Expert systems and coal quality in power generation

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Abstract

Coal quality, that is the properties of coal, has an impact on many parts of a power plant including the coal handling facilities, pulverising mills, boiler, air heater, ESP, ash disposal as well as stack emissions. Coals have different characteristics and heat content. The behaviour of a coal in a boiler is strongly influenced by its rank and by the mineral matter and other impurities associated with it. Coal properties can affect the efficiency, reliability and availability of both the boiler and the emissions control units. Therefore they affect the economics as well as the short- and long-term operation of the plant. Expert systems are used today in many aspects of power generation. The first step in the application of expert systems for coal quality assessment is to ensure that the sampling procedures used are as accurate and precise as is possible. This then provides a representative sample for the subsequent analysis. Online analysers can show variations in coal quality as they are occurring. However, online analysers can be expensive and their cost-effectiveness depends on the site and application. Despite questions about the accuracy of online analysers being raised, their use in coal mines as well as power plants continues to increase. The operation of coal-fired power plants involves multiple variables which have different levels of importance. A key contributor to an overall expert system is the method used to optimise the coal combustion in the boiler. This is affected by coal quality, boiler cleanliness and equipment deterioration as well as by the even distribution of the pulverised fuel to the burners. Expert systems for assessing coal quality and its implications for power generation have been and continue to be developed.

Acknowledgement

With thanks to Mr Gordon Couch for his contribution to this report

Acronyms and abbreviations

AI	artificial intelligence
AS	Standards Australia
ASPE	adaptive signal processing element
ASTM	American Society for Testing and Materials
BSI	British Standards Institution
CCS	carbon capture and storage
CFD	computational fluid dynamics
CPP	coal preparation plant
CQE™	Coal Quality Expert
CQIM	Coal Quality Impact Model
DIN prefix	used by German Standards
FGD	flue gas desulphurisation
FBC	fluidised bed combustion
GB prefix	used by the Standardisation Administration of the People's Republic of China
GCV	gross calorific value
GNOCIS	Generic NOx Optimisation Control Intelligent System
GOST prefix	used by Russian National Standards
GUI	graphical user interface
HHV	higher heating value (the same as the GCV)
IGCC	integrated gasification combined cycle
ISIS	Intelligent Soot-blowing System
ISO	International Organisation for Standardisation
LHV	lower heating value (the same as the NCV)
MIMO	multiple input multiple output
NCV	net calorific value
PCC	pulverised coal combustion
PCS	predictive controller set-up
PGNAA	prompt gamma neutron activation analysis
PRB	Powder River Basin (in the USA)
QOC	quadratic optimal controller
rom	run-of-mine (coal)
SCR	selective catalytic reduction
SI	standard international
SISO	single input single output

Contents

1 Introduction

In 2011, approximately 40% of the world's electricity will be generated from coal. Coal remains the most abundant fossil fuel and can therefore provide a reliable energy source for much of the next century. For a variety of reasons including, particularly, security of supply, it is almost certainly necessary in most countries to plan to generate power from several different sources, of which coal can be a major contributor. Coal quality (that is the properties of coal) has an impact on many parts of a power plant including the coal handling facilities, pulverising mills, boiler, air heater, ESP, ash disposal as well as stack emissions. Figure 1 is a diagram of a typical pulverised coal combustion power station. Table 1 is the stages that require monitoring in a coal-fired power generating plants (as shown in Figure1).

Coals have very different characteristics, and can have a heat content ranging widely, from 5 to 30 MJ/kg. The variation in the amount and nature of the ash-forming materials in coal are discussed in a previous Clean Coal Centre report by Couch (2006). The internationally-traded coals generally have heating values in the 22–30 MJ/kg range, and most have >26 MJ/kg. They also generally have lower ash contents than coals used inside the country of origin. The current major producers of hard coal are China, USA, India, Australia, Indonesia, South Africa, Russia, Kazakhstan, Poland and Colombia. The top coal exporters are Australia, Indonesia, Russia, Colombia, South Africa, USA and Canada while the top coal importers are Japan, China, South Korea, India, Chinese Taipei, Germany and the UK (World Coal Association, 2010). The traded coals with the lowest gross calorific value (GCV) come from Indonesia and are mainly ranked as subbituminous, but with low ash and sulphur contents, which is advantageous to some buyers/consumers (Trecazzi and others, 2007). Schiffer (2006) discusses the role of international coal trade in power generation.

The behaviour of a coal in a boiler is strongly influenced by the mineral matter and other impurities associated with it, both in terms of how much ash-forming material is there, and its composition. Analysis and significance of mineral matter in coal seams is discussed in detail by Ward (2002). In particular, the mineral matter can form slagging deposits in the hotter parts of the boiler and fouling deposits as the flue gas passes through the heat exchangers and are progressively cooled. Various coal properties can affect the efficient and consistent operation of both the boiler and the emissions control units which clean the flue gases before discharge. They therefore affect both the short- and long-term operability of the plant, and the economics of the operation. The major contributor to differences in coal properties is the presence of the mineral matter and other impurities, alongside the reactivity of the coal which is broadly associated with its rank.

Over the last few decades, many steps have been taken to reduce the emissions associated with coal-fired power generation with substantial reductions in those of particulate matter, SO_2 and NOx. The technologies for reducing and virtually eliminating these emissions are well developed, and are being more widely deployed as required by the appropriate regulatory authorities. For detailed information on these technologies (*see* Nalbandian, 2009, 2004; Nalbandian Soud, 2000). This inevitably means that the cost of the electricity generated rises and that coal-fired power plants become more complex. Their operation becomes subject to many parallel constraints, which are related to:
- the quality and consistency of the coal being used;
- the behaviour of the boiler and turbine in generating power, the gas volumes involved, its temperature, and the deposition of ash on heat transfer surfaces;
- the performance of the flue gas clean-up units and their interactions;
- the load-following characteristics of all the components.

An 'expert system' is a computer program or, more commonly, a suite of programs, that simulates the judgement and behaviour of a human (or an organisation) which has technical knowledge and a great deal of accumulated experience. The human manager typically looks at the information and evidence

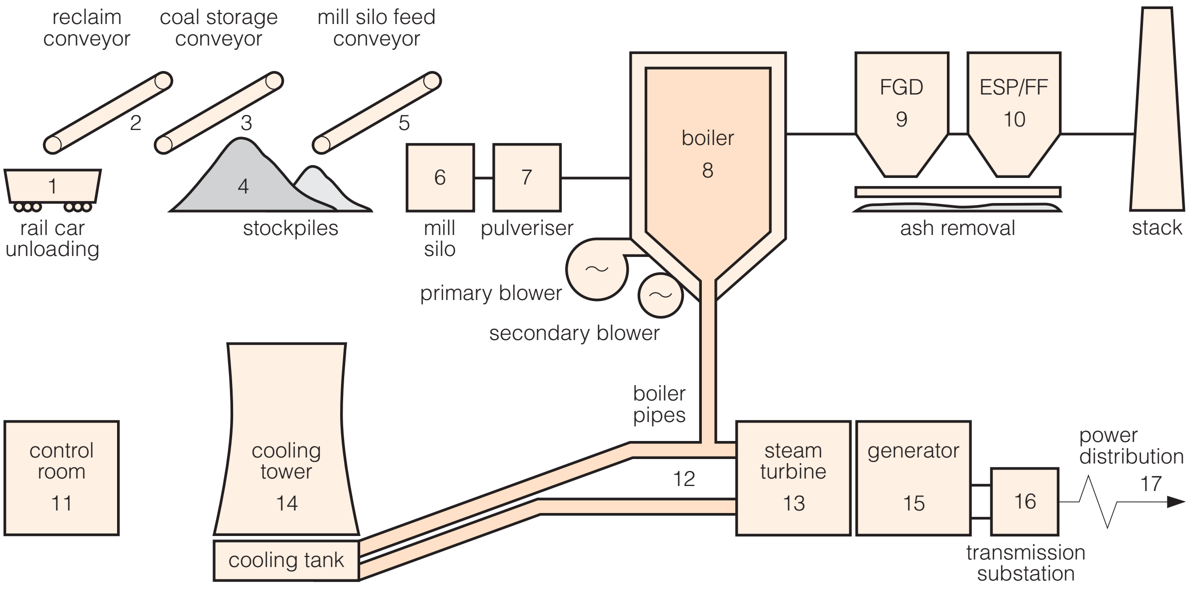

Figure 1 A typical layout of a pulverised coal fired power plant (Thermo Electron Corp, 2005)

available, and uses both technical knowledge and past experience to judge the optimum operating conditions for a plant at a particular time.

An expert system seeks to codify, prioritise and apply such knowledge automatically, using a computer program. It generally contains a knowledge base which formalises the accumulated experience, together with a set of rules for applying these as new conditions arise. It deals with the complex algorithms which are required to set the necessary conditions for safe and economic operation. Such systems can be applied to specific parts of an operating plant, and may also be used to determine overall operating characteristics in such a way as to optimise long-term plant performance. A critical input variable for coal-fired plant will always be the quantity and quality of the coal being fed to the boiler.

Human and organisational expertise consists of knowledge about a complex system, an understanding of the problems that arise during its operation, and skill at solving some of the problems which present themselves. Knowledge consists of:

- that which includes the published information, facts, and the theories and equations which are contained in textbooks and references. It includes knowledge which is taught at college and on courses;
- that which consists largely of ‘rules of thumb’ or heuristics, based on a combination of theoretical knowledge and of past experience. It is essentially derived and private knowledge which does not normally find its way into the published literature or into teaching material. Heuristics enable the human expert:
  - to make educated guesses when necessary;
  - to recognise promising approaches to problem solving and optimisation;
  - to deal effectively with erroneous or incomplete data.

The understanding and reproduction of such ‘rules of thumb’ are the central challenge in the development of expert systems. The ‘rules of thumb’ used are not necessarily universal, and will most likely have been developed by particular utilities using a relatively narrow range of coals produced in their region.

The operation of coal-fired power plants involves multiple variables which have different levels of importance. Thus different expert systems need development and validation in different locations, also

Table 1	The stages that require monitoring in a coal-fired power generating plant (as shown in Figure 1)
1	Rail car unloading
2	Reclaim conveyor
3	Coal storage conveyors
4	Stockpiles
5	Mill silo feed conveyor (coal bunker conveyor)
6	Mill silo (coal bunker)
	Applications for stages 1–6 include:
	– weighfeeders
	– on-line coal analysers
	– coal blending software
	– conveyor belt monitoring and protection controls
	– tramp metal detection
	– continuous point and level measurement
	– tripper car position measurement
7	Pulveriser (coal mill) and primary blower
	– preheat air to pulverisers
	– bearing temperature monitoring
	– coal flow distribution measurement and control
8	Boiler (coal-fired furnace)
	– SCR system catalyst temperature monitoring
	– bottom ash removal
	– lime and fly ash slurry density and flow monitoring
	– fly ash hopper level monitoring
	– opacity monitors
	– heat exchanger and boiler tube alloy verification
	– primary and secondary combustion air monitoring
	– water analysis monitors (sodium, silica, pH, conductivity, dissolved Oxygen, Oxygen scavenger)
	– plug chute detection
	– sampling probes
	– gaseous pollutant monitors (CO, CO_2, NOx, SO_2)
	– stack gas flow monitors
	– integrated continuous emission monitoring systems (CEMs)
9	Flue gas desulphurisation (FGD) scrubber
	– percent solids and slurry monitoring
10	Particulate matter control (ESP or fabric filter)
	– bottom ash slurry measurement
	– fly ash level measurement
	– carbon in fly ash gauges
11	Control room
	– data acquisition, monitoring and management
12	Boiler pipes
	– cooling water and condensate flow measurement
13	Steam turbine
	– data acquisition and monitoring of turbine parameters
14	Cooling tank, cooling tower, reservoir
	– density measurement
	– influent and discharge flow measurement
	– water analysis monitors (pH, conductivity, chloride)
15	Generator
	– data acquisition, monitoring and management
16	Transmission substations
	– power quality monitoring and analysis
17	Power distribution
	– data acquisition, monitoring and management
	– power quality monitoring and analysis

taking into account the many possible variations in plant design.

This review includes a discussion of the different patterns of coal supply in Chapter 2, and of coal sampling and analysis in Chapter 3. In Chapter 3 the discussion is of the main aspects of coal analysis both in the laboratory and online. There are significant limitations on what can be established and on the interpretation and use of the data obtained. Section 3.2.2 looks at the use of coal analysis as a basis for putting data into expert systems which can be used as management tools for:

- running coal preparation plants (CPPs);
- managing coal blending;
- assessing the comparative economics of using different coals in a particular boiler based on:
  - plant efficiency effects;
  - sub-system capacities and auxiliary power requirements;
  - steam attemperation requirements;
  - propensity for slagging and fouling;
  - maintenance and waste disposal costs;
  - possible replacement power costs resulting from changes in unit availability and capacity;
- controlling the soot-blowing cycles in a boiler. In pulverised coal combustion, the fuel can collect on the tube banks in the boiler. These tube banks are cleaned by high-pressure jets of steam in an operation called soot-blowing;
- monitoring the coal feed into a coal-fired boiler and optimising the boiler operating conditions accordingly. A given power plant tends to use a restricted range of coals. The operators learn how to run the boilers satisfactorily whilst coping with the changes in coal properties within the range.

Various aspects of the use of these systems are discussed in Chapters 4 and 5. This includes both the short-term effects, such as meeting the requirements for peak demand, and the overall long-term economics which are affected by plant reliability, availability and maintenance costs, as well as fuel costs.

Expert systems for assessing coal quality and its implications for power generation need to fit into the broader context of the management of large companies using a variety of energy sources who are seeking to maximise profit across the business value chain, within the prevailing legislative and regulatory framework. The long-term economics of power production from the different sources affect the choices made alongside considerations of energy security. These broader systems fall outside the scope of this report and it should be noted that relatively little information about them has been published.

2 Coal variability in power generation

Coal is extracted either from open (surface) pits and/or from underground mines. Sometimes the coal comes from several seams at different depths, or it may come from different parts of a seam. It may have quite variable characteristics even though it is apparently supplied from a single mine. Where the coal lies near the surface, open pit mining is usually preferable and more economic. For internationally-traded coals, and for some which are internally used or traded, coals may be stacked and blended either before or after transportation, to meet required/desired specifications. It may be that, in the future, coal will be gasified underground, so that the energy supply to the boilers or turbines used will be in the form of a clean syngas. Developments in underground coal gasification are discussed in another Clean Coal Centre report by Couch (2009).

The primary determinant affecting the variations in coal properties is the burial history of the original peat and its subsequent movement, compression and coalification. This results in differences of coal rank, controlled by differences in the geological conditions of temperature and, to a lesser degree, pressure during the coalification processes. Increasing rank results from progressive and irreversible changes in the chemical and physical properties of the coal, in the generalised sequence of: peat → lignite → subbituminous coal → bituminous coal → semi-anthracite → anthracite. The variations in the nature of different coals have been explored in earlier IEA Clean Coal Centre reports by Walker (2000) and Couch (2006). Evaluation methods for thermal coal quality were the subject of a review by Okamoto (1998).

Currently, the coal supply to a particular power plant may come from:

- a single local mine, with or without a CPP. Where the coal is supplied without preparation, as is the case with many lignite/brown coals and some higher rank coals as well, selective mining techniques may be used to minimise the variability. This is commonly referred to as minemouth generation;
- a number of nearby mines, so that the coals probably have broadly similar characteristics, as is the case both in Australia and South Africa;
- from distant mines, but in the same country. In countries such as China, India, Russia and the USA, coals may commonly be transported over distances of up to 1500 km. The coal supply to a power plant may then come from different mines and its characteristics change accordingly with variations from each mine;
- a mixture of indigenous coals, and coals which have been traded on the international market, as happens in both Germany and the UK;
- imported coals only, as, for example, in Denmark, Finland, and Japan. In South Korea some 176 Mt of coal is imported, including 100 Mt of coking coal, while production is <3 Mt, so that imports provide more than 98% of the coals used (IEA, 2009).

The nature of the coal supply to a power plant has a profound effect on the potential application of expert systems at the facility, as it does on the possibilities of using online coal analysis to provide useful data. The differences in coal supply pattern and the implications of the variations are not often discussed. When the use of online analysis and the application of expert systems to the operational implications of changes in coal quality are described, the distinctions are not commonly highlighted. Online analysis was discussed in detail in a previous Clean Coal Centre review by Nalbandian (2005).

Worldwide coal production totals 6.8 Gt/y, of which 0.95 Gt is brown coal, *see* Table 2 (IEA, 2009). The bulk of world coal production (5.86 Gt), including nearly all of its brown coal/lignite, is used within the country where it is mined and less than 15% of it is internationally traded. Of the 0.94 Gt which is traded, just over 70% (0.68 Gt) consists of steam coal, which is mainly used for power generation.

Table 2 Coal production and traded coal totals in 2008, Gt (IEA, 2009)			
worldwide coal production	hard/bituminous	brown coal	coking coal
6.8	5.85	0.95	Included in the hard coal figure
internationally-traded coal			
0.94	0.51 plus 0.17 of Indonesian subbituminous	0	0.26

This has implications for the nature and variability of the coals used at power plants, and a number of different patterns have emerged, for example:

- lower grade coals (with heat contents <16 MJ/kg) including most lignites/brown coals, and/or coals with a high ash content, are used at or near the minemouth. This is because transport costs are disproportionately increased by the amount of inert, noncombustible, material present in the form of mineral matter and/or water. These coals are commonly quite variable in their characteristics;
- the high ash coals which arise in coal exporting countries such as Australia and South Africa, where the higher grade, lower ash content, coal is sold internationally while the middling products from the CPP, containing maybe 25-40% ash, are used at nearby power stations;
- in the USA the use of western Powder River Basin (PRB) subbituminous coals has grown substantially from 264 t/y in 1998 to 402 t/y in 2008 (US BLM, 2009). This increase has been largely because the PRB coals have a low sulphur content, and blending these with higher sulphur eastern US coals has enabled utilities to reduce/control SO_2 emissions without the need to invest in flue gas desulphurisation (FGD) units on older plants. The blending of coals with considerable different characteristics has, however, presented significant challenges;
- in China, either the coal has to be transported long distances by rail or the power generated at minemouth power plants has to be transferred over similar distances. As a result of the concentration of coal producers and consumers in places like Hong Kong and Shanghai and along that coastline, coal has been imported to these areas in recent years;
- in Russia there are substantial transfers of coal westwards from the central Kuznetsk basin coalfield over long distances (Crocker and Kovalchuk, 2008). These supply the Moscow area and other parts of western and European Russia, so many power plants there deal with a mixture of local and more distant coals, and some fire a mixture of coal and natural gas;
- in India, coal is transported long distances, since the main centres needing power are a long way from the mines. Indian coals are generally of low grade due to their high and variable ash content. To encourage the use of coal washing, the government introduced a regulation to the effect that any coal transported more than 1000 km must have its ash content reduced to <32±2%. There are reports of significant coal supply shortages in various parts of the country (LCN, 2009). As a consequence, a number of power plant managers may accept any coal they can acquire without emphasis on quality.

Characterisation in production of thermal coal was discussed by Osborne and Hall (1997). In order to achieve strong partnerships with end users, the authors state that all aspects of the coal need to be understood including: handling and storage characteristics, pulverising behaviour, combustion behaviour, mineral matter and ash chemistry interactions, in addition to the characteristics of the coal and its ash in terms of environmental factors such as dust, self heating and emissions components. In order to ensure that quality is controlled, the coal chain must be regularly sampled and adjusted in accordance with the analytical results. Key control parameters are thus selected, which when monitored, provide a reliable indication of quality 'flow' in terms of both specification and

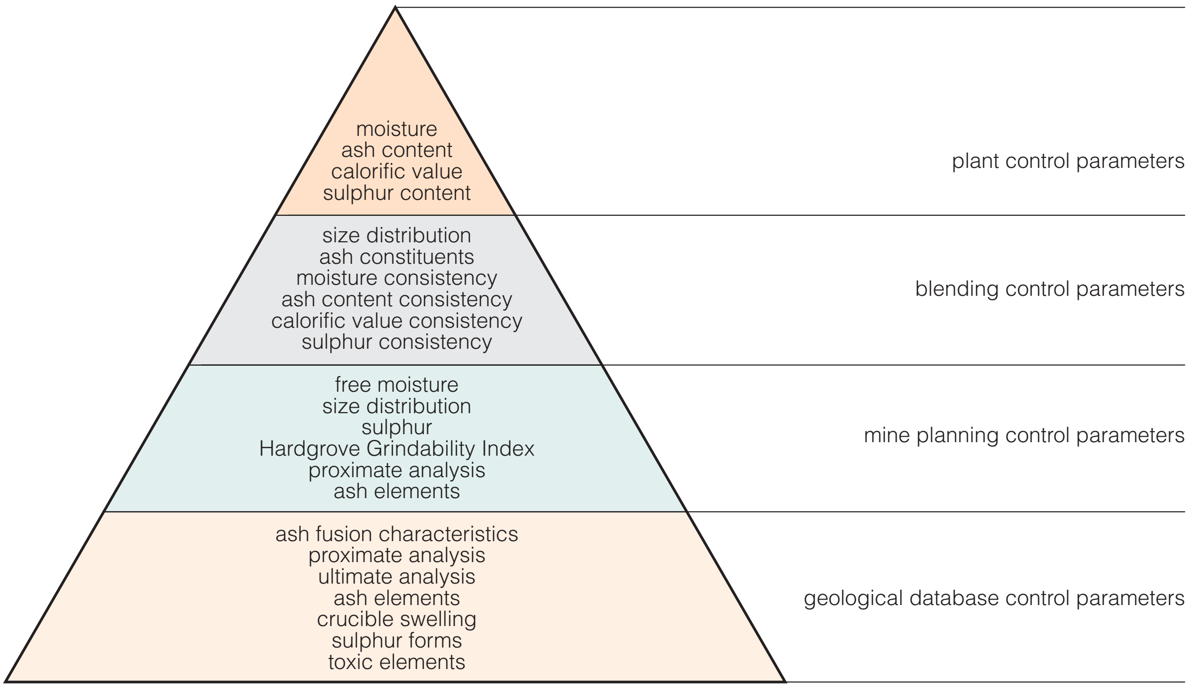

Figure 2 Examples of commonly adopted approaches to controlling key specified parameters in the coal chain (Osborne and Hall, 1997)

consistency requirements. Examples of commonly adopted approaches to controlling key specified parameters in the coal chain are shown in Figure 2. Schuster and Penterson (2002) discuss characteristic coal parameters and extensive operating experience with various coals in power plants in the USA and Europe.

Zehner (2002) presented an abstract of the guideline for the 'characterisation of power plants coals' in Germany. The guideline does not provide, as such, recommendations for the most efficient use of coals procured on the international market, because the properties of the coals differ greatly, as well as the design of the power plants. However, the guideline is intended to provide information with regard to which coal properties should be given special attention, which measures can be taken against negative effects, and which tools (that is, software as well as hardware) are available for the systematic and cost-effective operation of a plant. The guideline is directed at the technical staff of a coal-fired power plant as well as coal buyers. It is also expected to serve as an educational tool for new staff at the power plant.

Many power generators have choices to make about their coal source and whether to cofire biomass or petcoke. These choices depend on an economic evaluation of the effects of different coal properties and characteristics on plant operating costs. This applies to most power plants which use imported/traded coals including 'coal-rich' countries such as the USA and China. These generators can benefit from the application of an expert system based on the principles lying behind coal quality such as the Coal Quality Impact Model (CQIM) discussed in Section 5.1.

