 5 shows an example of how the minimum

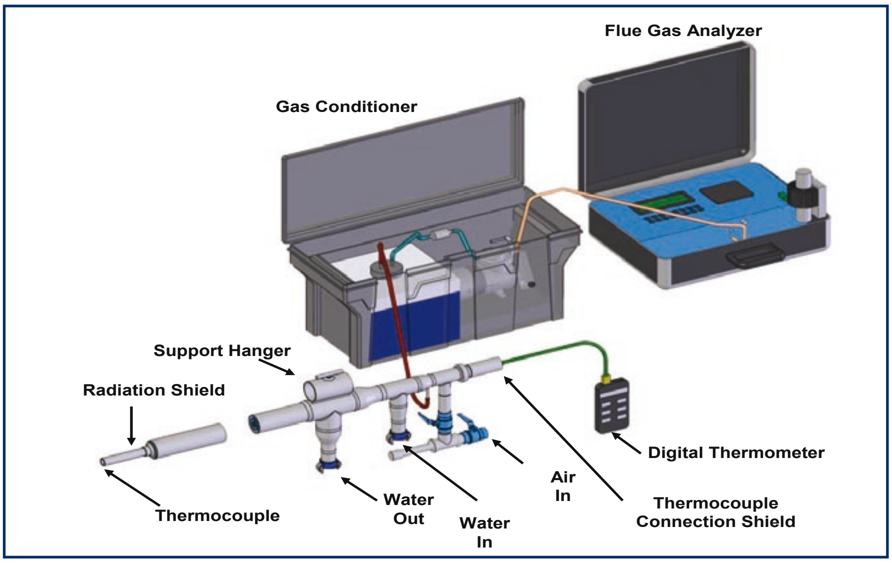


Figure 6: Storm Technologies, Inc – HVT testing equipment.

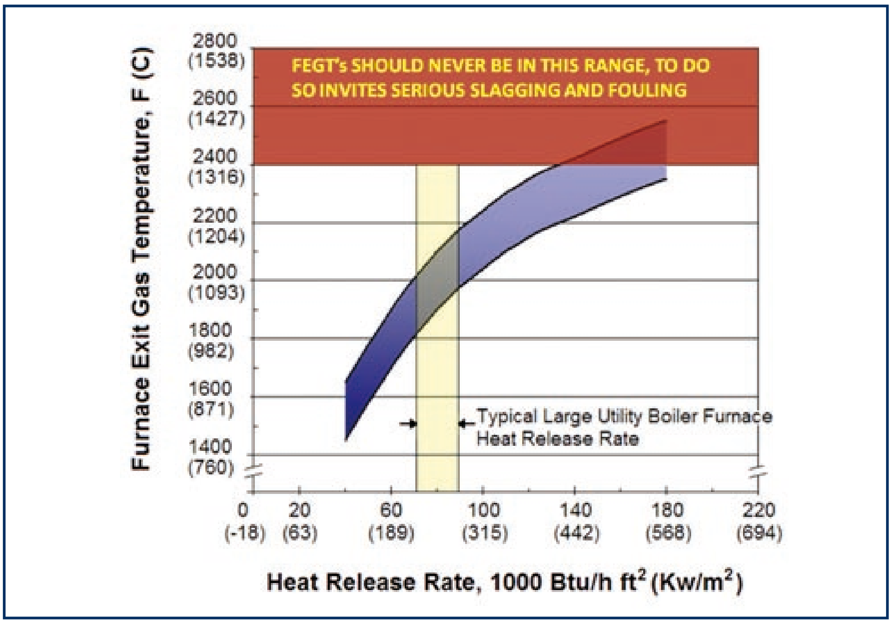


Figure 7: Example of a typical boiler, FEGT versus heat release rate.

and maximum stoichiometry changes with increasing air and fuel imbalances that are in typical and/or above average ranges.

In the previous example, keep in mind that seven per cent air imbalance and 14 per cent fuel imbalance is a conservative number for typical air and fuel imbalances. When conditions like this arise on a pulverised coal-fired boiler and the sub-stoichiometric zones are introduced with high iron ash levels, slag propensity worsens and water-wall tube wastage is likely to occur. Again, these factors illustrate the need for optimising the air and fuel inputs.

