Abstract

Online analysis can play a major role in minimising not only generation costs (fuel cost) but also operational issues at a coal-fired power plant. The technology is accepted and widely used in the coal producing sector but its application, until recently, remained somewhat sporadic in power generating plants. However, the demand for electricity at the lowest possible cost while meeting environmental compliance (minimising emissions) has led more utilities to examine the benefits of knowing coal quality characteristics and properties in real time. Online analysers in power plants can provide real time data on parameters such as ash and moisture content as well as elemental composition of the coal, thus showing variations in coal quality as they occur. Some analysers are mainly used to optimise coal blend to keep within emission guidelines without using excessive amounts of premium priced, low sulphur coals. A number of real time, pulverised-coal flow measurement instruments are now commercially available. Some have already been installed at demonstration and/or at commercial scale at a number of pulverised coal-fired power plants in several countries including Australia, Canada, Denmark, Finland, Germany, Japan, Republic of Korea, Portugal, Spain, South Africa, the UK and the USA. However, there are no commercially-proven devices currently available for online split control of coal flow in response to a flow meter. Work continues to develop such devices. In-duct/boiler-outlet gas monitoring systems are being evaluated at some coal-fired plants while online carbon in fly ash gauges are regularly used not only to ascertain the sale-ability of the combustion products but also to optimise carbon burnout, maximise the efficiency of the mills and control the amount of overfire air. The performance and accuracy of online analysers depend strongly on initial installation, calibration, subsequent maintenance and application environment. Applying online analysis in a coal-fired power plant involves extensive planning, preparation and evaluation prior to the installation and continued monitoring and maintenance after installation.
## Acronyms and abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
<th>Description</th>
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<tbody>
<tr>
<td>ACARP</td>
<td>Australian Coal Association Research Program (Australia)</td>
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<td>ACFM</td>
<td>Automatic Coal Flow Monitor (Denmark)</td>
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<td>ASTM</td>
<td>American Society for Testing and Materials (USA)</td>
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<tr>
<td>BAT</td>
<td>best available technology</td>
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<td>CAA</td>
<td>clean air act (USA)</td>
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<td>CAAA</td>
<td>clean air act amendments (USA)</td>
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<td>CEM</td>
<td>continuous emissions monitoring</td>
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<td>CERTH</td>
<td>Centre for Research and Technology Hellas (Greece)</td>
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<td>CFDF</td>
<td>computational fluid dynamics</td>
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<td>CFBS</td>
<td>Coal Flow Balancing System (USA)</td>
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<td>CFL</td>
<td>Coal Flow Loop (USA)</td>
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<td>CIA</td>
<td>carbon in ash</td>
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<td>CONAC</td>
<td>Cooperative Research Centre for Clean Power From Lignite (Australia)</td>
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<td>CRC</td>
<td>Cooperative Research Centre for Clean Power (UK)</td>
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<td>CQM</td>
<td>Coal Quality Manager (USA)</td>
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<td>CRF</td>
<td>Coal Research Forum (UK)</td>
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<tr>
<td>CSIC</td>
<td>Consejo Superior de Investigaciones Cientificas (Spain)</td>
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<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation (Australia)</td>
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<td>CV</td>
<td>calorific value</td>
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<td>DOE</td>
<td>Department of Energy (USA)</td>
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<td>DTI</td>
<td>Department of Trade and Industry (UK)</td>
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<tr>
<td>DUET</td>
<td>dual energy transmission</td>
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<td>EBA</td>
<td>Elemental Belt Analyser (USA)</td>
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<td>ECA</td>
<td>Elemental Coal Analyser (USA)</td>
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<td>ECSC</td>
<td>European Commission Research Fund for Coal and Steel (EU)</td>
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<td>ECT</td>
<td>Electric Charge Transfer (USA)</td>
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<td>EDF</td>
<td>Electricite De France (France)</td>
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<td>EEA</td>
<td>European Environment Agency</td>
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<td>EERC</td>
<td>Energy and Environmental Research Center (USA)</td>
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<td>EMIR</td>
<td>Espectógrafo Multiobjeto Infrarrojo (multi object infrared spectroscopy) (Spain)</td>
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<td>EPA</td>
<td>Environmental Protection Agency (USA)</td>
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<td>EPRI</td>
<td>Electric Power Research Institute (EPRI)</td>
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<td>ESP</td>
<td>electrostatic precipitator</td>
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<td>ETI</td>
<td>Energy Technology Inc (USA)</td>
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<td>FEGT</td>
<td>furnace exit gas temperature</td>
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<td>FF</td>
<td>fabric filter</td>
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<td>FGD</td>
<td>flue gas desulphurisation</td>
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<td>IEA CCC</td>
<td>IEA Clean Coal Centre (UK)</td>
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<td>IF</td>
<td>infra-red</td>
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<td>IGA</td>
<td>intelligent gravimetric analysis</td>
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<td>IPPC</td>
<td>integrated pollution prevention and control</td>
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<td>IRR</td>
<td>internal rate-of-return</td>
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<td>ISFTA</td>
<td>Institution for Solid Fuels Technology and Applications (Greece)</td>
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<td>ISM</td>
<td>Impact Size Monitor (Australia)</td>
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<td>ISO</td>
<td>International Organisation for Standardisation</td>
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<td>LCPD</td>
<td>large combustion plant directive</td>
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<td>LET</td>
<td>low energy transmission</td>
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<tr>
<td>LFM</td>
<td>low frequency microwave</td>
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<td>LIBS</td>
<td>laser induced breakdown spectroscopy</td>
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<td>LNB</td>
<td>low NOx burner</td>
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<td>LOI</td>
<td>loss on ignition</td>
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<tr>
<td>LPS</td>
<td>Laser Plasma Spectrometer (Australia)</td>
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<td>LRTAP</td>
<td>long range transboundary air pollution</td>
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<td>MAF</td>
<td>moisture-ash-free</td>
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<tr>
<td>MCA</td>
<td>multi-channel analyser</td>
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<td>MIC</td>
<td>Measuring Innovations Consulting (Germany)</td>
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<td>MIR</td>
<td>medium infra-red range</td>
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<td>NEC</td>
<td>national emissions ceilings</td>
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<td>NETL</td>
<td>National Energy Technology Laboratory (USA)</td>
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<tr>
<td>NIR</td>
<td>near infra-red range</td>
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<tr>
<td>NITA</td>
<td>Neutron Inelastic-scattering and Thermal capture Analysis (Australia)</td>
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<tr>
<td>NJDEP</td>
<td>New Jersey Department of Environmental Protection (USA)</td>
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<tr>
<td>NMR</td>
<td>nuclear magnetic resonance</td>
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<td>OFA</td>
<td>overfire air</td>
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<tr>
<td>PFTNA</td>
<td>pulsed fast thermal neutron analysis</td>
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<td>PGNAA</td>
<td>prompt gamma neutron activation analysis</td>
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<tr>
<td>PLC</td>
<td>programmable logic control</td>
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<td>PPC</td>
<td>Public Power Corporation (Greece)</td>
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<td>PRB</td>
<td>Powder River Basin (USA)</td>
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<tr>
<td>RCFS</td>
<td>Research Fund for Coal and Steel programme (EU)</td>
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<td>RMS</td>
<td>root-mean-square</td>
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<td>RSM</td>
<td>Rapid Sulphur Meter (USA)</td>
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<td>RSMD</td>
<td>root square mean difference</td>
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<td>SAI</td>
<td>Systems Applications Inc (USA)</td>
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<tr>
<td>SCR</td>
<td>selective catalytic reduction</td>
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<tr>
<td>SDD</td>
<td>standard deviation of difference</td>
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<tr>
<td>SIP</td>
<td>state implementation plan</td>
<td></td>
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<tr>
<td>SNCR</td>
<td>selective non-catalytic reduction</td>
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<tr>
<td>TDL</td>
<td>tuneable dioxide laser</td>
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<tr>
<td>TNC</td>
<td>thermal neutron capture</td>
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<tr>
<td>TNO</td>
<td>Netherlands Organisation for Applied Scientific Research (Netherlands)</td>
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<tr>
<td>TVA</td>
<td>Tennessee Valley Authority (USA)</td>
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<tr>
<td>UNECE</td>
<td>United Nations economic commission for Europe</td>
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<td>UNEP</td>
<td>United Nations environment programme</td>
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<tr>
<td>WKU</td>
<td>Western Kentucky University (USA)</td>
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<tr>
<td>WMMLC</td>
<td>West Macedonia Lignite Centre (Greece)</td>
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<tr>
<td>XRF</td>
<td>X-ray fluorescence</td>
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Coal quality and properties from the same mine can vary enormously. In the past, obtaining accurate measurements to determine coal properties such as ash, moisture and elemental content could be a time consuming and lengthy process. Online coal analysers began to be developed in earnest in the late 1970s in Australia, Europe and the United States. They have been in use, mainly by coal-producers, in coal mines and handling and preparation facilities since the mid-1980s and more recently in coal-fired power plants. Their task is to provide almost instantaneous information on properties, mainly ash, moisture and elemental composition. Today, online analysers are also used to improve coal flow and distribution, carry out in-duct/boiler-outlet gas measurement as well as carbon in ash monitoring. How coal properties influence emissions was discussed in detail in a previous IEA Clean Coal Centre publication by Davidson (2000).

Since the late 1980s, application of coal analysers in coal-operations plants shifted from merely monitoring to process control and shipment verification (consignment quality). Changes in heavy-media gravity, silo blend proportions and haul truck dispatch, among other operations began to be based on immediate results gained from the online analysers. Many producers realised rapid payback on their analyser investment by reducing the variability in coal quality. The greater product consistency results in improved recovery, better mine utilisation, lower costs and more contract flexibility.

Traditionally, coal quality in coal-fired power plants is determined by obtaining a suitable sample and sending it to a laboratory for detailed analysis using standard methods. The results are not only delayed but also, in many cases, non-representative due to the continuing change in the coal fed into the boilers and the size of the sample tested. They can also be unreliable because of the combined potential for error in sampling, preparation and laboratory analysis. Online analysers sample larger volumes and provide faster and therefore more representative information on the coal feed.

However, coal analysis for quality determination continues to be carried out in laboratories by a large number of coal producers throughout the world. For example, Jones (2004) shows that, in the UK, coal analysis for the largest coal supplier, UK Coal, is carried out in laboratories. Each individual train-load undergoes standard analysis for moisture, ash, sulphur and calorific value (CV). Coal sizing, volatile matter, chlorine and ash analysis of the coal are also undertaken on a weekly basis. Trace element analysis, carbon, hydrogen, nitrogen, hardgrove grindability index and ash fusion data are obtained on an annual basis (CRF, 2004).

The type of coal fired in a boiler impacts steam generating equipment, performance and total plant emissions. As properties of coals and their ash, moisture and elemental content vary widely, it is advisable that all coals that may be fired in a boiler should be tested and monitored to indicate chemical analyses, heating value and grindability. Today, online analysers are becoming more widely used in coal-fired power plants. A more recent development in the use of online analysis is to measure coal flow into the boiler, not only to improve efficiency by balancing coal flow distribution to burners for uniform combustion but also to reduce the emissions from these units.

Online analysis of coal is based on exposing a sample to a field of energy from a suitable source and detecting the resultant emissions. The inherent natural radioactivity of the coal can also be measured. Different techniques are used to measure ash, moisture and the elemental composition of the coal. These techniques are discussed in detail in previous IEA Clean Coal Centre publications by Kirchner (1991) and Kirchner and Maude (1994).

Data acquisition systems holding all measured parameter information in coal-fired power plants, including online analysis data, are today being used to create models and simulations. Furthermore these are being used in ‘intelligent’ computer-based plant optimisation processes. Many knowledge-based computer systems are in use or under development mainly to optimise the combustion process in order to reduce NOx emissions from baseline conditions. This is because reducing NOx emissions is closely linked to the combustion process and is a natural candidate for optimisation. The use of such systems is discussed in detail in a previous IEA Clean Coal Centre publication by Soud (1999) and will not be discussed further in this review.

In this review, developments in online analysis techniques and application since the mid 1990s will be presented. Coal-quality characterisation, as well as coal-flow and particle size distribution, in-duct/boiler-outlet gas, and carbon in ash monitoring, measurement and control in pulverised coal fired power plants are also discussed.
The coal-based, power generation process has many stages that require data monitoring and analysis. Figure 1 shows a layout of a coal-fired power plant and Table 1 lists the various stages in such a facility. In this report, online analysers used in stages 1 to 6 will be discussed. Continuous coal-flow measurement and control application (stage 7) to balance coal distribution to the burners and hence improve plant performance and reduce emissions will also be covered in this review. Other areas where online analysis is used or is being investigated and is discussed in this report include induct/boiler-outlet gas monitoring and fly ash carbon content measurement.

The standard method for assessing plant yield and overall performance is by sampling and analysis of the coal feed and the product streams. Similarly, for assessing particular unit operations, sampling and analysis provides the basis for the assessment. However, as sampling is a difficult procedure, it needs to be carried out using rigorous methods. This applies to both online and laboratory sampling analyses (Couch, 1996). Modern coal testing methods are discussed in detail by Sakurovs and others (2001a,b).

Obtaining representative samples of the many thousands of tonnes of coal in a consignment is difficult. Coal taken from the top or sides of a pile will almost always be different in quality from the rest of the pile due to size segregation and weathering/oxidation. Furthermore, on site as well as off-site laboratory analyses can be time consuming and hence do not necessarily reflect current operating conditions. Real time information on coal quality helps efficient management of coal stockpiles and improves plant performance.

Management of coal stockpiles was the subject of a previous IEA Clean Coal Centre publication by Carpenter (1999).

Quick (2004) states 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 2). 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 such as low NOx burners (LNBs). SO2 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). The Australian Coal Association Research Program (ACARP) manual of modern coal testing methods, states that the use of online analysis techniques may assist in resolving some of the problems when firing thermal coal in utility boilers (see Table 2).

CO2 emissions trading in the European Union began in January 2005 (Quick, 2004). The CO2 emission calculation is based on three factors which are multiplied together. These are: activity data, emission factor and oxidation factor. The activity data is the amount of fuel consumed multiplied by its net calorific value (CV). The emission factor is the carbon content of the fuel and the oxidation factor is the carbon

Figure 1  A typical layout of a pulverised coal fired power plant (Thermo Electron Corp, 2005)
<table>
<thead>
<tr>
<th></th>
<th>The stages that require monitoring in a coal-fired power generating plant (as shown in Figure 1)</th>
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<tbody>
<tr>
<td>1</td>
<td>Rail car unloading</td>
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<td>2</td>
<td>Reclaim conveyor</td>
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<td>3</td>
<td>Coal storage conveyors</td>
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<td>4</td>
<td>Stockpiles</td>
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<td>5</td>
<td>Mill silo feed conveyor (coal bunker conveyor)</td>
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<td>6</td>
<td>Mill silo (coal bunker)</td>
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<td></td>
<td>Applications for stages 1–6 include:</td>
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<td></td>
<td>– weighfeeders</td>
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<td>– on-line coal analysers</td>
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<td>– coal blending software</td>
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<td>– conveyor belt monitoring and protection controls</td>
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<td>– tramp metal detection</td>
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<td>– continuous point and level measurement</td>
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<td>– tripper car position measurement</td>
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<td>7</td>
<td>Pulveriser (coal mill) and primary blower</td>
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<tr>
<td></td>
<td>– preheat air to pulverisers</td>
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<td></td>
<td>– bearing temperature monitoring</td>
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<td></td>
<td>– coal flow distribution measurement and control</td>
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<td>8</td>
<td>Boiler (coal-fired furnace)</td>
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<tr>
<td></td>
<td>– SCR system catalyst temperature monitoring</td>
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<td></td>
<td>– bottom ash removal</td>
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<td></td>
<td>– lime and fly ash slurry density and flow monitoring</td>
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<td>– fly ash hopper level monitoring</td>
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<td></td>
<td>– opacity monitors</td>
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<td></td>
<td>– heat exchanger and boiler tube alloy verification</td>
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<td></td>
<td>– primary and secondary combustion air monitoring</td>
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<td></td>
<td>– water analysis monitors (sodium, silica, pH, conductivity, dissolved Oxygen, Oxygen scavenger)</td>
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<td>– plug chute detection</td>
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<td></td>
<td>– sampling probes</td>
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<td></td>
<td>– gaseous pollutant monitors (CO, CO₂, NOₓ, SO₂)</td>
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<td></td>
<td>– integrated continuous emission monitoring systems (CEMs)</td>
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<td>9</td>
<td>Flue gas desulphurisation (FGD) scrubber</td>
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<td></td>
<td>– percent solids and slurry monitoring</td>
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<td>10</td>
<td>Particulate matter control (ESP or fabric filter)</td>
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<tr>
<td></td>
<td>– bottom ash slurry measurement</td>
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<td></td>
<td>– fly ash level measurement</td>
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<td></td>
<td>– carbon in fly ash gauges</td>
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<tr>
<td>11</td>
<td>Control room</td>
</tr>
<tr>
<td></td>
<td>– data acquisition, monitoring and management</td>
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<td>12</td>
<td>Boiler pipes</td>
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<td></td>
<td>– cooling water and condensate flow measurement</td>
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<td>13</td>
<td>Steam turbine</td>
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<td></td>
<td>– data acquisition and monitoring of turbine parameters</td>
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<tr>
<td>14</td>
<td>Cooling tank, cooling tower, reservoir</td>
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<td></td>
<td>– density measurement</td>
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<td></td>
<td>– influent and discharge flow measurement</td>
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<tr>
<td></td>
<td>– water analysis monitors (pH, conductivity, chloride)</td>
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<td>15</td>
<td>Generator</td>
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<tr>
<td></td>
<td>– data acquisition, monitoring and management</td>
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<td>16</td>
<td>Transmission substations</td>
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<td></td>
<td>– power quality monitoring and analysis</td>
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<td>17</td>
<td>Power distribution</td>
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<td></td>
<td>– data acquisition, monitoring and management</td>
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<td>18</td>
<td>Consumer</td>
</tr>
<tr>
<td></td>
<td>– power quality monitoring and analysis</td>
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content of the ash. Emission control technologies for CO₂ are not currently used at commercial scale. Improving plant efficiency contributes towards reducing CO₂ emissions in coal-fired plant. Application of online coal quality and other analysers discussed in this review can result in reducing the amount of coal fired at a facility, increasing plant efficiency, reducing emissions and maintaining the level of carbon in ash, simultaneously.

A number of methods for testing the characteristics of coal are currently used and under development including online analysis. Sowerby (2002a) gives a general overview of online analysis instrumentation for the coal industry and Woodward (2005) discusses the current state of online coal analysis.

Online analysers provide real time data on parameters such as ash and moisture content as well as elemental composition of the coal, thus showing the variations in coal quality as they occur. Non-destructive and direct measurement of some parameters is not possible. Instead, they are inferred from measurements of the amount of mineral matter (primarily Si, Al, Ca and Fe). The calorific value of coal is not measured directly but determined through algorithms that use organic matter elements such as C, H and O (Lim and Abernethy, 2004). In plants where the coal is analysed directly on the conveyor belt, errors and delayed results due to standard sampling and sample preparation are minimised. However, online analysers continue to be considered expensive and their cost-effectiveness depends on the site and application. They can cost from approximately £30,000 to £150,000 for a single parameter unit, with prices rising to as high as £400,000 for some analysers. In addition, installation costs can be substantial (Page, 1998).

Quality control of coal is an essential requirement to optimise combustion efficiencies, to maximise the use of coal resources and to provide on-specification products. The key parameters that determine coal quality are ash content and specific energy (calorific value, CV). Both parameters are defined in terms of the behaviour of coal when it is burnt. For example, ash content is defined as the amount of residue after burning under prescribed conditions (Lim and Abernethy, 2004). Online analysis can help provide the coal industry as a whole with (Cutmore and others, 2001):

- improved product quality control. Total quality assurance is an increasing market need, particularly in the export sector, and accurate online analysis is an important element of a quality assurance programme;
- implementation of manual and automated process control for increased operating efficiencies. Automatic process control requires rapid feedback of parameters, which can only be achieved with online analysis;
- minimising or reducing the need for manned quality control laboratories (although some vendors consider analysers to be predominantly a process control tool while laboratories remain as the arbiter of contract compliance) (Woodward, 2005).