2.1 Coal quality impact on power plant operation

Quick (2004) considers that of all the coal quality impacts the most important is pollutant emissions. Other coal quality impacts on boiler involve corrosion, deposition, combustion stability, burnout and unburnt carbon in ash (*see* Figure 3). Ash deposition and slagging can cause problems with some coals (such as Powder River Basin (PRB) coals). Unburnt carbon in ash can be impacted by mill performance and grind quality, fuel/air distribution and fitting of combustion modification systems

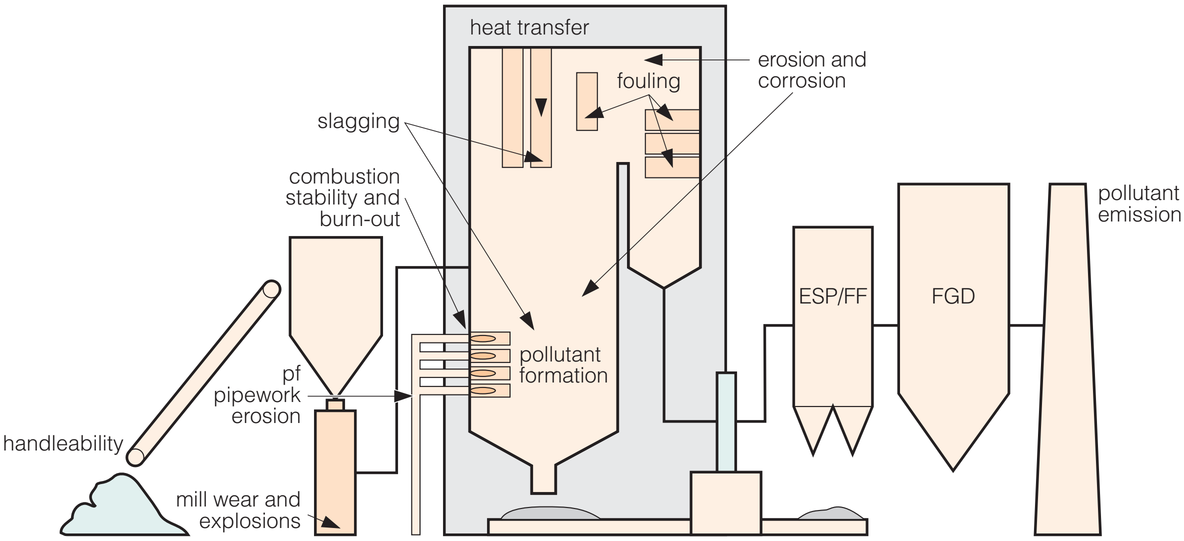

Figure 3 Coal quality impact in pulverised coal power plant (Quick, 2004)

such as low NOx burners (LNBs). SO_2 emission reduction is usually achieved either with the installation of flue gas desulphurisation (FGD) systems or switching to lower sulphur coals. NOx emissions are reduced by combustion modifications or the installation of NOx abatement and control systems. The interactions between these technologies and their impact on balance of plant are discussed by Nalbandian (2004).

Cole and Frank (2004) discussed coal quality impacts on power generation. They found that data from coal-fired power plants demonstrate that burning design specification coal translates to better plant reliability, capability and efficiency in meeting day to day dispatched generation requirements. They considered that performance of coal-fired plants that burn and continue to burn out of specification coal seems to be predictable, that is by being either unavailable for service, de-rated and/or consistently operationally unreliable when dispatched for full load generation. Furthermore, when online these plants required incrementally more coal to generate a kilowatt-hour.

Coal properties that most affect boiler operation, according to Cole and Frank (2004), are ash content, ash composition, sulphur content and moisture content. Higher ash content results in increased system throughput, increased erosion and shortened life of the coal, boiler and ash handling systems. Schimmoller (2003) discussed coal and ash handling in search of cost savings in coal-fired handling plant. Ash composition affects and influences the slagging of furnace walls and fouling of convection passes. Fouling decreases heat transfer and promotes wastage by external corrosion/erosion in the convection passes, air preheaters and the induced-draft fans. Excessive slagging blocks off the convection passes and plugs air preheaters. Sulphur content influences the operation and maintenance of feeders, pulverisers, furnace walls, platens, pendants, economisers, soot blowers, air preheaters, dust collectors and induced-draft fans. Pyrite causes excessive wear of the pulveriser internals. Ash, sulphur and moisture directly affect the heating value of the coal and limit the capacity of the combustion system. All these properties that are out of specification can cause premature failure, forced outages and derating. These are usually well documented within the facility. The data can be used to determine the economic impacts of firing out-of-specification coal on plants operation and to incorporate these impacts into the procurement processes (Cole and Frank, 2004).

Following an in-depth study of the economic impacts of firing out of specification coal in a power plant, Cole and Frank (2004) considered that for a typical 500 MW unit, an increase of 8% in the ash content and 2% in the sulphur content would result in 537 unplanned outage hours. If replacement power costs were relatively low at 30 US$/MWh, this would result in US$8,055,000 in lost revenue. At relatively high demand replacement power cost of 200 US$/MWh, the result is US$53,700,000 of unrealised revenue. Cole and Frank (2004) state that the total fuel costs for such a unit for one year (assuming a 75% capacity factor, 10 MJ/kWh heat rate and 11 US$/MJ fuel cost) are US$39,000,000. These figures are put into perspective as follows (Frank and Cole, 2004):

Total yearly fuel bill	**US$ 39,000,000**
Low demand replacement power costs	US$30/MWh
Lost revenue or equivalent fuel penalty	US$8,055,000
Percentage fuel penalty = 8,055,000/39,000,000 or 20.6%	
High demand replacement power costs	US$200/MWh
Lost revenue or equivalent fuel penalty	US$53,700,000
Percentage fuel penalty = 53,700,000/39,000,000 or 137.7%	

In reality, the authors consider that the actual lost revenue falls between the two values. However, this does not include the reduced boiler efficiency or increased maintenance costs caused by firing out-of-specification quality coal. Cole and Frank (2004) present coal beneficiation as a process to be utilised to produce specification coal for use in power stations to reduce the coal quality impact on power generation.

The parameters and plant operating conditions which may be affected by changes in coal quality and its composition include:

- **handleability** and **flow characteristics** in silos, stockpiles and conveyor belts. This in turn depends on:
  - surface moisture, and the range of ambient temperature conditions;
  - size distribution, and in particular the proportion of fine material;
  - the nature of the mineral matter present which can affect particle 'stickiness'. Increased stickiness is often associated with the presence of clays;
- **its behaviour during coal preparation** in different plant sections;
- the **conditions in the pulveriser**, which are affected by:
  - the coal hardness (which can be measured on an empirical and comparative basis) which is affected by the presence of hard minerals like quartz and pyrite;
  - the moisture content, as the mill inlet temperature needs to increase with higher moisture content coals, to ensure that the desired outlet temperature of around 70ºC is maintained;
  - the amount of coal required, which is affected by its heat value (or its specific energy);
- **combustion and ash deposition characteristics** when used in a pulverised coal combustion (PCC) boiler or in a gasifier on an integrated gasification combined cycle (IGCC) unit;
- the **emissions** from any combustion or gasification plant, which will be controlled to an extent by downstream flue gas cleaning units (for example to reduce NOx, SO_2 and particulate emissions);
- **economic factors** affecting the overall profitability of unit operation, such as its availability, capacity and maintenance costs.

Expert systems can be used to assess coal quality and to understand and manage the effects of its variations. These include computer programs which can be used to assess the practical impact of changes in coal composition. The input to these programs can be based on empirical results and/or on modelling various aspects of the process. The challenge is always to validate the outcomes. These are discussed in Chapter 5.

2.2 Coal characteristics and plant design

A range of properties/characteristics of coals that determine boiler design and are currently used in different parts of the world for power generation can be expressed as follows:

- a lower heating value (LHV) or net calorific value (NCV) from 5 MJ/kg to 30 MJ/kg. NCV or LHV is the useful calorific value in boiler plant. Gross calorific value (GCV) or higher heating value (HHV) is the calorific value under laboratory conditions. The difference is essentially the

latent heat of the water vapour produced;
- ash content can vary from 1% to 50% or even higher. Many standards do not define material with >50% ash as being 'coal'. The ash is formed from the mineral matter present, and, in lower rank coals, from organically bound impurities;
- moisture content can vary from 5% to 65%;
- the sulphur content of in situ coals can range from virtually nothing to as much as 10%, though in the coals used in power generation it is generally 0.5–2.5%;
- the age of a given deposit can be from 350 million years to as little as 2 million years, and the temperatures and pressures experienced depend on many factors, meaning that the degree of coalification is highly variable.

A power plant boiler is designed to burn a 'specification' coal, which is commonly defined as the coal from a nearby mine or the coal most likely to be purchased from further afield. The vast majority of coal-fired boilers use pulverised coal combustion (PCC), although it is possible that as more plants are required to capture and store the CO_2 formed, integrated gasification combined cycle (IGCC) units will also be built. As there are only a small number of these plants at the moment, this study focuses on pulverised coal combustion units.

A generic flowsheet for a typical modern pulverised-coal power generating unit is shown in Figure 1. The various stages, can include:
- mine and CPP, together with handling, storage and transport and blending (where applicable);
- pulverisers;
- boiler and heat exchangers (and steam to the turbine and condenser);
- low NOx burners with air staging;
- air and water preheaters for thermal efficiency;
- ash handling, with an electrostatic precipitator (ESP) or fabric filter. Note that carbon-in-ash levels are of significance;
- units for the reduction/removal of NOx, using selective catalytic reduction (SCR), SO_2, using flue gas desulphurisation (FGD) and particulate matter (using ESPs or fabric filters);
- CO_2 capture (in the future).

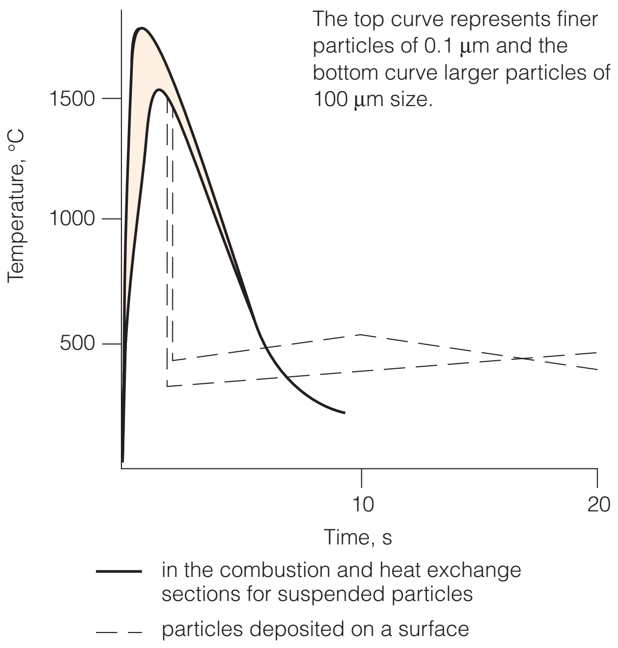

Figure 4 Generalised time-temperature cycle in pulverised coal combustion (Couch 1994)

In pulverised coal combustion, the coal is milled to a fine size and conveyed pneumatically to the burners in such a way that the feed is evenly distributed around the combustion chamber. On entering the furnace the coal particles heat rapidly and the volatile matter is distilled off, leaving minute sponge-like particles of carbon and mineral matter. The volatile gases mix with the oxygen in the air and burn quickly. Oxygen also reacts with the carbon, releasing heat. With the correct amount of excess air, and of turbulent mixing, virtually complete combustion can be achieved in less than ten seconds (*see* Figure 4).

The boiler design and flue gas cleaning units are optimised to obtain best performance from the specification coal while meeting environmental requirements. This determines the heat transfer areas provided in different parts of the boiler. Once these parameters are determined, the boiler operates most efficiently with coals which have properties near to those of the specification coal. In practice, PCC boilers have proved to be remarkably tolerant of some variations in coal quality, and cope well with coals from different sources. However some changes in coal characteristics can have serious deleterious effects on both short-term and long-term boiler performance and may affect aspects of the performance of the flue gas cleaning equipment.

The design also determines:

- the coal pulverisers;
- both forced draught and induced draught fan sizes;
- burner design and location;
- the heat transfer areas and detailed geometry of the steam superheater, reheater and economiser sections;
- the water pump size;
- the turbine used and its steam condenser.

The boiler design is markedly different for burning lignite, for example using flue gas recirculation to dry the incoming coal. Boilers firing anthracites commonly use the down-shot burner arrangement to achieve the longer residence times and ensure carbon burn-out. The boiler's physical size and capacity limit flexibility in operation. Therefore, once the major components in a PCC unit have been sized and designed in detail, the implications of changes in coal properties can be considered. Similar considerations will apply in principle to IGCC plants if they are more widely deployed. Since there are currently only a few such units, these are not discussed in this study. More are likely to be built as the need for CCS at power plants becomes more pressing. The various flue gas cleaning units are designed so as to meet the requirements for limiting emissions of SO_2, NOx and particulate matter.

For some highly variable coals, possibly to provide flexibility for mixing with other solid fuels, fluidised bed combustion (FBC) may provide the most satisfactory design solution. As FBC represents less than 2% of the worlds total coal-fired capacity, it is also not specifically considered in this study, although many of the principles used in expert systems would be equally applicable.

Most major plant components are required to operate continuously for periods of more than a year, to facilitate an annual planned maintenance schedule. In some units, attempts have been made to move towards a two-yearly maintenance. Hence unplanned damage to parts of the plant, which necessitates a shut-down (that is, a forced outage), is to be avoided. The use of expert systems to assess coal quality which may affect corrosion and erosion in parts of the plant can help to avoid, minimise or control such damage.

Most power plant descriptions only look at the efficiency of operation and of coal and component behaviour when operating under full load under steady-state conditions. In practice, and increasingly, many coal-fired units are load following and possibly even two shifting, in order to meet the demands of the market. When two shifting, the unit is normally kept on stand-by over night, when the power demand is at a minimum. These varying patterns of plant operation impose their own strains on plant components, associated with thermal cycling. In addition, the coal composition will have different impacts with changing conditions in the boiler and flue gas cleaning units. For example, coals with a high ash content are more likely to encounter problems with erosion in various parts of the plant than those with less ash.

Most coal-fired power plant units running in competitive markets operate for a considerable amount of time as load followers. This means that conditions in the boiler are changing with different impacts relating to coal quality due to slagging and fouling deposits, and of soot-blowing. In addition, the fly ash size and resistivity may vary, affecting the performance of the ESPs or fabric filters. Ultimately the fundamental objectives include boiler/power supply reliability and availability, together with profitable operation under changing market circumstances. Slagging and fouling in coal-fired boilers is discussed in detail by Barnes (2009).

According to Lenk and Voigtländer (2002) and Drenckhahn and Riedle (2005), when many of the existing coal-fired power plants were built, the stability of the power generation market was such that the operational goals were readily and accurately predictable. The liberalisation of the power market in many places and short-term fluctuations in the price of fuels have led to the need for more flexibility. As a result, there is a much greater need for well-validated expert systems to optimise plant operation. The needs will vary from plant to plant and country to country, in terms of:

- fuel supply and cost;
- the pattern of demand for power;
- local legislative and regulatory requirements, including the costs associated with CO_2 emissions.

The variations in a coal from one deposit may be sufficient to affect the behaviour of the coal in a boiler. As an example, there are four 500 MWe units at Loy Yang, Victoria, Australia using locally mined brown coal/lignite from a deposit near the surface, mined by open pit methods. These had been operating well for several years with regular planned annual shut-downs. Even though the ash content of the lignite is very low, at just 1–3%, it was the composition of the ash that proved to be problematic. When mining through a patch of brown coal which was high in sodium, the units could only run for some 800 hours (just over a month) before they had to be shut down and the fouling deposits removed (Couch, 2004).

In all cases a boiler unit is designed to operate in the optimum way when using its 'design coal', and boiler manufacturers usually define their guaranteed performance figures in terms of this coal. Coal-fired boilers can in practice use a range of coals, and often the decision to purchase from a specific source is finely balanced, based on the delivered price for the coal and the implications for the running costs of the plant when using it.

The provision of stacker/reclaimer units where coal is stocked will facilitate blending which can be used to even out some of the variations in coal properties and characteristics. The variability from an individual mine will be strongly affected by both the mining method used and on whether or not there is a CPP.

2.3 Market influences

As an example of the changes that can take place in the market, Anderson (2002) highlighted the conflicting drivers that affect coal purchasing decisions. The example relates to the supply and purchase of eastern US bituminous coals. 2001 produced the strongest seller's market seen in years. Total production was around 450 Mt (or roughly 12% of the world total production at the time). Many producers struggled to keep up with demand, some to the point of cutting corners on quality in order to meet production requirements. At the same time, several power generators purchased coals that often did not meet their plant specifications which resulted in them taking necessary measures to adapt to operating with coals with different qualities.

An extremely mild winter then followed, resulting in large stockpiles at both mines and power plants. Coal producers had to balance the needs of their customers against cost cutting measures which were required to maintain acceptable profits. Power generators who had struggled with the earlier supply shortages, had acquired useful knowledge about the ramifications of pushing generating units to their limits.

The conflicting drivers provided the impetus and opportunity to consider several factors, such as:

- optimising coal quality to meet both coal producer and power generator requirements including using expert systems which could play a role in the optimisation process;
- assessing the effects of impending emissions regulations being applied to power generators;
- re-examining the market methods used, and the relative advantages of long-term contract purchases versus short-term seller-buyer negotiations;

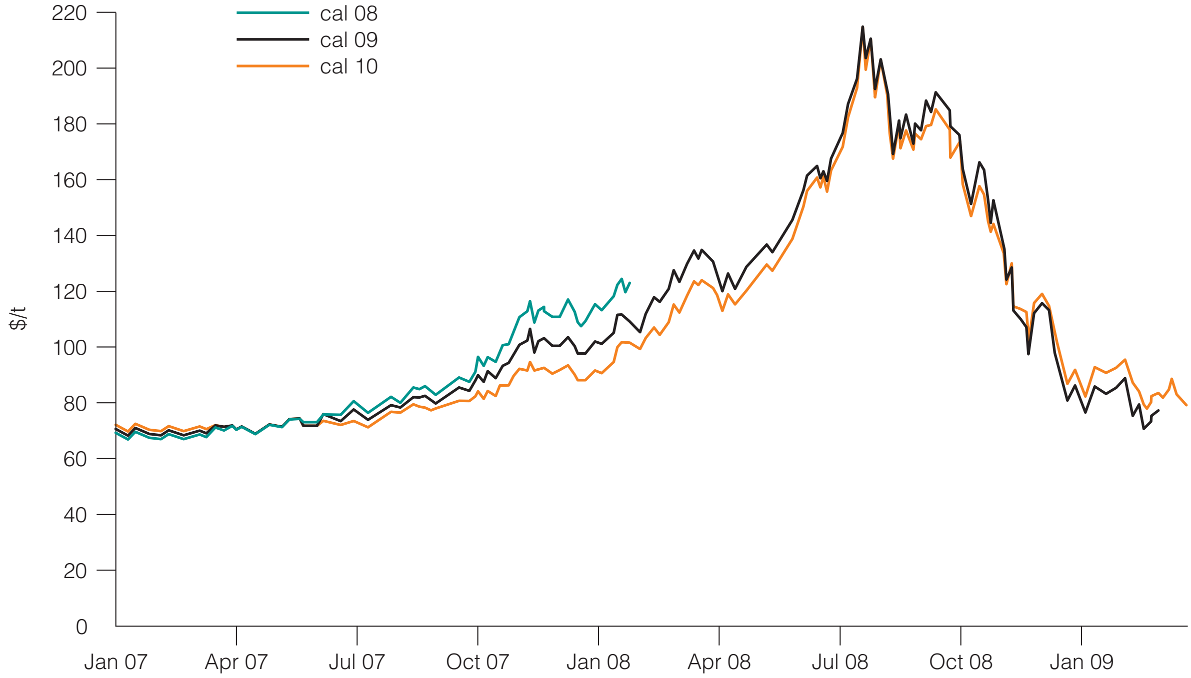

Figure 5 Spot prices for internationally traded coal delivered into north-west Europe (Drax Group plc, 2009)

Figure 6 Asian and NW Europe steam coal marker prices (MCR, 2011)

- matching coal costs to take account of varying electricity prices at different times of the day.

Different considerations apply in different situations but since the cost of the fuel represents a large proportion of the operating costs of most coal-fired power plants, the pressures imposed by the market need to be taken into account. Purchasing coals with different qualities for use in a particular power plant requires careful assessment of the various options and of the longer-term costs of these options. A wide range of factors influences the price of coal, and the variation in the costs of traded coals in 2007-09 is illustrated in Figure 5. These peaked at 218 US$/t in June 2008, to steadier values around the 80 US$/t range by 2009. The lines represent coal prices delivered into north-west Europe (as reflected by the Tradition Financial Services (TFS) API 2 index). The benchmark reference used to trade coal imported into north-west Europe. The API 2 index is an average of the Argus coal, insurance and freight (cif) Rotterdam assessment and McCloskey's north-west European steam coal marker. These price variations have a substantial impact on the costs of power generation for utilities using traded coals (*see* Figure 6).

These widely varying situations have a profound impact on what expert systems can be used, and on their efficacy. Much depends on whether or not a coal is washed since in a CPP the various size ranges are treated, and in each case cleaner and dirtier fractions are separated, and a reject stream of high ash material is usually dumped. Where the coal is washed, both the high grade product and the middling products are likely to be much more consistent in quality than the original run of mine (rom) coal. This is because stray pieces of shale and rock are separated, along with material from any dirt bands present, and because the density separation and size cuts involved tend to increase product consistency. Low rank coals are not generally susceptible to conventional water-based coal preparation techniques although it is possible to upgrade them by drying as described by Couch (1990) and Dong (2011).

3 Coal sampling and analysis

Coal is an organic sedimentary rock that contains varying amounts of carbon, hydrogen, nitrogen, oxygen and sulphur as well as trace amounts of other elements including mineral matter. It is a solid, brittle, combustible, carbonaceous rock formed by the decomposition and alteration of vegetation by compaction, temperature and pressure. It varies in colour from brown to black and is usually stratified. Coal analysis establishes the price of the coal by allocation of production costs and is used to control mining and cleaning operations and to determine plant efficiency. For a detailed study of coal analysis *see* Speight (2005).

Coal has been mainly used within its country of origin. Therefore, many different standards for coal testing, sampling and analysis have emerged. Although these are broadly similar in principle, there can be significant variations in their detail. Some (such as the German standards) are biased towards assessing the coking behaviour of a coal, rather than its combustion characteristics. Among the principal standards used are those of:

- the American Society for Testing and Materials (ASTM);
- Standards Australia (AS);
- the British Standards Institution (BSI);
- the Standardisation Administration of the People's Republic of China (with the prefix GB);
- German Standards (with the prefix DIN);
- Russian National Standards (with the prefix GOST);
- the International Organisation for Standardisation (ISO).

3.1 Sampling

The first step in the application of expert systems for coal quality assessment is to ensure that the sampling procedures used are as accurate and precise as possible. This then provides a representative sample for the subsequent analysis. If the initial sample is not properly taken then the analysis can be misleading. Experience has indicated that about 70–80% of the uncertainty/error of the analysis result comes from sampling, about 15–20% from sample preparation, and about 5–10% from the laboratory procedures involved, which demonstrates the importance of good sampling practice (CoalTrans International, 1998; Laurila, 1997) .

Sampling is discussed in detail in other IEA Clean Coal Centre reports by Carpenter (2002, 1999). The discussion here covers only some of the key points from these studies.

In the early stages of assessing the quantity and quality of the coal in a deposit, core samples from drilling will be used. These will provide a vital part in the assessment of which parts of a coal deposit are worth extracting, and possibly of the subsequent timing and sequencing of the mining. Selective mining is one of the techniques that can be used to improve the quality of mined coals. Improvement of coal quality fed to power plant by using selective excavation method at the Seyitömer coal mines is discussed by Aykul and Yalçin (2004). This is an expert system/procedure which will not be discussed in this report but which is an important preliminary to the efficient use of world coal resources.