The importance of diagnosing combustion efficiency

The high velocity thermocouple (HVT) probe traverse is the single most important test in diagnosing combustion related problems on a large utility furnace. On a utility boiler, as the load or output increases, radiant heat transfer decreases and convective heat transfer rises by design with a boost to boiler efficiency.

Furthermore, most boiler designs, tube spacing, tube surface areas and regional placement of surface area portions is based off a design furnace exit gas temperature (FEGT) for a given load. Typically as the load increases, furnace exit gas temperature rises as well (see Figure 7). Periodic use of the HVT probe can therefore be used to validate furnace exit gas temperature in relationship to the boilers design.

If the combustion system is non-optimum, the residence time within a furnace for carbon burn-out is reduced and this correlates with higher boiler exit gas temperatures, likely leading to over-heating of some of the tube metal circuits. This will induce such issues as tube exfoliation and solid particle erosion of the turbine blades, overheating of the carbon steel ductwork and induced air in-leakage and tube alignment issues. To exacerbate these issues, the impacts of coal ash chemistry variation with high furnace exit gas temperatures and/or increased slag propensity will

reduce heat transfer surface and/or create imbalances of the flue gas. This, in turn, thermodynamically challenges the boiler's capability to feed steam to the turbine at its design limits.

The HVT probe is intended to accurately measure flue gas temperature, but its greatest importance is the measurement of actual or 'true' furnace exit, excess oxygen, carbon monoxide and NO_X profiles.

Balance draft steam generators over 10 years of age can undergo high air in-leakage throughout the boiler setting and sometimes upstream of the excess O_2 probes. Furthermore, sometimes due to stratifications of the air and fuel inducing flue gas variations, O_2 measured just isn't representative of the average. On older units, it is not uncommon to find total leakage between the furnace exit and the economiser exit in the range of 10-15 per cent. This will result in indicated oxygen of 3-4 per cent at the economiser exit and zero per cent at the furnace exit, which can lead to serious reliability issues (especially with the units firing high sulphur fuels). Some of the issues are noted as follows:

- Secondary or delayed combustion elevates the combustion zone, reduces water-wall heat absorption and results in high FEGT. This combined with a reducing atmosphere can lead to:
- decreased combustion efficiency
- overheating of superheat/reheat tubes
- combined with the effect of a reducing atmosphere, tube wastage and the subsequent tube thinning can result in future tube failures.
- aggravation of coal-ash corrosion
- increased de-superheating spray flow

The resulting high FEGT combined with a reducing atmosphere can lead to the following:

- carrying over of cinders from sintered ash deposits on the super-heater and re-heater tubes. These deposits contribute to air heater plugging.
- slagging and fouling of heating surfaces. Reducing ash fusion temperatures are sometimes 250°F lower than oxidising ash fusion temperatures. Therefore, high exit temperatures combined with lower ash fusion temperatures lead to heavy slagging and fouling.
- increased cycle losses due to higher soot blowing frequency as a result of increased fouling and slagging of heating surfaces.
- high boiler exit gas temperature which can lead to accelerated deterioration of air heater heating surface and possible degradation of precipitator performance.
- high leakage can reduce the available induced draft fan capacity and subsequent de-rating of unit generation and availability.
- high leakage rates down stream of the furnace, but upstream of the excess O_2 probes can contribute to low steam temperatures due to the reduced mass gas flow over the super-heater and re-heater.

Temperature and oxygen profiles obtained by the HVT traverse can also be an indication of imbalances in air and fuel originating in the burner belt zone. Therefore, the flue gas chemistry can be compared to the measurement of burner performance, fuel imbalances, combustion (secondary) air imbalance, closed air registers, plugged fuel lines, etc. Consequently, any adjustments to the pulverised coal-fired burners and/or oil fired atomisers can be easily reinforced by the temperature, O_2, CO and NO profiles determined by a HVT traverse.

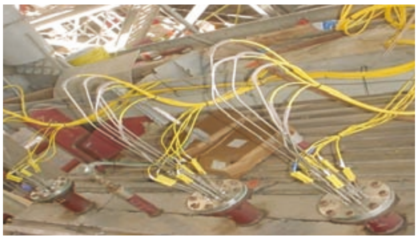
Representative sampling and measurements are absolutely necessary and good decisions cannot be made with 'bad' data. During a testing and burner tuning programme, it is also useful to compare side to side fly ash loss on ignition (LOI) and slagging tendencies with HVT oxygen profiles. In addition to the furnace exit traverse, the accuracy and representation of the excess O_2 probes, air in-leakage from the furnace exit to the economiser, air heater performance and O_2 rise to the stack should be checked periodically. Prospect units for evaluation should be equipped with representative sampling probes such that samples of the flue gas and ash are collected in a timely manner as required for combustion tuning and optimisation. An photo of a representative grid for measuring flue gas temperatures is seen in Figure 8.