2.1 Development of online analysers

There are a number of analytical techniques currently being investigated for online (rapid) analysis of trace elements in coal. In 2001, none of the techniques available then were deemed completely suitable for real time analysis for a variety of reasons. Some were destructive and requiredashing and dissolution of the coal. Some needed expensive equipment only available to a few laboratories. Others were limited by physical processes such as radioactive decay and therefore could not be considered as candidates for online analysis. However, at the time, there seemed to be some
Table 2  Thermal coal in utility boilers (Sakurovs and others, 2001)

<table>
<thead>
<tr>
<th>Problem</th>
<th>information required</th>
<th>suggested test methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>High carbon in ash</td>
<td>– detailed burning characteristics</td>
<td>– DTGA1</td>
</tr>
<tr>
<td></td>
<td>– nature and shape of unburnt carbon particles</td>
<td>– optical microscope, SEM2 investigations</td>
</tr>
<tr>
<td></td>
<td>– nature and shape of char particles formed during combustion</td>
<td>– DTF3</td>
</tr>
<tr>
<td></td>
<td>– maceral analysis</td>
<td>– maceral content and reflectance histogram</td>
</tr>
<tr>
<td>Boiler tube erosion</td>
<td>size, nature and shape of quartz particles and the quartz/iron mineral binary particles</td>
<td>SEM investigation of fly ash followed by QEM4 scan of boiler fly ash</td>
</tr>
<tr>
<td>Furnace slagging</td>
<td>mineralogy of:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>– coal mineral matter</td>
<td>low temperature ashing followed by quantitative XRD5. It is useful to also have standard ash analyses done at the same time</td>
</tr>
<tr>
<td></td>
<td>– deposits and fly ash</td>
<td>recognition of the melt or ‘glue’ mineral or glass phase. Relate these results to the coal mineral matter. Done by systematic use of SEM, and EMPA6. The latter allows the use of thermodynamic data. Mossbauer may be used to determine the forms of iron</td>
</tr>
<tr>
<td>Superheater slagging</td>
<td>as above, but with an emphasis on the nature of the initiating layer</td>
<td>as above</td>
</tr>
<tr>
<td>Fouling of low temperature areas</td>
<td>as above plus water soluble alkalis</td>
<td>as above</td>
</tr>
<tr>
<td>ESP performance</td>
<td>– electrical properties of the fly ash</td>
<td>fly ash resistivity</td>
</tr>
<tr>
<td></td>
<td>– collection efficiency</td>
<td>pilot scale testing</td>
</tr>
<tr>
<td>NOx emissions</td>
<td>– nitrogen in the coal</td>
<td>24 hour Kjeldahl method</td>
</tr>
<tr>
<td></td>
<td>– relative emissions compared to other coals</td>
<td>drop tube testing</td>
</tr>
<tr>
<td></td>
<td>– volatile/char partitioning</td>
<td>drop tube testing</td>
</tr>
<tr>
<td>SO2 emissions</td>
<td>– sulphur in coal</td>
<td>ultimate and ash analysis, SEM and EMPA of fly ash</td>
</tr>
<tr>
<td></td>
<td>– sulphur absorption in ash</td>
<td>pilot scale testing</td>
</tr>
<tr>
<td>Trace elements</td>
<td>– amount of elements in ash</td>
<td>standard chemical determination of the trace elements in the ash</td>
</tr>
<tr>
<td></td>
<td>– distribution of elements between ash and gaseous species</td>
<td>pilot scale testing, Chemical determination of selected trace elements in the ash after combustion</td>
</tr>
<tr>
<td>Storage and handling</td>
<td>– spontaneous combustion</td>
<td>adiabatic oxidation test, relative ignition temperature</td>
</tr>
<tr>
<td></td>
<td>– flow characteristics</td>
<td>Jenike shear cell, Durham cone test</td>
</tr>
<tr>
<td></td>
<td>– PCI (pneumatic conveying)</td>
<td>fines content, permeability coefficient, fluidisation pressure gradient, Hausner ratio</td>
</tr>
</tbody>
</table>

1  DTGA: differential thermo gravimetric analysis: provides a measure of the rate of removal of material (reactivity) of a coal sample under standard conditions.
2  SEM: scanning electron microscopy: an electron beam machine that has scanning capabilities that allows imaging of selected areas and point analyses.
3  DTF: drop tube furnace: is used to simulate the time-temperature history of combustion processes at bench scale.
4  QEM: quantitative evaluation of materials by SEM
5  XRD: X-ray diffraction: a measure of the diffraction of an x-ray beam as it passes through a crystalline substance, characteristic of the crystal structure
6  EMPA: electron micro probe analysis: a routine analytical technique that uses an electron beam to measure major and minor elements, can also be used for trace element analysis provided an improved analytical procedure is used.
The need for online analysers

Online coal analysers up to the late 1980s were mostly one of three types (Woodward and others, 2003):

- online moisture monitors/meters using microwave technology;
- online ash gauges using gamma ray attenuation technology (collectively known as either dual-gamma gauges, dual energy transmission (DUET) or low-energy transmission (LET) gauges;
- elemental analysers used for ash, sulphur and sometimes ash constituent information as well. These analysers relied on prompt gamma neutron activation analysis (PGNAA) for elemental analysis and they analysed sample streams rather than full process flow. In PGNAA, a field of neutrons is used to raise the energy levels of the various atoms present. As these atoms lose energy by emitting gamma-rays of characteristic energy and intensity. These gamma-rays can, with suitable detectors, be used to determine the amount of various elements present in the coal mineral matter and chemically combined in the organic matter. PGNAA is discussed further in Chapters 3 and 5. When PGNAA is combined with a moisture metre, as is generally the case, moisture, calorific value and mg/m³ SO₂ emission can also be determined.

From the late 1980s and throughout the 90s these systems saw the following improvements mainly due to users’ demand for less expensive gauges (Woodward and others, 2003):

- PGNAA analysers with integrated input hopper and sample conveyor and smaller footprint;
- dual-gamma ash meters which dispensed with the swing-arm standardisation feature;
- ash gauges based upon natural gamma emitters in the ash (potassium and thorium).

According to Woodward and others (2003), despite the improvements, a large gap remained in price and performance between the PGNAA elemental analysers and the dual gamma ash gauges. Where the user wanted to measure ash, moisture and calorific value, an ash gauge coupled with moisture analysers (both mounted over the existing conveyor) could be purchased and installed for more than US$120,000. If instead, the user required sulphur or more accurate ash (especially when the iron fraction of the ash varied significantly) and decided on PGNAA analysers, the cost would increase dramatically to US$500,000 or more, depending on the complexity of the installation. As a result, developments in elemental analysers followed to reduce cost and complexity of the systems and their installation. Today, according to Horsley (2005), on-belt PGNAA analysers that analyse full streams, thus eliminating sampling errors and reducing maintenance and installation costs, are commercially available at less than US$400,000.

Advanced online sensors and measurement instruments are today commercially available and used in several coal-fired power plants throughout the world. However, their uptake remains limited due not only to their cost but also complexity, accuracy and capability issues. Some systems have not met expectations and most can be improved by using better methods of testing and calibration. Sensor performance and reliability in power plant are discussed in detail by Hashemian (2005).

2.2 Calibration and testing

According to IIHR (1999), measurement is the act of assigning a physical value to some physical variable. In an ideal measurement, the value assigned by the measurement would be the actual value of the physical variable intended to be measured. However, measurement errors bring on an uncertainty in the correctness of the value resulting from the measurement. To give some measure of confidence to a measured value, measurement errors must be identified, and their probable effect on the result estimated. Uncertainty is simply an estimate of a possible value for the error in the reported results of a measurement. Uncertainty analysis provides a structured and rational framework of evaluating the significance of the scatter (precision errors) and trends (potentially associated with bias errors) in a set of data. Uncertainty assessment and methodology are discussed in detail by Stern and others (1999). Measurable and inferential parameters in online analysis are discussed by Kirchner and Maude (1994).

The American Society for Testing and Materials ASTM D6543, ‘standard guide to the evaluation of measurements made by online coal analysers’ was first published in 2000. The International Organisation for Standardisation ISO/DIS 15239, ‘solid mineral fuels – evaluation of the measurement performance of online analysers’ was being prepared for publication in late 2004. Both standards discuss the three-instrument Grubbs’ measurement procedure. The Grubbs’ estimator statistical technique uses standard deviations between independent measurements of a given variable to provide an estimate of the standard deviation between any one of those measurements and an unknown true value. The true value itself is not measurable but is implied within the calculations.

The technique can be applied in many ways. The method chosen for verification of online analyser performance relies on three independent measurements of each variable concerned. All three systems should be of similar precision, although this is not essential. The ideal approach is to compare the results obtained from an instrument under test with those obtained from two independent reference systems. In the case of an online coal analyser, the two alternative measurements would, most probably, be made by independent laboratories using samples taken from different locations in the coal stream while the analyser is in operation. However, according to Horsley (2005), the reality is that in many plants there are generally no suitable second locations for an independent laboratory sample. A single automatic sampler is used to generate samples ‘A’ and ‘B’ and a value is determined for sample error (which is thus common to both samples ‘A’ and ‘B’). Although the ISO standard discusses a two-instrument test for analyser imprecision, the
recommended method requires data from a three-instrument test. By comparing the analyser results with the laboratories results it is possible to establish an estimate of the standard deviation between the analyser or laboratories and an absolute standard. However, the true value of the absolute standard again remains unknown and cannot be measured directly. This Grubb’s estimator for each parameter can then be used as the basis for an appropriate performance guarantee.

The majority of online analyser calibration and testing experience in the coal industry is associated with the prompt gamma neutron activation analysis (PGNAA) analysers (discussed in detail in Chapters 3 and 5). According to Rose (2004b), these instruments have proven, during the last two decades, to give consistently reliable performance. A new PGNAA analyser is usually calibrated at the factory and then again after installation; 20–30 sets of data comparison values are used for field calibration against a user’s chosen laboratory. After the field calibration, a test (now based on Grubb’s estimator) using 50–60 sets of data is conducted to determine analyser measurement precision. What is involved in effective calibration of a PGNAA analyser in the factory and the field is presented by Foster (2004).

Rose (2004b) discusses in detail interrelated and persistent problems in the analyser calibration and testing process. The author states that the commonly used methodology results in an unknown calibration bias resulting from lack of knowledge of the variance of measurement error. Not taking calibration biases into account results in misleading precision estimates. These evaluations and testing problems may result in difficulties for the user of the analyser and, where performance warranties are in place, problems for the equipment supplier.

According to Rose (2004b), the three-instrument Grubbs’ model, which includes an estimated component of measurement variance, has proven useful in assessing analyser measurement performance. However, in calibrating analysers using ordinary least squares regression and ignoring the effect of measurement error as well as the effects of imperfect calibration, the opportunity to improve analyser measurements is missed. Rose (2004b) states that the unbiased estimates of calibration parameters and measurement variance, that are available through proper use of a latent variable model, will result in better industry decisions and in better analyser measurements. He concludes that simultaneous results obtained using a three-instrument test evaluated with the appropriate latent variable model would be unbiased estimates of optimum analyser calibration parameters and instrument precision.

It should be noted that most online analysers use one or more radiation source. Since the energy of the source decays with time, there may be a tendency for repeatability of results to decay gradually until such time as the sources are replaced. Any such effect can be checked by means of a static repeatability test in which the analyser is compared with itself using a standard test sample. Manufacturers use different techniques although the commonest reference measurement is that of an empty conveyor belt. Alternatively, sealed coal standards created from the subject coal, can be used (Horsley, 2005).

The performance and accuracy of online analysers depend strongly on initial installation, calibration, subsequent maintenance and application environment. Of prime importance is initial calibration. Reference samples that represent the range of coals fired at a plant must be used during the initial calibration process. Analysis of coals beyond the range of the initial calibration, will not have the same accuracy. Therefore, changes in coal supply can necessitate re-calibration. Re-calibration may also be necessary due to drift over time. However, changes in coal, due to variability from the coal supplier, or due to the plant switching to lower cost coals (which can be blended) are the main triggers for re-calibration (Horsley, 2005).

2.3 Application of online analysers

Application of online analysis techniques in pulverised coal power generation includes (Scantech, 2005):

- **stockpile feed monitoring**: where monitoring coal deliveries allows identification of quality variation outside contract specification. Coal within the specification but at the limits of the set parameter ranges can be identified before placing in stockpiles or conveying on to burner bunkers. Real time, online data can prepare plant operators to deal with potential combustion or handling problems. The information may also be used, where appropriate, to maintain emissions of air pollutants below the regulatory requirements. This may be achieved for example either by conveying coal that is suitable for immediate combustion directly to the burner bunkers without the need for stockpiling and reclamation or by stockpiling coal that is significantly outside the set specification for later blending or cleaning to remove high sulphur or high ash before firing. Continuous monitoring of moisture content at delivery allows the identification of potential handling problems due to high moisture or dust problems due to excessively dry coal. The former may be stockpiled and allowed to drain or be blended whilst the latter can be sprayed to control the dust but stay within boiler limitations;

- **bunker feed monitoring**: continuous, online monitoring of coal between stockpile and burner bunkers can alert the plant operator to the qualities of the coal to be fired, thus giving him/her time to make changes to minimise the impact of the coal quality variations. This can reduce or even prevent forced outages, reduce maintenance costs and avoid the need to meet load demand from higher cost sources. The coals can also be blended as they are recovered from the stockpiles using process control software to adjust feeder rates on a continuous basis in order to achieve the required tonnage rate and quality. Automated blending can also be used to maintain a consistent bunkered coal quality, not only to ensure efficient boiler operation but also to maximise the use of less expensive coal;

- **monitoring unburnt carbon in fly ash**: monitoring carbon in fly ash is a recognised technique to monitor...
boiler efficiency. A combination of boiler settings (for example, air flow) and coal fineness (depending on coal type and mill settings) can contribute to the amount of unburnt carbon in fly ash. The majority of existing systems require analysis which can take up to 48 hours and provide data that are useful only for historical data recording of the plant efficiency on a daily or weekly aggregate basis. Online analysis systems can obtain this information on a continuous basis (updates about every five minutes) with precision similar to conventional analyses. Real time monitoring allows the continuous, efficient operation of the boiler and permits mill and boiler settings to be optimised quickly.

Estimated online coal analyser unit sales 1985 to the present (Woodward, 2005) are shown in Figure 3 and estimated coal industry investment in coal analysers from 1985 to the present is shown in Figure 4.

According to Rose (2004a), there have been many successful global applications of online coal analysis system since the mid 1990s. In the USA these include:

- Naughton power plant in Wyoming: sorting of high/low sulphur coal to avoid sulphur dioxide emission excursions;
- Hunter power plant in Utah: saving 4 million US$/y on derates (derating is the reduction of a generating unit net dependable capacity to a point below the manufacturer’s nameplate rating);
- B L England power plant in New Jersey: blending Powder River Basin (USA) (PRB) coal with Eastern US coal to meet stringent state requirements (for example, the New Jersey State Department of Environmental Quality requires that the sulphur content of coal fired at the B L England electric generating station should not exceed a specific value);
- Gibson County Coal in Indiana: economic control of preparation plant by-pass stream;
- Numerous coal load-outs (for example, physical facilities at coal mines where coal is loaded for shipment into wagons, barges or lorries): blending for sulphur and/or ash to meet contract requirements.

Rose (2004a) states that not all applications were successful and some resulted in disputes between vendor and user regarding performance. In some cases the online analysis projects were considered a failure and consequently produced economic losses for all parties involved. Rose (2004a) continues to say that important factors to be considered at the outset to achieve successful installations must include:

- a clear understanding of what the project must accomplish to be judged successful. For example: reducing annual generating unit derates by 40% or reducing monthly quality penalties on coal shipments by US$60,000;
- a means of describing and specifying the performance required of the analyser to assure success of the project;
- a means of dynamic calibration and testing of the analyser after start-up that enables an unambiguous determination as to whether or not the analyser performance meets specifications. Generally, this requires a mechanical coal sampling system, one capable of collecting accurate samples of coal fed to the analyser and preferably designed to collect independent duplicate samples within reasonably short time intervals (30–60 minutes).
Today, major areas being addressed by plant optimisation products are pulveriser mill performance and the prediction and control of coal quality at the burners in real time through appropriate blending decisions in the yard. These, of course, impact all other downstream phenomena such as NOx emissions, slagging, SO2, opacity and, above all, generation costs. Real time analysis for coal blending is discussed in Chapter 8. Online analysers can provide the necessary real time data in order to help achieve the desired plant performance improvements. There are also some data analysis systems (models/software) that can be used to achieve this purpose. Some of these software based systems are already installed at a number of US and Canadian power plants.

Mill function in coal-based power generation is to grind the large and variable raw coal feed to supply dry and finely pulverised coal to the furnace for fast energy release. The pulverised coal is transported, via air, to the boiler furnace for combustion. Figure 5 Shows the importance of maintaining the correct air-to-fuel ratio to achieve optimum efficiency and performance. Mills are in general of the vertical spindle or tube-ball type. A primary control objective is to regulate the rate of flow of the pulverised coal/air mixture while maintaining the required degree of fineness of the pulverised coal as well as the safe and efficient operation of the mills. The effects of coal fineness on carbon burnout were the subject of a report by Colechin (2004).

Mills have to be able to deliver a rapid and consistent response to facilitate the accurate control of load. Parameters such as coal hardness and component wear and tear affect mill operation and performance and consequently plant operation and performance. According to the DTI (2003), it is possible to measure the particle size in a mill using acoustic techniques, thus providing valuable mill condition monitoring. The mill control system is responsible for the precise fuel supply and primary air flow, in a certain ratio to the coal flow, thus maintaining the efficient unit energy production and minimising air pollutant emission and problematic waste generation. In addition, mills consume large amounts of power. In addition to coal drying and transportation, coal grinding consumes about 0.5% of the power generated. Optimising mill performance can therefore improve the efficient and economic operation of the plant.

One aspect of optimising boiler thermal efficiency involves monitoring the temperature of the air leaving the coal mill. The coal is fed into the mill with air that is already heated. Further heat is generated by the milling action itself. The temperature of the coal/air mixture should be as high as possible without exceeding the temperature that can be tolerated, the explosive limit. Therefore, the hot air leaving the air heaters has to be mixed with cold ‘tempering’ air to ensure the mill outlet temperature is at an acceptable level. An automatic control loop can maintain this temperature at the optimum value by regulating the flow of tempering air (ETSU, 1998).

A number of parameters have to be set to achieve maximum combustion efficiency including:
- primary air/coal ratio;
- secondary air distribution;
- burner tilt (tangential/corner fired boilers);
- mill firing pattern.

Reducing the boiler overall excess air level improves the boiler efficiency by reducing the dry flue gas losses (that is energy which is wasted by heating excess air that is not needed for complete combustion). Lowering the excess air has an additional benefit in that it typically results in reduced NOx emissions. However, very low excess air can result in high carbon monoxide (CO) emissions, increased carbon in ash (CIA) content (or loss on ignition, LOI) and reduced boiler efficiency due to combustible losses (that is energy lost in the form of unburnt carbon in the ash or gaseous combustibles such as CO). Low excess air can also lead to zones of reducing atmospheres which can cause premature tube wear (Thomas, 2005). Online monitoring of in-duct/boiler-outlet gas is discussed in Chapter 7. Operation at below normal O2 levels in the burner zone is also a common cause of slagging, fouling, high tube metal temperatures and a possible loss in capacity for de-slaged or forced outages for tube repairs. Burner zone combustion uniformity plays an important role in optimising boiler efficiency and achieving good thermal performance, availability, reliability as well as controlling emissions. Traditional and emerging technologies for balancing coal flow distribution to burners for uniform combustion are discussed by Haumesser and others (2003). Continuous analysis of coal mass flow, particle size distribution and carbon in ash are discussed in Chapters 9, 10 and 11 respectively.

Boiler monitoring and control systems include gauges, meters, flame monitors and pressure measuring devices. These generate data that can be fed into the plant main control system. In an open loop setup, the corresponding graphical output on screen and/or paper is used in order to allow the plant operator to alter the necessary parameters to

**Figure 5** The importance of maintaining correct air-to-fuel ratio to achieve optimum efficiency and performance (Zhang and others, 2003)
maximise the efficiency of the combustion process. In a closed loop system, the control system carries out the modifications based on the received information from the online analysers.

Other than the boiler parameters themselves, the knowledge and dynamic control of coal quality are essential if efficiency is to be maximised and emissions are to be reduced economically. Analysers capable of online operation and data provision are now available for this purpose. Power plants that use coal from multiple sources can use these systems to match the coal quality to operating conditions such as load and emissions, or to avoid conditions which lead to derates. These analysers require initial installation and periodic ongoing calibration but can assist the plant operator in minimising fuel costs as well as lowering the incidence of derates. Combining the control of boiler parameters with real time knowledge of coal quality at the burners can help improve boiler efficiency, therefore reducing all emissions from the plant including particulate matter, NOx, SO2, CO, CO2 as well as trace elements. It may also lower the costs of operation by reducing or even preventing forced outages.

Applying online analysis in a coal-fired power plant involves extensive planning prior to the installation. Each potential application has unique characteristics and requirements that must be considered in order to achieve the desired outcome. Renner (1999) discusses the opportunities for applying online analysers in the coal industry and describes the planning and evaluation necessary prior to their installation. Limitations as well as opportunities in the use of online analysers in measuring ash, moisture and calorific value are presented by Woodward (2004) and ensuring a successful analyser installation project is the subject of a paper by Evans (2004a).
3 Ash measurement

Techniques that can be used to determine ash content of the coal include:

- **Scattering**: a beam of radiation from a suitable source is directed at a sample of coal. The amount that is scattered back gives a measure of the ash content;
- **Absorption**: similarly, the loss in intensity of a beam of radiation passing through the coal, because of absorption, allows the ash content to be determined;
- **Natural**: measurement of the natural radioactivity of coal allows determination of the ash content, because the mineral matter present in the coal itself emits low level radiation;
- **Excitation**: the presence of individual elements (including ash) can be quantified by subjecting the coal sample to a field of neutrons. This excites the coal nuclei and causes them to produce radiations which are characteristic of the elements present.

The five principle methods used to derive the ash content are (Couch, 1996; Horsley, 2005):

- X-ray backscatter;
- gamma-ray backscatter;
- dual energy gamma-ray transmission (DUET) (where two sources with gamma-rays at different energy levels are used);
- natural gamma ash monitors are widely used in the coal processing industry, where they have the advantage of not requiring a radiation source, they are insensitive to the variability of Fe and Ca (which can be a problem for the DUET technology in some applications), and they can handle much thicker depths of materials than either the DUET or PGNAA systems. However, the measurement technique relies on an association between the ash in coal and the naturally emitting isotopes of K, U and Th. Multiple linear regression analysis of the spectral peaks derives a calibration for ash. This relationship is linked to the geology of the deposit at the time of formation; different deposits may have different relationships due to different sources of the ash. This technology however is not recommended for power plants except where the plant is burning a single source of coal;
- prompt gamma neutron activation analysis (PGNAA).

These and other testing methods for analysis of minerals in coal and ash from coal combustion are presented by Creelman (2002).

PGNAA technology is considered the best available to perform online analysis of coal to determine the major elements of interest in the coal. As PGNAA measures the elements in the coal, it is also a means of determining sulphur content. The technology allows the entire sample volume to be penetrated thereby analysing the full stream of coal, representatively. Most PGNAA analysers use californium-252 as the neutron source (Snider and others, 2003). Edwards (2001) discussed optimising the accuracy in PGNAA online analysers.