Sampling is commonly carried out from rom coal on a conveyor belt, and from belts at various stages in the usage chain including the feed into a boiler or on to a stockpile. It is also carried out on the coal stored en route between the mine and the power plant, particularly where the coals are traded. The purchaser needs to be assured that the coal delivered is of adequate quality, and there will be adjustments made to the amount paid if off-specification material is supplied.

Where online analysis is undertaken of the coal carried on a conveyor belt, the device is calibrated (and re-calibrated) against a laboratory analysis of samples. Obtaining a representative sample implies that every particle has an equal chance of being selected. Thus the size distribution of the sample should also reflect the size distribution of the bulk coal since the composition of small particles may be different to that of larger lumps. Edwards and others (2005) discussed new developments in on-belt analysis. Foster (2004) presented two case studies on the use of across-the-belt analysers to meet train quality targets.

Coal is a difficult material to sample because of its variability, the number of significant contaminants/impurities present and its tendency to segregate by size or mass. Sampling is further complicated by the sampling equipment available, the quantity to be represented by the sample (sample mass), and the degree of precision required. In addition, the coal may be a blend of different coal types. How the coal was blended can have a profound effect on the way a representative sample is obtained; depending, for instance, on whether it is intimately mixed or not (CoalTrans International, 1997). Biased results can be introduced by the sampling procedure as well as by sample preparation and analysis.

The main sources of bias during sampling can be avoided by:
- choosing the most suitable location for the sampling point;
- using sampling equipment that meets the necessary specifications;
- taking precaution when sampling for a specific purpose. For example, avoiding a loss or gain in moisture when sampling to measure total moisture, and minimising breakage when sampling for size analysis.

Various standards specify the procedures for collecting representative samples under different conditions of sampling. As an example of the standards available, the BS ISO 13909 series, dated 2001, includes:
- general introduction to hard coal and coke – mechanical sampling (part 1);
- coal – sampling from moving streams (part 2);
- methods for determining the precision of sampling, sample preparation and testing (part 7);
- methods of testing for bias (part 8).

There is also a BS ISO standard number 15239, dated 2005, covering the evaluation of the measurement performance of online analysers for solid mineral fuels.

A comprehensive discussion on sampling of coal is presented by Laurila and Corriveau (1995). When establishing a sampling scheme, it is important to recognise that the variability in the components of lower rank coals are often greater than those in higher rank coals, especially of some of the ash constituents that might affect boiler deposition.

Generally, the standards specify the number and weight of increments to be taken for each sampling unit to achieve a given precision. An increment is a small portion of the coal samples collected in a single operation of the sampling device. The increments are taken throughout the entire samples so as to reflect the coal variability. They are combined to form what is termed the gross sample, which is then crushed and divided, following standard procedures, to produce the samples for analysis. Generally, the higher the number of increments taken, the greater the precision.

When sampling to determine whether a coal consignment meets the contract specification, it is important (and customary) to take samples and divide into three – one for the supplier, one for the buyer and one as a reference for independent, impartial analysis, in case of dispute.

Mechanical sampling systems that are capable of collecting unbiased samples from moving coal streams can be categorised into two types:
- cross-belt samplers (sweep arm or hammer samplers) that sweep a cross-section of coal from the moving conveyor belt into a hopper. They must be properly adjusted to avoid leaving any coal

fines on the belt that could compromise sample accuracy;
- cross-stream (or falling-stream or cross-cut) cutter samplers which collect a cross-section from a freely falling stream of coal. Thus the installation of these samplers requires a gap at a transfer point, typically between two conveyor belts.

Sampling coal when it is sticky is a problem since it can stick to or clog the samplers, causing bias in the results. The standards cover the size of the cutter opening (typically three times the coal top size), that the cutter should move at a uniform speed and, for cross-stream samplers, the speed of the cutter. The size and number of increments to be collected to minimise bias are also specified. A full cross-section of the stream should be taken whenever possible since it provides a more representative sample than a partial cross-section. Technological advances in mechanical sampling systems, and a comparison of cross-belt and cross-stream systems is given in Reagan and DeMatteo (2007) and Reagan (1999).

Bias testing

All sampling systems need to be checked for bias, that is for systematic errors that may have been introduced. Generally, a loss or gain in the mass of the increments during collection causes a systematic error. This can include spillage of coarse or fine particles, or failure to collect the fine particles at the bottom of a stockpile. A consistent bias occurs if the time intervals during systematic sampling coincide with cyclical variations in the coal quality.

Tests for bias can be tedious and expensive. A good bias test program design should not only determine the overall bias of the system but that of the components as well, so that their contribution, if any, to the overall bias is known. Some systems are inherently biased and the test simply determines the extent of that bias (Laurila and Corriveau, 1995). The actual bias test procedure depends on the local conditions, and the sampling system in use. Therefore standards, such as AS 4264.3 and BS 1017: Part 1, only give general principles for bias testing. Bias testing of mechanical samplers is covered in the new ISO/DIS 13909: Part 8 standard, which requires an annual bias test for mechanical sampling systems. The ASTM is currently discussing bias testing of mechanical sampling systems.

The first phase of any bias test is the preparation for conducting the test and a careful inspection of the sampling system and equipment to see if any systematic errors have been introduced. The latest ASTM standard is D7430-11: *Standard Practice for Mechanical Sampling of Coal* (ASTM, 2008). Both sampling and bias testing involve complex issues (Laurila and Corriveau, 1995) and Speight (2005).

The reason for including a detailed discussion of sampling in the context of the review of the work on expert systems is that the conventional sampling and analysis of the coal provides **the basis** for the coal quality information involved. From the quality data, action(s) may be taken to modify and adapt the downstream operating conditions so as to optimise overall performance.

3.2 Analysis

The data obtained from coal analysis may determine which parts of a coal seam are extracted (using exploration data). It provides vital data relating to the design and operation of a CPP, and the information establishes the value of the coal product, and thus, broadly, the price at which it may be marketed and the use to which it is put. Foster (2006) discussed testing a nuclear elemental static sample analyser to optimise the operation of a CPP. Although the experience was proven beneficial, Foster (2006) considered that it was too early to use such cutting edge technology to optimise operation, reduce costs and maximise profitability.

For the power plant operator several aspects of the analysis provide important information which will affect the economics of running the plant. This is because the quality of the coal being used affects its heating value, the amount of ash deposition and corrosion in the boiler, and the costs associated with flue gas cleaning. Prior knowledge of the exact composition of the coal being fed can help the boiler operator to minimise the overall and long-term operating costs of the individual units. The main components which may cause operational problems are associated with the mineral matter present, or sometimes, in the case of low rank coals, of organically-bound impurities. If the coal composition and its properties are varying as it is fed into a boiler this can cause additional uncertainties and, under such circumstances, the provision of information from online analysis can be of particular value.

However, both the laboratory and online methods of analysis have limitations, and for commercial users of coal it is important to understand what these are in order to make the best use of the information provided. This includes the data which is available to be fed into the plant expert systems.

Analysis data almost invariably reflects a combination of a wide range of properties, some of which are desirable, while others present either minor or even major challenges to the plant operator in terms of the overall economic performance of the generation units. The analysis is limited by the methodologies used which are necessary to achieve reproducibility and consistency in the results obtained. These however, do not necessarily represent or reproduce the conditions found during handling or inside the boiler and therefore the behaviour of various impurities present.

3.2.1 Laboratory methods

Laboratory analyses utilise methods that are reproducible and which get as close as possible to measuring the coal properties which affect its behaviour during handling and use. The tests carried out on coal are more thoroughly discussed in another IEA Clean Coal Centre report by Carpenter (2002). The principal limitation is that the laboratory conditions do not always parallel the operating conditions of a power plant in which the coal is used (such as PCC boilers). This is due to the heating rate of the coal particles (Rajoo, 2011).

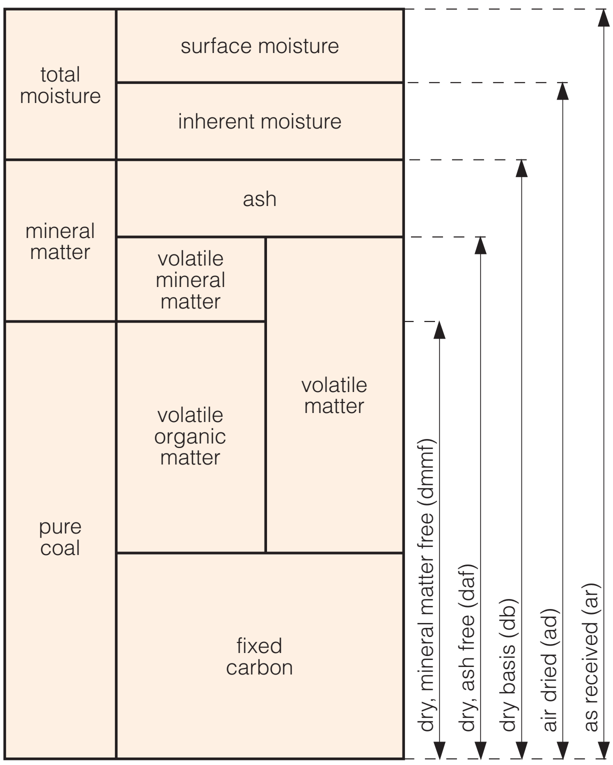

Figure 7 Relationship of the different analytical bases to various coal components (Ward, 1984)

One factor to be taken into account is that coal samples can oxidise, so that some of the properties will change with time, possibly before the sample has been analysed. The lower rank coals are generally more readily oxidised and as a result, more care is necessary in this respect. Oxidation of coal prior to combustion is discussed in detail by Nalbandian (2010).

A cause of confusion in the evaluation of coal data is the wide range of exclusions used in reporting coal analysis, and the failure of some workers and writers to identify clearly the basis of their results. Some commonly used bases are illustrated in Figure 7. Two others which are not illustrated are:

- moist, ash-fee (maf) which assumes that the coal is free of ash but contains water/moisture;
- moist, mineral matter free (mmmf) which assumes that the coal is free of mineral matter but contains water/moisture.

There are standard laboratory methods for determining the **proximate analysis** of coal (Nalbandian, 2010; ASTM, 2009a; Carpenter, 2002), comprising:

- moisture;
- volatile matter;
- ash contents.

It is also possible to use smaller samples and rapid temperature and atmosphere control with a thermogravimetric method (TA-129, 2009) to obtain a proximate analysis, though this is probably less rigorous and reproducible than the long-established standard methods. It can, however, produce indicative results much more quickly.

There are similarly standard laboratory methods for determining the **ultimate analysis**, comprising the weight per cent of carbon, sulphur, nitrogen and oxygen (by difference). Trace elements present are often measured as part of the ultimate analysis (Nalbandian, 2010; ASTM, 2009b; Speight, 2005; Carpenter, 2002). These will commonly include chlorine and mercury.

For combustion, other properties of great importance are:

- the calorific value or heating value;
- the ash composition;
- its behaviour at high temperature such as its softening and fusion temperatures.

Gross calorific value (GCV) or Higher Heating Value (HHV) is determined by burning a weighed sample of coal. This is carried out in a strong sealed vessel called a bomb calorimeter which is corrosion resistant. It has a thermal jacket whose temperature is controlled by a microprocessor system which also fires the ‘bomb’ and measures the resultant temperature changes. The test continues until equilibrium is reached. The GCV is calculated from the temperature rise in the water in the calorimeter (Carpenter, 2002). A microcomputer uses the sample weight and temperature data to derive the GCV, applying corrections for heat from the fuse and any combustion aids used (Liu and Lipták, 2003).

Ash analysis provides a measure of the incombustible material present, and the composition of the ash can provide some guidance about how it will behave in a PCC boiler. There are a number of different standards used (Carpenter, 2002). However, the conditions encountered in the boiler are markedly different from those used during the analysis with much higher temperatures and variable oxidising conditions. There may also be interactions between various ash forming components. This is why ash behaviour in terms of its slagging and fouling characteristics cannot be precisely predicted from the ash analysis results.

Under some circumstances it is necessary to know the heat capacity and thermal conductivity of a coal, and for metallurgical use (coke making), its free-swelling index and agglomeration index. In addition its mechanical properties such as hardness, grindability and friability which affect coal pulverisation and its handleability are also routinely determined by laboratory tests.

The list above illustrates the range of coal properties which can affect its behaviour and, to an extent, the various assessments of its probable behaviour when used in a boiler. These are based on a combination of the results from analysis and of experience built up over many years (Barnes, 2009; Couch, 1994).

3.2.2 Online analysis

The previous discussion has shown that obtaining samples that are representative of the many thousand tonnes of coal in a stockpile or consignment can be an exacting task. By its very nature, laboratory analysis carried out on the samples according to standard procedures can be time consuming, with results only available some time after the coal has been sampled. This could be a matter of hours if the coal is analysed on site or a few days if the sample is analysed at a distant location. Thus the analysis results do not necessarily reflect current operating conditions. Real-time information on coal quality could help to manage stockpiles more efficiently and, perhaps more importantly, coal-fired boiler operating conditions. This is discussed in a recent IEA Clean Coal Centre report by Nalbandian (2005).

Online analysers can show variations in coal quality as they are occurring. In systems where coal can be analysed directly on the conveyor belt, errors due to sampling and sample preparation are minimised. However, online analysers can be expensive and their cost-effectiveness depends on the site and application. Despite questions about the accuracy of online analysers being raised, their use in coal mines as well as power plants continues to increase. Their performance, in practice, has been found to relate strongly to initial installation, calibration, subsequent maintenance and application environment. Of these, the initial calibration was of prime importance. An analyser unit must be adapted to its particular installation by being carefully calibrated, using known samples that have been analysed in the laboratory (reference samples). The chosen samples must represent the range of coals which the machine might be expected to encounter in service. Analysis of coals beyond the range of the initial calibration do not have the same accuracy. Changes in coal supply can thus necessitate re-calibration. The calibration may also drift over time, requiring the analyser to be frequently re-calibrated (Nalbandian, 2005).

Standard methods for the evaluation of the performance of online analysers, including statistical assessment procedures, are currently being discussed by ISO (ISO CD 15239, entitled Solid mineral fuels . evaluation of the measurement performance of online analysers) and ASTM (Laurila, 1997; Page, 1998). An Australian standard (AS 1038.24 Coal and coke analysis and testing. Part 24: guide to the evaluation of measurements made by online coal analysers) has recently been published. These standards outline the principles of the reference test method. Due to the range of configurations for online analysers and their relationship to sampling/analysis systems, it is impossible to provide particular test methods to cover all situations. More detail on the evaluation and performance testing of online analysers is given by Laurila and Corriveau (1995). These include statistical methods for evaluating precision and bias, and sampling procedures designed to obtain samples that can be used for calibration, accuracy and verification. Renner (1999) describes the planning and evaluation necessary prior to the installation of online analysers. He also emphasises the importance of calibration and quality assurance, particularly the impact from mechanical sampling systems. In the late 1990s, despite frequent disappointments, online analysers were gradually approaching the levels of precision and reliability needed for confident usage. Today, online analysers are considered reliable and used more widely in a large number of coal-fired power plants. In 2001, Makansi explained how the then latest online coal analyser technology created profits for both suppliers and customers.

Online analysers have been employed (Nalbandian, 2005):
- to monitor the incoming coal at a site to determine whether it meets the required specification. In addition, the analysis data will provide information of direct relevance to controlling the operating conditions in the boiler plant which form a key component within an expert system for combustion purposes;
- to sort and segregate coal into different stockpiles, according to its quality. How far this is practical for coals arriving from a number of different sources is limited by the calibration range of the analyser;
- to blend coals from different stockpiles to meet the required specification. By maximising the amount of lower cost coal in a blend, savings can be made. It is also possible to blend coals automatically, for example by allowing the online analyser to control the feeders beneath the stockpiles involved;
- for monitoring coal during reclamation to check it meets the desired specification; and
- more recently, for pulverised coal flow measurement and control, although in 2001 there was no proven method for online control of the pulverised coal distribution in response to a signal from a

flow meter (DTI, 2001a). Magni and others (2005) discuss using Kalman Filter estimation of coal flow in power plants (*see* Section 4.4) while Roberts (2009a,b) examines a new online technology for particle size analysis, which influences coal flow characteristics, for improving boiler optimisation in coal-fired power plants.

Some of the main online measuring techniques in use include (Nalbandian, 2005):

- Natural gamma systems which require no radioactive source. They measure the gamma emission from the conveyed coal and calculate the ash content by combining this with a measurement of the weight of the load. In dual energy gamma-ray transmission systems, the bulk coal ash content is determined by combining measurements of the intensity of two narrow beams of high and low gamma-rays that are passed vertically through the conveyor belt. These analysers only work properly if the coal on the belt is well mixed since the small beam only determines a small area in the middle of the belt. Instruments are available that split the beam into a number of corresponding detectors that determine the ash content at separate points across the full belt width; these may provide a better measure of the ash content. Varying chemical composition, especially the iron content, can lead to inaccuracies. Triple energy gamma-ray transmission systems have been developed. Although natural gamma systems may not be the most accurate, they are generally less costly than other methods; Taylor (2001) discussed the online monitoring of the ash content of coal using natural gamma technology; Richie and Edwards (2009) described the use of online monitoring of natural gamma radiation in coal ash to maintain coal quality.
- Prompt gamma neutron activation analysis (PGNAA) provides the elemental composition of coal by measuring the gamma radiation emitted when coal is exposed to a neutron source. Carbon, hydrogen, sulphur, nitrogen and chlorine are measured directly and the ash content is indirectly determined by combining the elements that comprise the ash (mainly silicon, iron, calcium, aluminium, potassium and titanium). A separate ash analyser is included in some PGNAA systems. The heating value (if a moisture meter is present), ash fusion (slagging factors) and oxygen content can also be indirectly determined. Some systems require a small slipstream of coal to be diverted from the main coal flow to the analyser. Conventional PGNAA can give problems for brown coals and lignites with a high moisture content, or coals with large and variable ash constituents. Instruments using multiple sodium iodide detectors have been developed to cope with coals from multiple sources. Instruments have also been specifically designed for high moisture brown coals. Hennessy and others (2007), Edwards (2004) and Blenkinsop (2003) describe advances and application of PGNAA analysis in coal-fired plant.
- Microwave moisture meters determine the moisture content by measuring the attenuation and phase shift of microwaves passed through the coal. Microwave moisture measurements are often incorporated in dual energy gamma-ray transmission and PGNAA systems, enabling the heating value of the coal to be calculated. France (2005) discussed the use of microwave techniques in Australia for online coal analysis.
- The Neutron Inelastic-scattering and Thermal capture Analysis (NITA) system was developed by CSIRO (Australia) and is based on neutron-gamma analysis to provide multi-elemental analyses of large streams of material across a range of industrial applications including coal combustion for power generation. In neutron-induced gamma analytical techniques, neutrons bombard the material under investigation (the coal). Gamma-rays emitted as a result of the various interactions that occur can be measured to infer the elemental composition of the coal because the energies of these gamma-rays are characteristic of the emitting nuclei. These techniques use highly penetrating radiation which permits non-intrusive and non-destructive 'bulk' elemental analysis of coal in vessels, pipes and on conveyor belts. These systems produce measurements that are averaged over a large volume of coal. However, a safety risk posed by the use of high-strength neutron sources in an industrial environment must be noted and observed. Despite concern over potential radiation hazards, neutron-induced gamma activation has become a standard online analysis technique, as the penetrating power of neutrons makes it possible to conduct measurements on large volumes of coal (Lim and Abernethy, 2004, 2005).

- X-ray fluorescence (XRF) analysis is a widely used method of elemental analysis providing both qualitative and quantitative compositional information. Among its advantages are the wide range of measurable elements covering nearly the entire periodic system. X-ray fluorescence is the emission of fluorescent X-rays from a material that has been excited by bombarding with high-energy X-rays or gamma rays. XRF spectrometry has the potential to be very sensitive in measuring trace elements, but it has the disadvantage in that it requires 15–30 minute sample collection and pre-concentration. The method only works on elements with atomic numbers >25 and is incapable of detecting beryllium (Seltzer and Meyer, 1997). Most samples of XRF are either pressed to a pellet (disc shaped) or are converted to a homogeneous glass disc (bead) by fusion with lithium tetraborate. The fused bead technique overcomes heterogeneity effects and is generally required for obtaining highest analytical accuracies for minors and majors, in particular for silicon oxide and iron oxide. On the other hand, pressed pellets are more suitable for trace analysis (van Kroonenberg, 1996).

More recently, a prototype coal analyser using pulsed fast thermal neutron analysis (PFTNA) was built and the first commercial model was being developed in 2001 (Belbot and others, 2001). In PFTNA-based elemental analysis, coal continuously flows in a vertical chute that is irradiated with pulsed neutrons. During the neutron pulse, high-energy neutrons interact with the elements such as C and O emitting characteristic gamma rays. In between pulses, neutrons scatter off light elements in the coal and slow down to thermal energies. These lower-energy neutrons initiate thermal capture reactions with elements such as H, S and Cl emitting gamma rays characteristics of these elements. Neutron activation is used for the measurement of Na, producing isotopes that have longer half-lives (in the order of seconds) than the fast and thermal capture reactions. The gamma rays produced from each type of nuclear reaction (fast neutron, thermal neutron and activation) are acquired and stored in different spectra. This reduces the background as compared with the spectra taken with a radio-isotopic source. The analysis of the experimental data was performed using a de-convolution computer code developed for the automatic extraction of the intensities of the characteristic gamma rays. Belbot and others (2001) discuss the performance of the prototype and the development of a commercial model of such an analyser.

Hatt (2007) discusses the SODERN CNA analyser which uses an electrical neutron source or tube. According to Hatt (2007), this is a new generation of analysers which offers operational and analytical advantages. The use of electrical neutrons allows the direct measurement of the carbon, oxygen, sulphur and the elements of the mineral matter in the coal safely and reliably.

Both ash and moisture analysers need to know the amount of coal at any point in time to enable an assessment of the required measurement. Weighing becomes particularly important when blending coals. The weighing system must be accurate and repeatable. Odgaard and Mataji (2005) discussed a method for estimating moisture content of the coal in coal mills. The estimation was performed with a simple linear dynamic energy balance model and an optimal unknown input observer. The observer was designed for the purpose and tested on four sets of experimental data from a coal mill. The results indicated that the observer estimation was successful with different moisture contents.

In a detailed report on online analysis of heating value, the Electric Power Research Institute, USA (EPRI, 1999) considered that online analysers allow for the use of real-time plant control and applications of tools such as the Coal Quality Evaluator (C-QUEL™) which was developed to assess and predict the impact of coal quality on power plant performance and power production costs. As with all expert systems, C-QUEL™ requires input data from online coal analysers, distributed control systems (DCS) and performance monitoring systems. Specific plant operating conditions can be thus determined for operators dealing with changing coal supplies. For more detail on the C-QUEL™ system *see* Mitas and others (1991). According to EPRI (1999), a knowledge of real-time heating value derived from the use of online analysis can also affect coal-related mass flows and annual coal usage. Online coal analysers used where coal quality varies significantly and frequently and where changes in coal quality affect downstream processes. Blending of two or more coal streams to obtain

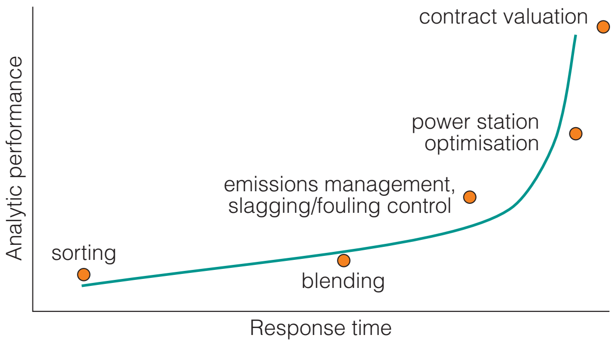

Figure 8 Schematic of performance versus response time for various potential analyser applications (EPRI, 1999)

specific performance is an example of how online analysis would be beneficial. Fuel flexibility by matching coal burnt with the electricity market can be fine-tuned. A low-heat, low-cost coal may be utilised during off-peak hours when incremental generating costs are most critical to keeping the plant online and capacity is not critical. A high-heat, more costly coal cal be used during peak hours when the price of power is high and capacity is tight. According to EPRI (1999), with the use of online analysers, the blending ratio can be varied continuously to allow for variations in the input streams, heating value, capacity and emissions requirements. This would result in better utilisation of the higher-cost coal.