Storm Technologies' multi-point emissions sampling systems (as seen in figure 9) can minimise the effort required to conduct such a test. These are custom-designed and built with an integrated in-line gas sampling grid for measuring flue gas constituents such as temperature, oxygen, CO, NO_X as well as being used as an in-line fly ash sampling 'grid' system from collecting representative samples of fly ash for unburned carbon analyses. The inter-relationships of total boiler performance must be considered when optimising combustion. Unit load response, "A methodical and proven approach must be taken to ensure elimination of the "garbage in = garbage out" side of boiler optimisation."

reliability, and capacity are all related and therefore a successful approach must be comprehensive, taking into account boiler performance, mechanical adjustments, fuels, soot blowing, airflow measurement, actual in-furnace O_2 and other factors such as the fuel quality being fired. For boilers equipped with low NO_X burners, there are certain essentials that are a useful checklist. Some of these are as follows:

- The furnace exit must be oxidising (preferably three per cent)
- The fuel lines must be balanced.
- On oil fired boilers, such areas as the measurement of steam and oil differentials is essential
- On coal fired boilers: The fuel lines balanced to each burner by 'clean air' test ± two per cent or better; Fuel lines should be balanced by 'dirty air' test, using a dirty air velocity probe, to ± five per cent or better; Fuel lines balanced in fuel flow to ± 10 per cent or better. Another critical parameter to optimising fuel balance and carbon burnout is the need for fuel line coal fineness to be 75 per cent or more passing a 200 mesh screen. 50 mesh particles shall be less than 0.1 per cent.
- Combustion airflow must be measured and controlled
- Secondary air distribution to burners should be within ±5-10 per cent.
- On pulverised coal fired boilers: primary and secondary airflow shall be accurately measured and controlled to ± three per cent accuracy (locally measured vs. indicated); Primary air/fuel ratio shall be accurately controlled when above minimum; Fuel line minimum velocities shall be 3300 fpm
- Over-fire air shall be accurately measured and controlled to ± three per cent accuracy.
- Mechanical tolerances of burners and dampers shall be ±1/4" or better.
- Fuel quality and preparation must be optimum.
- On oil fired boilers fuel oil temperature, quality and atomization mediums should be considered
- On coal fired boilers: fuel feed to the pulverizers should be smooth during load changes and measured and controlled as accurately as possible. Load cell equipped gravimetric feeders are preferred; fuel feed quality and size should be consistent. Consistent raw coal sizing of feed to pulverizers is a good start. These essentials are practical, proven, and effective. I consider these as prerequisites for optimising combustion. Non-compliance with the essentials will compromise the boiler's full potential. Too often, the evaluation of boiler performance, burner design, OFA systems and/or fuel changes are solely based upon computational fluid dynamics (CFD) models and/or some other 'Engineering Tool' model that evaluates conditional changes in design or the fuels fired. With such models, there are many assumed variables. Therefore, it should be taken into consideration that these programmes are slave to the inputs and neural networks and/or other computerised operational programs are only as good as the inputs!

One of the most commonly overlooked details with testing is obtaining reliable and representative measurements. Utility boilers are often extremely large in size and therefore to determine flue gas composition, fly ash unburned carbon and temperatures throughout the system, a methodical and proven approach must be taken to ensure elimination of the 'garbage in = garbage out' side of boiler optimisation. Conversely, integrating the APPLES method of conducting baseline performance and/or evaluating empirical data with advanced engineering technology is the best approach to excellence in boiler optimisation. ■



Figures 8 (above) and 9 (below).

Feature information

Stephen Storm is an executive vice president with Storm Technologies Inc. technical field service division. Having a broad background in evaluating combustion, performance & efficiency opportunities on utility and industrial systems, Stephen is also one of the primary trainers for Storm Technologies' Performance and Combustion training course. He can be contacted at:
stephen.storm@stormeng.com