Traditionally, PGNAA based systems rely on the measurement of thermal neutron capture (TNC) gamma-rays through the use of Californium 252 (252Cf) neutron sources with one or more NaI detectors in a transmission geometry relative to the sample. PGNAA analysers provide a measure of coal quality through summation of the quantities of elements that constitute mineral matter (primarily Si, Al, Fe and Ca). They are sensitive to changes in segregation and profile loading, some operate on sample by-lines and some operate on full flow over the belt instruments. They are also expensive and subject to sampling error.

While PGNAA is the more sophisticated and hence more expensive technology, DUET is the most widely used method for monitoring coal ash content.

A DUET online analyser can also be used over a conveyor belt. The transmission of the high energy beam is dependent on the mass through which it passes while the transmission of the low energy beam depends on both the mass and the mineral matter content of the coal. The influence of coal thickness change on the ash gauge reading is studied by Gu (1998). Such an analyser depends on using a simplified two-component model of coal, based on a combustible part with an atomic number around 6, and a mineral matter part with an atomic number around 12. The principal mineral matter components are aluminium (atomic number 13) and silicon (atomic number 14), often occurring as oxides or hydrides. The presence of variable amounts of iron (atomic number 26), and other elements can make calibration difficult. The technique is more readily applied to bituminous coals, rather than to those of lower rank which are often more variable (Couch, 1996).

According to Lim and Abernethy (2004) the DUET technique infers ash content from changes in average Zn/A (the ratio of the atomic number Z to the power of n divided by the atomic weight A, the value of n is between 4 and 5) and is thus disproportionately sensitive to changes in high-Z elements. Fe and, to a lesser extent, Ca are the two elements of most concern for coal producers relying on DUET gauges. Also, the DUET technique uses a highly collimated gamma-ray beam which only samples a relatively small proportion of the coal on the belt. Manufacturers and plant personnel need to ensure that the location selected gives a representative view of the coal; the zone of analysis is along the centre line of the belt, and hence the installation should avoid areas of lateral segregation (Horsley, 2005).

According to Horsley, 2005), the Scantech Coalscan DUET system compensates for the impact of variable Fe and Ca in coal by providing inputs in the software to permit operators to choose the correct calibration set for a particular source of coal. As with all online analysers, it is essential that the unit be calibrated over the full range of expected coals. The organisation has also developed computer modelling software which can predict the expected performance and any impact of variable Fe or Ca, based on proximate and ash analysis data.
Neither laboratory nor online measurements are absolute. The results are subject to variance in sampling, sample preparation and testing. In laboratory ash analysis, a pulverised coal sample is oxidised completely under carefully controlled conditions in a ceramic crucible at 800°C over a period of some two hours. The residue, which consists of the non-combustibles in oxide form, is defined as the ash content. Laboratory ash forms slower than ash deposits in a boiler and at lower temperatures. Online analysers measure the elemental composition of most of the mineral matter present in the raw coal to differing degrees of accuracy, depending on the method used. A composite mineral matter content can then be deduced. The results need to be correlated over a considerable period of time. Any assessment of the accuracy of the results needs to be related to the time frame during which the measurements were taken. As online analysers measure changes in real time, unlike laboratory analysis, they can detect almost instantaneously when high ash material is in the feed.

The Gamma-Metrics Coal Quality Manager (CQM) is an online coal-analyser developed by Thermo-Electron Corporation (USA). As stated previously, most PGNAA analysers use californium-252 as the neutron source. In CQM, the hydrogen in the analyser and the sample slow down the fast neutrons emitted by the Cf-252 until they are thermal neutrons travelling at a speed that allows them to be absorbed into the nucleus of an atom. A sodium iodide crystal is used to measure the energy of the gamma rays emitted by the atoms in a sample. The energy signals are gathered into a histogram of the number of gamma rays seen at each energy level for one minute. This is the ‘spectrum’ that is then analysed. Thermo Electron calibrates each detector crystal to develop the spectrum response for all elements that will be seen in a coal feed. Then each analyser detector is calibrated in the factory with carefully designed standards in a manner that eliminates all inter-element correlations. The result is a robust calibration that is not coal source dependent and especially useful when firing coal blends (Snider and others, 2003).

In the system, average one-minute analyses of mass flow determination to weight, rely on a tachometer input from a sample belt along with a density gauge signal from the coal as it passes through the analysis tunnel. The CQM sample stream has an optimal and constant cross-section for neutrons and gamma rays. The stream flowing through the system and used in calibration verification usually ranges from 4 t/h to 20 t/h and allows for easy access to representative samples of the coal feed. CQM provides minute-by-minute analysis of SiO₂, Al₂O₃, Fe₂O₃, CaO, TiO₂, K₂O and Na₂O in the ash. In some applications, the CQM can be used to blend coal of differing ash composition in order to keep the blended coal ash fusion above temperatures which would otherwise result in slagging or fouling problems (above 2175°F (1190°C)). The system has been used successfully in the cement industry and more recently was applied in the coal-fired power generating sector. An example of the CQM application and performance at the Hunter coal-fired power plant in Utah (USA) is given in Chapter 12 (Snider and others, 2003; Woodward and others, 2003).

The Scantech Coalscan PGNAA is available in two versions. A bi-line system (Coalscan 9500) which can accept coal from primary samplers at a combined rate of between 5 and 50–70 t/h. This is suitable for power plants which have twin feed conveyors to the coal bunker, where either or both conveyors may be in operation. A single analyser can then monitor both conveyors. The bi-line system is also more suited to conveyors where the feed is either intermittent, or runs at very high or very low belt load rates beyond the normal range of on-belt PGNAA. Inclusion of this analyser in a sampling system allows easy verification with conventional analysis. Examples of dual belt monitoring include Hendrina power plant (South Africa) and Loy Yang power plant (Australia).

As an example of what may be achieved with online ash analysis, Faine and Katterhenry (1998) presented the benefits of installing the Energy Technology Inc (ETI) (USA), PGNAA online ash analyser at the Kentucky May Coal Company, M&T mine located near Long Fork in Pike County, KY (USA). Although the mine produces only ~18 kt per month of run-of-mine coal with ash content averaging about 23% and ranging from 6% to 34%, it is a commercial operation showing the actual benefits of applying online analysis techniques at the facility. The mine recovery rate following the installation increased from approximately 60% to about 73%. About 40% of the production was reportedly rejected before installing the online analyser. This dropped to 27% after its installation, adding to mine profitability. It appears that the analyser also enabled the mine to ship 60% of its run-of-mine production directly to customers without washing, which resulted in an annual saving of nearly US$ 500,000. Payback for the online analyser was achieved in less than two months due to the savings resulting from the 130 kt of run-of-mine coal being shipped directly to the user without incurring coal preparation cost. Today the ETI ash analyser is marketed under the combined coal online, ash, moisture and elemental belt analyser, which combines the ETI system with the Analyser Systems (ASYS) (USA) EBA analyser (see Chapter 5).

Online coal ash measurement technologies to achieve greater efficiency and cost improvements are commercially available and used worldwide. Utilisation of these systems depends on the particular application, required precision and coal quality parameters, including ash content, that are of interest.
4 Moisture measurement

Techniques for measuring moisture content include:

- **Capacitance**: based on using a capacitor that measures an increase in the coal dielectric constant as a result of a rise in moisture content. Capacitance meters were used in the 1980s but have been largely superseded by microwave meters (Couch, 1996);

- **Microwave**: when the coal is placed in a microwave field between a suitable transmitter and receiver some of the microwave energy will be absorbed by the coal and the wave attenuated, such that the detected intensity, in terms of amplitude, at the receiver will be less than that being transmitted. A rise in moisture content will increase the degree of attenuation. In addition, microwaves undergo a measurable phase-shift which is also related to moisture content. Phase-shift is defined as the change in the originating signal. Measurement of the microwave attenuation and/or phase-shift with suitable equipment makes it possible to determine the moisture content of the coal. Phase based measurement techniques have been shown to be superior in accuracy of measurement and immunity to variation in material properties such as ash content and particle size (Cutmore and others, 2001; 2000). However, according to Horsley (2005), that is not the case in all applications. A combination of phase shift and attenuation can often provide better results.

Alternative technologies include (Cutmore and others, 2001):

- infra-red analysers are used in a variety of process industries, but rely on the measurement of absorption by moisture in a very thin surface layer. Consequently such probes may be compromised by particle size effects and biased presentation of material. According to Horsley (2005), they may also be ineffective if the material is layered (for example, from different silos) and not very effective on black materials in general (Horsley, 2005);

- nuclear-based analysers measure the hydrogen content in the sample, which may be different to the hydrogen content contributed by water only. Such analysers may also depend sensitively on material presentation and elemental composition;

- very low frequency electromagnetic probes, such as capacitance or conductance probes which operate in the frequency region where the DC conductivity dominates much of the response. In turn, this conductivity is a function not only of moisture content but also of ionic composition and chemistry.

The majority of applications in the coal industry, according to Cutmore and others (2001), have typically involved on-conveyor, microwave-based, measurement of moisture in 50–250 mm beds of coal at moisture contents in the range 10–20 wt%. Microwave based moisture analysers, operating in the 2.5–3.5 GHz frequency band, have been used in such applications. These gauges, although successful, may be improved in order to increase their uptake by:

- lowering cost of analysers;

- wider applicability to thick coal beds or high moisture products;

- improved reliability in operation;

- greater accuracy.

According to Cutmore and others (2001), the microwave transmission technique has the following advantages:

- the technique is a bulk sampling method. A high percentage of material is analysed and therefore the inherent sampling errors of either manual laboratory analysis or surface techniques are reduced;

- the moisture content estimate is mostly insensitive to any biased presentation of moisture, for example, stratification in material with different moisture content. Total wave phase shift is representative of the integrated moisture that exists across the entire sample cross section;

- no physical contact is made between the sensors and the material. This is especially important for materials that are damp or wet, since caking may be a problem in sensors that make contact with the material.

The Commonwealth Scientific and Industrial Research (CSIRO) (Australia) developed a low frequency microwave (LFM) moisture analyser primarily for measurement of bulk moisture in non-standard coal applications involving high moisture material at high conveyor bed depth. However, the technology is also used in measurement involving lower bed depth. A modern modulation scheme, using the general method of up and down-conversion, adapted for measurement of carrier phase was used for the measurement of the phase and amplitude of the transmitted signal. This advance was possible due to the use of inexpensive high performance microwave components developed for the mobile communications industry in the past few years. The transmit and receive circuits were implemented on a standard, low cost, printed circuit board substrate. The analyser uses a continuous dual frequency system allowing for rapid moisture measurement with less perturbation as a result of short-term tonnage or moisture variation. The dual frequency arrangement also allows for narrow-band optimisation of the analyser. Due to the operating frequency of the LFM technique, conventional microwave horn antennas were too large to use conveniently above a conveyor belt. Conversely, open wave-guide structure would result in poor wave directivity which is required to direct most of the wave energy through the coal. Micro-strip patch array antennas were developed using standard, low cost and low profile substrate to provide comparable directivity to higher frequency antenna systems. Wave leakage around the conveyor is thus maintained to acceptable levels (Cutmore and others, 2001, 2000).

Two LFM moisture analysers were installed and commissioned at Dalrymple Bay Coal Terminal (Queensland, Australia) in a large facility that loads more than 40 Mt/y of coal into ships. The analysers were installed on two ship-loading conveyors that each load at rates between
2000–10000 t/h with bed depths of up to 600 mm for porous bituminous coal in the moisture range 16–21 wt%. Each belt is fed by stockpile reclaimers, resulting in large tonnage variations on short (approximately 1 minute) timescales. The tonnage can vary by a factor of 4 (and therefore the material mass per unit area of the coal presented to the analyser varies by a similar amount). Figure 6 shows the moisture variation over entire shipments, with a one-minute moving filter applied. Superimposed on the data are the sampled values determined from manual sampling for each tonnage segment (shown as solid segments). The results demonstrate that the analyser was able to track most large step changes indicated by the sampled data, accurately and reliably. Cutmore and others (2001) state that it should be noted that the level of performance described is for a fairly difficult industry problem. Application of this technology to more ‘standard’ application should result in similar, if not enhanced, performance.

France (2004) discussed online moisture analysis at the Gladstone coal loading port in Queensland, Australia. He stated that one of the most important outcomes of his study was to identify the effects of differing coal types to a standard microwave moisture analyser. While this issue is very important to loading facilities, it is also a factor in applying microwave moisture analysers to power plants, which nowadays also have a variety of coal sources. France (2004) concluded that microwave moisture analysis technology has the capability to provide precise, real time information to process operators. He equalled the precision of this type of analyser to that of conventional sample plant and laboratory combinations.

The development of a low resolution NMR online coal moisture and particle size analysis technique is currently being researched at the University of Nottingham (UK) under the European Commission Research Fund for Coal and Steel (ECSC) project 7220-PR/118 entitled ‘online analysis of coal’.

![Figure 6 Analyser moisture variation over two separate, entire ship-loads (Cutmore and others, 2001)](image-url)
Elemental analysis is a more recent development in online analysers. The main technique used to measure elemental composition of the coal is *Excitation* (for example, prompt gamma neutron activation analysis (PGNAA)) (see Chapter 3).

Although X-ray fluorescence (XRF) spectrometry has the potential to be very sensitive in measuring trace elements, 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. The pellets are either pressed in undiluted form or are first mixed with a binder. A small dilution still ensures high X-ray intensities as required for trace analysis. Unlike with fusion, the volatile elements remain in the prepared specimen, the pressed pellet. For example (van Kroonenberg, 1996):

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample preparation</th>
</tr>
</thead>
<tbody>
<tr>
<td>coal (sulphur content)</td>
<td>pressed pellet</td>
</tr>
<tr>
<td>coal ash</td>
<td>fused bead</td>
</tr>
<tr>
<td>limestone</td>
<td>pressed pellet with some binder (boric acid)</td>
</tr>
<tr>
<td>water treatment sludge</td>
<td>pressed pellet</td>
</tr>
<tr>
<td>slurry gypsum</td>
<td>pressed pellet</td>
</tr>
</tbody>
</table>

Average values for trace elements in international coals are given in Table 3. Analytical methods relating to mineral matter in coal and ash from coal combustion are discussed in detail by Creelman (2002).

Elemental online analysis is considerably more difficult to undertake (and/or less accurate) where the coal comes from a number of sources, as is the case in many coal-fired power plants today. Coal blending is discussed in Chapter 8. The assumptions on which PGNAA analysers rely, that is coal characteristics which can vary considerably in different coals, can cause problems necessitating the development and application of different calibration curves. These assumptions are the bound moisture, the moisture-ash-free (MAF) calorific value and the fraction of the ash not measurable by PGNAA.

The pulsed fast thermal neutron analysis (PFTNA) technique is similar to the PGNAA in that a source of neutrons is utilised to excite a target nucleus. The excited nucleus then radioactively decays by the emission of prompt and delayed gamma rays and other radiation such as beta particles. The emitted radiation is characteristic for the particular target nucleus and can be used to identify it. Development and evaluation of PFTNA based online elemental analysis is discussed further in Chapter 5.

Today, online elemental analysers can be used on conveyor belts and to divert coal with different qualities to different stockpiles for subsequent blending. The instruments can be used to control blending of higher and lower quality coals to produce a feedstock of consistent properties, for example sulphur content.

Early elemental analysers relied on PGNAA and they analysed sample streams rather than full process flow. More recently, through- or cross-belt PGNAA analysers have been developed in order to reduce the cost and complexity of installation of these systems. Several cross-belt PGNAA analysers have already been installed in the United States and Australia. The US Thermo Gamma-Metrics company developed and has already installed at commercial scale a number of their cross-belt Elemental Coal Analyser (ECA). According to Woodward and others (2003) cross-belt analysers have several advantages compared with the PGNAA sample stream analysers including:

- no sampling system required to feed the analyser: that is no sampler, no connecting conveyors, no vertical clearance requirement and no allocation of additional floor or ground area to accommodate the analyser is necessary. However, this makes it more difficult to obtain the physical samples recommended to carry out optimal in-field calibration;

### Table 3 Average values for trace elements in international coals (Creelman, 2002)

<table>
<thead>
<tr>
<th>Element</th>
<th>average, mg/kg</th>
<th>average range, mg/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic (As)</td>
<td>2.69</td>
<td>0.36–9.8</td>
</tr>
<tr>
<td>Boron (B)</td>
<td>47</td>
<td>11–123</td>
</tr>
<tr>
<td>Beryllium (Be)</td>
<td>1.0</td>
<td>0.1–2.0</td>
</tr>
<tr>
<td>Cadmium (Cd)</td>
<td>0.093</td>
<td>0.01–0.19</td>
</tr>
<tr>
<td>Cobalt (Co)</td>
<td>4.5</td>
<td>1.2–7.8</td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>0.091</td>
<td>0.03–0.19</td>
</tr>
<tr>
<td>Lead (Pb)</td>
<td>7.0</td>
<td>1.1–22</td>
</tr>
<tr>
<td>Selenium (Se)</td>
<td>2.15</td>
<td>0.15–5.0</td>
</tr>
<tr>
<td>Chromium (Cr)</td>
<td>17.6</td>
<td>2.9–34</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>10.8</td>
<td>1.8–20</td>
</tr>
<tr>
<td>Manganese (Mn)</td>
<td>40</td>
<td>8–93</td>
</tr>
<tr>
<td>Nickel (Ni)</td>
<td>11.1</td>
<td>1.5–21</td>
</tr>
<tr>
<td>Zinc (Zn)</td>
<td>12.7</td>
<td>5.1–18</td>
</tr>
<tr>
<td>Fluorine (F)</td>
<td>120</td>
<td>15–305</td>
</tr>
<tr>
<td>Chlorine (Cl)</td>
<td>440</td>
<td>25–1420</td>
</tr>
</tbody>
</table>

Online analysis and coal-fired power plants
Elemental analysis

- installed cost: an installed cross-belt PGNAA analyser could be less than US$300,000 inclusive of a moisture metre. This is in contrast to installing sample stream PGNAA analysers which could cost US$450,000–760,000;
- installation time: as there is no additional supporting structure required and no pipes, electrical lines, ladders or electrical panels to be moved, and no new samples and conveyors to be added, installation time is significantly less;
- location flexibility: a cross-belt analyser can be located where it is needed. There are no constraints on particle size, whereas the sample-stream PGNAA analysers are usually limited to 3 inch (76 mm) top-size;
- ease of relocation: as cross-belt analysers are simpler in design they are easier to relocate should the conveyors be moved or the preferred location changed;
- ease of maintenance: although these analysers have tunnel belt liners which occasionally need replacement, they require no level sensors, belt drives or input hopper wear parts which can be subject to intermittent failure and replacement. Some analysers are designed so that there is no contact between the belt and analyser thus removing the need for belt liners.

However, Woodward and others (2003) and Horsley (2005) present the following as limitations of a cross-belt analyser:
- diminished accuracy performance: cross-belt analyser performance is not as good as sample-stream analyser performance due to the variable and non-optimal physics of the coal on the conveyor and the need to subtract the varying effects of the material in the belt itself.
- calibration complications: obtaining physical samples to compare to the analyser is challenging in many cases. Use of reference blocks is also more difficult because of the size of the standards required, especially in wide belt applications.
- conveyor belt materials of construction: cross-belt analysers are not recommended for steel cable belts because of the high and varying iron content in the belt.
- belt designs using PVC reinforcing should be avoided due to their Cl content. This is because Cl content is very responsible to PGNAA and can complicate calibration and lower accuracy.

Performance results of the ECA, according to Woodward and others (2003), are favourable, despite the predicted fall-off in accuracy compared to sample stream analysers which is in the order of 50% or so. The ECA accomplished precision performance of sulphur of 0.05–0.06% and ash of 0.5–0.7%. Figures 7 and 8 show, favourably, laboratory versus analyser comparisons at one of the system installations.

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).

A full-scale NITA prototype analyser was built and tested on 61 bulk (up to 200 kg each) coal samples comprising a mix of run-of-mine and product samples provided by 3 different coal plants. Each sample was mixed, crushed and sub-sampled using a rotary sample divider followed by rifle splitters, to obtain the sub-samples used for chemical laboratory analysis. A standard DUET gauge was also used in the test for comparison and to provide an independent
measurement of sample thickness. Two duplicate sub-samples from each 24 samples were provided to three independent laboratories for analysis. The coal samples ash content was between 6.7% and 49.3% and the range of moisture values encountered was 3.9–21.1%. The results of the ash analysis are shown in Table 4 for each of the thicknesses considered. The total root-mean-square (RMS) error (including sampling error) is around 0.5–0.6% ash for 200 and 300 mm data but significantly poorer for the 100 mm data. If an allowance is made for the estimated sampling error of 0.33%, the 200 and 300 mm RMS errors reduce to ~0.4–0.5%. In contrast Lim and Abernethy (2004) found that both measured and calculated DUET RMS errors are ~2%. If the 200 and 300 mm data are combined, a total RMS error of 0.7% ash is obtained with neutron-gamma data alone and 0.6% if DUET and neutron-gamma data are combined. These reduce to 0.6% and 0.5% respectively if the estimated sampling error is removed.

Furthermore, 24 bulk coal samples, taken in equal proportions from each of the two major coal-producing areas in Australia, were used to test the likely performance of NITA for specific energy measurement. Spectra (1200-second counting time) were collected using both the prototype developed for ash measurement, as well as with a laboratory version optimised for specific energy measurement. The results indicated that an accuracy of ~1.5% relative is likely for coals from a single location or geologically similar locations, and that a similar accuracy could be achieved for samples from significantly different locations, provided appropriate calibration procedures are observed and the gauge design optimised. Applications requiring specific energy measurement rather than ash are usually related to monitoring of power plant coal feed. In Australia, unlike in many other countries, most power plants tend to fire coal from one or several ‘similar’ locations (Lim and Abernethy, 2004).