The cost of analysers reflects the variation in parameters that can be measured with each technology, highlighting the need for an individual case to be made for any analyser choice. Highly accurate measurements may or may not be required for a particular use. The economics and choice of technology depends on the reason behind its installation and therefore there is a trade-off in response time. These relationships are show in Figure 8 (EPRI, 1999) outlining an approach for trading off analytical performance and response time versus the requirements of the application.

There are situations, such as small operating units, where the use of online ash analysers is not convenient or cost-effective. In these cases a portable subsurface gauge is available for determining the ash content of coal within a stockpile. These gauges are based on the natural gamma-ray technique. Consequently, they require no artificial radiation sources and are relatively inexpensive. A natural gamma ash gauge can measure the ash content of low ash coal (<20% ash) with an accuracy of 0.6% (Mathew and others, 1993). The gauge requires calibration for each coal type, since coals of different origin require different calibration equations. However the accuracy of ash determination by such a method is relatively unaffected by variations in ash composition or normal variations in moisture content. It should be noted that a large number of measurements have to be taken over the whole of the coal stockpile while it is being built up in order to determine its average ash content.

The use of remote monitoring with online analysis in the power generating industry is growing. Brummel (2006) discusses a suite of software/programs to carry out data acquisition, analysis, diagnostics and automated processing in coal-fired power plant for the early detection of abnormalities in the operation of gas turbines and other equipment in the facility. This allows for making more informed decisions with regard to taking a course of action when necessary, with better timing resulting not only in financial benefits but also improving operational and maintenance practices in the facility. Hedvall and McKenzie (2007) discuss the benefits of real-time quality monitoring.

Tillman and Duong (2007) reported on managing slagging at the Monroe, 3100 MWe (net) capacity power plant in South Michigan (USA) using online coal analysis and fuel blending. The station consists of four wall-fired boilers (775–795 MWe (net) each) firing blends of southern PRB subbituminous coal with low and medium sulphur Central Appalachian (LSCA and MSCA, respectively) bituminous coal. The units utilised small ESPs with typical specific collection area values of 191 and 286 ft^2/1000 acfm (~11 and 16 m^2/1000 m^3/h) depending upon unit. A typical ESP specific collection area is between 11 and 45 m^2/1000 m^3/h (200 and 800 ft^2/1000 acfm) flue gas volume depending on fly ash resistivity. Particles with resistivity in the range of 10^7-10^{10} ohm-cm are amenable to collection with ESPs. High resistivity particles are difficult to collect, which result in poor performance of an ESP (Soud, 1995). Today, the plant fires a blend of coal. The coal handling facility supports using three piles, each of a different type of coal, and the facility is capable of blending various percentages of LSCA, MSCA and PRB coals. The plant employs an X-ray Fluorescence (XRF) analyser (*see above* and (for more detail) Nalbandian, 2005). The XRF analysis program includes the following systems (Tillman and Duong, 2007):

- a coal sampler retrieving coal from the belt and crushing it to a size appropriate for the analyser;
- an online analyser capable of evaluating the coal for numerous constituents;
- a software package that provides information to the supervising operator, the shift supervisor and various engineers.

The analyser, coupled with a moisture meter provides the plant with the following information (Tillman and Duong, 2005):

- as-received heat content;
- moisture;
- ash;
- volatile matter;
- fixed carbon;
- sulphur;
- silica;
- alumina;
- titanium;
- iron oxide;
- calcium oxide;
- magnesium oxide;
- potassium oxide;
- sodium oxide;
- phosphorus pentoxide.

Other minerals are also evaluated by the XRF analyser including barium and manganese. Some of these data are converted, using the computer software package, into additional measures for the plant operations and engineering personnel including:

- volatility (volatile matter/fixed carbon ratio);
- opacity indications (silica plus alumina percentage);
- base/acid ratio;
- calcium/iron ratio;
- sulphur loading;
- ash loading;
- slagging alkalinity

Techniques were also developed to calculate the ultimate analysis from the analyser signals and data. According to Tillman and Duong (2007) these, coupled with data from the plant information system, provide the plant with the capability for calculating heat and material balances about the boiler as well as residence times in each section of the boiler (furnace, secondary superheat section, primary superheat section, reheater, economiser). Furthermore, these data provide the basis for calculating furnace and boiler cleanliness factors plus temperatures in all zones of the boiler and, consequently, gas velocities through each section and gas velocities impacting the ESPs. The analyser program is considered an essential exercise and the Monroe facility has committed to ensuring >90% availability of the analyser system including sampler, crusher, analyser and software. The instruments are calibrated monthly to ensure that instrument drift is minimised.

Chemical fractionation data analysis along with typical measures (for example, base/acid ratio) are used at Monroe to manage slagging and fouling. Chemical fractionation experiments are carried out on the parent coals and on the coal blends. According to Tillman and Duong (2007), this work is performed recognising that the traditional measures of coal quality are necessary but not sufficient to define the properties of low rank coals. These data then provide a basis for evaluating the slagging properties of coal blends using a regression equation derived from the chemical fractionation database and based upon the behaviour of calcium. The equation permits relating the chemical fractionation data to prior base/acid and slagging alkalinity data from the coal analyser. Tillman and Duong (2007), consider that continuous experimentation has shown that the blends do not behave like the weighted average of the two parent coals. When burning high percentage blends (for example ~65% PRB) understanding the influences of blending on the parameters measured by the online analyser and transmitted to the operators is essential. The program has proven successful in managing slagging and fouling and was extended to provide guidance for the operators managing opacity through controlling SO_3 injection to influence ash resistivity using models driven by data from the online analyser (Tillman and Duong, 2007).

4 Quality assessment with expert systems

An expert system is intelligent computer software, which can comprise a suite of programs, that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution (OECD, 2003).

4.1 Characteristics of expert systems

Every expert system consists of two principal parts (Engelmore and Feigenbaum, 1993):
- the knowledge base;
- the inference engine.

The knowledge base contains both factual and heuristic knowledge. Factual knowledge consists of all information available to plant operators and included in the plant digital/distributed control system (DCS). Heuristic knowledge is the less rigorous, more experiential and more judgmental knowledge of performance or what commonly constitutes the rules of 'good judgement' or the art of 'good guessing' in a field. In contrast to factual knowledge, heuristic knowledge is rarely discussed and is largely individualistic. The knowledge base is used with either 'if/then' statements (condition and action) or the rule of 'good judgement'. In an 'if/then' program, the 'if part' lists a set of conditions in some logical combination. Once the 'if part' of the rule is satisfied, the 'then part' can be carried out/concluded and the appropriate action taken. Expert systems whose knowledge is represented in rule form are called rule-based systems (Engelmore and Feigenbaum, 1993).

The inference engine makes inferences by determining which rules are satisfied by facts, ordering the satisfied rules, and executing the rule with the highest priority.

Expert data editing systems make so-called intelligent imputations based on a specified hierarchy of methods to be used in imputing an item. One item may use a deterministic approach followed by a hot-deck approach, while another item might require a model-based approach. Each item would be resolved according to its own hierarchy of approaches, the next being automatically tried when the previous method has failed. Hot-deck imputation is a means of imputing missing data using the data from other observations in the sample at hand.

According to Maxson (2005), to deal with highly complex processes that don't easily lend themselves to first-principles modelling, the process engineering community has increasingly harnessed neural network technology. Neural networks computationally mimic the nervous system of the human body. The system uses inputs (stimuli) to predict outputs (responses) based on the patterns 'learned' by the system. Training the system to develop a corresponding model is done by using historical and/or measured data. The goal of the model is to characterise outputs given inputs. Inputs consist of data that are known to impact the process. Neural networks have proved successful in many applications with accuracy in general >95% and often higher than 99%. Maxson (2005) considers that there are proponents for both sides, some who adamantly oppose anything except first principles and others who believe the heuristic approach made practical by high-speed computers and neural nets renders a first-principles approach obsolete. In truth, however, Maxson (2005) finds that both approaches have merit. Tools that can blend the best of both approaches generally demonstrate the broadest applicability and effectiveness.

An example of the demands that are made on a modern expert system applied to new plant is the Cliffside 6 supercritical unit. This will generate 800 MWe and replace four small units built in the 1940s at Rutherford, NC, USA (McGinnis and others, 2009). The plant is subject to strict emission limits for NOx, SO_2, sulphuric acid mist, mercury and particulate matter. In addition the effective control of other acid gases including HCl and HF will be required, for both environmental reasons and because of their impact on plant maintenance. The chlorine content of the coal is therefore of significance.

As the plant uses high sulphur coals from Kentucky and Virginia, the design adopted combines spray dry FGD and wet FGD systems. In the integrated process, sulphuric acid mist, HCl, mercury and particulates are removed at the spray dry FGD stage. Additional mercury and HCl removal occurs in the downstream wet FGD unit. The principal process steps are as follows:

- the flue gas is cooled in a spray dryer adsorber using a lean lime slurry. Significant amounts of mercury are captured and as the outlet temperature is well below the acid dewpoint, the SO_3 condenses as a sulphuric acid mist which reacts with the lime slurry. The solid calcium sulphate is captured in the fabric filter;
- SO_2 capture in the spray dry scrubbing stage is minimised by temperature control and sub-stoichiometric reagent feed to minimise lime usage;
- most of the SO_2 capture is achieved in the wet FGD using lower-cost limestone, and wallboard quality or landfill gypsum is produced;
- the purge stream required to control chlorides and inert fines for wallboard gypsum is returned as a component in the lime slurry feed to the spray dry scrubber.

The control of NOx emissions will be by the use of low NOx burners and overfire air, followed by a SCR unit (McGinnis and others, 2009).

Plants using different coals and operating in places with different emissions regulations may have a less complex series of unit operations, although in due course a CO_2 absorber may become an additional requirement. However, the above illustrates the range of factors that need to be considered and included within the overall control algorithms of an expert system. The emissions control systems need to be able to accept the required load-following characteristics of the boiler while meeting the necessary emission limits despite variations in the process conditions. It is additionally important to maintain the quality of the saleable byproducts and to minimise the amount of carbon-in-ash.

4.2 At the mine

Coal is extracted either from open (surface) pits or from underground mines and, as discussed in Chapter 2, there are different supply patterns to power plants. Coal quality in the deposit is assessed on the basis of cored borehole samples taken during exploration work. Some of this is needed to assess the practicality and costs of mining, and some may be undertaken to assist in the detailed planning concerning which segments of the deposit to exploit as part of the ongoing operation of a mine. Variations in coal quality, and in particular the amount of extraneous dirt present, do not always show up in the results from borehole analysis – these are affected by the mining method used as well as the nature of the coal seam. In terms of both coal quality and its variability, much depends on whether the coal is treated in a CPP and then on the extent of the processing. In recent years, computer aided designs and models have been developed for decision making purposes with regard to planning mines and the potential exploitation of certain coal deposits. Such model are discussed by Cichoń (2004) and Roumpos and others (2004). However, these are not discussed in this review.

The management of the rom product from different parts of a mine requires careful consideration. For example, blending can produce an optimum product for consistent performance in power plants. This commonly requires a carefully monitored stacker/reclaimer set-up, and online analysis devices may be able to facilitate the sorting process. Each mine is likely to have developed its own expert system for maximising the overall return from the mine and power plant. Woodward (2005) explained how to use an online analyser to perform sorting in a Western US coal mine.

A global perspective of CPP is presented by Bethell (2007) describing coal processing circuitry and practices. Coal sizing, cleaning de-watering and reject disposal devices, techniques and practices are also discussed. Arnold and others (2007) review current coal preparation plants (CPP) practice, principally in the USA and Australia. The automation and control of some of the unit operations, such as Romjigs and Batac jigs are discussed along with the various applications of dense medium in baths and cyclones. For coal preparation – automation and control *see* Couch (1996); DTI (2001b). Computer-based systems which aim to ensure consistent operation and maximise the profitability of CPPs are in widespread use. They are backed up by process modelling and plant audits which provide the knowledge base and input for the operation of a CPP. The status of coal preparation research was the subject of a study by Honaker and others (2007) and future challenges in coal preparation plant design and operation were discussed by Davis (2007). Cierpisz (2001) presented the application of computer-based monitoring and control systems in coal preparation plants.

Most online coal analysers used on CPPs are simple ash gauges (Woodward, 2007). Most are located on the product side of the plant, to monitor performance although more than a hundred are used to monitor the plant feed. It is noteworthy that Woodward (2007) says that almost all plants use a human operator to interpret the analyser results and effect process changes rather than attempting automation. This implies that the application of expert systems as understood in this report, to the operation of CPPs, is very limited, although some sub-systems within a plant include feed-back control loops.

The possibility of using commercial online analysis systems for monitoring the ash content of low grade lignites in Greek mines was the subject of a study by Kavouridis and Pavloudakis (2007). Pilot-scale tests were carried out by installing the online analyser on the conveyor belt that transported the lignite from the mine pit to the bunker of Kardia mine, Ptolemais basin. The study results showed that the precision of the online analyser was not satisfactory and did not allow the precise determination of the ash content in real time. Kavouridis and Pavloudakis (2007) consider that the poor performance of the chosen online analyser was due to the multi-seam structure of the lignite deposit. The deposit consisted of many lignite layers of varying thickness separated by waste layers which led to significant fluctuations of the produced lignite quality. The most important causes for the errors were attributed to the intense variation in ash content and the fluctuation in the mineral matter composition, especially the changes in FeO_3 and CaO content and also the rapid changes in lignite weight per conveyor belt unit area. Several solutions were investigated in order to overcome these problems. It was decided that online analysis can be applied successfully in this mine if a detailed and reliable spatial database of the quality characteristics of each lignite seam were developed. However, this would require a time-consuming and rather expensive drilling programme.

Kavouridis and Pavloudakis (2007) consider that the following must be examined as alternatives:
- simultaneous use of online analysers that incorporate different operating principles and are capable of measuring other lignite quality parameters apart from ash content. These would provide more data which can lead to improved ash monitoring precision after processing with software especially developed for such application;
- implementation of a sampling and laboratory analysis program for regular mapping of the quality characteristics of the lignite seams that appear in each mine bench. The lignite samples obtained from each seam can be analysed for elemental ash composition, so that the calculation of the absorption coefficient variations (that is, shifting of calibration line) is possible. This process would have to be carried out in time intervals that allow tracing of the qualitative changes in each seam;
- it would be possible to choose (either manually or automatically) the set of calibration coefficients that gives the optimum online analysers accuracy based on the contribution of each bucket wheel excavator (BWE) to the production of the mine and tracing the operating point of the excavation. Kawalec (2004) discussed the short-term scheduling and blending in a lignite open-pit mine utilising BWEs.

According to Kavouridis and Pavloudakis (2007), more experimental work needs to be carried out to investigate the possibility of using online analysers in mines where the lignite deposits have lower and less fluctuating contents of FeO_3 and CaO in ash.

4.3 Blending

Laboratory- and full-scale coal blending studies were the subject of a detailed review by Rozendaal and others (1998). Coal blending for power generation can be carried out in one of two ways. Different coals can be stored in separate stockpiles and weigh feeders can be used to balance the different amounts of coal fed onto a conveyor feeding a power plant boiler. Alternatively, coals may be stacked on large stockpiles in layers and reclaimed in such a way as to achieve a representative blend. Management of coal stockpiles is discussed in other IEA Clean Coal Centre reports by Nalbandian (2010) and Carpenter (1999).

Dynamic coal blending can be used to improve overall plant economic performance where there is a choice of coals to use and the blending can maximise the use of the lowest cost coal. In order to operate a dynamic coal blending system, reliable information about the different coal qualities is essential. In addition it is necessary to have an understanding of the effects of changes in the blend under the operating conditions in different parts of the power plant sequence (Sehgal and Shea, 2001): pulverisers → burners → boiler furnace → superheaters → reheaters → economiser → air preheater → SCR unit → ESP/fabric filters → FGD unit → CO_2 absorber → stack

Most coal-fired power plants use a fixed coal blend which is tailored for optimum performance under full load conditions. Often this blend is of a much higher quality than is needed during part-load operation, and of a lower quality than is needed when output peaks. Fixed blends also lack the flexibility to adapt to changing plant conditions such as increased ash deposition or deteriorating precipitator performance which can cause costly derates (Sehgal and Shea, 2001). A detailed review of the state-of-the-art in coal blending in 2001 for power generation was prepared by Wall and others (2001).

US DOE reports published in 2001 and 2007 cover the demonstration of advanced integrated control systems for simultaneous emissions reduction. At each stage of the systems, the coal properties, along with the volume of injected air, determines the conditions, gas velocities, temperatures, ash quantity and properties, and the amounts of the various gaseous components, some of which need to be removed (Shea and others, 2002).

A software product applied to dynamic blending called CoaLogic was reported to have been installed in thirty boilers in North America for a variety of purposes. In one example of its application, an 800 MWe plant in Canada was subject to frequent derates because the stack frequently exceeded opacity limits. The coal came from a nearby mine with five seams, one of which produced coal with a high opacity potential, supplying approximately 30% of the coal used at the plant. Coal from the other seams had a variable heat content. It was also considered that the plant derating may have been the result of limited mill capacity.

The amount of coal mined from different seams is largely carried out independently of the power plant, so the operator has to accept the coal supplied. Stack opacity is affected not only by the coal blend being fired but also by which coal has been in use for the previous few hours and the influence that its ash chemistry has on the ESPs. These tend to become de-conditioned with low sodium, low sulphur coals. The de-conditioning of precipitators refers to the reduction in removal efficiency that occurs when these devices are subjected to coals with low ion content over an extended period of time (Sehgal and Hickinbotham, 2001). Particulate control with electrostatic precipitators is discussed in detail in previous Clean Coal Centre publications by Zhu (2003) and Soud (1995). Controlling opacity and heating value at the burners, therefore, requires an ongoing estimation of coal characteristics such as sodium, calcium, and ash, and operating conditions such as load and the type of coal that has been burned for the previous few hours.

A particular challenge has arisen in the USA where substantial quantities of subbituminous PRB coals are blended with eastern bituminous coals in order to meet sulphur emissions requirements. Fuel blending with PRB coal is discussed by McCartney and Williams (2009). Similar problems can arise elsewhere, particularly where Indonesian subbituminous coals are blended with other traded coals nearly all of which are bituminous.

The ash characteristics of subbituminous and bituminous coals differ significantly. The high sodium and calcium contents which are common in subbituminous coals result in a lower ash fusion temperature, and considerably increased slag formation which results in changes in heat transfer in large sections of the boiler. Use of the PRB coal can result in unit derates and forced outages for cleaning and to repair or replace boiler tubes that have overheated because they were covered in slag, or have been damaged by slag falls (Smyrniotis, 2005).

The use of computational fluid dynamics (CFD) modelling can provide a tool to mitigate such problems. CFD modelling can target areas of both the radiant and convective sections of the boiler and to add chemicals such as magnesium hydroxide, which reduce both slagging and fouling using a methodology called targeted in-furnace injection (TIFI). The company involved in this particular development is Fuel Tech Inc (Fuel Tech, 2009), but others offer alternative systems and approaches (Gelbar and Kunkel, 2002).

4.4 Application to boiler feed

Coal quality impacts coal handling, pulverising, combustion, ash deposition and soot-blowing, corrosion and erosion, low NOx burners, air staging, SCR, FGD and ESPs – hence overall emissions as well as carbon-in-ash. That is, the varying coal properties can affect the efficient operation of both the boiler and of the emissions control units. They therefore affect both the short and long-term operability of the plant, and the economics of the operation.

The key impacts are connected with:
- the performance of the pulverising mills;
- coal distribution to the burners;
- ash deposition and in particular its slagging and fouling behaviour;
- long-term corrosion and erosion effects;
- interactions between the various emissions control units.

Magni and others (2005) discuss Kalman filter estimation of coal flow in power plants. The Kalman filter is a set of mathematical equations that provides an efficient computational (recursive) means to estimate the state of a process, in a way that minimises the mean of the squared error. Kalman filtering is used mainly to estimate system states that can only be observed indirectly or inaccurately by the system itself. The filter is powerful in several aspects: it supports estimations of past, present, and even future states, and it can do so even when the precise nature of the modelled system is unknown (Welch and Bishop, 2006). The estimation was carried out for a reference conventional, once-through, 660 MW supercritical coal-fired plant reproducing an actual unit located in Italy. The dynamic simulator of such a plant used as test bench included all the water steam systems (boiler, steam turbine, balance of plant), the air-gas system, the mills and all the control loops. Figure 9 shows the represented original control scheme of the pulverised coal flow to the furnace. The scheme includes a proportional-integral master controller driven by the error between the coal flow request (received from the power plant load controller) and an estimation of the total pulverised coal exiting the mills. The output of the control represents the mill feeder speed request for all the mills in operation (maximum of 6). Magni and others (2005) consider that the feeder speed gives a good representation of the coal flow entering the mills and is controlled, for each mill, by a dedicated proportion-integral regulator. With regard to the coal flow estimation exiting each mill, its dynamic behaviour is represented by means of two transfer functions taking into account the contribution of the pulverising

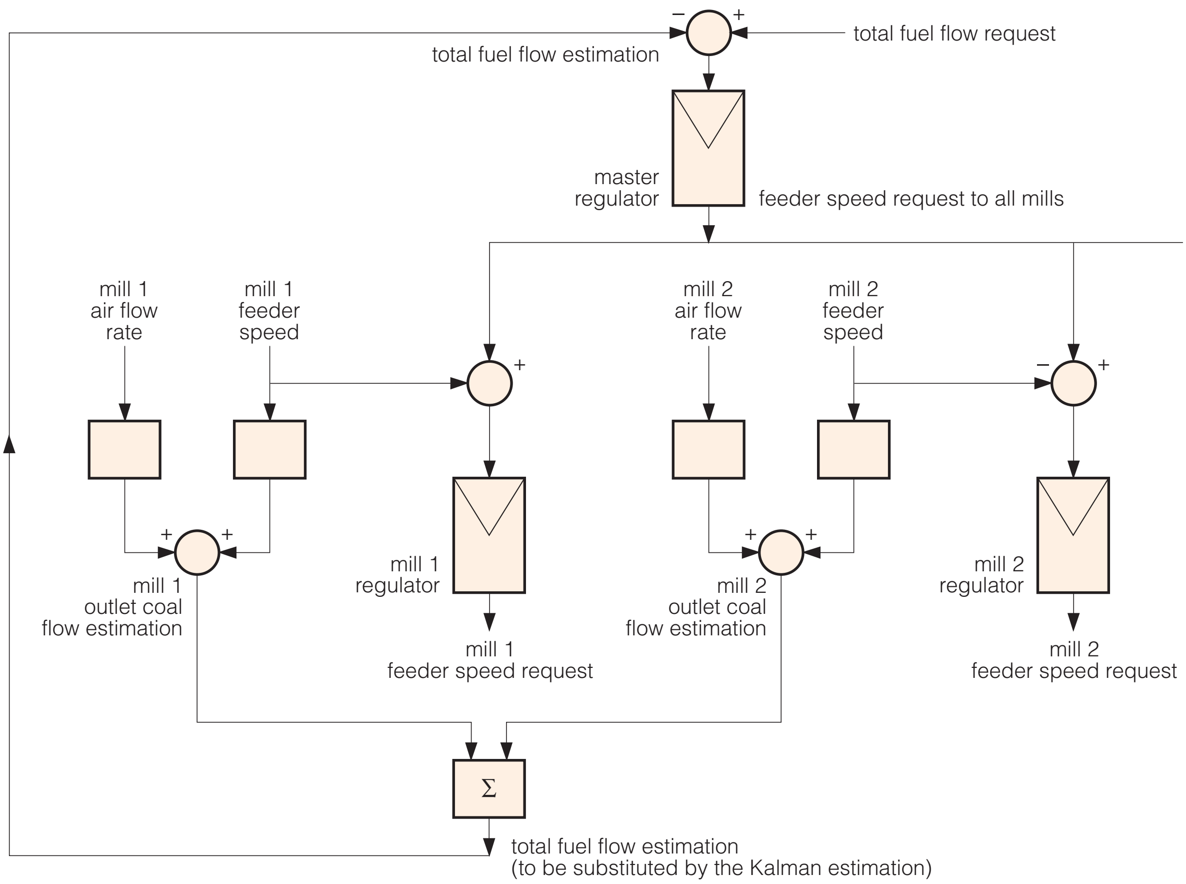

Figure 9 The represented original control scheme of the pulverised coal flow to the furnace (Magni and others, 2005)

time delay of the coal entering the mill and the contribution of the lead effect of the air flowing inside the mill and carrying the pulverised coal to the furnace. The two transfer functions used for coal flow estimation had been identified on the basis of a trial and error procedure.