Coalscan (9500 series) is a PGNAA type belt, online analyser developed by Scantech (Australia). The real time elemental analyser, which is used at several coal facilities worldwide, allows active control over coal quality and provides timely information on ash, moisture, sulphur and energy content. This facilitates decision making that maximises the value of the resource and minimises operating costs. Applications of this Scantech technology in coal-fired power plant include (Horsley, 2005; Scantech, 2005):

- analysis and blending control of coal during reclaim from stockpile to ensure quality targets are met;
- analysis of coal on delivery to power plants to monitor contract compliance and optimise placement on stockpile;
- blending coals to take advantage of lower cost, lower quality coal whilst meeting specifications to improve cost efficiency;
- analysis of coal to optimise boiler feed quality, minimise unplanned/forced outages from slagging or fouling and ensure sulphur emission compliance.

Many of the power plants supplied with this technology use the analyser’s ability to measure sulphur as the key justification for acquiring these systems. The analysers are mainly used to optimise coal blend to keep within emission guidelines without using excessive amounts of premium priced, low sulphur coals. Careful blending of coals can obviate, in some cases, the need for FGD. According to Horsley (2005), online analysis is designed for process control, to optimise the use of the coal and pro-actively control the boiler operation; it is not designed to replace laboratories. The Coalscan elemental analyser is installed at 20 facilities (including production and power generation units) in Australia, China, Republic of Korea, South Africa and the USA. The company also supplies ash and moisture monitors which are used, to date, at 42 facilities in Australia, Canada, China, Indonesia, Malaysia, Russia, the USA and Vietnam (Horsley, 2005).

Analyser Systems (ASYS) (USA) developed the Elemental Belt Analyser (EBA), based on PGNAA techniques with digital signal processing, for real time, elemental bulk analyses for materials travelling on a conveyor belt. The analyser provides minute-by-minute analyses under belt load conditions from about 100 t/h to nominal flow. The system promises freedom of analysing material streams without flow constraints, making it suitable for installation at crusher outlets without incurring extra cost for material handling (surge bins or variable speed belt drives). The combined ash, moisture and elemental belt analyser (AM-EBA) is a combination of the EBA and ETI (see Chapter 8) online analysis techniques. The AM-EBA promises improved

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**Table 4  Summary of results for ash analysis and comparison with DUET (Lim and Abernethy, 2004)**

<table>
<thead>
<tr>
<th>Ash, %db</th>
<th>Depth, mm</th>
<th>No of data points</th>
<th>Total rms error¹, %</th>
<th>Estimated rms error², %</th>
<th>CC³</th>
<th>Measured DUET rms error, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7–30.8</td>
<td>1/2/300</td>
<td>25</td>
<td>0.5</td>
<td>0.4</td>
<td>0.996</td>
<td>2.38</td>
</tr>
<tr>
<td>6.7–49.4</td>
<td>100</td>
<td>40</td>
<td>1.0</td>
<td>0.94</td>
<td>0.996</td>
<td>1.87</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>43</td>
<td>0.55</td>
<td>0.44</td>
<td>0.999</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>43</td>
<td>0.51</td>
<td>0.39</td>
<td>0.999</td>
<td>1.86</td>
</tr>
<tr>
<td></td>
<td>2/300</td>
<td>86</td>
<td>0.70</td>
<td>0.62</td>
<td>0.998</td>
<td>1.86</td>
</tr>
<tr>
<td></td>
<td>2/300</td>
<td>86</td>
<td>0.59</td>
<td>0.49</td>
<td>0.999</td>
<td>1.86</td>
</tr>
</tbody>
</table>

1 Total rms error, including sampling error
2 Estimated rms error if estimated sampling error is removed by subtracting in quadrature
3 Correlation coefficient

---

Online analysis and coal-fired power plants
measurement precision, long-term calibration stability, reliability and operational efficiency. It is a real time, belt-load independent, full stream analyser which measures ash, sulphur, nitrogen, chlorine and coal ash elements. Experience with the ASYS/ETI full stream elemental analyser is presented by Swindell (2004) while elemental analysis of blending control at the A&G coal (USA) (Paragon unit train load-out) through integration of the ASYS/ETI full stream elemental analyser is discussed in detail by Grigsby and others (2004).

The Minnkota Power Cooperative Milton Young power plant is a two unit, cyclone-fired, minemouth plant located near Center, ND (USA). Unit 1 (250 MWe) began operation in 1970 and unit 2 (460 MWe) began producing power in 1977. Coal is supplied from an adjacent lignite field. Both units are base load, operate at 95% availability and, according to Schwalbe and others (2004), are ranked among the lowest cost lignite-fired producers in the USA. Furnace slagging and fouling associated with the lignite fired at the plant have continually impacted boiler operation. In 1998, the project ‘matching coal quality and boiler operation’ began at the facility. Work began soon after on boiler optimisation and to determine the effects of coal quality on cyclone performance. Impacts of coal quality on plant performance were observed including the variability of lignite having a significant impact on cyclone performance. Sampling showed that variations of 800 Btu/lb (1860 J/kg) from cyclone to cyclone occur in the coal being fired. This makes it difficult to control optimum cyclone air to heat input ratio when coal flow is controlled on a lb/h (kg/s) basis and large variations exist in coal heating value from cyclone to cyclone. Also, ash content varies from 5% to 25.5%. Center lignite can contain high levels of illite clay material which has a 1–3 Al/Si ratio and high levels of potassium that cause wall slagging and high temperature fouling contributing to the mass of deposits. Furthermore sodium and calcium are primary contributors to deposition problems. Sodium is the key variable monitored for the purpose of predicting convection pass fouling rates. Sampling showed that sodium varies from 0.6% to 13.0% and calcium varies from 6.8% to 24.0%. Moreover sodium content from mine core samples showed strong correlation to furnace fouling rates. An increase of 5.5–7.0% in average sodium content of coal burnt during an operating period will cause plugging of the gas passages to occur 30–40 days sooner (Schwalbe and others, 2004).

According to Swindell (2004) with respect to coal quality as reported by the online analyser at the Minnkota plant, the most important observations made at the time were:

- online analysis showed the same correlation to cyclone slagging that conventional sampling had shown. Coals with base to acid ratio less than 0.6 cause cyclone slagging and require firing oil;
- online analysis showed that about 15 consecutive truckloads (2600 tons/2360 tonnes) of coal with base to acid ratios greater than 1.5 and ash less than 6% affect opacity and eventually result in exceeding opacity limits;
- with very limited experience, it seemed that online analysis could be used to quickly correlate changes in coal quality to changes in boiler operating parameters;
- the analyser is used to monitor coal on a truck-by-truck basis as it is delivered from the mine. When a coal quality parameter is out of an acceptable range, mining personnel make changes in load and haul operation;
- the analyser is also used to detect and reduce the amount of coal delivered with a base to acid ratio less than 0.6;
- it is also utilised to avoid delivery of consecutive truckloads of high base to acid ratio, low ash coal.

Swindell (2004) concludes that the project goals were met and favourable results were demonstrated. Evaluating the ability of the full stream elemental analyser to provide precise and accurate data for lignite coal was a complex and challenging task. However, the exercise has shown that online analysis can provide information necessary for effective blending and solutions to ash-related problems, thus resulting in effective coal quality management.

Belbot and others (1999, 2000, 2001) reported the development of an online elemental coal analyser based on the pulsed fast thermal neutron analysis (PFTNA) technique. The analyser uses a pulsed deuterium-tritium (d-T) sealed tube generator that produces 14 MeV neutrons. This type of neutron source was chosen because it reportedly enables the use of both fast and thermal neutron reactions. By separating the fast from thermal reactions, with the use of a pulsed source, more elements can be measured with greater accuracy. A prototype analyser was built at the Western Kentucky University (USA) and was discussed in detail by Belbot and others (1999). Belbot and others (2001) discuss the development of a commercial analyser. This commercial model is housed in a temperature controlled land-sea container and is sufficiently shielded so that the emitted neutron radiation is below occupational limit immediately outside the container in areas where personnel will be present. This allows maintenance and other work to be carried out near the analyser while it is in operation. A sampler and conveyor belt are used to divert coal from the main conveyor belt and feed it to the top of a vertical chute inside the analyser. An exit conveyor below the analyser returns the coal back to the main conveyor belt. The speed of the conveyor belt below the analyser is adjusted so that the main chute is always filled to the top with coal. The analyser can handle coal up to 10 cm in size at a maximum flow rate of 300 tons/h (272 tonnes/h).

The main chute is surrounded by a neutron generator, several gamma ray detectors and a neutron detector for monitoring the output of the neutron generator. All aspects of analyser operation such as data collection, analysis and display of data, coal movement, diagnostics are controlled by a master computer programme. The programme is equipped with diagnostics that monitor the devices associated with the analyser and alert the operator of any errors and provide him/her with the appropriate corrective action. The programme also allows remote control of the analyser so that the operator need not be located nearby thus eliminating the need for a control room and making the analyser more compact (Belbot and others, 2001). In 2004, Belbot and others discussed the evaluation and performance of the PFTNA online coal analyser at TVA’s Cumberland coal-fired power plant. Thomas (2005) stated that the results were
somewhat disappointing. Work continues on improving the performance of the analyser.

EADS Sodern (France) has developed the CNA PGNAA type, elemental, belt analyser that measures the atomic composition of the coal from which the heat, ash, mineral, sulphur, volatile matter contents, acid to base ratio and slag viscosity are computed. The CNA comprises a measuring chamber, an electronic cabinet and radiation shielding which also serves as casing for the analyser. Coal is transported onto the conveyor belt which goes through the middle of the measuring chamber. The measuring chamber includes a neutron emission module containing the neutron tube, materials to optimise neutron utilisation, gamma photon detectors and absorbent material. The neutrons emitted by the tube scan the material on the conveyor belt and the resulting gamma photons are collected by the detector (a photoscintillator). This results in brief electrical impulses which are transmitted to the electronic acquisition devices whose task is to measure their energy and to produce a histogram (spectrum) of the coal analysed (Flahaut and others, 2002). The Sodern system comes with a readout screen that indicates all the proximate data (moisture, ash, sulphur, heat value). In addition it shows ash chemistry constituents, base/acid ratio, and $T_{250}$ temperatures. This type of information, when accurate, could be useful in a power plant that incurs problems with fouling or slagging. An advantage of the Sodern analyser is that it mounts directly over the belt and does not require a sampling system. Installation costs of the analyser are in the US$ 1 million range (Thomas, 2005).

Woodward (2005) discusses the current state of online coal analysis including the development and installation of conveyor-belt analysers for full stream sampling. In his review he states that belt analysers are acceptable with:

- steady flow or with variations not outside 50–100% of CEMA full load (see Figure 9);
- modest accuracy requirements;

- sampling system nearby to assist in field calibration and performance evaluation;
- belt size between 75 and 150 cm;
- idler angle between 35 and 45 degrees;
- no tramp metal detector nearby;
- belt scale nearby and preferably upstream;
- no steel cords in belt.

According to Horsley (2005), Scantech systems accept belts between 80 and 200 cm and trough (idler) angles between 25° and 45°, over the range of nodes.

A sample stream analyser is preferred when (Woodward, 2005):

- superior accuracy is required;
- user wants the analyser to estimate ash fusions;
- there is already a sampling system with which the analyser can be integrated;
- belt loading is highly variable and sometimes quite low (0–40% of CEMA maximum);
- belt size exceeds 150 cm, especially if the coal is layered, or according to Horsley (2005), bed depth exceeds 350 mm approximately. At greater depths, neutron-gamma interactions at the base of the bed may be masked by the thick coal bed above.

Considerations in applications of cross-belt analysers are discussed further by Empey (2004). Foster (2004) presented two case studies on the use of PGNAA belt analysers to meet quality train targets for both total ash and sulphur at a 6–8 Mt/y Western US mine and total sulphur at a multimillion t/y mine at Illinois Basin (USA). The success of both applications led to the acquisition of a second unit for both customers.

Elemental analysis based on X-ray fluorescence (XRF) for online determination of steam coal constituents was the subject of an Austrian project between GKB-Bergbau GmbH and INDUTECH Bachmann und Klein GmbH. The former is
the last considerable remaining producer of lignite in Austria and the latter is a company which has been performing online analysis of coal for over a decade. Investigative work on the online analysis of sulphur content in the lignite from the GKB mine began in 1999 following a previous, successful research and development project between the companies for the online ash and moisture determination of the same coal. The sensor of the XRF coal analyser is mounted in a steel box directly above the coal stream. The measurement is taken through a window in the bottom of the box. Low energy X-rays are used to excite the characteristic radiation of the coal. The signal is sensed with a silicon detector and fed to a multi-channel analyser. Spectrum evaluation is carried out with a standard PC. The technique can be used for the detection of elements with an atomic number of 10 and above and to determine derived values such as ash content, calorific value and in some cases also the content of volatile matter. Application of the project began in 2000 with the development of an analyser for the continuous and precise measurement of the sulphur content at the Voitsberg coal fired power plant. Measurement is carried out online on a bypass of the lignite to be delivered to the plant according to standards. The particle size of the bypass is <7 mm. After numerous tests, adjustments and calibration, the results obtained with the online analyser of the sulphur content in the lignite was considered sufficient for the purposes of the supplier. The standard deviation of the XRF values in a long-term test was 0.08% at a medium total sulphur content of 0.91% (based on conventional analysis) (Landsman and Bachmann, 2002).

INDUTECH were also involved in developing an XRF analyser with EPRI and Process Control Inc (USA). A prototype analyser was tested in 1998 at the Detroit Edison Monroe power plant where a blend of Appalachian and PRB coals are fired. Initial tests required a 5-minute stream of coal to perform a short proximate analysis. The device measured moisture, ash and sulphur. The calorific value was inferred from the data and from these values SO2 emission was determined. The prototype had excellent correlation with ash spectra when compared to classical ASTM analysis. The installation is discussed in greater detail by Fiscor (1999). The author states that although the technique is not as precise as PGNAA, it is economically more viable and offers 95% of the features of a PGNAA analyser at less than half the cost. Fiscor (1999) also says that as the system requires no radioactive sources, it provides greater reliability and safety. According to Horsley (2005), a similar installation was was installed in Australia but had problems with material presentation due to variable pyrite which caused varying matrix effects. The system was replaced by an on-belt PGNAA instrument. Improved online XRF elemental analysis of coal is discussed by Klein and Ritter (2004).

Chadwick and others (2003) presented their findings on application of another technique called laser induced breakdown spectroscopy (LIBS) for elemental analysis in the coal industry. In the LIBS technique a laser pulse is used to form a small, high-temperature and high electric field region on the surface of the sample being analysed. A portion of the sample is vaporised during the laser pulse to form a plasma of the sample components containing electronically excited atomic species. Fluorescence from the plasma is resolved using an optical spectrograph to yield the elemental composition of the coal. According to Song and others (2002), LIBS has been used extensively in both qualitative and quantitative studies for the analysis of elemental species in solid, liquid, gas and aerosol substances. The Cooperative Research Centre (CRC) for Clean Power from Lignite (Australia) has developed a compact, self contained device that determines the elemental composition of coal and coal ash using LIBS technology. The device, known as the Laser Plasma Spectrometer (LPS), can undertake simultaneous elemental analysis of coal components and can identify Al, Ar, B, Ba, C, Cu, Cl, Ca, F, Fe, H, He, Mg, Mn, N, Na, O, P, Pb, Si, Sr, Ti and Zn. The technology is marketed by Laser Analysis Technologies Pty Ltd (Australia) as the Spectrolaser series of analytical instruments. Development and evaluation of the Spectrolaser for coal testing is discussed by Body and Chadwick (2002). The Spectrolaser instruments are integrated analysis systems comprising excitation laser, optical spectographs and gated detectors. The instruments are also fully software controlled. These instruments are now operating in coal applications in Australia, exclusively in the analysis of low ash lignite at Loy Yang Power and Hazelwood Power. They are also installed in Indonesia in Kalimantan to analyse a range of sub-bituminous and bituminous coals.

According to Chadwick and others (2003), the technique can be improved further by applying multi-variate analysis to the data to correlate the measured sample fluorescence (from all the observed elements and molecules) to other bulk properties of the coal. Applications include the measurement of calorific/heat value and moisture in the coal as well as trace elements that are not otherwise directly determined. Correlation between LIBS spectra and material bulk properties is however still at an early experimental stage. Work continues to investigate its wider application across coals of different rank and composition and also its application in long-term process optimisation. Forecast analytical cost savings are approximately 100,000 US$/y for a power plant implementing the technology. Chadwick and others (2003) conclude that this enables the user to recover the capital cost of the equipment within twelve months.
Available and experimental techniques that can be used to estimate the rank of coals include (Sakurovs and others, 2001a):

- coal fluorescence
  - rank determination (available): by measuring the extent of fluorescence of macerals in the coal that is altered on continued exposure to light;
  - fusibility (experimental): using fluorescence to measure the percentage of fusible material in a coal
- imaging (research tool): using X-rays, gamma-rays; ultrasound, capacitance, positron (positive electrons) and magnetic resonance;
- intelligent gravimetric analysis (IGA) (moisture and gas adsorption) (available): an automated method for measuring moisture and gas uptake and release by coals. IGA measures the weight rate of change of coal or char submerged in an atmosphere;
- high temperature nuclear magnetic resonance (NMR) (direct measure of coal fluidity) (available): measures the relaxation of the nuclear magnetic momentum at elevated temperatures. The signals measure the extent to which a coal becomes plastic during heating;
- room temperature NMR (available): is a low cost technique that allows the examination of NMR signals of coal at room temperature. The technique measures the characteristics of the proton nucleus and correlates these signals with other characteristics of the coal. It can also distinguish between water associated with mineral matter in coal and water associated with the organic part of the coal;
- whole coal reflectance (rank determination) (available): an automated technique developed to measure vitrinite reflectance with greater accuracy and speed compared to conventional methods. This technique, rather than attempt to differentiate vitrinite from other macerals by analysis of its appearance under a microscope, uses the property that the random reflectance of vitrinite is normally distributed to estimate the amount of vitrinite present in the coal;
- infrared techniques (available): measure the reflectance of infra-red (IR) light, which is related to the structure of the coal.

The development of instrumentation for the online analysis of coal for application in coal mines and power plants is the subject of a research programme of the European Commission Research Fund for Coal and Steel (ECSC Project 7220-PR/118). The scope of the work involved the development, improvement and testing of online analysis systems (such as gamma-ray transmission, nuclear magnetic resonance (NMR) and infra-red (IR) spectroscopy) that are capable of accurate, real time prediction of coal rank and properties and, suitable either for mining and blending or for power plant control. Work on the project began on 1 November 2001 and was given a completion date of 31 October 2004. However, a new completion date was set for 30 April 2005 due to delays by some participants. The participants and their activities in the project are (Andrés and others, 2004):

- Consejo Superior de Investigaciones Científicas (CSIC) (Spain) (Coordinator): sample collection and analysis from other partners and spectra acquisition. Review of former data and testing of new numerical methods. Good results obtained using cluster classification and promising in the mid-infra-red range;
- RWE Rheinbraun AG (Germany) (Contractor): test operation in Hambach mine, including optimisation sampling and calibration. Planning of the second unit. Test finalisation and normal operation in Neurath. Estimation of reliability. Preparation in Niederassen and Garzweiler mines;
- EVN AG (Austria) (Contractor): analysis of operation and development of relationships between coal analysis and measured parameters in the coal boiler. Evaluation of sampling methodologies. Effect of the coal brand in the analysis;
- University of Nottingham (UK) (Contractor): using low resolution 1H NMR online, installation of the equipment, analysis of the coals and correlation with several properties. Development of pulse sequences and application of data treatment to improve analytical results;
- Public Power Corporation SA (PPC) (Greece) (Contractor): Determining the correlation of ash measurements (online and laboratory). Field test of the analyser in Megalopolis mine. Improving the calibration to accommodate lignites with special ash characteristics.

The objective of the project is to develop an online coal analyser based on infrared spectrometry. In phase 1, CSIC demonstrated the feasibility of designing a device based on infrared spectroscopy for coal analysis and gave guidelines for its design. The guidelines were that the system should be based, roughly, on medium infrared range (MIR), should not have mobile parts and spectra acquisition should be carried out by transmission techniques, avoiding those based on reflection which led to higher calculation errors. Such a device does not currently exist according to Andrés and others (2004). Using transmission and reflection techniques, data analyses were carried out and spectra of new samples were generated in both near- and mid- infra-red (NIR and MIR) ranges. A spectrometer, capable of operation in the 400–7500 cm⁻¹ range (MIR and part NIR) was installed. Numerous tests were carried out on a variety of coals from different mines. Andrés and others (2004) state that early results indicate that the technique is usable and yields good prediction values in line with the requirements of the International Organisation for Standardisation/American Society for Testing and Materials (ISO/ASTM) norms. Further work continues on the project.

Within the scope of the ECSC project (discussed above), different open cast lignite mines in Germany were equipped with selected online measuring systems. The work included (Andrés and others, 2004):

- test operation of a system in Hambach mine for optimisation of the sampling procedure;
- reference samples in Hambach mine to check and improve the analytical precision of the sampling procedure;
- planning and start construction of a second online analyser for the Hambach mine;
- preparation and start replacement of an existing online analysis system with a new one at the Garzweiler mine;
- calibrating and putting the new system into operation.

The purpose of the project was the implementation of online X-ray fluorescence (XRF) analysis techniques, in two stages, to improve the mine performances. Stage one involved the installation of an online analyser for the main coal stream at the Hambach mine on one conveyor belt transfer point before the coal bunker. In stage two, a second online analysis system was installed at another conveyor belt transfer point at Hambach, also prior to the coal bunker. Also in stage two, two online analysers were installed at the coal bunker entry at the Garzweiler mine and the existing online control system at the bunker exit was removed.

Test operation of the XRF-based online analyser and sample preparation (stage 1) at Hambach began in January 2003 with integration into the plant data system planned for three months later. In May 2003, 62 reference samples were taken of the coal after the second mill (same material as taken for online analysis) for laboratory analysis to test the precision of the online analyser. The total material was collected over a time in which 5–8 data sets of the online analysis were made. The online data were compared with the data from the laboratory testing and with the coal database for the mine. The online and laboratory data were used to recalculate the calibration functions using the reference samples as calibration samples. A good fit was reached but for some coals and parameters, especially for iron, further improvement was deemed necessary. The second analyser was installed in stage 2 of the project (also in 2003). However, in the second setup, the mill is equipped with a sieve to produce an upper grain size of 2 mm for the material taken for analysis instead of 4 mm as was the case with the first analyser. This is expected to show a better recovery of iron. If so, the finer milling equipment will also be installed at the first analyser (Andrés and others, 2004).

At the Garzweiler mine, the planning for the transfer of the existing analysers located at the stockpile entry since 1985 and the analysers situated at the stockpile exit since 1997/99 was completed in early 2003. The new analysers were installed only at the stockpile entry on the basis that when entry is well controlled no more online analysis at the stockpile exit is necessary due to the improvements in coal quality data management achieved with the modern system. The replacement was completed in September 2003. A reliable mechanical sampling device for the mine was not available. Near the end of 2003, tests were undertaken to ascertain whether a rod type sizing system (similar to that at the Hambach mine) was suitable for sampling of the Garzweiler coal. After installing the analysers, the system was tested for one month. Calibration was made on the basis of old calibration samples and then adjusted by means of selected samples of the new set of calibration samples. New calibration will be undertaken after installation of the new mechanical sampler (Andrés and others, 2004).

The Public Power Corporation SA (PPC) (Greece) investigated the possibility of using a commercial dual energy gamma ray transmission analyser for the analysis of lignites from the West Macedonia Lignite Centre (WMILC) under the ECSC online analysis of coal project. One such analyser was installed on a conveyor belt that transports run-of-mine lignite either to the silos of the thermal power plant Megalopolis B or to the mine stockyards. The only data available for analyser calibration were the elemental analyses of the mineral matter contained in the homogenised lignite that is fed to the power plant. The data were considered not representative of the range of qualitative fluctuations of the run-of-mine lignite. Therefore, further static and dynamic tests were carried out to improve the calibration of the device. For the purposes of static testing, eight samples of lignite were prepared and each sample underwent ten online measurements. The total number of measurements was 80. Each measurement was then compared with the average ash content determined by two independent laboratories. Summary results of the static comparative tests, shown in Table 5, indicated that the online analyser measurements met specified targets.

Dynamic tests of the online analyser were carried out in two phases. The conveyor belt, fitted with the online analyser and sampler, feeding rate was 1600 t/h which is close to the maximum capacity of the system (2000 t/h) at the plant and is the rate used under normal operating conditions. Fluctuations of the conveyor loading rate were therefore at a minimum and the duration of each measurement, at 30 s, reduced the possible occurrence of testing interruptions. Each sample was formed of 15 increments. Each increment was collected in a 2-minute period and weighed 82 kg. During the sampling procedure, five successive increments, collected within a 10-minute period, were mixed, forming a single intermediate increment that was compared with the average online analyser measurement that was recorded for the corresponding 10-minute period. This means that the number of laboratory analyses required was 120 and the collected increments were 600 (see Figure 10). The entire sampling process was coordinated from the plant control room at Megalopolis B. The start of each sampling cycle was controlled by the operator of the system. The quantity of the lignite collected in each intermediate increment was 410 kg.

### Table 5 Static online measurement deviations compared to ash concentrations determined in laboratory analyses

<table>
<thead>
<tr>
<th>Different range between online measurements and laboratory analyses</th>
<th>Number of measurements within the range</th>
<th>Results</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;±1.5%</td>
<td>70</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>&lt;±3.0%</td>
<td>10</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>80</td>
<td>80</td>
<td></td>
</tr>
</tbody>
</table>
corresponding to 0.155% of the entire lignite quantity passed through the online analyser in 10 minutes, which varied between 250 and 270 t. The results of the first phase of the dynamic comparative tests are given in Table 6, showing that the target of 80% deviation in ash content <±1.5% was not met and also that in five cases the deviation exceeded ±5%. Andrés and others (2004) state that it is worth noting that even though 41 tests were carried out, only 101 lots were collected (instead of 123) due to operational problems with the conveyor belt.

According to Andrés and others (2004), results evaluation must take into account that the sampler is located within (after) the pulveriser that produces lignite of 4 mm grain size. Therefore, the collected increments were more homogeneous compared to the lignites that passed through the online analyser. Also, during the dynamic tests carried out in phase 1, it was impossible to feed the system with the whole range of lignites produced from the Megalopolis mines (lignites from all the different seams of the three mines in the Megalopolis area). The lignite fed to the system corresponded to the marginal qualitative characteristics of the lignite deposits rather than the lignite characteristics that are more likely to be fired in the power plant under normal operating conditions. It was concluded that in phase 1, overall performance of the online analyser was satisfactory. Phase 2 dynamic testing began after the following modifications:

- isolation of the device from external radiation (construction and placement of a metal cover);
- reduction of the measurement ranges for the source of high frequency (Am) for reducing the noise that is recorded in the receiver;
- increased measurement frequency from 60s to 25s for increased analyser sensitivity.

The results obtained during this phase are given in Tables 7 and 8, the first of which refers to pair comparisons between increments while the other refers to pair comparisons between samples. Comparison between the results of dynamic testing in phases 1 and 2, shows considerable improvement in the system, as presented in Table 9.
Based on the results obtained in the second phase of dynamic testing, Andrés and others (2004) concluded that:

- the dual energy gamma ray transmission analyser works well, exhibiting ±1.5% deviation, in most cases, from the laboratory measurements;
- analyser measurements were precise and independent from the belt conveyor load and the frequency of the ash content fluctuations;
- where the deviations of the online analyser measurements of ash content in comparison to standard laboratory analysis are higher, these may be attributed to:
  - analyser operational problems, especially where mineral matter fluctuations were large;
  - limitations in the applied pair comparison procedure (for example, improper timing of the online measurement and increment collection and stochastic errors introduced during sample processing);
- where the targeted deviations range of ±3.0% is exceeded these are due to lignite feed from certain parts of the mine where the deposits have extreme quality characteristics;
- general analyser performance is considered adequate for monitoring fluctuations of the lignite ash content where it is supported by a reliable database of the deposit quality characteristics; otherwise, the systematic measurement of a second parameter, such as lignite density, could improve the precision of the ash content measurement.

Further work planned at the facility involves investigating the improvement of the online analyser precision and evaluation of system reliability in extended operating periods. Furthermore, the relationship between online ash content measurement and ash composition will be studied in order to understand and maybe explain the reasons for the deviations between the online measurements and the laboratory analysis results (Andrés and others, 2004).

Also under the EU ECSC project, two XRF-based online analysers (after the automatic samplers and no further pulverising; pre-filter coal size 1 mm) were installed and started operation at the Neurath, lignite-firing, power plant in Germany in Sep/Oct 2002. Each system analyses about 700 samples a day, depending on power generation. The data showed, on several occasions, that the supplied coal qualities were not according to specification. In 2002, the analytical precision of the systems for several parameters and concentrations was considered insufficient. Therefore, tests were carried out to optimise the calibration functions and plans were developed to reinforce the systems. Fifteen coals after undergoing different pulverising and milling procedures were analysed with two different analysers (a built in and a semiconductor analyser with and without Helium covering). The procedures included:

- milling: 1 as in power plant after the built in mills
  2 milled <2 mm by hammer mill
  3 milled <1 mm by roller mill (prototype)
- pre-filter: a 1 mm (as built in)
  b 0.4 mm (as in the mines)
- analysis: x existing analyser (with gas-filled detector)
  y advanced analyser (semi-conductor)

Evaluation of the above showed that (Andrés and others, 2004):

- for sulphur and calcium, the existing combination was sufficient;
- for iron, milling 2 and analyser y were sufficient, better results were not achieved with finer milling;
- for silicon, aluminium and potassium, a significant improvement was achieved by finer milling and use of analyser with helium, z, especially in the cases of coals containing sand and poor clay.

Best XRF intensities were achieved after milling the raw lignite to <1 mm and application of helium flushing which is important especially for the determination of aluminium and silicon. However, as these measures were deemed expensive and did not guarantee good results, and as no long-term experience with the prototype mill was available, the decision was taken in November 2003 to carry out the following in steps:

- first integrate a fine mill in one analyser;
- test the function and reliability of the mill in the system;
- install the advanced analyser and carry out tests for data precision;
- reinforce the second system.

Andrés and others (2004) state that this procedure had the advantage that investment risks were small but the disadvantage that after each step, an adjustment or re-calibration of the system was necessary.

Two further XRF-based online analysers were installed at the German Niederauheim power plant in 2002, also under the ECSC online analysis of coal project. Initial tests indicated the following main problems which were duly resolved (Andrés and others, 2004):

- a strong electronic signal interfering with the XRF signal. Occurrence and intensity of the signal interference was dependent on the velocity and load of one conveyor belt of the coal pulverising station. All attempts to eliminate the interference by shielding, ground connection or insulation failed. Finally a special electronically controlled power supply (ups) was installed very close to the analysers. This eradicated the interference;
- the second shredder of the sample preparation unit did not achieve its specified performance as the resulting sample surface was too rough for XRF measurements. After numerous tests including varying the knife size and distance as well as the coal throughput, it was decided that the existing shredder could not achieve the required sample fineness and coal throughput. As a result, a new design of a roller pulverising mill was developed initially at pilot scale. Following several weeks of testing with different coal types and optimisation, the mills were constructed in June 2002;
- initial measurements (June/July 2002) indicated that when outside temperature was above 35°C, the built-in cooling unit for the XRF detector was insufficient and an
additional cooling unit had to be installed for each analyser.

Technical difficulties were encountered at first operation in October 2003. These were resolved and a second test operation began in December 2003. The analytical precision of the system was due to be tested in the first half of 2004 (Andrés and others, 2004). No further information was available at the beginning of 2005.
Traditional measurement of trace metal species is based on extractive systems. Typically, this consists of a heated inert extraction probe, with a cyclone and/or filter to remove particulate matter entrained in the flue gas stream and a series of liquid-filled ‘bubblers’ containing a range of oxidising agents designed to trap the trace metals in the solution. Whilst the techniques are reliable, they can suffer from a number of practical limitations. In general, they require significant volumes of flue gas to sample in order to build up concentrations of the metals in the liquid phase and this requires sampling times of the order of one hour. Hence, the method gives poor temporal definition and is effectively suitable only for time average measurements. Preparation of each sampling train is also time consuming and so, costly. Finally, as the period required to analyse the collected solution is typically of the order of a day or more, such methods are not usable for online, real time measurement and control (Irons and others, 2000).

According to Irons and others (2000) the only methods that appear to be capable of direct trace metal species measurement in the gas phase involve a spectroscopic approach including:

- **mass spectroscopy**: conventional mass spectrometers are not considered suitable for online plant use due to size, complexity and cost of equipment. Portable instruments have not been used to measure the elements of interest in coal-firing plant and are likely to be ‘not sufficiently’ sensitive;
- **atomic emission spectroscopy**: as the atomic vapours of many elements emit light at characteristic wavelengths when heated in a flame, these, theoretically, can be measured (at the relevant wavelengths) in the high temperature zones of a combustor. However, the intensity of the emission is proportional to the fourth power of the absolute temperature and therefore a very accurate measurement of the temperature at the measurement point is required to allow quantitative measurements. Also, the intensity of the atomic emission would be very small and impossible to distinguish from the general background radiation from the flame;
- **atomic fluorescence spectroscopy**: the atomic vapours of many elements absorb radiation at a particular wavelength to produce excited atoms. A fraction of these excited atoms lose energy and emit radiation, often at a different wavelength to that of the excitation source. In this process, which is called atomic fluorescence, the fluorescence can be measured by a suitable detector located at right angles to the light source beam. The elements in the case of coal firing fluoresce in the ultraviolet region of the spectrum and so the fluorescence signal is not temperature dependent and can be very sensitive. However, this method is not usable in the furnace section of a combustor as the small fluorescence signal would be swamped by background radiation from the flame. Although it may be possible to use this approach in the cooler sections of a boiler, this would necessitate filtering of the flue gas stream as reflection of light from the particles would add to the detected signal. The technique requires a light source that emits an intense and very narrow spectral peak at the required wavelength. Producing such a narrow peak using a broad band light source and filters or monochromators is not possible. According to Irons and others (2000), hollow cathode lamps that produce light by application of a high voltage between an anode and a cylindrical cathode coated with the element of interest produce the necessary sharp peaks and are commercially available;
- **atomic absorption spectroscopy**: the atomic vapours of many elements absorb light at characteristic wavelengths for the element. At low levels of absorption, the concentration of elemental vapour is proportional to the amount of light absorbed. The light sources used in atomic absorption spectroscopy are the same as those used in atomic fluorescence. However, where a sufficiently sensitive detector is used, the intensity of the sources need not be so high for atomic absorption. The detector is located so as to receive the light from the source directly and the atomic vapour generated between the source and detector. The atomic vapours of the elements in pulverised coal combustion also absorb in the ultraviolet region of the spectrum. The technique is suitable for use in the cooler sections of a boiler. However, the method is less sensitive to particulate matter in the gas stream than atomic fluorescence;
- **laser induced breakdown spectroscopy**: in this technique a laser beam is focused at a point in a gas stream where measurements are to be made. Rapid pulsing of the laser generates a high intensity spark which results in the formation of a high temperature plasma at the measurement point. The temperature is sufficient to break down many gaseous and solid species to form an atomic vapour, from which the emissions can be measured with a detector coupled to a spectral analyser. The laser does not require tuning to any particular wavelength as it is only used to generate the spark. The technique also produces strong emissions due to the high temperatures generated. However, in practice, the noise generated in the spark reduces the sensitivity to below the levels required to measure the species of interest at the concentrations likely to be present in the flue gas;
- **tunable diode laser absorption spectroscopy**: in this technique, the laser wavelength is tuned to the infrared absorption wavelength of the target atoms and molecules and the laser beam passed through the measurement area. By tuning the laser beam wavelength to the desired gas absorption line and by precise measurement of the absorption level of that beam it is possible to determine the concentration of the gas. Resolution of the measurement is generally expressed in ppm.

Atomic absorption spectroscopy is one of the most common types of analyser used for mercury measurement in coal-fired plant as it is well developed, sensitive, relatively inexpensive and can analyse a gas stream directly. Online and
conventional methods for trace metal species measurement in the gas phase are discussed by Irons and others (2000) and in a previous IEA Clean Coal Centre publication by Sloss and Davidson (2001). Atomic spectroscopy is discussed in detail by Bings and others (2004) while plant and environmental monitoring using state-of-the-art laser diagnostics is presented by Deguchi and others (2005) and Duret (2004). Continuous emissions monitoring (CEM) techniques and application were the subject of a previous review by Sloss (1997). The use of flue gas CEM data to determine coal analysis is the subject of a paper by Munukutla and Craven (2004). However, CEM will not be discussed further in this review.

One of the main factors in optimising boiler combustion, efficiency and emissions is to have the overall oxygen level (air to fuel ratio) as low as possible while maintaining acceptable boiler operation. To achieve optimum levels is often difficult given that many problems, such as emissions production, corrosion and slagging occur as a result of localised conditions within zones in the boiler rather than from macro conditions. In addition, combustion optimisation at a point in time may be inadequate as load, coal composition, air and coal flow as well as distribution change continuously. An online measurement system that indicates when the combustion is outside the optimum zone throughout the boiler would help in achieving maximum performance and minimum undesirable consequences through manual or advanced process control (Palmer and others, 2003).

Oxygen analysis in flue gas made major advances in the 1980s with the introduction of reliable in situ measurement tools. Extractive, mainly paramagnetic devices were widely used as the only source of continuous measurement until the introduction of the zirconium oxide in situ measurement techniques. According to Horton and others (2002), paramagnetic analysers performed well when the sample system worked properly. However, the sampling system created problems in getting a reliable measurement. Also, the system, being extractive, was considered labour intensive and frequently changing. Most of the problems with the sampling systems were caused by acid condensation from the SO3 in the boiler flue gas. Since the oxygen readings were unreliable, the operators had a tendency to ignore them. Today, the real time, continuous, in situ zirconium oxide analyser is the standard for measuring oxygen in coal-fired boiler outlets.

Michel and others (2001) reported on the state-of-the-art of emerging combustion control sensors. The authors found that zirconia probes were the most appropriate for O2 control at high temperatures (up to 1900°C), cross-dut laser spectrometry appeared increasingly attractive in aggressive environments such as coal-fired boilers and also that zirconia sensors were emerging for CO measurement. There are numerous suppliers of zirconia-based, flue gas oxygen analysers including Enotec (Germany), Yokogawa (Japan), ABB Group (Switzerland) and Ametek, Emerson Process Management, GE Energy, Marathon Sensors Inc, Rosemount Analytical, Teledyne Analytical Instruments (USA). Using these sensors and the data they provide to achieve optimal distribution of air within the boiler can result in reducing emissions, corrosion monitoring, slagging reduction and increased efficiency. Currently all suppliers of these sensors either provide the ability or are developing methods to balance the combustion in the boiler (achieve optimal distribution of air in the boiler). For example see Palmer and others (2003).

Deguchi and others (2005) reported on the state-of-the-art of laser diagnostics in plant, online, in situ flue gas measurement including laser induced breakdown spectroscopy (LIBS) and tunable dioxide laser (TDL) absorption spectroscopy.

According to Muta and others (2004), the effectiveness of TDL absorption spectroscopy for online, real time measurement of O2 and CO in the furnace has been confirmed in pilot and actual installations. TDL are designed to focus on single absorption wavelengths specific to a compound of concern in the flue gas. A simple TDL instrument uses a diode to generate light within a narrow frequency range that contains a relatively unique absorption wavelength of the flue gas constituent of interest. The laser frequency is either ‘tuned’ by changing the temperature of the diode or by changing the current being fed to it or both so that it matches the spectral absorption line of interest. The degree of absorption at a specific locked on wavelength can be used to calculate a concentration, or the concentration can be calculated using a small wavelength range about the absorption line of interest that is built up in a signal averager. Multiple constituents can be monitored by multi-plexing the instrument with more than one diode (usually up to four).

Detection limits are dependent upon pressure and temperature of the gas and the path length, among other things, with shorter path lengths producing higher detection limits. Instrument performance and technical noise (for example optical fringes) will also affect the detection limits that can be achieved. Factors that contribute to the operation of TDL include materials of construction, type of structure, tunability and source, which can be continuous-wave or pulsed (US EPA, 2005).

Advantages of TDL are that the technology can measure flue gas at high combustion temperatures and it scans a small spectrum of wavelength to determine measurement so is not affected by background interferences. However, measurement of flue gas constituents depends on the source laser, the technology has a higher cost compared to traditional methods and accuracy depends on the path length which varies inversely with dust loading. TDL technology is currently being installed for evaluation purposes in a number of US coal-fired power plants including the following TVA (USA) facilities:

- Gallatin, tangentially-fired, 275 MWe unit 3;
  - TDL system: ZoloBOSS (see Zolo Technologies Inc, 2005);
  - TDL system to measure: O2, CO, CO2, H2O and temperature;
  - Objective: to reduce water wall wastage and NOx through combustion optimisation;
- Johnsonville, tangentially-fired, 110 MWe, unit 6;
  - TDL system: Opsis Laser Diode Analyser (see Opsis AB, 2005);
- TDL system to measure: O₂ and temperature;
- Objective: combustion optimisation;
- Paradise, cyclone-fired, 1100 MWe unit 3;
- TDL system: LDS 6, In situ Laser Gas Analyser (see Siemens AG, 2004);
- TDL system to measure: O₂ and temperature;
- Objective: replacing existing O₂ measurement instrumentation and combustion optimisation.