The simulations demonstrated that it is not possible to improve the response of the coal flow control loop with the actual coal flow estimation. However, with better estimation of coal flow, improvements may be achieved. To achieve greater improvements, two different approaches were undertaken to obtain a better coal flow estimation using Kalman filtering. The first approach involved using a black box model of the mill-boiler-turbine system for the simulation of the coal mass flow with a Kalman filter. The second approach used non-linear physical model based estimation with Kalman filtering. In both cases, the Kalman estimation gave corresponding data with the effective coal mass flow, both in steady state condition and in transients. In the test case, closing the coal flow control loop with the Kalman estimation in substitution of the missing measurement allowed for better tuning of the control system, leading to a significant improvement in its dynamic performance without compromising system stability. Magni and others (2005) found that even the amplitude of the disturbances on the main steam temperature and pressure, induced by electrical power request variations, were significantly reduced. The authors concluded that all these factors, combined with the resulting control system robustness to modification of the coal calorific value, concur in making the Kalman filter a good solution to the coal mass flow control problem in power plants.

4.5 Predictive modelling

Vesel (2009) discusses the application of multi-variable model-based control in the power generation sector. He attributes the slow uptake of the technology partly to the higher performance requirements and the much faster dynamic behaviour of power plant components compared to industrial processes. This required computing power that until recently was either not available or not cost-effective. Vesel (2009) considers that, for utility application of multi-variable control technologies, there have been three overlapping generations of advanced controls which are currently in use. The first generation used neural networks to build the multi-variable model. The second generation was the linear multi-variable model-predictive controls. The third generation relies on state-space-modelling. State-space models are a flexible family of models which fits the modelling of many scenarios. The strongest feature of state-space models is the existence of very general algorithms for filtering, smoothing and predicting. For detailed information on state-space models *see* Poncia (2003).

According to Poncia (2003), there are a number of reasons to adopt model-based predictive control in a power plant context. For example, the inclusion of several constraints such as limits on the operability of actuators, admissible ranges on the thermodynamic variables imposed to guarantee safe operation. Also, the possibility of delaying easily with the compensation of measurable disturbances such as the power needs of the grid. Different techniques have been adopted in recent years including estimation of states and plant parameters online with an extended Kalman filter (Welch and Bishop, 2006).

Poncia (2003) discusses in detail the application of multi-variable techniques to the control of fossil fuel power plants. He concludes that solutions that replace the classic multiple single-input single-output configuration have not found application in the industrial realm. This is attributed mainly to the caution and uncertainty with systems that revolutionise well-assessed technologies and design procedures. Due to this reasoning, attention is mainly devoted to structures where the classic regulation is kept in operation and a multi-variable solution corrects it, in order to improve the trajectories of the thermodynamic variables. The design process is achieved in a sequence of steps involving (Poncia, 2003):

- choice of the control architecture, alternatively controlled reference value or control action correction. Both architectures consist of a multi-variable controller that corrects the action of a traditional regulation system;
- development of a non-linear model of the power plant, used for simulation and verification purposes. The model is validated against experimental data from the real plant;
- synthesis of the reduced-order models that are incorporated in the control algorithm. The models can be identified from simulation or experimental data in a fast and reliable way by applying state-space identification techniques;
- model-based predictive control strategies have been demonstrated to be effective and reliable for the control of many chemical and thermal processes;
- controller synthesis and verification over the operating range of the place, according to design specifications.

Furthermore, Poncia (2003) considers that the benefits of the introduction of a control action correction multi-variable controller based on state-space model based predictive control have been illustrated by presenting his findings of an application to a simulated 320 MW oil-fired plant. He observes that:

- the application of the multi-variable solution allows a reduction of thermal stresses and pressure oscillations when extreme conditions are encountered;
- amplitudes of the control variables are also reduced, thus diminishing the stress and effort of the actuators;
- the results suggest the possibility of eliminating the temperature control by attemperation, a solution that results in efficiency losses and increases the possibility of damage in the turbine;
- the improved control system is conceived in such a way that when the multi-variable controller is disconnected, the traditional regulation devices guarantee safe operation of the plant.

Vesel (2009) discusses the implementation of a multi-variable predictive control system at the Colstrip

(USA) coal-fired power plant. The system was designed to be a co-ordinating supervisory layer on top of the basic single-loop proportional-integral-derivative (PID) controls. PID is a generic control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an ‘error’ value as the difference between a measured process variable and a desired set-point. The controller attempts to minimise the error by adjusting the process control inputs. According to Vesel (2009), acceptance of, and confidence in, such a system by plant operating staff takes time. The application of multi-variable predictive control in coal-fired power plants is also discussed by Immonen and others (2007). The authors consider that the advanced model predictive control systems improvements in plant operation can include:

- NOx reduction;
- heat rate improvement;
- reduction in unburnt carbon in ash;
- reduction in CO_2 production per MWh generation;
- maintenance of CO at a desired level;
- improved availability;
- accelerated ramp rates.

In 2007, Ma and others published a study on a comprehensive slagging and fouling prediction tool for coal-fired boilers and its validation and application. The ash behaviour prediction tool, called AshPro^{SM}, integrates boiler CFD simulations with ash behaviour models including ash formation, transport and deposition, as well as deposit growth and strength development. The results from the CFD model provided the basic information used in the ash behaviour model. The software was applied to a 512 MW tangentially-fired boiler to evaluate the localised slagging on furnace walls and fouling in convective pass. The predicted deposit pattern was found to be reasonably consistent, particularly in the overfire air region, indicating that the model was providing accurate prediction although Ma and others (2007) consider that this could be improved by fine tuning the ash behaviour model and better integration between the two models. Following the application of the system at the 512 MW boiler, the authors concluded that the prediction tool can be used to determine the deposit thickness, chemical composition, physical properties and heat transfer properties in a specific region of the furnace wall and convective pass. It can be used to assess the combined impact of ash formation and deposition phenomena on power plant performance and can also be used to assess the impact of coal quality, ash properties, fouling and slagging in the operation of the plant as well as used for design and operational purposes. According to Ma and others (2007), further efforts continue to improve the prediction of the model.

4.6 Non-linear modelling techniques

Conventional methods of empirical modelling for predicting the effects of coal quality changes on boiler performance use linear statistical techniques. However, some parameters can be predicted more accurately using non-linear techniques and an application of this is described by Bulsari and others (2009). An example is given of the use of a non-linear model at the Naantali power plant, near Turku in Finland, to improve combustion efficiency while keeping NOx and other emissions within desired limits.

The No 2 boiler on which the tests were carried out was supplied in 1964, and produces some 90 MWe of power and 175 MWth of heat. It burns about 44 t/h of coal at full capacity. The coal comes from six different Russian mines, and there are differences in coal characteristics between every shipment. Quantitative knowledge of the effects of process variables such as the set points for the flow rates of air and coal make it easier to operate under optimal conditions.

Non-linear modelling is based on empirical or semi-empirical data that takes at least some non-linearity into account. Older techniques have included polynomial regression and linear regression with non-linear terms. New developments use feed-forward neural networks, multivariate splines and kernel regression, and have been found to be particularly valuable in process modelling.

The Naantali boiler uses coal as the main fuel with up to 2% of added sawdust. Oil is only used for start-up. In developing the non-linear model, plant data were collected. Fuel flow rates, fraction of sawdust, air flow rates and a variable indirectly indicating the amount of excess air were selected as input variables for the first phase of the work. Output variables included emissions, the amount of feed water as a measure of the power generated, unburnt carbon in fly ash, flue gas temperature and steam temperature.

It was found that the non-linear models developed could predict NOx emissions while facilitating the more efficient operation of the boiler. It was also possible to follow the effects of input variables or pairs of input variables on parameters such as the amount of carbon in ash. It is claimed that the use of such models can provide for the setting of process variables to meet optimisation objectives in the presence of constraints (Bulsari and others, 2009).

The PiT Navigator for coal-fired power plant, is a non-linear model predictive control (NMPC) system developed by Powitec Intelligent Technologies GmbH (Germany). The system uses proprietary optical and acoustic multi-sensors and digital image processing software for flame analysis. The parameters determined by the multi-sensors are used in combination with conventional combustion data to create statistical and adaptive models of the process. The non-linear models are used to regulate coal and combustion air distribution and flow, thus optimising the combustion process and increasing efficiency. When installed, amortisation is expected in less than two years. According to Powitec (2011) the system can achieve the following results:

- up to 0.5–1.0% reduction in fuel combustion;
- reduction in slagging and fouling in the boiler;
- up to 0.5% increase in boiler efficiency;
- up to 30% reduction in CO and NOx emissions;
- reduction in CO_2 emission;
- 20% reduction in carbon in ash;
- increased availability.

The system has been installed in a number of coal-fired plants. According to Powitec (2011) the system has been deemed to meet expectations and perform satisfactorily. Customers have declared it as flexible and easy to use and achieve set targets.

5 Expert systems

According to Coker and others (2006), expert systems are software that behaves in much the same way as a human expert would in a certain field of knowledge. An expert system is a class of computer program developed by researchers in artificial intelligence during the 1970s which appeared commercially in the early 1980s. The programs are a set of rules that analyse information, usually supplied by the user of the system about a specific class of problems, as well as provide analysis of the problem and recommend a course of action for correction. According to US DOE (2007), artificial intelligence is commonly defined as the science and engineering of making intelligent machines, especially intelligent computer programs. Relative to applications in coal-fired power plants, artificial intelligence consists of aspects of considerations that deal with (US DOE, 2007):

- **neural networks**, which mimic the capacity of the human brain to handle complex non-linear relationships and 'learn' new relationships in the plant environment;
- **advanced algorithms or expert systems** that follow a set of pre-established rules written in codes or computer language;
- **fuzzy logic**, which involves evaluation of process variables in accordance with approximate relationships that have been determined to be sufficiently accurate to meet the needs of plant control system.

A number of artificial intelligence systems are available today for use in coal-fired power generation. In this section the discussion is mainly on expert systems that are used to assess the impacts of coal quality in the plant. However, other expert systems such as those that aim to optimise the combustion process are also presented.

The Clean Coal Technology (CCT) demonstration programme began in 1985. It is co-funded by the US government and industry to demonstrate a new generation of innovative coal utilisation processes including software/expert systems development in a series of facilities built across the USA. The projects are conducted on a commercial scale to prove technical feasibility and provide the information required for future application (US DOE, 2001). Three computer/expert software systems were developed under the CCT programme for application in coal-fired plant including (US DOE, 2001):

- Coal Quality Expert (CQE™), a program that provides detailed analyses of the impacts of coal quality, operational changes and /or environmental compliance alternatives on emissions, performance and power production costs;
- Generic NOx Control Intelligent System (GNOCIS), an advanced software-based system that optimises boiler operation to achieve reduced NOx emissions while improving unit performance;
- Plant Economic Optimisation Advisor (PEOA™), a system designed to assist in meeting emissions regulations while optimising overall plant economic performance. The PEOA system demonstration was discontinued because of operating problems. This software is not discussed further in this review.

According to US DOE (2001), these projects incorporate aspects of artificial intelligence (AI), which involves computer-based decision-making processes that mimic those of the human brain. The use of different forms of AI in plant operation and control is discussed by the US DOE (2007) and Bartos (2005). The CQE™ and GNOCIS projects are discussed in greater detail in Sections 5.1 and 5.4 respectively.

5.1 Coal Quality Expert (CQE™)

During the early 1990s there were extensive efforts by the US DOE to develop a software tool for utilities, coal producers and equipment manufacturers that could analyse the impacts of:

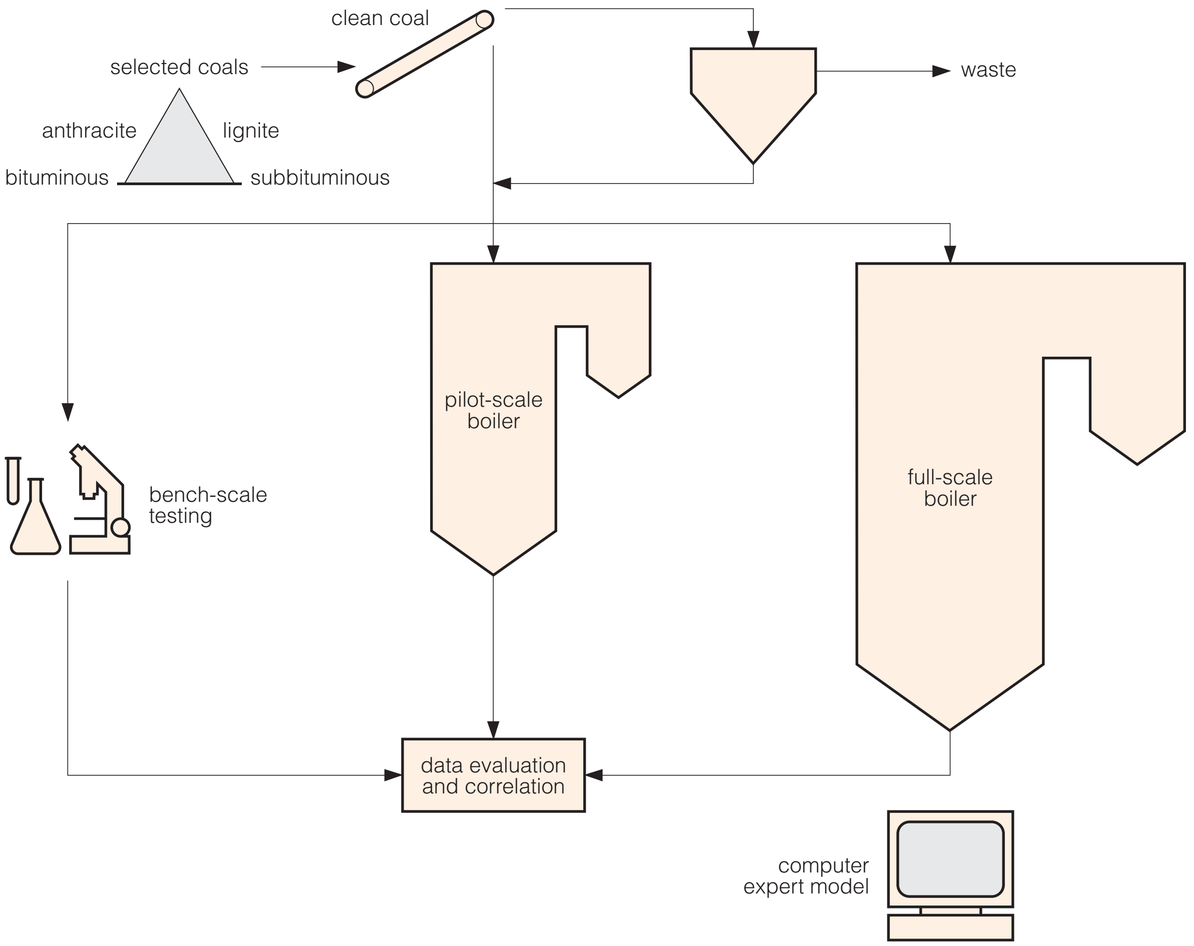

Figure 10 CQE™ process flow diagram (US DOE, 2001)

- coal quality on power plant performance, emissions and costs;
- hardware provision (and plant modifications);
- operational changes;
- environmental compliance alternatives.

The software was called the **Coal Quality Expert (CQE™)** (*see* Figure 10) and was correlated with the results obtained from the earlier predictions from the Electric Power Research Institute (EPRI) Coal Quality Impact Model (CQIM) (US DOE, 2001). Since its introduction in 1989, CQIM has been obtained by over 100 PRI member utilities and purchased by an additional 16 users including non-EPRI US utilities, international utilities and coal producers. Black & Veatch (B&V) estimate that CQIM is used on a regular basis by about 50 users (B&V, 2011). CQIM naturally focused on the use of US coals in US power plants, although it has proved to be applicable more generally. CQIM has been applied to a wide range of fuel-related evaluations by B&V, utilities and coal companies. These evaluations have included the following (B&V, 2011):

- evaluate potential coal supplies and assist in coal sales/procurement;
- establish 'unit-specific' coal specifications and property range limits;
- develop/evaluate premium/penalties for key coal quality parameters for use in coal contracts and negotiations;
- assess changes in maintenance/availability costs;
- quantify advantages/disadvantages of blending and cleaning coals;
- quantify advantages/disadvantages of gas cofiring;
- evaluate performance and economic trade-offs from burning high sulphur coals that require FGD versus burning compliance coals;

- screen alternative coals prior to test burns, collected expected impacts to help write test burn procedures and evaluate results of tests burns;
- develop strategies to address emission limits;
- support engineering studies to predict impacts of equipment modifications on overall unit performance and economics;
- document and standardise the coal procurement decision process.

Juniper and Pohl (1997) describe and assess the CQIM model, briefly, in an Australian producer context whilst Conroy and Bennett (1996) and Bennett and Conroy (1997) examined the ability of CQIM to predict the performance of Australian coals in processes that occur in a coal-fired power plant. They considered that CQIM reduced the possible errors in using empirical correlations by using the known performance of one coal to calibrate its predictions for other coals fired in the same power plant. They concluded that Australian coal producers should continue to evaluate future versions of CQIM.

The CQE™ project scope included:
- the collection and analysis of data to form the basis for the algorithms, methodologies and sub-models used;
- verifying the accuracy and integrity of the software;
- coal characterisation, bench- and pilot-scale combustion testing, and full-scale utility boiler tests;
- software development.

Harrison and others (1997) describe early experience with the CQE™ model. When the NETL report *Development of a Coal Quality Expert™ a DOE assessment* was published in 2000, CQE™ had been distributed to about 25 utilities in the USA and to one in the UK, through EPRI membership (DOE/NETL, 2000). The CQE™ is a personal computer software package. It is a predictive tool which can help a coal-burning utility select the economically optimum coal for a specific boiler, based on emissions constraints, operational efficiency, performance limitations and cost. The software predicts the operating performance and associated costs of coals not previously used at the facility. Data obtained from bench-, pilot- and full-scale testing were used to develop, adapt and verify the algorithms in the CQE™. Field tests in utility boilers were performed at six sites.

The goal of the project was to include information based on:
- the characterisation and cleanability/washability assessments of various coals;
- bench- and pilot-scale combustion testing of the coals in question;
- full-scale utility demonstration tests.

The CQE™ utilises several previously existing models developed by EPRI (with US DOE support in some cases) as part of other programs and were not the focus of the CQE™ project including (US DOE, 2001):
- Coal Quality Impact Model (CQIM): CQE™ uses the CQIM code to evaluate performance of many auxiliary systems in coal-fired power plants. CQIM was developed by Black & Veatch (B&V) for the EPRI. The CQIM code can be used to perform maintenance/availability, derating, sensitivity and economic analyses as well as to model coal cleaning, blending and transportation.
- NOx Prediction Model (NOxPERT): NOxPERT predicts NOx emissions as a function of coal parameters, operating data and furnace type.
- Common Systems Evaluator: a program that models equipment systems serving more than one unit at a plant.
- Acid Rain Advisor (ARA): ARA was designed to assist the user in evaluating options for compliance with the Clean Air Act Amendments (CAAA). ARA provides the means to rapidly select combinations of SO_2 reduction technologies at various units in a system while viewing system-wide results. It can be used either on a stand-alone basis, in conjunction with CQIM or within CQE™.
- Boiler Expert: a model that consists of two routines: slagging expert (SLAGGO) and fouling

expert (FOULER):
- SLAGGO simulates the entire cycle of ash formation, deposit initiation, growth and removal processes based on coal properties and boiler design and operating parameters. It consists of several models and sub-models including ash formation, ash transport, deposit growth, thermal properties and deposit removal models as well as mineral matter transformation and alkali vaporisation sub-models; pyrite kinetics are excluded. Coal properties, boiler internal aerodynamics and transport mechanics are accounted for to predict changes in cleanliness of the waterwall and superheater tubes in the furnace. Deposit removal by soot blowing is also modelled;
- FOULER predicts convective pass fouling based on boiler design, temperature and gas distributions, ash size and composition distributions, and soot blowing and load drop parameters. Thermal resistivities of each heat exchange section are utilised to iteratively calculate boiler temperature profiles and cleanliness factor is determined from the difference in heat transfer between dirty and clean tubes. time intervals between soot blowing cycles can be optimised with FOULER.

- CQE™ expands the boiler performance modelling capabilities of CQIM to interface with and use results from these routines.

According to the US DOE (2001), CQE™ offers significant benefits in the selection of coal-based fuels and in the design and operation of coal-fired power systems. It has the capability of predicting power plant performance with a minimum number of bench-scale tests, resulting in lower cost to achieve the desired assessments compared with traditional approaches.

In practice, the uptake of this specific program has been limited, as it was largely aimed at and validated for a US market. It has now been largely superceded by Vista™, which is discussed in the next section. Many of the larger utilities have effectively developed their own software based on similar principles and validated with the coals they are using. Coal choice is commonly more limited than is implied in some of the discussion about models.

5.2 Vista™

The new generation model of coal quality impact, Vista™, expands the capability of CQIM and has been developed to meet the changing needs of the electricity generating industry (B&V, 2011). The Vista program is funded by a 'User Group' of between 22 and 25 utilities and energy companies who devote resources to the continued improvement of the program. The User Group meets annually to discuss potential technical enhancements and modifications to the program and uses both an 'Executive Committee' of members and votes among the members at large to set in place the direction for Vista development. The Vista program development consists of co-operative effort between three groups: EPRI, who own the program; the Vista User Group, who fund the program and direct its development; and Black & Veatch, who implement the directives of both the Vista User Group and EPRI (Anderson, 2011).

Vista quantifies the cost and performance impacts associated with burning alternate coals in a power plant. It uses equipment-specific engineering models rather than generic correlations to evaluate performance impacts with predictions based on equipment configuration and component information coupled with detailed calibration data supplied by the user. The model incorporates detailed predictive performance models for all equipment affected by the coal quality including a detailed steam generator heat transfer model. Further models are used to determine maintenance and availability costs and derates. All models use calculations based primarily on engineering principles, and in some cases empirical formulas, and include the impacts of changes in performance of one system or component on another. The primary task of Vista is to provide the user with total fuel-related costs for alternative coals on a system-by-system basis via a summary of projected performance. The predictions consider the following impacts for the combustion of each coal supply (B&V, 2011):

- plant efficiency effects;
- equipment system capacity;
- auxiliary power requirements;
- steam attemperation requirements;
- propensity for slagging or fouling;
- a variety of emissions-related calculations, including sulphur dioxide (SO_2) and sulphur trioxide (SO_3), nitrogen oxides (NOx), particulate emissions (PM), stack opacity, CO and CO_2 emissions, heavy metal emissions such as mercury, and acid gas emissions;
- maintenance costs;
- waste disposal costs;
- replacement power costs resulting from predictions of differential unit availability and capability;
- fuel and fuel transportation costs.