Sappey and others (2004) reported on the testing of the Zolo Technologies wavelength-multiplexed TDL system on the tangentially-fired boiler at Valmont, PRB-fired, 220 MWe, power plant in Boulder, CO, USA. Preliminary results indicate that the sensor has potential. However, in order to quantify H₂O concentration and temperature with sufficient accuracy, the authors state that a significant amount of laboratory experimentation will need to be completed to confirm assignments, measure line-strengths and determine line-broadening parameters. Work continues to achieve these objectives. Diode sensor research and development for measurement of constituents in combustion flows is discussed further by Sanders and others (2002), Webber and others (2000), Furlong and others (1998) and Mihalcea and others (1997).
According to ASYS (2005), today online PGNAA analysers are used to monitor raw material streams, to sort material by particular quality defining elements or contaminants and, to blend different materials to obtain uniform blend composition. In all applications, since flow rates on conveyors vary, care must be taken to ensure that the analyser has the ability to cope with the changing belt load conditions. These applications involve:

- Monitoring: analysers are installed at the outlets of crushers in quarries and mines. They provide real time analysis of the produced material stream going to stockpiles or to the plant for further processing downstream. The ongoing analyses allows for better knowledge of mine deposit resources and can contribute towards extending the mine life by extracting only as much of the high grade material as is necessary to maintain target quality in the product;
- Sorting: using coal quality parameter, the PGNAA

### Table 10 Comparison of fuel characteristics fired at the B L England, cyclone-fired, unit 1 (Bhamidipati and others, 2004)

<table>
<thead>
<tr>
<th>Fuel characteristics</th>
<th>Eastern Bituminous coal</th>
<th>30% PRB coal blend*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proximate analysis, %</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. moisture</td>
<td>5.15</td>
<td>10.29</td>
</tr>
<tr>
<td>b. ash</td>
<td>9.80</td>
<td>7.46</td>
</tr>
<tr>
<td>c. volatile matter</td>
<td>35.79</td>
<td>35.29</td>
</tr>
<tr>
<td>d. fixed carbon</td>
<td>49.59</td>
<td>46.95</td>
</tr>
<tr>
<td><strong>Ultimate analysis, %</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. hydrogen</td>
<td>5.21</td>
<td>5.70</td>
</tr>
<tr>
<td>b. carbon</td>
<td>71.54</td>
<td>67.70</td>
</tr>
<tr>
<td>c. nitrogen</td>
<td>1.31</td>
<td>1.23</td>
</tr>
<tr>
<td>d. sulphur</td>
<td>2.39</td>
<td>1.57</td>
</tr>
<tr>
<td>e. oxygen</td>
<td>9.44</td>
<td>16.35</td>
</tr>
<tr>
<td>f. ash</td>
<td>9.80</td>
<td>7.46</td>
</tr>
<tr>
<td>Heating value, Btu/lb</td>
<td>12855 (7.1 MCal/kg)</td>
<td>12053 (6.7 MCal/kg)</td>
</tr>
<tr>
<td>Free swelling index</td>
<td>7.8</td>
<td>7.2</td>
</tr>
<tr>
<td>Hardgrove Grind Index</td>
<td>57</td>
<td>51</td>
</tr>
<tr>
<td><strong>Ash fusion temperature – reducing atmosphere, °F (°C)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. initial deform</td>
<td>2115 (1157)</td>
<td>2124 (1162)</td>
</tr>
<tr>
<td>b. softening</td>
<td>2190 (1199)</td>
<td>2178 (1192)</td>
</tr>
<tr>
<td>c. hemi</td>
<td>2340 (1282)</td>
<td>2236 (1224)</td>
</tr>
<tr>
<td>d. fluid</td>
<td>2400 (1316)</td>
<td>2337 (1281)</td>
</tr>
<tr>
<td>slag viscosity factor (T250 value)†</td>
<td>&gt;2500 (&gt;1371)</td>
<td>2494 (1368)</td>
</tr>
<tr>
<td>Chlorine, %</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Fouling index</td>
<td>0.17</td>
<td>0.22</td>
</tr>
<tr>
<td>Slagging index</td>
<td>0.83</td>
<td>0.60</td>
</tr>
<tr>
<td>Base/Acid ratio</td>
<td>0.34</td>
<td>0.39</td>
</tr>
</tbody>
</table>

* Blend limited to 30% based on extensive testing conducted in 2001/02. This blend was demonstrated to provide the necessary regulatory improvement in sulphur emissions without adversely impacting unit operation.
† Set to ensure proper tapping of the cyclones and furnace. Fuel blends with a higher percentage of PRB coal would have required extensive modifications to the boiler and ESPs.
analyser can be used to sort mine product into different grades with minimal overlap in the chemistries of the various stores. This is especially important when blending coals downstream; blending: using PGNAA with the appropriate feeder control can achieve the least possible chemistry variation in the blend because the analysis takes place continuously immediately after blending, allowing quick detection and correction of possible compositional excursions. An online, real time PGNAA analyser can also reveal feeder problems such as plugging or starving quickly.

Significant savings can be achieved by blending expensive coals with cheaper ones at power plants. Use of an appropriate blend should not require boiler design modifications but can often achieve environmental compliance. Optimal blend proportions are necessary to avoid operational problems, for example, in pulverisers which can affect the level of unburnt carbon in fly ash. Combustion of coal blends is discussed in greater detail in a previous IEA Clean Coal Centre publication by Carpenter (1995) and more recently by Helle and others (2001), ACARP (2001), Arias and others (2003) and Bennett (2003).

Many utilities have or are considering firing coal blends at their plants. A switch to firing coal blends or a different coal must be preceded by a study on the potential impact on a unit including:

- emissions (particulate matter, NOx, SO2 and CO);
- boiler load;
- main and reheat steam temperatures;
- main and reheat desuperheating spray flows;
- pulveriser limitations, including power and drying capabilities;
- FD and ID fan limitations;
- boiler efficiency;
- fly ash LOI;
- precipitator performance;
- furnace observations.

Courtemanche and others (2001) discussed these issues after a series of tests were conducted at the Presque Isle in Marquette, Michigan (USA), unit 6, 90 MWe boiler which at the time fired bituminous coal only. Various combinations of Powder River Basin (PRB), petroleum coke and bituminous coals were fired during the test period at the facility. The authors concluded that the firing of PRB decreased the NOx emissions marginally and LOI dramatically while increasing the boiler main steam temperature. The increased moisture and lower HHV of the PRB coals decreased the boiler efficiency, decreased the milling system load carrying capability, decreased the mill outlet temperatures and increased the ID fan power requirements. Furthermore,
increased slagging of the furnace walls increased the furnace exit gas temperature (FEGT) which had an adverse effect on deposition on the superheater platens in the upper furnace. Also, the soot-blowing cycle had to be increased by three times the normal cycle just to maintain tolerable boiler conditions. Using online analysers to determine the quality of the coal blend and its specified parameters, for example ash, moisture and sulphur content, can help towards reducing such adverse impacts on plant and achieving successful operation and environmental compliance in a coal-fired unit.

An example of compliance blending of PRB coal using a cross-belt online analyser at the B L England power plant is discussed by Bhamidipati and others (2004). The B L England plant unit 1, cyclone-fired and located in New Jersey (USA), is required by statute to limit the sulphur in the coal fired at the plant. This is established in a fuel permit issued by the New Jersey Department of Environmental Protection (NJDEP). In 2004, the compliance level was 1.7% sulphur in fuel on an annual basis and 1.9% sulphur in fuel on a monthly basis. To comply with this standard a blend of PRB and eastern bituminous coals is fired at the plant. The characteristics of the eastern bituminous and onsite blended coals are summarised in Table 10.

Coal blending is done onsite at the facility by layering piles onto the conveyor belt system (see Figure 11). Control of the blend depends on the accurate loading of the single conveyor belt from each of the coal stockpiles. An existing four-idler belt scale (1), located on the conveyor belt (17), is used to measure the total coal flow to the bunkers. The scale has a measurement accuracy of 1%. A second belt scale (2) was installed as part of the on-site blending system modifications to measure the quantity of bituminous coal on the conveyor belt (16). This two-idler belt scale has an accuracy of 2–3%. The amount of the PRB coal supplied for the blend is controlled based on the difference of the measured weight of bituminous coal (scale 2) and the total weight of the blend (scale 1). It was determined that the lower accuracy of the new scale would not impact significantly the overall accuracy of the measurement of the blend. Control of the reclaim feeders on the conveyor belt (16) is based on the signals

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Table 11 Grubbs’ Estimator from Hunter power plant CQM analyser performance validation test (Snider and others, 2003)

<table>
<thead>
<tr>
<th></th>
<th>Sulphur</th>
<th>Ash</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>CaO</th>
<th>K₂O</th>
<th>TiO₂</th>
<th>Moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grubbs’ Estimator precision with the field calibration</td>
<td>0.026</td>
<td>0.265</td>
<td>0.194</td>
<td>0.113</td>
<td>0.018</td>
<td>0.069</td>
<td>0.018</td>
<td>0.007</td>
<td>0.789</td>
</tr>
<tr>
<td>Grubbs’ Estimator precision with a calibration adjustment based on the test data</td>
<td>0.025</td>
<td>0.204</td>
<td>0.124</td>
<td>0.101</td>
<td>0.019</td>
<td>0.032</td>
<td>0.014</td>
<td>0.004</td>
<td>0.968</td>
</tr>
</tbody>
</table>

---

**Figure 12** A typical layout of a pulverised coal fired power plant (Thermo Electron Corp, 2005)

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Online analysis and coal-fired power plants
Coal blending

a) Ash calibration

b) Sulphur calibration

c) SiO₂ calibration
d) Aᵢ₂O₃ calibration

e) Fe₂O₃ calibration
f) CaO calibration

g) K₂O calibration
h) TiO₂ calibration

Figure 13  Ash, sulphur and ash oxide results of validation test at Hunter  (Snider and others, 2003)

provided by the two-idler belt scale (2) to establish the fuel blend bunkered for unit 1 (Bhamidipati and others, 2004).

Such onsite blending would require frequent laboratory analysis of the highly variable coal fired at the plant, especially the bituminous coal, in order to comply with the fuel in sulphur requirements set by the State in the plant fuel permit. The inventory would also need to be separated between trains. Furthermore, to ensure reliable operation of a cyclone-fired boiler, it is important to understand other fuel
properties, such as the heating content and coal ash viscosity temperature ($T_{250}$) of the blend. To avoid these issues, an online coal analyser was installed as part of the onsite blending upgrades to control the coal stockpile feeders. A cross belt type, Thermo Gamma-Metrics nuclear coal analyser was installed on the conveyor belt (17) to monitor the sulphur in the blended, continuously. The online analyser is used for controlling and reporting the sulphur content of each bunker loading operation for unit 1. The analyser is also used to provide effective monitoring of other fuel properties, such as ash elemental analysis and moisture, significant to boiler operation and preventing unacceptable variations in stack emissions. The accuracy of the cross-belt, online analyser was demonstrated through the use of extensive sampling to satisfy the ASTM 6543 calibration requirements. According to Bhamidipati and others (2004), an agreement between the regulatory body and the utility requires control of sulphur in the fuel be reported based on the online coal analyser with quarterly sampling and analysis of the coal used to verify the coal analyser accuracy. Leetham and Ackerman (2004) discuss Thermo Electron (USA) involvement in online analysis.

Snider and others (2003, 2004) discussed the installation of an online CQM coal analyser in Nov 2001, for improved boiler efficiency at the Hunter coal-fired power plant near Castle Dale in Utah (USA). The purpose of the installation was the control of ash fusion temperature of the coal blend to reduce unit slagging and forced outages. Coal is delivered at the site by tandem truck and is normally discharged at the blending system truck dump where it is stored in one of three stockpiles. Coal from the three piles is reclaimed as a blend and conveyed to the screening transfer building. The coal is then conveyed to a second transfer tower and on to a surge bin ahead of the storage barn feed belt. Coal from a second truck dump is also discharged into the surge bin. Coal from the surge bin is then conveyed to the storage barn. The CQM analyser was installed on the storage barn feed belt where it could be used to control the blend of coal from the three stockpiles and to monitor the quality of the coal dumped at the direct feed truck dump (see Figure 12). A cross-belt sampler was installed on the storage barn feed belt. The sampled coal from the primary sampler discharged directly into the feed hopper on the CQM. The CQM controls the feed of coal through the analyser and the sample system with a variable speed belt and discharges it, via a chute, into the sample crusher. The crusher discharges coal on to a secondary feeder belt. A two way cross-belt secondary sampler located on the secondary feed belt allows two samples to be collected from the belt in separate sample containers. The secondary feed belt discharges reject coal onto the sample reject conveyor which transports it back to the barn feed conveyor.

At the end of 2002, a three-way validation test was conducted at the Hunter facility to evaluate the performance of the CQM analyser in its analysis of ash, sulphur and ash oxides. The test consisted of collecting two independent samples from 45 one-hour runs of coal and comparing the laboratory results with the analyser readings for the sample period. The samples were analysed for moisture, ash, sulphur, ash oxides and ash fusion temperatures. The results of the test are shown in Table 11 and Figure 13. The statistic used to assess analytical performance was Grubbs’ Estimator, recommended in ASTM6543, the standard for assessing performance of online coal analysers. The Grubbs’ Estimator is considered an unbiased on-sigma precision estimate. The validation test also measured the accuracy of the ash softening temperature formula. Using data from the test allowed the determination of an optimal calibration for the ash oxide analysis from the CQM. Figure 14 shows the results which indicate an improved estimate of ash softening temperature (Snider and others, 2003).

The project has proven successful and the benefits to the Hunter facility of installing the CQM PGNAA online analyser, according to Snider and others (2003), included:

- the intended objective of reducing forced outages at the

![Figure 14 Ash softening temperature, calibrated results](Snider and others, 2003)
plant by controlling the ash fusion temperature of the coal was achieved. Average unit capacity at the station was also improved since the CQM analyser was used for precise blending control (see Figure 15). The minute-by-minute data from the analyser allows the plant to supply more consistent coal blends to the units and to maximise the ash softening temperature of the blend;

- electrical generation and maximum rated capacities were achieved at the facility following the installation of the analyser due to the more reliable coal blending and coal quality control;

- consistency of delivered coal improved due to close monitoring of the quality of the coal being delivered to the plant by the fuel suppliers;

- faster identification and correction of equipment problems in the plant. With the continuous analysis of the coal blend, when operating problems occur, it can be almost immediately determined whether or not there is a coal quality issue. If not, the operator can move quickly to identify the true source of the problem and fix it. Thus, there is less potential for lost generation as both quality and equipment problems are identified and addressed sooner.

**Figure 15** Average unit capacity at Hunter before and after blending programme (Snider and others, 2003)
In large multi-burner furnaces, pulverised coal flow to individual burners can vary considerably, with ±10% being typical of a plant where pulverised coal distribution has been optimised. Air flows to individual burners can also vary, though generally there is significantly better distribution of the air than the coal.

In conventional pulverised coal fired power plants, the coal is pulverised in mills and then transported pneumatically via heated primary air to multiple burners within the boiler. Each large boiler has a number of pulverising mills each feeding a specific number of burners through outlet pipes. Despite the use of matched outlet pipes and rifle devices, uneven distribution of the coal occurs, inevitably. Balancing burners under a range of boiler conditions requires measurement of pulverised coal to individual burners. Online measurement allows optimum balancing in real time, in response to any changes in the coal feed, velocity and particle size. The potential benefits from improved combustion uniformity include decreased coal usage, increased boiler availability (due to reduced fouling and slagging) and reduced NOx emissions. A number of methods have been explored to measure pulverised coal flow in power plants (DTI, 2001). The most promising of these are based on either electrostatic, microwave or ultrasonic/acoustic techniques. These are currently at an early stage of commercial installation and work is ongoing on various methods to control either secondary air flow to each burner or to adjust the pulverised coal flow based on these measurements.

There are three types of pulverised coal distribution systems to transport coal from the pulverisers to the burners, direct, semi-direct and indirect. The majority of power plants use the direct systems which are the simplest. Direct systems comprise the primary air fan, the mill and the air piping from the mill to the burners. The primary air fans receive a mixture of ambient air and preheated air from the boiler wind box. Direct systems may use either air or flue gas to dry the coal and act as transport medium. Coal flow from the pulveriser can be increased on demand. Where a vertical spindle mill is used, the coal feed to the mill is increased with a corresponding increase in the flow and temperature of the air to the pulveriser. Control over the primary air is provided either by a speed controller regulating individual fans or by varying the entry dampers on a common manifold system. Where a tube mill is used, the air flow through the mill is increased, as is the coal flow, to ensure mill level is maintained. There are a number of techniques for air flow measurement and on a primary air system it is often via a venturi or aerofoil. To regulate coal flow into a mill, speed of the coal feeder is varied (DTI, 2003). Figure 16 shows a typical solids distribution system. In this case, solids from the mill pass through a trifurcating junction into three pneumatic conveyors. In larger plants, a series of bifurcating junctions result in one mill typically feeding eight burners (Zhang and others, 2003).

The air entering the mill passes through air heaters and

![Figure 16 A typical coal distribution system (Zhang and others, 2003)](image)
provide accurate data. The uptake of these systems was slow to begin with mainly due to their cost and limited commercial experience. However, their use in the last few years has increased somewhat and is expected to increase further with better understanding and greater acceptance of these technologies and their capabilities. Some systems currently available on the market and used at commercial scale in coal-fired power plants will be discussed in the following sections.

Another area of investigation to improve online analysis of pulverised coal mass flow is based on using knowledge-based systems that do not entail the costly installation, in time and monetary terms, of coal flow meters at a facility. Some of these condition monitoring, supervising and controlling systems will also be discussed in this section.

### 9.1 Real time coal-flow measurement and control

Modern instrumentation and processing power have led to a range of commercially available devices capable of detecting the solids flow within the pulverised coal pipe-work. Although instruments measuring pulverised coal flow have shown great promise the problem of how to rectify or optimise the placement of the pulverised coal in the utility boiler remains unresolved.

There are many different principles, developed by both suppliers and research institutions, but according to DTI (2001) electrostatic detection, microwave injection and acoustic measurements appear to be the main contenders. There are many methods of measurement for pulverised coal mass flow and velocity within the transportation pipes based on a variety of physical properties of the pulverised coal. These methods include (Miller and others, 2000):

- **acoustic**;
- **capacitive**;
- **electrostatic**;
- **magnetic resonance**;
- **microwave**;
- **optical**;
- **restrictive** (such as venturi or Coriolis tubes);
- **thermal** (based on hot wire anemometry).

According to Miller and others (2000), many of these methods use cross correlation to derive (particle) velocity by measuring the time displacement of the signals from two sensors. Accuracy of this approach can be high provided the sensors are located in a relatively un-disrupted flow. Close proximity to a bends or regions of recirculating flow will reduce accuracy.

Multi-phase flow technologies in coal-fired power plant is the subject of a review by DTI (2004). Multi-phase flow is the concurrent flow of two or more phases (gases, liquids or solids). Situations where multi-flow might exist in a coal-fired power plant include:

- discharge of coal from transport, storage, milling or classification;
- pneumatic transport of coal to burners;
- combustion of coal in a pulverised coal flame;
- transport and deposition of ash/slag particles through the combustion chamber and convection section of the boiler;
- particle separation in precipitators;
- emission of the remaining particles to the atmosphere and their precipitation to the ground or transport in the environment.

The most promising of the coal flow measurement methods listed above (those that have reached commercial readiness) appear to be microwave, electrostatic and acoustic based systems. While the other techniques are capable of providing some form of measurement, they are considered either not ready or not suitable due to other interfering effects or, they are commercially or technically impractical in a power plant environment (Miller and others, 2000).

In a detailed review on technology status of pulverised coal flow measurement and control methods for utility boilers, Miller and others (2000) found the following to be the key issues of pulverised coal flow measurement and control:

- pulverised coal flow measurement instruments, which at the time appeared to be most successful, are based on electrostatic and microwave technologies;
- in isolation, pulverised coal flow meters provide limited benefits. Using their capability to improve combustion performance will determine the extent of their application;
- in 2000, there were no proven devices capable of online adjustment of pulverised coal flow distribution. The alternative approach is to control combustion air flows to match the individual burner coal flows. This can provide performance benefits but may be limited by factors including FD fan margin, flame stability and boiler temperature profiles. The additional cost of providing air flow measurement and control to individual burners may be prohibitive;
- integration of pulverised coal flow meters into the boiler control system offers some potential benefits with respect to transient control, rates of load change and pulverised coal flow system safety. However, the magnitude of any such benefits are yet to be demonstrated;
- non availability of a low cost, robust and reliable means of online adjustment of pulverised coal flow distribution will limit, dramatically, the market potential of pulverised coal flow meters. With the development of flow control devices, software based combustion optimisation systems would have the ability to adjust flow and combustion air flows in response to combustion indicators (for example, NOx, CO and carbon in ash) and may obviate the requirement for pulverised coal flow meters;
- although the potential market for such meters is quite large (estimated at about 30,000 pulverised coal flow pipes in Europe, Russia and North America), for many of the plants, pulverised coal flow meters and associated control equipment will not be cost effective. The estimated market for only a quarter of these sites is around £30 million for pulverised coal flow meters alone assuming an average price of £4000 per pipe.
9.1.1 Acoustic systems

Millen and others (2001, 2002) discussed the development of an online acoustic system for mass flow and velocity measurement of pulverised coal. The CSIRO ultrasonic PF mass flow measurement system, designed for easy transportation between mills, consists of three parts:
- ultrasonic head units mounted on the boiler pipes (incorporating a 60 kHz ultrasonic transducer assembly, and air purge window and a dustless connection);
- pulser units mounted within 1–2 meters of the head units (to drive the transmitting transducers and collect ultrasonic waveforms from the receiving transducers);
- a controller unit mounted within 15 meters of the pulser units (to send control information to the pulser units, process data received from the pulser units and convert the data to coal and air mass flow values for the plant control room).

The system makes a direct measurement of flow velocity but density measurement must be calibrated using an independent system. For calibration CSIRO Minerals (Australia) have used both a beta-ray transmission gauge and a coal sampler. The beta-ray transmission gauge comprises of a beta-ray isotope and scintillation detector. The transmission of beta-rays is dependent primarily on the mass per unit area of material in the beta-ray beam and is not affected by air turbulence. However, beta-ray transmission is not regarded as a suitable technique for the long-term industrial online determination of pulverised coal mass flow because it requires the use of radio-isotope sources in combination with thin windows. The beta-ray transmission gauge is itself calibrated in the laboratory using plastic sheets of known thickness. A simulation of the beta-ray transmission gauge indicates that the use of plastic sheets for calibration is a reasonable simulation of evenly distributed coal. Typically, the beta-ray transmission gauge is installed on the duct or pipe, downstream from the ultrasonic transducers, such that the beta-ray beam and the ultrasonic pulse are essentially interrogating the same segment of pipe. CSIRO Minerals have also used a fuel sampler technique to extract pulverised coal to calculate fuel flow and compare with the mass flow measurement system. The sampler head has four sampling tips and by means of an angular gear mechanism, the sampling tips can be rotated in circles within a circular pipe. The use of such a sampler can be useful where the coal is unevenly distributed within the pipe and it is difficult to obtain a representative value of coal flow using a single beta-ray transmission gauge (Millen and others, 2001, 2002).

The CSIRO ultrasonic pulverised coal mass flow measurement system was installed at two New South Wales (NSW, Australia) hard coal fired power plants (Sowerby, 2002b). The first system was installed at the Bayswater power plant (4 units at 660 MWe each) in mid 1998 and the second was installed at the Mount Piper station (2 unit at 660 MWe each) in early 2000. Each boiler unit is supplied with pulverised coal from seven tube-ball mills. The coal is pneumatically conveyed from each mill in four feed pipes to the boiler burners. Figure 17 shows the measured coal mass flows for the four pipes at the Bayswater station for a 12-hour period in October 1998. The coal mass flows, expressed as a percentage, vary over a range of approximately 20% to 30% during the 12-hour period apart from a 1-hour period commencing at approximately 0810 hours. In this 1-hour period, the coal mass flow in pipe 2 increased from about 27% (before 0810) to 37% and the coal mass flow in pipe 3 decreased from 25% to 13%. That is, during this period the coal split between pipes 2 and 3 is 37:13 instead of 25:25. Another way of expressing this mal-

![Figure 17 Coal mass flow rates as a percentage of the total flow through four pipes at Bayswater power plant (Millen and others, 2001)](image-url)
distribution is the ratio of coal to airflow rates. During the period after 0810 hours the coal to air ratio was approximately 0.65 in both pipes 2 and 3 (Millen and others, 2001, 2002).

Another acoustic coal mass flow measurement system was under development in 2001 between CSIRO and the Cooperative Research Centre (CRC) for Clean Power From Lignite (Australia). This system was being developed for deployment in lignite-fired power plants in Victoria, mainly because of the high moisture content of brown coal. According to Millen and others (2001), the same amount of pulverised coal, whether anthracite or lignite, enters a boiler to generate a similar MW output. However, duct dimensions in boilers firing lignite are much larger and therefore the pulverised coal density is much lower in the duct work compared to plants firing anthracite. The differences in coal density, temperature, particle size and moisture and the likelihood of increased mal-distribution of pulverised coal in lignite ducts compared to anthracite have led to the development of the new acoustic prototype specially designed for use in lignite ducts. The prototype tests were carried out at the Yallourn Energy lignite station in Victoria, Australia (Millen and others, 2001, 2002).

### 9.1.2 Electrostatic systems

Electrostatic sensors measure the electric charge carried by particles as they travel through pipelines. Passive electrostatic meters are considered effective for determining relative mass flows and velocities. However, because electrostatic charge is carried on the surface of the pulverised coal particle, this method may be prone to error when the particle size distributions between pipelines become uneven during classification. High-impedance electrodes amplify and analyse the DC and (or) AC charge components, which are both affected by the pulverised coal concentration. The sensors can be either intrusive antennae or non-intrusive in the form of a ring mounted in the wall of a meter (DTI, 2001).

ABB Ltd in cooperation with Teesside University (UK) developed a non-restrictive, non-intrusive electrostatic charge detecting meter. The ABB PfMaster meter is commercially available and takes the form of a short section of pipe or spool piece inserted into the pulverised coal pipework. It is therefore fully constructed and calibrated at the factory. The meter detects particle AC charge with an array of circular sensors embedded in the inside face of the spool section. The latest version is designed to minimise installation effort and can be fitted between standard flexible pipe couplings. The charge induced into the antennae from a particular particle of coal is highly dependent upon its position within the pipe. This was addressed by using a pair of sensors of different width. The narrow sensor is more sensitive to particles near the walls, whereas the wider sensor detects particles further away. Combining the signals allows a flat response to be calculated. Particle velocity is also measured on an absolute basis using cross-correlation, with quoted accuracies of ±2% (DTI, 2001). A schematic of the measuring system is shown in Figure 18 (Keech and others, 2003).

Experiments were carried out into pulverised fuel split control at the Coal Research Laboratories (UK). Low volatile pulverised anthracite was used as the conveyed material. The ‘vertical upward’ flow was supplied from a conveyor fed from a hopper. Output from each conveyor was led into separate hoppers each fitted with a load cell so that the mass flow rate in each conveyor could be measured. Initial solids split was set using a flow diverter valve and the split value was controlled using a modified butterfly valve in one of the conveyors. Relative mass flow rate signals were obtained from two ABB PF Master electrostatic meters and fed to the controller, whose output varied the butterfly valve, thus altering the restriction to the flow. The aim was to equalise the split to ±0% after it had been set at some value determined by the diverter at ±x%. The solids concentration range used was typical of that used in power generation applications. A personal computer (PC) processed the signals from the meters calculating the solids mass flow rates in each conveyor. Output signals were provided to the controller that varied the flow restrictor, a modified butterfly valve, to alter the ‘split’ to the desired set point value. The project was intended as a prelude to large-scale control of pulverised coal in the power generation industry using larger meters and flow control dampers. However, the technique described by Zhang and others (2003) can be directly applied to the chemical and process industries. Investigation continues to develop split control devices that can be controlled using pulverised control meters as the flow metering-sensor. Zhang and others (2003) demonstrated a simple laboratory version that, on a full-scale plant, has the equivalent in the form of a flow damper. Active rifle box designs are undergoing trials in a number of countries.

To date, the ABB Automation PF Master systems have been installed in 10 coal-fired power plants in five countries: Canada, Republic of Korea, Portugal, UK and the USA (Asquith, 2005).

The Electric Charge Transfer (ECT) electrostatic coal flow measurement technology measures the electric charge present...
in any two-phase flow transport. The system is developed by TR-Tech Int. On (Finland) and marketed currently in the USA and Canada in a partnership Foster Wheeler North America (USA). Siemens AG (Germany) is a non-exclusive partner for marketing the system and application focusing mainly on China and Europe. It consists of receiving antennas in each coal conduit that are connected to a signal conditioning unit housed in a cabinet. The latter in turn is connected to a PC that is used for data processing and analysis. Proprietary software is used to determine the mass flow balance between the conduits of a mill and particle velocity and display the results to the operator. The data are also fed, via a network, to the plant DCS system or a continuous combustion optimisation software running on a separate PC. The antennas are installed through the horizontal or vertical wall of an existing conduit and inserted into the coal stream (they are intrusive). Three antennas are needed in each conduit for coal flow balance measurement and six for coal flow and velocity measurements. Their location in the pipe wall is determined so that the effects of coal ropes on the measurement results are minimised. Antennas are made of tungsten carbide to ensure long operating life. The installation is simple and requires a mill taken out of service for only a few hours. Following the installation of the antennas, the ECT measurement is verified by a standard ASME or Rotorprobe sampling procedures (Rosin, 2005a).

The ECT technology uses the signals to determine the following characteristics of the flow (Kersch and others, 2001):

- measuring the relative coal distribution between the conduits. It can also be configured to measure the flow velocity and the absolute flow in each conduit;
- the data collection rate also allows monitoring of unsteady phenomena in the coal conduits that may cause problems during plant operation. The signals can be used to detect coal conduit layout due to insufficient primary air-flow from the mill and coal conduit surging which results in furnace pressure and emissions fluctuations;
- ECT can be applied to monitor particle size changes of the coal flow. The antennas and the hardware used for this are the same as in the coal flow distribution application. Thus, the ECT system can be used to monitor mill performance online and assist in maintaining required coal fineness to minimise unburnt carbon.

To date, ECT systems have been installed in about 30 coal-fired power plants in five countries: Finland, Republic of Korea, Spain, UK and the USA. Most of these installations were in the last five years. According to Kersch and others (2001), ECT advantages include:

- all information is continuous and online;
- measurements are not affected by coal type, moisture, ash content or coal roping;
- the electronics can be located up to 365 m from the conduits, no cabinets are needed on the burner decks;
- the abrasion resistant antennas in the coal conduit are passive and require no power supply;
- installation is easy and can be carried out during short mill outages.

Kersch and others (2001) summarise the following benefits for the combustion and mill operation of installing and online coal flow monitoring, measurement and control technology:

- NOx and CO reduction with balanced burners;
- unburnt carbon level reduction, increased boiler efficiency (using ECT technology for reduced NOx and unburnt carbon is discussed by Laux and others, 1999);
- lower SCR ammonia spray rates with subsequent improvements of air heater plugging tendency, washing cycles and reduced slip rates;
- reduced standard deviation of fly ash unburnt carbon, more consistent fly ash for sale;
- even boiler oxygen profile, potential to reduce excess air level;
- potential for reduced furnace and heating surface slagging;
- more even steam temperature profiles;
- reduced water wall corrosion as a result of specific air to fuel biassing near the side walls;
- reduced firing system tuning time due to knowledgeable approach;
- mill performance monitoring for LOI minimisation by measuring fuel fineness online;
- quick identification of mill problems (surging, layout);
- reduced auxiliary power and increased fineness by mill primary air optimisation;
- potential to detect coal layout early, before damage to piping, burners or wind-box occurs.

In 2003, Laux and others reported on the benefits and experience with online coal and air flow measurement and automatic control on pulverised coal fired boilers. In 2005, the ECT air to coal flow balancing system was installed at the Hadong unit 1 (300 MWe) coal-fired plant near Pusan in the southern part of the Republic of Korea. The objective of the installation is minimising both NOx and unburnt carbon. The following benefits were achieved (Rosin, 2005b):

- NOx reduction from an average 207 ppm to 182 ppm (12%) (occasionally 28%) reduction;
- unburnt carbon reduction from 3.97% to 3.92%;
- boiler efficiency increased by 00.18%;
- more even furnace temperature distribution.

TR-Tech Int. Oy (Finland) are currently in the process of patenting an online ECT soot cleaning optimisation add on system (Rosin, 2005b).

Eskom (South Africa) are developing an electrostatic system that uses a patented set of “finger” probes and complex signal conditioning to derive the mass flow of pneumatically conveyed particles. Due to many reasons including funding, time and restructuring, Eskom have not focused on improving the absolute accuracy to better than 90%. Coal quality, pulvereised coal particle size and moisture are not compensated for. However, the system was installed at two sites in the last two years for the purpose of real time measurement of the relative differences in mass flow between the different pulvereised coal pipes from a mill and a boiler. Given that at any instance in time one mill, and to a lesser extent, one boiler will have the same coal going into the boiler, the relative accuracy of the mass flow system is high. This is used to determine the real time pulverised coal mass
flow distribution between different pipes from a mill and different mills in a boiler. The two installations include (Van Tonder, 2005):

- a permanent installation in 8 pipes (600 mm diameter) on one mill at the Matimba power plant;
- a temporary system in 36 pipes (600 mm) on six mills of one boiler at the Lethabo power plant.

It is planned to convert the temporary system to a permanent, but portable system, that can be moved to other units to carry out pulverised coal distribution tests.

### 9.1.3 Microwave systems

**Microwaves** are relatively low frequency electromagnetic waves that are able to monitor the whole pipe area and are relatively insensitive to particle roping or deposition. As concentration is directly measured from the pulverised coal particles rather than inferred from a generated characteristic (for example noise or electrostatic charge), it is claimed that absolute coal flows can be measured after calibration. Location of these meters must be considered as basalt linings in pulverised coal pipes could absorb microwave energy (DTI, 2001).

According to Elsen and others (2004), when using electromagnetic waves to measure mass flow, it is necessary to measure both particle concentration (density) and particle speed (velocity). Concentration is obtained using attenuation or the phase shift of the wave. Velocity is measured using either the Doppler Effect or the electrostatic charge transfer technique. Combining or multiplying density by velocity by the area gives the desired mass flow measurement. Thus, the measurement has to rely on measuring multiple variables, which can change rapidly and affect the accuracy and repeatability of the measurement technique. For example, all temperature variables need to be measured and compensated for, since they will affect both the density and velocity measurement. Velocity can be difficult to measure because each coal particle has a different size and shape and will slip in the primary air at different relative velocities. The more variables that have to be measured, the greater the potential for inaccuracies.

MECONTROL Coal is a microwave based meter developed by Promecon Prozess- und Messtechnik Conrads GmbH (Germany) for measurement of coal flow and distribution from the mill to the burners (see Figure 19). This system is also known as Pf-FLO™. The latter is the system marketed by Air Monitor Corporation (USA). Pf-FLO testing and application is discussed by Earley (2000, 2001).

Concentration and velocity measurements are performed by a pair of intrusive sensors aligned parallel to the longitudinal axis of the pipe. The microwave signal is transmitted to the individual pipe sensor pairs from a cubicle mounted on the boiler containing a microwave generator that multiplexes up to 32 pipes. Measurement range is 10 g/sec to 20 kg/sec.

According to Promecon (2005) the system is characterised by:

- absolute measurement across the total cross section of the coal pipe;
- not affected by roping or density fluctuations within the pipe;
- easy online calibration without reference measurement (isokinetic measurement), although calibration for each pipe is required since the pipe itself forms part of the

![Figure 19 MECONTROL Coal/Air/UBC measurement locations (Promecon, 2005)](image-url)
measurement. However, replacement of any transmitter/receiver does not affect previous calibration;
- accuracy unaffected by coal grading;
- high sensor durability;
- simple sensor installation and replacement does not require re-calibration;
- programmable logic control (PLC) system provides reliability and integration to the plant DCS.

Between 1998 and May 2004, MECONTROL Coal was installed in 28 coal-fired power units on a total capacity of approximately 12 GWe in four countries including Denmark, Germany, Japan and the USA.

Another microwave type meter was developed by Measuring Innovations Consulting (MIC) (Germany), established in 2001. The system uses high frequency microwave energy transmitted perpendicular to the flow of pulverised coal in a coal pipe between the pulveriser and the burner. Microwave energy is reflected by the moving pulverised coal particles and based on the amount of reflected energy the system determines the relative coal flow in each of the pipes of that pulveriser. The system uses two sensors per coal pipe which are located about 90º apart around the circumference of the pipe. These can, in some cases, be inserted through existing coal sampling ports. The sensor tip is mounted flush with the inside of the coal pipe and therefore is considered non-intrusive. Sensors are calibrated at the source and therefore do not require any field calibration although adjustment on site to sensor amplification may be required. As the measuring technique recognises only moving particles, sensor orientation is not considered an issue. To date, MIC has installed sensors in both vertical as well as in horizontal runs of coal pipes (Elsen and others, 2004; Jensen and others, 2003).

Microwave technology can provide a measurement of the relative (percentage) coal flow in each of the coal pipes. That is, the number of particles (concentration) passing through the microwave beam are counted and based on analysis of the number and the intensity of the signal returns (larger particles return more energy than smaller ones), the system determines the relative flow in each of the coal pipes. According to Elsen and others (2004), if the total mass of coal entering the pulveriser (typically measured at coal feeder) is also known, the mass flow in any given coal pipe of that pulveriser may be determined. Even with large variations in the coal characteristics, the system can accurately determine the coal distribution in each pipe. As temperature is not used in the mass flow calculation the system does not require any temperature measurement or correction.

Following the successful demonstration of the MIC (portable) system in April 2003 on unit 1 (660 MWe) at the JEA St John’s River Power Park station, the decision was taken to install a permanent system in Autumn 2003 (Elsen and others, 2004).

### 9.1.4 Extractive methods

Extractive methods to measure and control coal flow distribution require the withdrawal of a sample of the pulverised coal from the pipe in order either to weigh or bottle for analysis. The limitation of such systems is that measurement is performed at an average velocity with no direct feedback to enable velocity changes. One such extractive system currently being studied is the M&W Asketeknik (Denmark) Automatic Coal Flow Monitor (ACFM) in which samples of the pulverised coal are collected from the pneumatic transport pipes between the mills and burners (Burchardi, 2005a). The sampling unit consists of a motorised rotating samples arm with four coal extraction nozzles. The measuring unit separates the coal particles from the extracted gas stream and collects them in a measuring tube where the volume is measured. The measurements are transmitted to the control room for evaluation and control of the coal flow (Burchardi, 2004).

According to DTI (2001), this is a complex, expensive system with many moving parts that was developed as a portable test instrument rather than as a system designed to be fitted to pipes permanently. The cost of installing the M&W technology at existing facilities which have a large number of pipes can be prohibitive. Application of this system is more cost-effective with modern plants operating with a limited number of pipes.

Another extractive system combines automatic sampling and coal flow measurement of the Espectrógrafo Multiobjeto Infrarrojo (multi object infrared spectroscopy) (EMIR) system developed by Inerco (Spain) with the online particle size analysis Insitec technology developed by Malvern Instruments (UK). The Inerco Laser diffraction-based particle sizing technology is discussed further in Chapter 10. In this combined system setup a retractable probe with four rotating tips is used for isokinetic sampling of pulverised coal from the transport pipes that feed the burners. The representative sample is then delivered to the Insitec online analyser for particle size measurement (see Figure 20).

Testing of the combined system was carried out at the Guardo unit 2 power plant in northern Spain. The 350 MWe

![Figure 20 Basic layout for particle size initial testing at Guardo (Pugh and Delgado Lozano, 2003)](image-url)
unit is fired with a mixture of anthracite and bituminous coal. Six ball mills with static classifiers operate in the plant and the pulverised coal is transported pneumatically to the burners. Each mill supplies four burners. Average coal particle size transported to the boiler is 92% <74μm, measured by traditional sieving techniques. By the end of November 2002, numerous investigations of the combined, further improved EMIR III and Insitec monitoring system had been carried out under different operating conditions at the facility. According to Pugh and Delgado Lozano (2003) testing at Guardo demonstrated a successful integration of the EMIR III and Insitec systems for online measurement of coal flow and particle size distribution in coal-fired power plant. The system has been used to monitor the quality of coal supplied to the burners, helping in combustion optimisation and minimising NOx emissions.

The Automatiche Kohlenstaub Optimierungs und Mess-Anlage (AKOMA) (automatic coal-dust optimisation and measurement) is an extractive sampling system for measuring and balancing coal flow in individual burner lines developed by E.ON Engineering GmbH (Germany). The principle of the technique is the isokinetic extraction of pulverised coal samples by using a zero-pressure probe that measures, continuously, the static pressure of the main gas flow and the extracted part-flow. The correct positioning of the sampling probe in the cross section of the burner line, is therefore a prerequisite for good reproducibility. This can only be achieved by means of an indexing device. The system can achieve measuring uncertainties of <2% and has been selected by VGB (Germany) (VGB-Guideline 123 C/2.9) as the recommended technology for pulverised coal sampling. It is also used as a calibration and reference method for online pulverised fuel monitoring systems (Frank, 2005).

Evaluation of extractive coal sampling methodologies was the subject of an interim report by the Electric Power Research Institute (EPRI) (USA) published in March 2005. A coal flow and measurement laboratory, or Coal Flow Loop (CFL) was built in Detroit (USA) solely for the purpose of helping operators understand and test the uncertainties of these techniques and their measurements. EPRI (2005) state that with the arrival of in situ technologies that purport to have improved EMIR III and Insitec monitoring system had been accomplished on coal pipes which split into two pipes and the second positioned just upstream of the rifler. The flow control elements have been designed to make it possible to balance the coal flows without affecting the primary air flow balance and can be installed while the pulveriser is online. The technology was tested at laboratory scale (Lehigh Energy Update, 1996, 1999). In the full-scale field test, adjustable coal flow control elements were installed at two boilers, one with coal pipes which split into two pipes and the second with three-way splitter junctions after the mills. In both cases, the flow control elements were found to be capable of producing large changes in outlet coal flow distribution, resulting in either closely balanced coal flows or highly unbalanced flows, depending on the settings used. The resulting coal flow distributions were found to be repeatable and coal flow imbalances were reduced to less than 5% in both cases (see Figures 21 and 22). Lehigh University Energy Research Centre where the work is carried out plan to license the technology for manufacture and installation in coal-fired power plants.

According to DTI, in 2003, there were no commercially available methods for online control of pulverised coal distribution in response to a signal from a flow meter. Online flow meters are used either for investigative purposes, to improve the distribution of combustion air flow to individual burners or optimisation (in some cases online) of the air and coal balance at each burner. Although this approach can provide significant benefits, it may be limited by constraints such as forced draught (FD) fan limits, flame stability and costs for additional monitoring and control of combustion air. Pulverised coal distribution control approaches and devices currently used and under development are described in DTI (2001). To date, none of these has demonstrated successful pulverised coal distribution adjustment capability online.

Lehigh Energy Update (2003) reported on the field testing of an online coal flow balancing technology. The authors have completed the development of a technology for balancing coal flows to burners in piping systems where a single pipe is divided into two, three or four outlet pipes at a splitter junction. The ‘hardware’, which can be retrofitted into an existing coal pipe network, requires use of a rifler with specially designed adjustable flow control elements. The development are described in DTI (2001). To date, none of these has demonstrated successful pulverised coal distribution adjustment capability online.

GE Energy and Environmental Research Corporation (USA) developed and in 2003 began demonstrating the GE Energy Coal Flow Balancing System (CFBS). CFBS is an integrated system that comprises real time, continuous coal flow measurement with automatic, actuated damper control. Proprietary algorithms and diagnostics are used to determine damper adjustments. The first integrated CFBS utilises microwave based coal flow measurement principles. The GE automated coal flow balancing damper is a variable orifice device used to trim coal flow to burners. The welded

9.1.5 Control and balancing

Control of pulverised coal distribution may be achieved by (DTI, 2001):

- secondary air distribution: feedback from online coal flow meters enables secondary air placement to be optimised to match the coal mal-distribution. This is usually simpler to implement on existing boilers than re-distributing the pulverised coal;
- distribution devices: enable pulverised coal distribution to be fully controlled, allowing burners to operate at optimum design specifications. This type of system is less likely to be limited by other constraints, such as fan power, flame stability or impingement; or
- combustion optimisation: additional data from the pulverised coal flow meters may be used with neural network combustion optimisation software to achieve greater improvements. However, optimisation may be possible using combustion indicators, such as NOx and carbon in ash, for pulverised coal distribution control without flow measurements.
construction damper encloses two ceramic-coated adjustable blades that form an elliptical opening. The ceramic coating and welded construction provide wear resistance and durability. One blade is actuated to trim coal flow automatically while the other blade is manually adjusted for extending the range of damper control. The damper allows remote operation or, automatic operation when coupled with an online coal flow measurement system. Controller capabilities include safety and diagnostic features, redundant PA velocity indications and a coal flow distribution function that allows lateral coal flow biasing (Gauthier and others, 2004).