Key features of Vista which were not available with CQIM include (B&V, 2011; Anderson, 2011):
- Windows operating platform which eliminates the need for other operating systems and bring Vista into the mainstream of supposed operating systems, simplifying internal product support needs;
- standalone, workgroup or corporate client/serve environments which provides flexibility in how Vista can be used from single-user to corporate availability;
- data share via standard structured query language (SQL) databases facilitating external access to the Vista data and allowing Vista to communicate with other corporate tools;
- user interface similar to other Windows products so that the user does not have to learn an entirely new interface structure;
- user third-party tools for report writing, thus optimising output flexibility and allowing user customisation;
- graphical representation of input unit data, simplifying the data input process and allowing a visual verification of configuration accuracy;
- modelling of dry FGD, SCR and SNCR systems, furnace sorbent injection, coal additives, flue gas (duct) sorbent injection, and active and passive mercury capture;
- ability to model stoker-fired units;
- ability to model coal and oil cofiring, coal and gas cofiring or complete coal to gas or coal to oil conversions;
- extensive biomass-specific calculations with improvements in every area of the program;
- ability to model components not handled directly by the calculations (that is, cyclone particulate collectors) using a Black Box equipment item. A Black Box generally describes a complex electronic product defined by its functional or operating characteristics and is packaged as a singular unit. The internal parts are typically hidden from view and little understood (Coker and others (2006).

Vista also incorporates the following improvements which were not available in prior versions of CQIM (B&V, 2011):
- ability to input data using a variety of units, including ‘standard’ English and standard international (SI) units;
- improvements in the ability to model petroleum coke and other opportunity fuels;
- improved mill drying analysis;
- ability to model primary air fans dedicated to mills;
- improvements for fan modelling especially in off-design operation;
- ESP enhancements;
- improved wet lime and limestone FGD modelling;
- improvement maintenance/availability calculations including significant enhancements to the boiler tube failure predictive modules;
- improved unburnt carbon modelling.

Additional flexibility planned for future releases of Vista include (Anderson, 2011):

- implementation of new steam generator heat transfer model, which will expand the number of boilers and steam cycles which can be directly modelled by Vista;
- ability to model carbon capture systems;
- continued expansion of coal and biomass cofiring and biomass only fired boilers.

In summary, the Vista coal quality impact model/analysis provides a complete examination of the effects of the coal on unit performance, availability, fuel costs, operation and maintenance costs and other parameters. This, combined with other information from the unit can be used to develop a comprehensive economic model of a power plant (B&V, 2011).

According to Eyre (2011), the evaluation of fuel quality impacts on power plant performance is important to ensure that the best value coals are purchased, rather than simply the cheapest coals. This is because the adverse impacts on ash saleability, emissions performance or unit efficiency can quickly negate the benefits of a slightly cheaper $/GJ coal price. As many different factors must be considered, computer models are ideal for assessing the true value of coals. While Vista is considered the most comprehensive model available for fuel quality assessment, Eyre (2011) notes that it takes appreciable time and effort to build and calibrate new Vista models. In order to obtain accurate results, a detailed power plant model developed by an experienced Vista user is required, otherwise results can be misleading. While this can be a viewed as a negative, the advantage is that detailed calibration ensures that Vista's predictions are fine-tuned to ones's own specific power plant.

An advantage of Vista over simpler models is that it assesses impacts of fuel quality on power plant maintenance and availability. While it is not always easy to validate these predictions against observed performance, the very high level of detail Vista employs and the historic M&A database referenced by Vista gives confidence in the results. Conversely, the evaluation of several other fuel quality impacts can be equally performed by much simpler tools. For example, calculations of fuel transportation costs, emissions (especially CO_2 and SO_2), reagent demand and by-product (ash and gypsum) sales are relatively easy. Even more advanced calculations, such as impacts on boiler efficiency or auxiliary power demand can be performed by any competent engineer. Overall, according to Eyre (2011), relatively simple, fast spreadsheet tools which can give 90% of the complete cost-in-use assessment are generally sufficient for making correct fuel purchasing decisions, while Vista modelling can be valuable for detailed engineering studies or major fuel-related projects.

5.3 The State Technologies Advancement Collaborative (STAC) project

The STAC is a collaborative project between the US DOE, National Association of State Energy Officials and the Association of State Energy Research and Technology Transfer Institutions. The project title is: 'the use of real time measurement and artificial intelligence to improve efficiency and reduce emissions at coal-fired power plants'. The objectives of the project which are currently under development by the Energy Research Company (USA) are to develop a technique to measure coal properties in real time and to process the data such that coal-fired electric utility operators can adjust their operation to avoid slagging and fouling (STACenergy, 2009).

The project involved laboratory coal measurements in which coal samples collected from power plants that experience a range of problems typical of the power plant industry in relation to slagging and fouling were measured. This was to define elemental concentrations that can be used to determine slagging and fouling indices for use to control boiler operations. Analysis was carried out with the Laser-Induced Breakdown Spectroscopy (LIBS). The data were analysed and a literature and technological review of coal/ash related slagging and fouling indicators were performed. According to Romero and others (2007) simulated coal tests were run in a custom-built LIBS analyser to determine the capacity of the LIBS technology to detect the major elements present in the coals that are likely to have an impact on slagging. An inventory was assembled and tested for coals used at utility boilers with a range of slagging propensities. Artificial neural networks were created to correlate the LIBS spectral signals to ash fusion temperature. In 2007, parametric tests were planned to be carried out at a utility boiler to create a database to be used by an advisory expert system. Finally, an online advisory expert software would be deployed at the utility plant to work along with signals from the LIBS system and plant DCS, to recommend action for mitigating slagging (Romero and others, 2007).

The LIBS system was then installed at the Brayton Point 650 MW coal-fired plant to collect coal samples which were then analysed. Three coals with distinct slagging/fouling characteristics were processed through the LIBS system and indices determined from the elemental concentration analysis were calculated. Parametric tests, coupled to the measurements made, were then performed. Field tests at the plant investigated the impact of the selected coals on boiler operation and emissions, in relation to the differences in coal quality. The acquired data were analysed in terms of filtering data, determining trends and preparing the said data for artificial intelligence (AI) modelling and development. The demonstration results of the project were reported by Romero and others (2008). The results demonstrated that LIBS coal analysis performed on an hourly basis would be capable of providing feedback on ash deformation temperatures with sufficient resolution to alert the station personnel to changes in as-fired coal quality. According to Romero and others (2008), by having a timely warning that the slagging potential of the coal ash has changed, the boiler operators would be in a position to take action to adjust the furnace exit gas temperature or initiate a more aggressive water-wall or leading edge superheating soot blowing. These adjustments might involve parameters such as fuel air ratio, burner tilt angle, air register setting and mill loading patterns, depending on the boiler. Work on LIBS in the project continues. The results of the project upon completion will be disseminated to other coal-fired power plants. Finally, a report detailing the project's procedures, results and recommendations will be published (STACenergy, 2009).

5.4 Combustion optimisation systems

A key contributor to an overall expert system includes the methods used to optimise the coal combustion in the boiler. This will be affected by coal quality, boiler cleanliness and equipment deterioration as well as by the even distribution of the pulverised fuel to the burners. In addition, the air supply to low NOx burners and to overfire air ports needs control.

Many of the variables, including fans, dampers, pumps and valves which control flows, can be operated by the plant's control system. Some methods model the furnace and make changes over time while others take measurements which can be used to change the operating conditions in real time. Either can be incorporated into an overall expert system.

Computational fluid dynamic (CFD) simulations can be used to improve the performance of systems throughout a power plant including combustion optimisation and thus improvements in efficiencies and reduction in emissions. There are numerous publications on the topic of CFD modelling in coal-fired plant including Moreea-Taha (2000), Stopford (2002), Schweitzer and others (2006) and Laborelec (2011).

There are a number of different systems (Spring, 2009b), including:

- Zolo Technologies method for optimising combustion chamber conditions using turnable diode laser absorption spectroscopy (TDLAS). This maps multiple paths across the fireball and can thus identify which burner may need tuning (Zolo Technologies, 2009).
- NeuCo's CombustionOpt which combines neural network and model predictive control technologies to provide closed-loop optimisation of fuel and air mixing. It adjusts the control settings to position dampers, burner tilts, overfire air and other parameters (NeuCo, 2009). It has helped more than 200 generating units to achieve reduced NOx emissions.
- the Babcock and Wilcox Flame Doctor which utilises signals from existing optical flame scanners to diagnose poor operation in individual burners (Babcock, 2009). By continuously

monitoring the status of all the burners, Flame Doctor makes it possible to optimise overall furnace performance in spite of load changes, fuel quality variations and equipment deterioration. The current version is suitable for wall-fired and cyclone-fired units.
- ABB's Predict&Control system which is based on combustion optimisation using advanced model predictive multi-variable controls. This has been applied at the Colstrip plant in Montana, USA where there are four units with a total capacity of 2094 MWe (2 x 307 MWe and 2 x 740 MWe) using PRB subbituminous coal (Immonen and others, 2007). The background to these developments is explained by Bonavita and others (2003).
- The Greenbank Group Advanced Instrumentation and Measurement (GAIM) StackMaster, which is a real-time particle size analyser, and the PfMaster Coal Flow Monitoring System. The systems are used for boiler optimisation. The GAIM StackMaster carries out an online, non-intrusive measurement of particulates in stack flue gas using laser technology. The PfMaster Coal Flow Monitoring System is designed for use on pulverised-coal feed into the boiler using sensors to measure the coal distribution and velocity during the feed. The system enables continuous online measurement, balancing and monitoring of the coal flow (The Greenbank Group UK, 2010).

The GE Energy Zonal™ combustion system measures local flue gas excess oxygen (O_2) and combustible gases, primarily carbon monoxide (CO), using a multi-point spatially distributed monitoring grid placed in the upper back-pass region of a boiler. The System includes an array of zonal combustion analysers in communication with the Zonal™ system interface providing system level monitoring and control. The analysers comprise a sensor unit connected to a local controller via a special cable. The analysers are located immediately outside the boiler and house an O_2 sensor and a thermistor combustibles sensor. The analysers draw exhaust gas flow through a particulate filter and probe, across the sensors and return the gas to the boiler without the need for sample gas pumps and sample gas conditioning systems. The analysers are placed high in the boiler back pass where air in-leakage is minimal providing a more accurate measure of actual furnace excess air conditions. Also in this region the burner flow paths are highly stratified. This stratification along with the predominant boiler flow structure allows tracing of burners and overfire air to specific combustion sensors. The signals from the analysers are sent to the Zonal™ system interface computer for real-time combustion profile topography mapping, data reduction, averaging and trending. The system allows operators to respond to poor combustion conditions rapidly, by adjusting boiler-operating conditions or redistributing air flows to select burners and overfire air injectors. Improving local combustion conditions allows the boiler to operate at reduced excess O_2, reduced mean furnace exit gas temperatures, and lower carbon in ash levels (GE Energy, 2010; Widmer, 2011).

The Zonal™ System was recently installed on Lakeland Electric McIntosh Unit 3 (360 MW), opposed wall fired boiler equipped with overfire air. A series of baseline boiler tests were conducted to determine how changes in overall excess O_2, overfire air level, and local burner conditions affect zonal combustion measurements. The trends in these measurements are used to illustrate how operators can utilise the system to monitor and improve local burner combustion conditions and overall boiler performance (Nareddy and others, 2011). In June 2011, GE Energy started another Zonal system at Louisville Gas & Electric Mill Creek Unit 3. There are plans for further Zonal systems to be installed in the near future (Booth, 2011).

Boiler OP™ is an intelligent combustion optimisation software developed by the Energy Research Centre (USA) and the Potomac Electric Power Company (USA) (Sarunac and others, 2001). It utilises an optimisation procedure that consists of the following three steps:
- conduct parametric tests and build a database which relates the effect of boiler operating parameters on emissions and performance-related parameters such as loss-on-ignition, steam temperatures and heat rate;
- correlate the test data by riding spurious/errant points or outliners; develop a network model and verify it for accuracy and trending;
- employ an optimisation algorithm to determine optimal solutions based on optimisation objectives and imposed constraints.

The software combines an expert system, neural networks and an optimisation algorithm into a single program. Boiler OP™ has been applied successfully to over 20 utility boilers, ranging in size from 80 to 750 MWe. The NOx reductions achieved are between 15% and 35% (Wu, 2002).

Payson and others (2001) presented QuickStudy, an adaptive, model-predictive controller, developed by ESA/Environmental Solutions (USA). A dynamic model is built online during normal plant operations or from historical data. The model is then used to predict future system trends so that appropriate actions can be taken to optimise the process. The QuickStudy system contains up to 16 predictive controller set-up (PCS) blocks. Each PCS consists of two closely-coupled subsystems: an adaptive signal processing element (ASPE) and a quadratic optimal controller (QOC). The ASPE creates the process model in real time by minimising the difference between the predicted and actual process behaviour. Using the model prediction, the QOC then generates a control action that minimises the projected future difference between the set point and the actual operating data. A PCS can accept up to 16 inputs including the output of another PCS. This allows construction of de-couplers and general multiple input multiple output (MIMO) controllers. The adaptive process controller has several advantages including (Payson and others, 2001):
- the models can be built from online or offline data;
- the elimination of the need for plant tests;
- the ability to control while learning;
- capabilities for model management;
- all parameters are visible to the user.

QuickStudy was installed on a 80 MWe single reheat drum-type boiler at Allegheny Energy Supply Albright Station (USA). The main objective was to reduce NOx emissions subject to all stack emission constraints, while maintaining optimum heat rate. The system reduced NOx emissions by an average of 15%. CO emissions were controlled below 250 ppm, and average opacity levels were improved slightly. In addition, there were no changes in furnace slagging conditions. The system also resulted in a minimum of 2% increase in the heat rate. The increase was considered to be due to lower stack O_2 levels, lower stack gas volumetric flow rates, and lower stack gas exit temperatures (Payson and others, 2001).

Maxson (2005) presents Knowledge^{3}™ (Kn^{1,} Kn^{2}, Kn^{3}) a platform for process modelling, optimisation and control, respectively. Rules written on the Knowledge^{3}™ platform include mathematical and logical operations, allowing the user to combine data for better and more detailed results. The rules can also be used to visually alert users that an improper operating condition has occurred, or is developing, allowing proactive intervention. The platform also allows the development of predictive models, using neural networks, for key outcomes resulting from a process. Knowledge^{3}™ is designed to automatically retrain neural networks based on data acquired online, when their predictive performance has become inaccurate. In this way, the models are not static and accuracy is maintained when conditions change. The optimisation tool uses the modelling described above to provide predicted results for a specified set of inputs. Control is achieved when coupling Knowledge^{3}™ with a dedicated control system to close the loop with the already determined optimised set points. Knowledge^{3}™ comes with a graphical user interface that allows the product to be used offline or online, thus permitting users to test and validate results, build models and perform diagnostics in both real time and archived environments. The interface is also configurable, allowing user to customise the look and feel of individual screen s according to their needs (Maxson, 2005).

Voss and others (2009) discussed making the most of available assets (for example, existing coal-fired fleet) by using intelligent combustion optimisation software to upgrade boiler performance. The authors consider that in many cases software-based optimisation is the method of choice for upgrading existing boilers as it offers the best achievable results cost-effectively or at cost-value ratio. Voss and others (2009) declare that financial benefits are accomplished via numerous controllable-loss management strategies, including excess O_2 control, optimised air/fuel mixing, balancing of temperature as well as reducing superheater and reheater spray flows, controlling emissions (NOx, CO) and LOI (loss on ignition). Furthermore, the authors consider that in view of climate change, the reduction of greenhouse gas emissions, such as CO_2, may offer further opportunities, that is by marketing certified emission reductions. Typically, the payback of applying combustion optimisation is achieved within a year of utilisation. Thus the benefits of utilising such systems continue to accrue by providing ongoing annual savings that grow as the cost of fuel and environmental compliance increases.

In 2002, the US DOE launched a Clean Coal Power Initiative (CCPI) to address 21st century energy issues through multiple solicitations. The CCPI-1 project established the application of advanced optimisation software at Dynegy's three-unit, 1768 MW Baldwin Energy complex located in Baldwin, Illinois (USA). NeuCo Inc, the project's participant and technology provider, demonstrated five optimisation products that were integrated through NeuCo's ProcessLink® technology, *see* Figure 11. ProcessLink uses neural networks, expert systems, and fuzzy logic to link individual optimisation modules to maximise specified performance objectives and operator priorities. These software products were developed to optimise the combustion and soot blowing processes, reduce the ammonia consumed by SCR systems, and improve unit thermal performance and plant-wide availability. The software installation was completed at the end of 2006 and was followed by a one-year evaluation and documentation period. Quantitative project benefits included: reduced NOx emissions by 12–14%; improved average heat rate (fuel efficiency) by 0.7%; increased available MWh by an estimated 1.5%; reduced ammonia consumption by 15–20%; and commensurate reductions in greenhouse gas, mercury, and particulates. These benefits translated to lower costs, improved reliability, and greater commercial availability with significantly reduced environmental impacts. The optimisers, commercialised as part of this project, are expected to pay for themselves in well under one year when deployed on typical plant types and fuel categories that comprise the US fossil power industry. This represents a highly cost-effective way of addressing some of the industry's most pressing challenges and leverages the benefits of investments in SCR equipment, low NOx systems, and modern control and instrumentation systems (US DOE, 2009).

Many modern plants incorporate a continuous emissions monitoring system (CEMS) which may be able to contribute useful data relevant to boiler optimisation. This could be incorporated within an overall expert system for a particular plant.

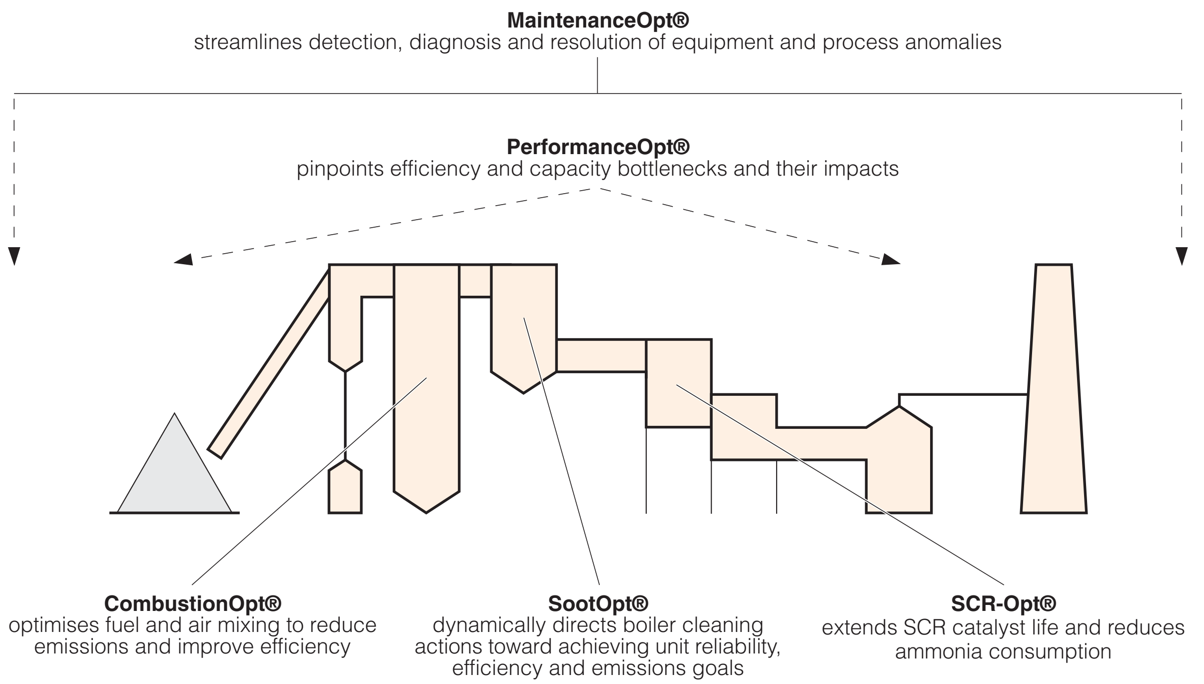

Figure 11 ProcessLink® software flow diagram (US DOE, 2009)

In general, the overall expert system for controlling plant operations has to incorporate a number of individual contributions effectively involving control circuits covering parts of the plant.

These comprise principally:
- the quantity and quality of the coal being fed to the pulverisers and hence to the burners;
- the quantity and distribution of the air supplied to the burners and elsewhere;
- the temperature and quantity of water supplied to the boiler walls;
- the procedures for boiler and heat exchanger cleaning using soot blowers;
- flue gas cleaning stages, including:
  - SCR for NOx reduction and removal;
  - an ESP or baghouse filter for particulate removal;
  - FGD for SO_2 removal; and, in the future;
  - carbon capture units to absorb most of the CO_2 present.

In many places, the plant will also have to fit into the supply pattern from a number of different generators supporting a market-led pricing structure. This means that the price paid for the power generated varies and it will almost certainly be most valuable at times of peak demand. Unplanned unit shut-downs can be particularly costly if alternative power sources have to be used to meet demand.

Makansi (2005) discusses unifying process control and optimisation to achieve a sustained performance advantage in the market. He considers that integrating the many advanced applications, sensors and online analysers for control, automation and optimisation into a system can reflect process and financial objectives. One such technology is the PASS Monitoring, Energy and Asset Management system which utilises one platform where data from online analysers and sensors are used for real-time decision making. For example, by interpreting real-time performance data, the system would provide information on how much ammonia the SCR system should be using at a given time and the cost-benefit offset of that usage. It may also be used to advise on the best blend of coal to fire to minimise reagent use and maximise profit. The decisions are made based on the combined net effect of real-time operational variables, performance and phenomena such as tube deterioration, deferred maintenance decisions, the coal heat content and ash characteristics and slagging. For world suppliers of automation systems for coal and other industries *see* Kirrmann (2010).

Hill (2009) presented his findings on application of data-driven combustion optimisation solutions to case studies in two coal-fired units totalling 740 MW. Unit 1: 400 MW, wall-fired, load-following unit with low NOx burners and overfire air (OFA) ports. The goal in this case study was optimisation for low NOx emissions under low-load operation. Unit 2: 340 MW cyclone-fired, load-following unit also with OFA ports. The goal in the second case study was optimisation for stable cyclone flame temperature. Both units fire PRB subbituminous coal. According to Hill (2009) StatSoft Power Solutions have developed a data-driven technology that:
- uses all historical data routinely collected;
- identifies in the data specific operational parameters that are critical for optimal boiler performance;
- builds data mining models, describing how exactly the important parameters affect the performance of a furnace;
- uses those models for combustion optimisation for robust, low-variability operations/ performance;
- identifies optimised parameter ranges and relationships for critical operational parameters that can be implemented into the existing control system.

Typical results for low NOx operations in Unit 1 showed lower NOx during testing and more robust performance (that is, lower variability in NOx measurements with fewer or no spikes). Continued improvements were noted after formal validation testing ended. In Unit 2, the optimisation process results showed higher flame temperatures and less variability in flame temperatures. Hill (2009)

concluded that:
- the methods used in the case studies are applicable to any type of coal-fired furnace;
- the only requirement is a process historian (that is a database that collected and stores operational parameter data);
- the techniques can be used to optimise boiler performance using the existing control systems and methods;
- the key for improved performance of any complex system (such as furnaces, SCR and selective non-catalytic reduction (SNCR) processes) is optimisation in the presence of uncontrollable external factors (for example, fuel quality).

A substantial amount of software development was carried out during a unit optimisation project of the Hammond (USA) coal-fired facility. Turner and Mayes (2004, 2005) describe the development of an integrated approach to unit optimisation and the development of an overall 'unit optimiser' that is able to resolve conflicts between individual optimisers. A demonstration project of the integrated approach was conducted at Southern Company's (USA) plant Hammond. The unit optimiser was considered during the project together with the following individual optimisers:
- online thermal efficiency package;
- Generic NOx Optimisation Control Intelligent System (GNOCIS) boiler optimiser;
- GNOCIS steam side optimiser;
- ESP optimisation;
- Intelligent Soot-blowing System (ISBS).

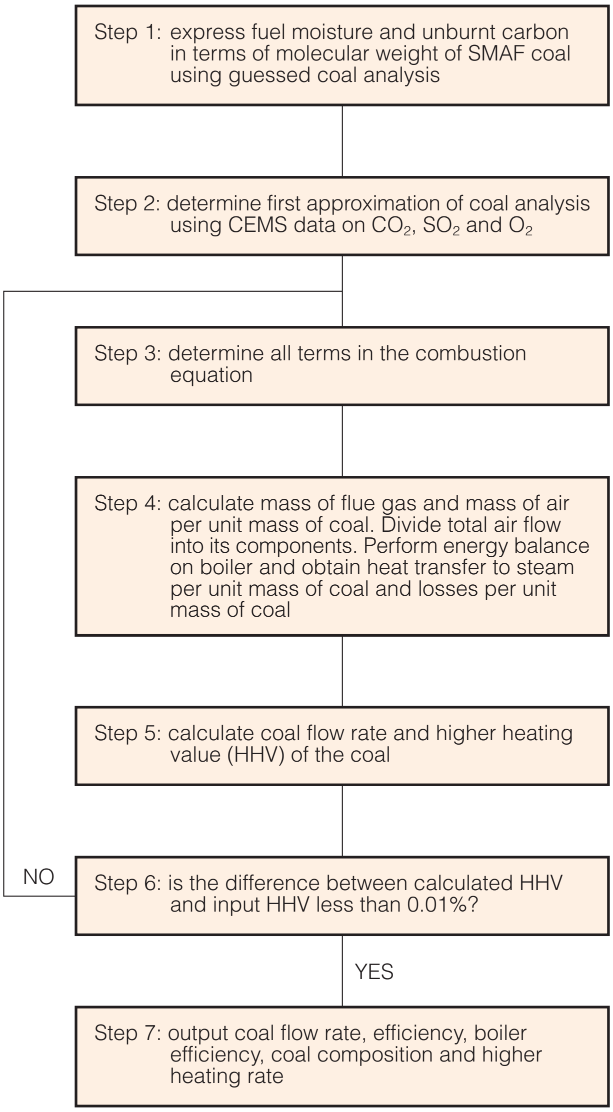

Figure 12 The procedure for the online heat rate calculation (Turner and Mayes, 2004)

The online thermal efficiency package is a detailed efficiency calculation for the power unit. The calculation procedure started with a detailed (ultimate) coal analysis that is generally not available in real time. However, more recent developments in heat rate calculation shows that coal composition can be determined from online analysis of the flue gas composition. Figure 12 shows the procedure for the online heat rate calculation. Following testing of the package good agreement was noted between the results from online heat rate calculation and the ultimate analysis methodology. However, a comparison of a daily calculated online heat rate to an accurate assessment showed that the online calculation did not exhibit the same variability as is expected for plant operation during that day. Turner and Mayes (2004) considered that development of an online heat rate calculation was an ambitious target and that the model predictions were not yet satisfactory.

GNOCIS, developed collaboratively by UK's PowerGen and USA's Southern Company and URS, is an online enhancement to DCS which aims mainly to reduce NOx emissions and improve boiler performance. It was one of the first closed loop optimisation systems installed on coal-fired boilers in the USA. As of

December 2001, GNOCIS has been installed on units representing more than 10,000 MWe of generation capacity in both the USA and Europe. The system has achieved NOx reductions of more than 10% and efficiency improvements of more than 0.5% (US DOE, 2001).

The new generation GNOCIS optimisation system, incorporates closed loop implementation, advanced neural network, and online learning techniques. It can accept information from several sources including process, emissions and plant-wide cost data. The technology uses an integrated neural network based control system model of the combustion characteristics of the boiler that reflect both short-term and long-term trends in boiler performance. It includes a radial basis function neural network engine and other proprietary code that interfaces with the control system and allows for continuous smooth optimisation. A constrained non-linear optimisation procedure is applied to identify the best set-points for the boiler. The recommended set-points may be implemented automatically without operator intervention (closed loop) or, at the operator's discretion, displayed for manual implementation (open loop). The proprietary software ensures a smooth transfer of control biases into the DCS (Wu, 2002).

Turner and Mayes (2005) considered that the results of the project show the level of detail and complexity of optimiser modelling. The project also focused thinking on the actual application of multiple optimisers on a single unit. The authors recommended demonstration of the operation of the unit optimiser on a UK coal-fired power plant. A typical demonstration would include three separate optimisers, namely:

- emissions minimisation: GNOCIS to reduce NOx emissions and carbon in ash (CIA);
- boiler optimisation: using online thermal efficiency modelling;
- ESP optimisation: to optimise SO_3 injection rate.

Turner and Mayes (2005) concluded that if several optimisers are installed on a unit then there should be an audit of the variables controlled by each individual optimiser. The remote location of individual models/optimisers from a power plant distributed/digital control system (DCS) results in making closed loop installation difficult. Potential conflict between optimisers can be reduced by either prioritising the objectives of different optimisers (for example, environmental objectives achieved ahead of efficiency objectives) or adding rules to optimisers (for example, including a steam temperature model within the boiler optimiser, GNOCIS).

Dynamic NOx and heat rate optimisation at the Entergy White Bluff, Units 1 & 2, 800 MW coal-fired plant (USA) was discussed by Labbe and others (2006) and Coker and others (2006). The plant was retrofitted with a modern DCS for the boiler and auxiliary controls in early 2000, which achieved significant control and ramp rate improvement. The modifications enhanced unit reliability, improved thermal performance and provided continuous dispatch capability. However, in order to further improve unit heat rate and reduce NOx emissions, while enhancing ramp rate capability, required a dynamic optimisation approach that addressed unit limitations such as O_2 and steam temperature control during unit ramping, coal mill changes and soot blowing. The optimisation process applied a combination of neural nets and model predictive control. The system achieved steam temperature and O_2 control along with air damper optimisation resulting in NOx reduction of more than 15% and heat rate performance improvement approaching 1% with an estimated annual value of US$1 million (Labbe and others, 2006).

Coker and others (2006) also discussed the use of the model data and expert system for effective soot blowing at White Bluff which is equipped with a large number of soot blowers. Soot blowing served several purposes including maintaining sufficient gas path openings to meet the air requirements for full load, the prevention of large accumulation of slag that could have deleterious effects during slag falls and the favourable distribution of energy for highest cycle efficiency. To achieve this the expert system, based on the model data, selects the most effective soot blower to meet the existing soot blowing requirements. The soot blower activates following an evaluation of satisfactory permissive logic at the DCS level. The smart soot blowing automation system reduces the burden of soot blower monitoring on the operator, soot blower steam consumption and soot blower tube erosion while increasing boiler efficiency and superheat steam temperature, thus contributing to the plant heat rate improvements (Coker and others, 2006).

5.5 The 'smart grid'

A new generation of software-based resources, technologies and devices are being introduced and deployed to build what is called the 'smart grid' (Spring, 2009a; Charnah, 2009; Martini, 2009). This is a developing concept, but the ideas lying behind it are likely to become more widely deployed. According to ABB, a smart grid is a self-monitoring system, crossing international borders and participating in wholesale energy trading while providing a stable, secure, efficient and environmentally-sustainable network. The use of the smart grid would emphasise and integrate renewable generation, distributed generation and storage options, and include dispersed energy storage in electric vehicles. When established, the lines between generation, transmission, distribution and the consumer may become more blurred than they now are. For power generators, the smart grid means managing resources, integrating distributed generation and storage opportunities and getting ready for the growth in the use of plug-in electric vehicles.

In order to achieve the objectives of the smart grid, major developments are required:
- in energy storage technologies. This presents major challenges, but work is ongoing, particularly with the use of flywheels which can react in a matter of seconds to the system operators signal;
- in the levels of grid monitoring and automation, particularly of the low voltage distribution systems which are currently not well understood, and where there is limited information about the condition and efficiency of the lines as well as about the amount of electricity being used;
- to provide more flexible conditions and meters which will allow for bi-directional flows of power both from and into the grid, so that small generators can supply the electricity they produce without affecting the stability of the system;
- with the increased use of high voltage direct current transmission lines to transfer electricity over long distances with minimal power losses (a concept which is commonly described as a super grid);
- the cost structures used should encourage power usages including the charging of electric vehicles, in off-peak periods.

Mohseni (2010) discussed the passage of the American Recovery and Reinvestment Act of 2009, with US$3.4 billion allocated to the development of a smart grid technologies. The Act is helping to drive new utility sector investment in the USA. The technologies used to control power distribution grids are likely to become ever more sophisticated, and the expert systems used to optimise the performance of coal-fired generation units will need to fit into this new context.

According to Gruia (2011), a smart grid will enable utilities to:
- increase power availability;
- improve energy efficiency;
- accommodate renewable power;
- prepare for growing power load.

Gruia (2011) considers that a smart gird is increasingly being regarded as a way to drive the aim for increasing efficiency in power generation. It is made up of three basic components: intelligent devices, two-way communications and information management. A smart grid overlays the electricity generation, transmission and distribution grid infrastructure with communication and information infrastructure to empower data collection and device control for energy management, efficiency and cost control. Gruia (2011) discusses helping utilities bridge the gap to smart grid, an emerging form of telecommunication in the power industry.

6 Conclusions

Coal quality, that is the properties of coal, affects many parts of a power plant including the coal handling facilities, pulverising mills, boiler, air heater, ESP, ash disposal as well as stack emissions. Coals have different characteristics, and can have a heat content ranging widely, from 5 to 30 MJ/kg. The behaviour of a coal in a boiler is strongly influenced by the mineral matter and other impurities associated with it. In particular, the mineral matter can form slagging and fouling deposits in the boiler. Coal properties can affect the efficient and consistent operation of both the boiler and the emissions control units. They therefore affect both the economics and short- and long-term operation of the plant. The major contributor to differences in coal properties is not only the mineral matter and other impurities but also the reactivity of the coal which is broadly associated with its rank.

The operation of coal-fired power plants involves multiple variables which have different levels of importance. Computer software in the form of neural networks and expert systems have been, and continue to be, developed to monitor, address and control, online, the many aspects of operation in a coal-fired power plant. These different expert systems need continuous development and validation in different locations, taking into account the many possible variations in plant design.

Typical application of real-time, online analysis in coal-based power generation include feed forward and feed back control at mines, beneficiation plants and power plants. These systems can also provide quality and control checks on shipments of coal and stockpiles (in the mine and/or power plant). A number of quality parameters and process variables can be measured and calculated with dedicated online analysers including moisture content, elemental content as well as sulphur, ash and the energy content in the coal.

Real-time information allows mine/plant personnel or expert systems to make immediate decisions and take necessary action to achieve best results. For example, real-time analysis which takes place on a conveyor belt gives a more representative result on immediate coal quality being fed into a furnace compared to actual sampling and interference with the flow of the coal on the belt and the time lapse between the sampling and getting the laboratory results. Similarly, online monitoring and analysis on a boiler duct to measure carbon-in-ash can be used to improve boiler operation and thus result in a financial benefit.

Coal analysis, laboratory and/or online, can determine which parts of a coal seam are extracted. It provides vital data relating to the design and operation of a coal preparation plant, and the information establishes the value of the coal product, and thus, broadly, the price at which it may be marketed and the use to which it is put. For the power plant operator the analysis provides important information which will affect the design, operation and economics of running the plant. This is because the quality of the coal being used affects its heating value, the amount of ash deposition and corrosion in the boiler, and the costs associated with flue gas cleaning. However, laboratory and online methods of analysis have limitations, and for commercial users of coal it is important to understand what these are in order to make the best use of the information provided. This includes the data which are available to be fed into the plant expert systems. The analysis is limited by the methodologies used which are necessary to achieve reproducibility and consistency in the results obtained. These however, do not necessarily represent or reproduce the conditions found during handling or inside the boiler and therefore the behaviour of various impurities present.

Expert systems are software that behaves in much the same way as a human expert would in a certain field of knowledge. An expert system is a class of computer programs developed by researchers in artificial intelligence during the 1970s and appeared commercially in the early 1980s. The programs are a set of rules that analyse information, usually supplied by the user of the system, about a specific class of problems, as well as provide analysis of the problem and recommend a course of action for correction. Every expert system consists of two principal parts: the knowledge base and the inference engine. The knowledge base contains both factual and heuristic knowledge. Factual knowledge consists of all information available to plant operators and included in the plant digital/distributed control system (DCS). Heuristic knowledge is the less rigorous, more experiential and more judgmental knowledge of performance. The knowledge base is used with either 'if/then' statements (condition and action). In an 'if/then' program, the 'if part' lists a set of conditions in some logical combination. Once the 'if part' of the rule is satisfied, the 'then part' can be carried out/concluded and the appropriate action taken. Expert systems where knowledge is represented in rule form are called rule-based systems. The inference engine makes inferences by determining which rules are satisfied by facts, ordering the satisfied rules, and executing the rule with the highest priority.

Expert systems can be used to assess coal quality and to understand and manage the effects of its variations. These include computer programs which can be used to assess the practical impacts of changes in coal composition. The input to these programs can be based on empirical results and/or on modelling various aspects of the process. The challenge is always to validate the outcomes. A number of expert systems are available today for use in the coal-fired power generation field including at the mine, in coal blending and the boiler feed system. Expert systems are used to assess the impacts of coal quality in the coal-fired power plant while other software aim to optimise the coal combustion process.

A new generation of software-based resources, technologies and devices are being introduced and deployed to build a developing concept called the 'smart grid'. A smart grid is a self-monitoring system, crossing international borders and participating in wholesale energy trading while providing a stable, secure, efficient and environmentally sustainable network. The use of the smart grid would emphasise and integrate renewable generation, distributed generation and storage options.

A sustained performance advantage can be achieved by unifying process control and optimisation. Integrating the many advanced applications, sensors and online analysers for control, automation and optimisation in a modern power plant into a unified system can reflect not only process performance but also financial objectives. There are currently technologies in the market that utilise 'one platform' where data from online analysers and sensors are used for real-time decision making. The decisions are made based on the combined net effect of real-time operational variables, performance and phenomena such as tube deterioration, deferred maintenance decisions, coal heat content and ash characteristics and slagging.

Finally, and as stated above, expert systems are a recently-developed class of computer program that have been in commercial use only since the beginning of 1980s. With the introduction of increasingly more powerful and complex hardware and software, these systems will continue to develop and affect not only coal-fired power generation but all aspects of energy production.

7 References

Anderson A (2002) After the storm: the new bituminous coal landscape. *Paper presented at the electric power 2002 conference*, St Louis, Missouri, USA, 19-21 Mar 2002, 10 pp (Mar 2002) http://www.myvistasource.com/

Anderson A (2011) Black & Veatch (B&V), Overland Park, KS, USA. *Personal communication;* (7 Apr 2011)

Anderson A, Deschaine R, Stallard S, Woodward R, Smolenack A (2007) *1+1=3: more from your online coal analyzer*. Black &Veatch/ThermoFisher Scientific, 12 pp, May 2007 http://www.thermo.com/eThermo/CMA/PDFs/Product/productPDF_1663.pdf

Arnold B J, Klima M S, Bethell P J (2007) *Designing the coal preparation plant of the future*. Englewood, CO, USA, Society for Mining, Metallurgy and Exploration, 200 pp (2007)

ASTM (2008) *ASTM D7430-11 Standard Practice for Mechanical Sampling of Coal*. vp http://www.astm.org/Standards/D7430.htm (2008)

ASTM (2009a) *ASTM D5142-09 – Standard Test Methods for Proximate Analysis of the Analysis Sample of Coal and Coke by Instrumental Procedures*. 5 pp, http://www.astm.org/Standards/D5142.htm (2009)

ASTM (2009b) *ASTM D3176 – 09 Standard Practice for Ultimate Analysis of Coal and Coke*. 3 pp, http://www.astm.org/Standards/D3176.htm, (2009)

Aykul H, Yalçin E (2004) Improvement of coal quality fed to power plant by using selective excavation method at Seyitömer coal mines. In: *Proccedings of the thirteenth international symposium on mine planning and equipment selection 2004*, Wroclaw, Poland 1-3 Sep 2004. Hardygóra M, Paszakowska G and Sikora M (eds.), London, UK, Taylor and Francis Group, pp 171-179 (2004)

Babcock (2009) Field Engineering Services: Flame Doctor™. 3 pp http://www.babcock.com/services/field_engineering_services/flame_doctor.html (2009)

Barnes I (2009) *Slagging and fouling in coal-fired boilers*. CCC/147. London, UK, IEA Clean Coal Centre, 43 pp (Apr, 2009)

Bartos F J (2005) *Artificial intelligence: smart thinking for complex control*. Milford, NH, USA, R. Morley Incorporated, 4 pp www.barn.org/pr01.htm (Nov, 2005)

Belbot M, Vourvopoulos G, Paschal J (2001) A commercial on-line coal analyser using pulsed neutrons. *Paper presented at the sixteenth international conference on applications of accelerators in research and industry*, Denton, TX, USA, 1-5 Nov 2000, 4 pp (2001)

Bennett P, Conroy A (1997) *Project C3091: Australian coal quality impact model*. Brisbane, Qld, Australia, Australian Coal Research Ltd, 3 pp (Aug 1997)

Bethell P J (2007) Today's coal preparation plant: a global perspective. *Designing the coal preparation plant of the future*. B J Arnold, M S Klima, P J Bethell (eds.), Englewood, CO, USA, Society for Mining, Metallurgy and Exploration (SME), pp 9-19 (2007)

B&V (2011) Introducing Vista™. Black & Veatch (B&V), Overland Park, KS, USA, 3 pp, http://myvistasource.com/files/vista/vistamain.htm (2011)

Blenkinsop M (2003) Analysis advances. *World Coal*; 4 pp, www.worldcoal.com (2003)

Bonavita N, Martini R, Matsko T (2003) Improvement in the performance of online control applications via enhanced modeling techniques. *ERTC Computing*, 27 pp, http://www05.abb.com/global/scot/scot267.nsf/veritydisplay/d4d83bd40816781c85256f9b005a4e4f/$File/Improvement%20in%20the%20Performance%20of%20Online%20Control%20Applications.pdf (2003)

Booth M (2011) Irvine, CA, USA, General Electric Company, GE Energy, Power Services, Boiler Optimisation Services. *Personal communication*, vp (11 Jul 2011)

Brummel H-G (2006) *On-line monitoring of power plants*. Berlin, Germany, Siemens Power Generation, 13 pp (2006)

Bulsari A, Wemberg A, Anttila A, Multas A (2009) Combustion efficiency. *World Coal*. **18**, (6); 35-40, www.worldcoal.com (Jun 2009)

Carpenter A M (1999) *Management of coal stockpiles*. CCC/23. London, UK, IEA Clean Coal

Centre, 65 pp (Oct 1999)
Carpenter A M (2002) *Coal quality assessment – the validity of empirical tests*. CCC/63. London, UK, IEA Clean Coal Centre, 100 pp (Sep 2002)
Cichoń T (2004) Planning mines by digital methods. In: *Proccedings of the thirteenth international symposium on mine planning and equipment selection 2004*, Wroclaw, Poland 1-3 Sep 2004. Hardygóra M, Paszakowska G and Sikora M (eds.), London, UK, Taylor and Francis Group, pp 7-12 (2004)
Cierpisz S (2001) Application of computer-based monitoring and control systems in coal preparation plants. In: *Proceedings of the international conference on challenges in coal and mineral beneficiation*, Dhanbad, India, 7-8 Dec 2001. New Delhi, India Tata McGraw-Hill Publishing Company Limited, pp 3-13 (Dec 2001)
Charnah R (2009) Smart grids – how do we get there? *Energy World;* **376**; 2 (Nov 2009)
Clark D Harrison C D, Kehoe D B, O'Connor D C, Stallard G S (1997) *Recent Experience with the CQE™,* 16 pp, http://www.netl.doe.gov/publications/proceedings/97/97cct/cct_pdf/97CCT1_1.PDF (1997)
CoalTrans International (1997) Coal sampling and analysis: redefining the definitions. *CoalTrans International*; **12** (1); 30-36 (Feb 1997)
CoalTrans International (1998) Sampling and inspection: seeing to be coping with quality. *CoalTrans International*. **13** (1); 34-41 (Feb 1998)
Coker S, Labbe D, Speziale A (2006) Netting a model predictive combo. *InTech*, 4 pp (Jul 2006)
Cole R, Frank R (2004) Coal quality impacts on power generation. *CPSA Journal*; 3 (2); 10-15 (Summer 2004)
Connor S (2009) Alternative contract models increase the options for power generators. *PEi, Power Engineering International*; **17** (5); 26-29, www.peimagazine.com (May 2009)
Conroy A, Bennett P (1996) *Australian coal quality impact model*. Mulgrave, Victoria, Australia, Australian Coal Industries Research Laboratories Ltd (ACIRL), 2 pp, www.acarp.com.au (Oct 1996)
Couch G R (1990) *Lignite upgrading*. IEACR/23. London, UK, IEA Coal Research, 72 pp (May 1990)
Couch G (1994) *Understanding slagging and fouling during pf combustion*. IEACR/72, London, UK, IEA Coal Research, 118 pp (Aug 1994)
Couch G R (1996) *Coal preparation – automation and control*. IEAPER/22. London, UK, IEA Coal Research, 61 pp (Feb 1996)
Couch G R (2004) *The potential for coal use in Pakistan*. CCC/83. London, UK, IEA Clean Coal Centre, 39 pp (Apr 2004)
Couch G R (2006) *Ash management in coal-fired plants*. CCC/118. London, UK, IEA Clean Coal Centre, 69 pp (Oct 2006)
Couch G R (2009) *Underground coal gasification*. CCC/151. London, UK, IEA Clean Coal Centre, 129 pp (Jul 2009)
Crocker G, Kovalchuk A (2008) *Prospects for coal and clean coal technologies in Russia*. CCC/138, London, UK, IEA Clean Coal Centre, 56 pp (Oct 2008)
Davis V L Jr (2007) Future challenges in coal preparation plant design and operation. *Designing the coal preparation plant of the future*. B J Arnold, M S Klima, P J Bethell (eds.), Englewood, CO, USA, Society for Mining, Metallurgy and Exploration (SME), pp 21-29 (2007)
DOE/NETL (2000) Development of a Coal Quality Expert™. A DOE assessment. http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=047EC7166EFF8F6465393E3C28314516?purl=/68100-pLgMXF/webviewable/, 19 pp (Nov 2000)
Dong N (2011) *Utilisation of low rank coals*. CCC/182, London, UK, IEA Clean Coal Centre, 92 pp (Apr 2011)
Drax Group plc (2009) *Annual report and accounts 2008.* Selby, North Yorkshire, UK, Drax Power plc, 4 pp, http://www.draxgroup.plc.uk (2009)
Drenckhahn W, Riedle K (2005) Customer benefit and power plant development. *VGB PowerTech*. **85**, (5); 77-83 (2005)
DTI (2001a) *Pulverised fuel (PF) flow measurement and control methods for utility boilers*. Technology status report 014; London, UK, Department of Trade and Industry (DTI); 14 pp (Jan 2001)

DTI (2001b) *Coal Preparation*. Technology status report 015; London, UK, Department of Trade and Industry (DTI); 14 pp (Jan 2001) http://www.berr.gov.uk/files/file19296.pdf
Edwards M (2004) Regarding quality . . . *World Coal*; **13** (12); 45-47, www.worldcoal.com (Dec 2004)
Edwards M, Harris A, Smith K (2005) Analysis matures. *World Coal*; **14** (12); 41-46, www.worldcoal.com (Dec 2005)
EIA (2009) Coal production 1949-2008. Energy Information Administration. Annual Energy Review 2008, http://www.eia.doe.gov/emeu/aer/pdf/pages/sec7_6.pdf, 1 pp (2009)
Engelmore R S, Feigenbaum E (1993) Expert systems and artificial intelligence, 5 pp, http://www.wtec.org/loyola/kb/c1_s1.htm (May 1993)
EPRI (1999) *On-line analysis of heating value*. TE-113817, Palo Alto, CA, USA, Electric Power Research Institute (EPRI), 84 pp (Nov 1999)
Eyre D (2011) Fuel Technology, E.ON New Build & Technology Limited, Technology Centre, Ratcliffe-on-Soar, Nottingham, UK. *Personal communication*, vp (30 Jun 2011)
France G (2005) Under control. *World Coal*; **14** (6); 19-21, www.worldcoal.com (Jun 2005)
Foster S (2004) Two case studies – use of across-the-belt analysers to meet train quality targets. *Paper presented at the international on-line coal analyser technical conference*, St. Louis, Missouri, USA, 8-10 Nov 2004, 17 pp (Nov 2004)
Foster S (2006) Using a nuclear elemental static sample analyzer to optimize the operation of a preparation plant. *Paper presented at the Coal Prep 2006, coal & aggregate processing exhibition and conference*, Lexington, KY, USA, 1-4 May 2006; 18 pp (2006)
Fuel Tech (2009) Technologies to enable clean efficient energy. www.ftek.com, vp (2009)
Gelbar D, Kunkel R C (2002) Optimizing boiler design for PRB coal. *Power*; **146** (6); 66-74 (Sep 2002)
GE Energy (2010) *Zonal* Combustion Tuning System: fact sheet*. Irvine, CA, USA, General Electric Company, 2 pp (May 2010)
Gruia R (2011) *Helping utilities bridge the gap to smart grid*. Mountain View, CA, USA, Frost & Sullivan, www.frost.com, 17 pp (2011)
Harrison C D, Kehoe D B, O'Connor D C, Stallard G S (1997) *Recent experience with the CQE™*. Pittsburgh, PA, USA, National Energy Technology Laboratory (NETL), 16 pp, http://www.netl.doe.gov/technologies/coalpower/cctc/resources/pdfsprog/cctcnf95/97CCT1_1.PDF (Nov 1997)
Hatt R (1998) *Coping with coal quality impacts on power plant operation and maintenance*. paper presented at the Eleventh Utility Coal Conference, St Louis, MO, USA, 23-25 Feb 1998, 3 pp, http://www.coalcombustion.com/PDF%20Files/Coping103.pdf (1998)
Hatt R (2007) Looking even closer. *World Coal*; **16** (12); 39-42, www.worldcoal.com (Dec 2007)
Hedvall C, McKenzie F (2007) First response. *World Coal*; **16** (12); 37-38, www.worldcoal.com (Dec 2007)
Hennessy M J, Pain A, Edwards M (2007) Looking online. *World Coal*; **16** (5); 47-48, www.worldcoal.com (May 2007)
Hill T (2009) Optimization strategies based on historical data for existing coal burning furnace technologies. *Paper presented at the 2009 energy and environment conference*, Phoenix, AZ, USA, 1-4 Feb 2009. www.statsoftpower.com, Tulsa, OK, USA, StatSoft Power Solutions, 22 pp (2009)
Honaker R Q, Luttrell G H, Bethell P (2007) Status of current coal preparation research. *Designing the coal preparation plant of the future*. B J Arnold, M S Klima, P J Bethell (eds.), Englewood, CO, USA, Society for Mining, Metallurgy and Exploration (SME), pp 181-198 (2007)
IEA (2009) *Coal information 2009*. Paris, France, OECD/IEA, vp (2009)
Immonen P, Matsko T, Antoine M (2007) *Efficiency up, emissions down*. Wickliffe, OH, USA, ABB Utility Automation System, ABB Review 4; 53-57 (2007) http://www05.abb.com/global/scot/scot267.nsf/veritydisplay/a6a75a9549dd32ae85257404004c5041/$File/ABB_Review_07.pdf
Juniper L, Pohl J (1997) What price coal quality in electric power generation. *The Australian Coal Review*; 37-41 (July 1997)
Kavouridis K V, Pavloudakis F F (2007) Evaluation of an on-line analysis system for low-grade

and inhomogeneous Greek lignite. *Energy & Fuels*; **21** (4); 2204-2211 (7 Jun 2007)
Kawalec W (2004) Short-term scheduling and blending in a lignite open-pit mine with BWEs. In: *Proccedings of the thirteenth international symposium on mine planning and equipment selection 2004*, Wroclaw, Poland 1-3 Sep 2004. Hardygóra M, Paszakowska G and Sikora M (eds.), London, UK, Taylor and Francis Group, pp 53-59 (2004)
Kirrmann H (2010) *Automation overview*. Baden, Switzerland, ABB Research Centre, Ecole Polytechnique Fédérale de Lausanne, 17 pp (Jan 2010)
Laborelec (2011) *Computational fluid dynamics (CFD)*. www.laborelec.com, vp (2011)
Labbe D, Hocking B, Ray B, Anderson J, Klepper P (2006) Dynamic NOx/heat rate optimization. *Paper presented at the 16th annual joint POWID/EPRI control and instrumentation conference, 49th annual ISA POWID symposium*, San Jose, CA, USA, 4-9 Jun 2006, 11 pp (2006)
Laurila M J (1997) Standard sampling and analysis. *Coal Age*; **102** (11); 43-44 (Nov 1997)
Laurila M J, Corriveau M P (1995) *The sampling of coal. The practice of quality control in coal processing and utilization*. Chicago, IL, USA, Intertec Publishing, vp (1995)
LCN (2009) Coal shortages plague NTPC stations. *London commodity news*. London Commodity Brokers, 7 (21 Jul 2009)
Lenk U, Voigtländer P (2002) Power generation technologies in liberalised markets: potential and risks. *VGB PowerTech*: **82** (6); 32-38 (2002)
Lim C S, Abernethy D A (2004) On-line coal analysis using fast neutron-induced gamma-rays. *Paper accepted for publication in Applied Radiation & Isotopes as part of the conference proceedings of the 8th international conference on applications of nuclear technology,* Crete, Greece, Sep 2004, 13 pp (2004)
Lim C S, Abernethy D A (2005) On-line coal analysis using fast neutron-induced gamma-rays. *Applied Radiation and Isotopes*; 63; 697-704 (2005)
Liu D H F, Lipták B G (2003) Coal analyzers. In: *Instrument engineers handbook, fourth edition, volume one: process measurement and analysis*. Lipták B G (ed). Boca Raton, FL, USA, CRC Press. pp 1295-1298 (27 Jun 2003)
Ma Z, Iman F, Lu P, Sears R, Kong L, Rokanuzzama A S, McCollor D P, Benson S A (2007) A comprehensive slagging and fouling prediction tool for coal-fired boilers and its validation/application. *Fuel Processing Technology*; 88; 1035-1043 (2007)
Magni L, Paderno J, Pretolani F (2005) Kalman filter estimation of the coal flow in power plants. *Paper presented at the 44th IEEE conference on decision and control, and the European control conference*, Seville, Spain, 12-15 Dec 2005, MolB 18.2, pp 1270-1275 (2005)
Makansi J (2005) Unifying process control and optimization. *Power*; **149** (7); 56-63 www.powermag.platts.com (Sep 2005)
Makansi J (2001) Online coal analysis. *World Coal*; 10 **(12)**; 35-40, www.worldcoal.com (Dec 2001)
Martini F (2009) Switching on the vision – towards smart grids. *Energy World*; **376**; 14-17 (Nov 2009)
Mathew P J, Aylmer J A, Barker D, Dow J C, Phillips P L, Vogel M (1993) *Natural gamma ash gauges for coal stockpiles and wagons.* Report no. 1466, Project no. C146, CSIRO Division of Mineral & Process Engineering, Clayton, South VIC, Australia, vp (Jul 1993)
Maxson A (2005) Knowledge3™: a platform for process modelling, optimization, and control. *ORBIT*; **25** (3); 18-24, http://www.ge-mcs.com/download/bently-nevada-software/3q05_kn3.pdf (2005)
McCartney R H, Williams R L Jr. (2009) Fuel blending with PRB coal. *Power Engineering*; 113 **(3)**; 54-60 (Mar 2009)
McGinnis D G, Rader P C, Gansley R R, Wang W (2009) Cliffside 6 integrated emissions control system. *Power Engineering*; **113** (4); 38-47 (Apr 2009)
MCR (2011) *McCloskey Coal Report* (McCloskey Coal Information Services). Market round up: Asian and NW Europe steam coal markers. **252**; 1 (28 Jan 2011)
Mitas D, Stallard S, Anderson-Higgs A, O'Connor D (1991) Coal quality analysis linked to power plant control. *Power Engineering*; 29-32 (May 1991)
Mohseni M (2010) Smart grid: from concept through completion. *Solutions*; **31** (1); 6-7 (Summer 2010)

Moreea-Taha R (2000) *NOx modelling and prediction*. CCC/31, London, UK, IEA Clean Coal Centre, 49 pp (Apr 2000)
Nalbandian H (2004) *Air pollution control technologies and their interactions*. CCC/92, IEA Clean Coal Centre, London, UK, 75 pp (Nov 2004)
Nalbandian H (2005) *Online analysis and coal-fired power plants*. CCC/100, London, UK, IEA Clean Coal Centre, 66 pp (Sep 2005)
Nalbandian H (2009) *NOx control for coal-fired plant*. CCC/157, London, UK, IEA Clean Coal Centre, 51 pp (Oct 2009)
Nalbandian H (2010) *Propensity of coal to self-heat*. CCC/172, London, UK, IEA Clean Coal Centre, 47 pp (Oct 2010)
Nalbandian Soud (2000) *Developments in FGD*. CCC/29, IEA Clean Coal Centre, London, UK, 85 pp (Mar 2000)
Nareddy S, Swanson L, Widmer N C, Krajna A (2011) Zonal* Combustion Monitoring System at Lakeland Electric, McIntosh unit 3. *Paper presented at the EUEC 2011 14th annual conference*, Phoenix, AZ, USA, 31 Jan-2 Feb 2011, vp (2011)
NeuCo (2009) CombustionOpt®. http://www.neuco.net/solutions/combustionopt/default.cfm (2009)
Odgaard P F, Mataji B (2005) *Estimation of moisture content in coal in coal mills.* Aalborg, Denmark, Department of Control Engineering, Aalborg University, 6 pp (2005)
OECD (2003) Glossary of statistical terms. Expert system, http://stats.oecd.org/glossary/detail.asp?ID=3384 (Mar 2003)
Okamoto A (1998) Evaluation method for thermal coal quality (Japan) (III). *Coal and Safety;* **(12)**; 18-39 (Mar 1998)
Osborne D, Hall R (1997) Characterisation in production and transportation of thermal coal. *The Australian Coal Review*; 29-32 (Nov 1997)
Page D (1998) On-line coal quality monitoring. In: *Proceedings of the XIII international coal preparation congress*, Brisbane, Qld, Australia, 4-10 Oct 1998. Indooroopilly, Qld, Australia, Australian Coal Preparation Society, Volume 2, pp 439-449 (1998)
Payson E P, Burge R L, Kowalcheck J L, Schrecengost R A (2001) Adaptive process controller shaves NOx and cuts heat rate. *Power Engineering*; 105 **(9)**; 70-74 (Sep 2001)
Poncia G (2003) Chapter 7: multivariable power plant control. In: *Thermal power plant simulation and control*, D Flynn (ed.), Stevenage, Hertfordshire, UK, Institution of Engineering and Technology (IET), pp 179-202, www.knovel.com (2003)
Powitec (2011) *PiT Navigator for coal-fired steam generator*. Essen, Germany, Powitec Intelligent Technologies GmbH, vp, www.powitec.de (Apr 2011)
Quick W (2004) Requirements for coal characterisation: a power generator's view. *Presented at the Coal Research Forum (CRF) 4th annual meeting*, EDF Cottam Power Station, Cottam, UK, 19 May 2004, 16 pp (May 2004)
Rajoo P (2011) Johannesburg, South Africa, Eskom Technology Division, Research & Development Department, Fuels and Combustion Technologies. *Personal communication*, vp (27 June 2011)
Reagan P (1999) Sampling innovations. *World Coal*; **8** (4); 28-34, www.worldcoal.com (Apr 1999)
Reagan P, DeMatteo J (2007) Sampling considerations. *World Coal*; **16** (5); 41-45, www.worldcoal.com (May 2007)
Renner C (1999) Applying on-line analysis. *World Coal*; **8** (6); 55-60 (Jun 1999)
Richie M, Edwards M (2009) Natural gamma monitoring. *World Coal*; 18 **(9)**; 29-32; www.worldcoal.com (Sep 2009)
Roberts J (2009a) On-line system makes light of coal particle size analysis. *Modern Power Systems*; **29** (8); 33-35 (Aug 2009)
Roberts J (2009b) Measuring up. *World Coal*; **18** (8)**;** 34-38, www.worldcoal.com (Aug 2009)
Romero C E , Yao S, Moreno R X, Weisberg A, Craparo J, Mulligan L, De Saro R (2007) Using Laser-Induced Breakdown Spectroscopy (LIBS) measurements for coal qulaity monitoring and upgraded power plant control. In: *Proceedings of the 2007 conference on environmental monitoring, evaluation, and protection*, Albany, NY, USA, 15-16 Nov 2007. Bethlehem, PA, USA, Lehigh University, http://www4.lehigh.edu/default.aspx, vp (2007)
Romero C E , Yao S, Moreno R X, Harlow D G, Delph T, Ozturk M (2008) Laser measurement

of coal ash composition demonstrated at power plant. Lehigh Energy Update; 26 (2); 2 pp (Jul 2008) http://www4.lehigh.edu/default.aspx
Roumpos C, Akylas N, Terezopoulos N (2004) A decision making model for lignite deposits exploitability. In: *Proccedings of the thirteenth international symposium on mine planning and equipment selection 2004*, Wroclaw, Poland 1-3 Sep 2004. Hardygóra M, Paszakowska G and Sikora M (eds.), London, UK, Taylor and Francis Group, pp 721-726 (2004)
Rozendaal C M, Witkamp J G, Meijer R, Benneker R J M, Hoogendoorn A (1998) *Performance prediction in advanced coal fired boilers*. Contract no. JOF3-CT95-0005; project area 2-project 201; Laboratory and full scale blending studies. Arnhem, Netherlands, KEMA, 48 pp ftp://ftp.euro-cleancoal.net/pub/pdf/JOF3-CT95-0005-pdf-files/JOF3-CT95-0005-201-Rozendaal-KEMA.pdf (1998)
Sarunac N, Romero C E, Levy E K, Weston W C (2001) Anatomy of a successful combustion optimization project. In: *Proceedings of the MEGA symposium*, Chicago, IL, USA, 20-23 Aug 2001. Air & Waste Management Association (2001)
Schimmoller B K (2003) Coal and ash handling: in search of cost savings. *Power Engineering*; **107** (4); 22-27, www.power-eng.com (Apr 2003)
Schweitzer Y, Cartina G, Chudnovsky B (2006) Application of neural network combined with CFD modelling and combustion tuning in large coal-fired boilers. *Paper presented at the ASME 2006 power conference (Power 2006)*, Atlanta, GA, USA, 2-4 May 2006, pp 417-428 (2006)
Schiffer H-W (2006) All around the world. *World Coal*; **15** (1); 25-30, www.worldcoal.com (Jan 2006)
Schuster H, Penterson C (2002) *Experience with various coals in power plants in the United States and Europe.* Danvers, MA, USA, Babcock Borsing Power Inc, 18 pp http://www.babcockpower.com/pdf/t-175.pdf (2002)
Sehgal R, Hickinbotham A (2001) TransAlta adopts dynamic coal blending to deliver the right fuel at the right time. *Power Engineering*; **105** (11); 86-88 (Nov 2001)
Sehgal R, Shea S (2001) Dynamic coal blending helps improve the bottom line. *Power*; **145** (3); 59-62, http://findarticles.com/p/articles/mi_qa5392/is_200105/ai_n21474387/pg_2/?tag=content;col1 (May/Jun 2001)
Seltzer M D, Meyer G A (1997) Inductively coupled argon plasma continuous emissions monitor for hazardous air pollutant metals. *Environmental Science and Technology*; **31** (9); 2665-2672 (1997)
Shea S, Sehgal R, Maxson A, Celmins I (2002) *Demonstration of an advanced integrated control system for simultaneous emissions reduction. Final Technical Report*. DOE Project No. DE-AC22-95PC95254, http://www.osti.gov/bridge/servlets/purl/794282-0DZnCl/native/794282.pdf, 301 pp (Feb 2002)
Smyrniotis C (2005) Computer modelling brings slag control into the 21st century. *Power*; **149** (8); 61-62 (Oct 2005)
Soud H N (1995) *Developments in particulate control for coal combustion*. IEACR/78, London, UK, IEA Coal Research, 57 pp (Apr 1995)
Speight J G (2005) *Handbook of coal analysis*. Hoboken, NJ, USA, John Wiley & Sons, 240 pp (2005)
Spring N (2009a) The smart grid and generation. *Power Engineering*; **113**, (9); 44-50 (Sep 2009)
Spring N (2009b) Putting combustion optimisation to work. *Power Engineering*; **113**, (5); 44-48 (May 2009)
STACenergy (2009) *The use of real time measurement and artificial intelligence to improve efficiency and reduce emissions at coal-fired power plants*. State Technologies Advancement Collaborative, www.stacenergy.org, 5 pp (2009)
Stopford P J (2002) Recent applications of CFD modelling in the power generation and combustion industries. *Applied Mathematical Modelling*; **26** (2); 351-374 (Feb 2002)
TA-129 (2009) Thermal analysis application brief. Proximate analysis of coal and coke. http://www.tainstruments.co.jp/application/pdf/Thermal_Library/Applications_Briefs/TA129.PDF, Tokyo, Japan, TA Instruments Japan, 2 pp (2009)
Taylor P M (2001) Natural gamma technology put to the test. *World Coal*; **10** (12); 51-53 www.worldcoal.com (Dec 2001)

The Greenbank Group UK (2010) *Greenbank enhancing performance*. www.greenbankgroup.com, Woodville, Derbyshire, UK, 8 pp (2010)
Thermo Electron Corp (2005) Woburn, MA, USA, *Thermo Electron Corporation*, vp, http://www.thermo.com/com/cda/product/detail/1,1055,14590,00.html (2005)
Tillman D, Duong D (2007) Managing slagging at Monroe power plant using on-line coal analysis and fuel blending. *Fuel Processing Technology*; 88; 1094-1098 (2007)
Trecazzi C S, Clemente F A, Freme F L, Keen D L, Luppens J A, Pierce B S, Rockey C F, Welham K (2007) *Working document of the NPC global oil & gas study*. Washington DC USA, National Petroleum Council, Coal Impact Subgroup of the Demand Task Group of the NPC Committee on Global Oil and Gas, 53 pp (Jul 2007)
Turner D M, Mayes I (2005) *Advanced optimisation – coal fired power plant operations*. Report number: COAL R279, DTI/Pub URN-05/660, Nottingham, UK, E.ON Uk, PoweTechnology Centre, 29 pp (Mar 2005)
Turner D M, Mayes I (2004) *Advanced optimisation of coal-fired power plant operations – final project report.* DTI P140, Ratcliffe-On-Soar, Nottinghamshire, UK, Power Technology, 29 pp (Aug 2004)
US BLM (2009) US Bureau of Land Management. *Powder River Basin Coal Production*, http://www.blm.gov/wy/st/en/programs/energy/Coal_Resources/PRB_Coal/production.html
US DOE (2001) *Clean coal technology: software systems in clean coal demonstration projects*. Topical report number 17; Washington, DC, USA, US Department of Energy; 20 pp (Dec 2001)
US DOE (2007) *Power plant optimization demonstration projects*. Albany, OR, USA, US Department of Energy (US DOE), National Energy Technology Laboratory (NETL), 27 pp www.netl.doe.gov (Sep 2007)
US DOE (2009) Clean coal technology programs: program update 2009: includes power plant improvement initiative (PPII) and clean coal power initiative (CCPI) projects. Washington, DC, USA, US Department of Energy (DOE), 100 pp (Oct 2009)
Van Kroonenberg L J (1996) *XRF-analysis at a power plant*. Amsterdam, Netherlands, NV Energieproduktiebedrijf UNA (Power Production Company UNA), 6 pp (Oct 1996)
Vesel R (2009) The million dollar annual payback. *Power Engineering*; **113** (7); 72-76, www.power-eng.com (Jul 2009)
Voss A, Hlawenka A, Haug M, Schreiber M (2009) Making the most of available assets – how intelligent add-on technology helps to upgrade boiler performance. *VGB PowerTech*; **89** (6); 73-76 (2009)
Walker S (2000) *Major coalfields of the world*. CCC/32. London, UK, IEA Clean Coal Centre, 131 pp (Jun 2000)
Wall T, Elliott L, Sanders D, Conroy A (2001) *A review of the state-of-the-art in coal blending for power generation: final report – project 3.16.* Technology assessment report 14, Callaghan, NSW, Australia, Advanced Technology Centre, The University of Newcastle, 93 pp (May 2001)
Ward C R (1984) Chemical analysis and classification of coal. In: *Coal geology and coal technology*. Ward C R (ed), Melbourne, Vic, Australia, Blackwell Scientific Publications, pp 40-73 (1984)
Ward C R (2002) Analysis and significance of mineral matter in coal seams. *International Journal of Coal Geology;* 50; 135-168 (2002)
Welch G, Bishop G (2006) *An introduction to the Kalman Filter*. TR 95-041, Chapel Hill, NC, USA, Department of Computer Science, University of North Carolina at Chapel Hill, 16 pp www.cs.unc.edu/~welch and www.cs.unc.edu/~gb (Jul 2006)
Widmer N (2011) Irvine, CA, USA, General Electric Company, GE Energy, Power Services, Boiler Optimisation Services. *Personal communication*, vp (2 Jun 2011)
Whitworth S, Shah S, Zhuang H (2006) *DCS Integration for Intelligent Sootblowing.* Electric Power 2006, Atlanta, GA, USA, 9 pp, http://www.clydebergemann.com/_upload/ISB_DCS_Integration.pdf?documentID=41688 (2006)
Woodward R (2005) Precision sorting. *World Coal*; **14** (12); 35-40, www.worldcoal.com (Dec 2005)
Woodward R (2007) Coal analyzers applied to coal cleaning: the past, present and future. *Designing the coal preparation plant of the future*. B J Arnold, M S Klima, P J Bethell (eds.), Englewood, CO,

USA, Society for Mining, Metallurgy and Exploration (SME), pp 135-143 (2007)
World Coal Association (2010) Coal facts 2010: coal statistics. London, UK, World Coal Association, 3 pp (Sep 2010)
Wu Z (2002) *NOx control for pulverised coal fired power stations*. CCC/69, London, UK, IEA Clean Coal Centre, 64 pp (Dec 2002)
Zehner H P (2002) Characterisation of power plant coals. *VGB PowerTech*; 9; 36-43 (2002)
Zhu Q (2003) *Developments in particulate control*. CCC/72, London, UK, IEA Clean Coal Centre, 50 pp (Sep 2003)
Zolo Technologies (2009) About Zolo Technologies Inc, http://www.zolotech.com/sub/about-us/index.php (2009)