CFBS was installed and successfully operated at a 25-burner equipped, 380 MWe PRB-fired boiler. The system addressed coal flow deviations of over 25% and maintained coal flow balance to within 10% by open-loop manual adjustment and to within 5% in a closed-loop control. The latter is achieved over a wide range of mill loads (see Figure 23) (Widmer, 2005; Gauthier and others, 2004). The system is reportedly also capable of biasing the burner firing rate to overcome local furnace stratification and performance issues making it particularly beneficial for units that have non-symmetrical burner firing configurations or experience significant imbalances in temperatures, excess oxygen and slag and fouling behaviour. Reductions in NOx emissions and LOI due to burner coal flow balancing at the unit are shown in Figure 24.

9.2 Online condition monitoring

Perceptive Engineering Ltd (UK) have developed an online process condition monitoring and control system for the improved performance of coal mills. The model targets specific operating problems encountered with mills, for example the loss of coal feed to the mill. If not detected, and corrected in time, the reduction of the pulverised coal output...
leads to loss of heat input to the boiler and subsequently loss of load. Another problem that may be encountered in mills is undetected equipment wear resulting in grinding failure and forced outages. The modelling process of a specific plant results in developing online estimator of the many process variables including mill level, mill outlet temperature, mill differential pressure, mill power consumption, mill air flow, mill vibration and air/fuel ratio. The system generates a statistical model of the combustion process based on historical data. It then carries out an online multivariate data analysis technique to reveal process problems that may be encountered before they become serious. Imminent failures, process abnormalities and inefficient operating zones may be reportedly highlighted using this tool. The system may also be used to generate inferential sensors to backup existing online analysers. Integration of process condition monitoring is shown in Figure 25.

Expected benefits resulting from online process condition monitoring include (Lovett, 2005):

- fault detection and diagnosis of anomalous conditions leading to reduced downtime;
- achieving optimum operation leading to increased production as well as efficiency;
- identification of abnormal process operation thus reducing emissions and waste by-product;
- quality control in that online quality measurement can be used to enhance both operator awareness and control performance;
- improved alarm management due to greater accuracy for alarm thresholds.

Another system utilising microcomputers to improve the performance of pulverising mills is the knowledge based operator support system (KBOSS), developed in two parts. The first part is designed to provide real time functions for individual mills including (Fan and Rees, 1997):

- data acquisition and processing;
- online parameter estimation and mill performance prediction;
- fault diagnosis and prognosis;
- incipient alarming;
- problem analysis;
- optimal problem-solving solutions.

In this part, if problems arise during operation, such as an error occurs between the model and the process exceeding a certain level, KBOSS analyses the cause and sends out different levels of alarm to the operator while simultaneously displaying analysis results including possible causes for the problem in order of priority. The system also suggests available methods and procedures to deal with the fault. In order for KBOSS to work online for all fault conditions, the information database for the system must be very large. The multi-layered structure of the system also allows for levels of dealing with problems. For example, in the case of simple problems, it is not necessary to go through the whole information data base and levels A, B and C but only through...
lower-level knowledge (level A). If the problem is more complicated then levels A and B are used to resolve the issue and so on and so forth. The efficiency of the system is thus improved and the computation burden reduced (Fan and Rees, 1997).

It is expected that at the beginning of operation the system will not be completely accurate but this can be gradually modified online, improving performance with ongoing operation. System parameters may be changed systematically to suit the change of mill operating status and different types of mills. The system can also be expanded to possess control function (part two) enabling it to intervene directly in mill control.

In part two, the system monitors the unit fuel demand, the status of each individual mill and mill dynamic performance. It evaluates mill coal-grinding capability and, depending on the online dynamic grinding capability and performance, adjusts the mill load sharing coefficients, automatically. The system also controls the number of mills in service to supply the coal demand. The operator is provided with options to choose between different mill controls, such as optimal coal grinding, preserved mill MW power and mill maintenance.

To simulate mill coal moisture and grindability variation, the mill model parameters were defined as a function of time and raw coal quality (that is, non constant). For example, in the simulation, coal moisture content was increased by 10% and grindability was decreased by 20%. Such changes cause a longer coal grinding residence time, higher power consumption, high mill level and recirculating load and high mill differential pressure (dP). Use of coal with high moisture content can cause mill blockage and high bowl pressure. As the main concern for safe mill operation is the high mill dP, a maximum allowed mill dP was assumed in the simulation. The simulation showed that once mill dP exceeds the limit, the mill is run back to minimum, instantly. Mill blockage reduces the cross-sectional area of the pulverised coal transportation pipe. This can result in a higher velocity air flow and a larger pressure drop. That is, in such instances, the high dP may not be caused by a high mill load. Where this is known, mill run-back may be avoided. Based on this Fan and Rees (1997) state that mill run-back should depend on:

- mill dP;
- mill level;
- mill power;
- mill load;
- mill conditions.

Simulation of the system showed that it can not only reduce mill run-back but also improve mill-grinding efficiency and unit load following capability. KBOSS is an add-on system to an existing mass/mass mill controller and therefore is easy to test and implement without too much risk of disturbing the existing system operation (Fan and Rees, 1997).

Optimisation of pulverised coal flow from mill to burner was the subject of a EUREKA project started in February 1998 and completed in December 2002. The project aim was to model and carry out in situ measurement of pulverised coal flow from mill to burner to develop a practical operator support system, increase fuel efficiency of coal-fired plants and reduce emissions and waste due to non-homogeneous burning (Eureka, 1999). The project budget was €1.4 million and funded by Eureka Netherlands. The project members were Kema Nederland BV (Netherlands, main: 42.5%), Fortum Power and Heat Oy (Finland, partner: 6.5%) and Electricite De France (EDF) (France, partner: 22%) and an unnamed German partner that withdrew from the project in June 2001. According to Winters (2005), no final report was published of the findings of the Eureka Project 1934 due to withdrawal of partners, takeover and change of strategies and because the project did not reach a position result.

Another project is currently running within the Research Programme of the Research Fund for Coal and Steel in which online process performance calculation methodologies are being developed. The project, RFC-CR-03007, also investigates advanced online methods for ash behaviour and deposition formation monitoring. The objective is to implement these into power plant control systems for operator support to improve boiler availability and performance. The overall objective of the project is to develop advanced steam boiler monitoring methods based on the analysis of fuel, fuel ash and furnace conditions. The main objectives are summarised as (Vainikka, 2005a):

- quantitative estimation of deposition formation;
- estimating the impact of deposition formation on boiler operation;
- studying the interrelation between fuel blend characteristics → deposition formation → boiler efficiency;
- suggesting improvements to current power plant operation procedures;
- offering means for operators to meet regulatory obligations (emission levels) and achieve better boiler overall performance;
- provide indication of the financial consequences of boiler fouling.

The project began on 1 September 2003 and has a completion date at the end of August 2006. Project contractors include:

- VTT Technical Research Centre of Finland / VTT Processes (Finland) (Project Coordinator);
- Fundación CIRCE (Spain);
- Technische Universiteit Delft (TU Delft) (Netherlands);
- EVN AG Power Generation Division (Austria);
- Cranfield University Power Generation Technology Centre (UK);
- Centre for Research and Technology Hellas (CERTH)/Institution for Solid Fuels Technology and Applications (ISFTA) (Greece);
- FORTUM Power and Heat (Finland).

The periodic reports of this project remain confidential. However, a high temperature (400–600°C) deposit formation/corrosion monitoring probe has been developed. The air/water-cooled probe can be applied in studying deposit formation and hot corrosion in full-scale boilers. Future plans include improving the probe design to assist in developing methods that support plant operators in daily decision making and plant and fuel blend optimisation (Vainikka, 2005b).
10 Particle size analysis

Online particle size analysis is critical to improving grinding and mill control. Coal grinding to the optimum size is an essential but highly energy intensive part of the coal processing operation. Benefits from improved grinding control are primarily greater milling efficiency, more stable operation, higher throughput and improved downstream processing. Grinding the coal finer than necessary can lead to increased energy costs, reduced throughput, increased mill liner consumption and increased consumption of grinding media and reagent. Insufficient coal grinding can result in changing the temperature and residence time of the pulverised coal particles in the boiler and also a greater amount of carbon remaining in the fly ash which impacts its saleability. Requirements for an online particle size analyser include rugged and reliable equipment and ease of calibration and standardisation. However, to date commercial equipment which meets these requirements has been very limited (Sowerby, 2002b). The author suggests but does not elaborate on one approach to improving the control of grinding mills, which is to develop and apply acoustic emission techniques.

DTI (2001) discusses acoustic/vibrations and electrostatic methods for particle size distribution measurement. Acoustic methods can be either intrusive (vibrations generated by particles colliding with a specially installed structure are measured) or non-intrusive (aerodynamic sound generated by the turbulent nature of the flow is monitored). One acoustic method involves a metal beam being inserted into the pulverised coal pipe and dimensioned to exhibit the desired range of resonant frequencies. Experiments included well characterised coal blends being conveyed along a pipe into which the beams had been installed. Accelerometers in this case were mounted on the beams and the outputs analysed using a neural network system to extract size distribution information in terms of six particle size ranges. The results of experimentation were encouraging in that the measured values for different size fractions were within 10% of the true values. Hancke and Malan (1998) discuss this model analysis technique in detail. Online acoustic particle size distribution analysis of pulverised coal is discussed further by Hancke and Malan (1996) and Malan and Hancke (1998).

Millen and others (2001, 2002) discussed the development of an online acoustic system for particle size determination of pulverised coal. CSIRO patented a technique for online particle size measurement, especially the oversize fraction, and solids loading in pneumatic transport pipes. The essence of the measurement scheme is to monitor the acoustic waves produced by collisions of the pneumatically transported particle with a specially designed acoustic sensor. Each impact produces an independent pulse, the duration and amplitude of which conveys information about the particle size and velocity. The largest particles present in the pulverised coal produced the signals of greatest duration and amplitude. This provides a method for examining the largest part of the particle size distribution accuracy and therefore provides information that can be used to improve grinding control.

According to Millen and others (2001) when a pneumatically conveyed particle strikes a surface, acoustic waves are launched into the material. By measuring these signals it is possible to determine information about the particle size and velocity. In the simplest view of an elastic collision between a sphere and the plane surface of a solid, the force imparted by the impact over its duration is equal to the change in momentum of the particle. For particles of a given density the acoustic signal is therefore related to the mass of the particle and hence the cube of the particle size. The impact times for sub-millimetre particles are shorter than a few micro-seconds. For instance, using the material properties of coal, a velocity of 20 m/s and a particle size of 100 μm, the impact duration is approximately 0.2 micro-seconds. This short duration allows the measurement of many tens of thousands of impacts per second, producing a statistically significant data set. The Impact Size Monitor (ISM), developed by CSIRO, consists of an impact sensor and a positioning arm which is directly inserted into the pneumatic flow to be analysed for coal particle size. The impact sensor contains a piezoelectric transducer that converts the impacts to electrical pulses, which are electronically processed and logged on a multi-channel-analysier (MCA). The electronics are an adaptation of components commonly used in nuclear counting instruments.

An ISM was tested in a horizontal re-circulation flow rig which is designed to model conditions of pneumatic transport in a coal fired power plant fuel duct. The closed-loop system is designed to circulate dust at velocities up to 35 m/s in 300 mm diameter pipe work with a total length of 20 m. Millen and others (2001) report that four grades of glass ballotini of mean particle size (by number) of 61, 74, 103 and 133 μm respectively (determined by laser diffraction) were used to simulate pulverised coal flow in the loop. The size distributions as measured by the ISM are shown in Figure 26. The correlation between the mean sizes given by the ISM and laser diffraction is presented in Figure 27. The calculated correlation coefficient and RMS error were 0.985 and 5.5%, indicating good agreement between the techniques over the range of sizes found in pulverised fuel. According to Millen and others (2001), the ISM can also be used to monitor the distribution of coal within a pipe. This would be achieved by moving the sensor around the pipe and recording information at various locations. This may provide a useful indicator of high wear areas on boiler feed pipes. It could also be used as a tool to optimise the position of the transducers for the acoustic coal mass flow system. The current prototype only permits inspection across a pipe diameter but a future commercial unit could deploy a sensor which can be moved in circles around the pipe, similar to the fuel sampler described by Millen and others (2001) in Chapter 9. Deploying an impact sensor in industrial flows is a major issue due to the rate of wear on the sensor due to particle abrasion. Another important consideration in determining the lifetime of the sensor is the variation of sensitivity as the depth of the front face epoxy layer is reduced. CSIRO continue to seek industrial partners to test the ISM system in a coal-fired power plant (Millen and others, 2002).
Other methods currently used for measuring particle size of powders include optical and electrostatic methods. The majority of these are not suitable for online applications (DTI, 2001). However, one optical device, based on laser scattering/diffraction technique, is currently being tested in French pulverised coal power plants to measure, online, the size distribution of pulverised coal through the pipes which feed the burners. The device is the Malvern Insitec system from Malvern Instruments (UK). This system, according to Pugh (2005), is currently being used in France, Japan, South Africa and the USA, and in on-going projects in seven other countries. The system is also being tested under the European Commission – DG Research, Research Fund for Coal and Steel programme (RFCS), project RFCS-CR-03005 – ‘online measurement of coal quality parameters by inference of sensor information’.

Laser diffraction is a standard method used in many industries for characterisation and quality control. A number of such instruments have been developed for laboratory use. The device being currently tested is already used in cement plants. The purpose of testing the system is to determine its suitability for pulverised coal application (Rampelberg, 2005a).

In such a device, when a particle passes through a laser beam it causes light to be scattered at an angle that is inversely proportional to its size. A detector collects the scattered light. Analysis of the ensuing diffraction pattern enables calculation of the size distribution of particles in a given sample. Within certain limits, the scattering pattern of a group of particles is identical to the sum of individual scattering patterns of all the particles present. Figure 28 shows a simplified schematic of the laser diffraction device and Figure 29 shows such a device in application. Samples are collected from the pipe by a probe. After analysis the sample is injected in the pipe. The optical heads (emitter and receiver) are protected from fouling by the use of windows which are constantly cleaned.
by clean air and are free of any moisture and oil to avoid
deposit of particles on the windows (Rampelberg, 2005b).

The project has started recently and the first series of tests
carried out in an existing pulverised coal-power plant show
that the device reacted quickly to modifications in fineness
distribution indicating its ability for online coal particle size
measurement. Different series of tests will be carried out to
validate the technique for further pulverised coal application
(Rampelberg, 2005a).

The DTI (2001) and Miller and others (2000) presented work
carried out by Armour-Chelu and others (1998) in which the
latter investigated the charging of particles, due to contact
with pipe walls, using a small-scale test rig and olivine sand
as a medium. Results indicated that electrostatic measuring
methods could be employed to infer the charge development
trends in particulate materials and that signal processing of
the data could reveal information about particle flows in the
pipe. Examination of the data indicated a potential method
for measurement of particle size distributions, and Armour
Chelu and others (1998) described a route for further
development. The results of pilot scale tests using a non-
intrusive electrostatic method for measuring mass flow rate of
pulverised fuel indicated that although there was some
success in measuring concentrations, particularly at the lower
end of the concentration range (<0.5 kg/m³), significant
further development was required to prove the technical
feasibility of the approach.
Carbon in fly ash gauges

Online carbon in fly ash analysers may be considered an ideal tool to monitor the quality of fly ash on a continuous basis to maximise its sales and minimise disposal as well as laboratory analysis costs. Where possible, by using the data in a signal feedback system, a plant operator may be able to increase combustion performance, achieve lower NOx emissions and improve boiler efficiency. In 1997, a survey and demonstration of online carbon in ash monitors was carried out by Sorge and Larrimore of Southern Company Services (USA).

Promecon Prozess- und Messtechnik Conrads GmbH (Germany) developed an online analysis system for measurement of the unburnt carbon in the fly ash. The system, called MECONTROL UBC, comprises a central measurement unit and multiple remote sensors mounted into each ash measurement location. The measurement unit can manage the operation of up to 8 remote sensors and communicate the measurement data to the plant DCS by means of standard 4–20 mA analogue signals or Modbus interface. Sensors are designed to withstand the environment they perform in and to meet the industrial requirements of the power industry. Figure 30 is a simplified schematic showing the principle of the MECONTROL UBC system set up. The figure does not show the real situation at Dürnrohr power plant. The system shows accuracy in a broad measuring range and is independent of variations in coal type, a variety of which is fired at the facility (Otter, 2005; Promecon, 2005).

Investigation on the MECONTROL UBC online analyser for measurement of unburnt carbon in fly ash was undertaken at the EVN Dürnrohr coal-fired power plant in Austria within the ECSC project on online analysis of coal (see Chapter 3). Calibration and trial runs of the analyser were carried out in the first half of 2003. The flue gas stream is divided into three ducts and testing probes are located ahead of the ESP. All three test probes were operational by April 2004. Following are the tasks undertaken in this project (Andrés and others, 2004):

- analysis of operation under a variety of representative firing and operational conditions, load, type of coals and differing flue gas velocities;
- investigating the precipitation characteristics of different coal ash;
- studying the impacts on boiler efficiency and availability of operational constraints such as plant start-up, load shifts and on change-over from gas to coal and vice versa;
- evaluating online corrosion monitoring to relate conditions in the boiler with different coal types;
- carry out comparative evaluation of sampling methodologies for different operating and characteristic parameters.

The reconstruction of the boiler and the commissioning of the new installation in 2004 meant little work was carried out with the testing of the online analysis system for carbon in ash measurement at the time (Andrés and others, 2004).

In 2005, Otter discussed the installation of the

![Figure 30 A simplified schematic of the MECONTROL UBC system set-up](Promecon, 2005)
MECONTROL UBC system at the EVN Dürnrohr unit. The background and purpose of the tests were the measurement of the unburnt carbon concentration in a clearly defined sample volume and calibration of the online measured system by laboratory values with samples from the measuring chamber. Expectations of the online fly ash analyser were that:

- the system can be used for the certification of fly ash according to the standards for ash utilisation in the cement industry;
- optimisation of fly ash sales – if unburnt carbon content is low, the measurement can be used to optimise boiler settings as well as mill settings in order to reduce the fuel and internal power consumption as well as emissions (for example, NOx);
- by controlling the primary and upper air according to the coal mass flow, the unburnt carbon can be reduced, combustion efficiency maximised and emissions reduced;
- an optimum balance could be achieved between operating and maintenance costs.

In order to optimise online analysis application in the plant, the MECONTROL Coal (see Chapter 9) was also installed at the facility. These analysers are currently being tested at the EVN Dürnrohr unit. Future plans include creation of an ‘information window’ in which coal particle velocity, temperature and temperature difference are controlled online. If an unacceptable divergence from normal operation occurs, an alarm signal based on the analysers data should be generated to alert the operator to take appropriate action.

Microwave technology is also used in the ABB Carbon in Ash Load Instrument which is a real time, non extractive monitoring technique that may be integrated into a closed loop-optimisation control system. The technology promises a potential reduction of unburnt carbon in ash by 1–5% when tied to the control system.

The M&W Asketeknik RCA (Residual Carbon Analyser) 2000 system is marketed as an extractive, online instrument that provides real time information on combustion efficiency through monitoring of the unburnt carbon in the fly ash. The technology consists of three units (Burchardi, 2005b):

- the ash sampler: the sampling of the fly ash is done by utilising the difference between the pressure inside the flue gas duct and outside. An ejector is installed in the flue gas duct. This pulls the flue gas through the sampling pipe to the cyclone where the fly ash is separated from the flue gas;
- the transducer: the collected sample of fly ash is subjected to a special light and the reflection is a measure of the amount of the unburnt carbon in the sample. The signals from the reflection are processed in a microprocessor and sent to the control unit for further processing;
- the control unit: which undertakes the processing of the transducer signals and controls all function of the individual RCA 2000 components. An operator’s control panel, with display, provides possibilities for made selection and error messages as well as showing the selected measuring results.

The system measures the value of unburnt carbon in the fly ash every 3 to 15 minutes depending on the load of the boiler. More than 250 RCA 2000 units are installed in many countries including China, Denmark, England, Germany, Republic of Korea, Scotland, Spain and Sweden (Burchardi, 2005b).
One of the larger US utilities that has experience with testing online analysing systems is the Tennessee Valley Authority (TVA). Work at the TVA on online analysers began in the early 1980s to develop the Rapid Sulphur Meter (RSM) in co-operation with the Electric Power Research Institute (EPRI) and Systems Applications Incorporated (SAI). The system was PGNAA based and used a Californium-252 source to measure sulphur only. A few years later the Continuous Online Nuclear Analysis of Coal (CONAC) analyser was also developed at the Paradise facility to determine a variety of constituents of coal with the goal of indicating the heating value, ash content and ash constituents of coal. It appears that the outcome of these projects was somewhat less than successful. In the early 1990s, TVA acquired two Gamma-Metrics analysers for the Widows Creek plant to monitor the coal feeding the bunkers to prevent high sulphur coal from being fed to the low sulphur units. It was anticipated that, as an extra benefit, these analysers would provide information for power plant control. This did not actually happen. According to Thomas (2005), determination of heating value was an elusive goal. One of the analysers was eventually moved to the Paradise facility to monitor the coal being produced by the Paradise wash plant. A moisture-ash-free (MAF) heating value was manually input into the analyser. In this application, the analyser worked well by providing feedback to the operator to manually adjust the specific gravity of the washing units for control of the washed coal S content. Thomas (2005) states that, while these analysers were excellent for wash plant control and coal blending, they were rarely used to provide additional information outside proximate analyses. Suppliers of such analysers would claim that the instruments could indicate ash chemistry values, but in TVA’s experience at the time, the data rarely appeared to be accurate. Also, it was considered that while SO\textsubscript{2} heat value, ash and moisture content are useful parameters to have at the plant as they provide data on the coal feed burning within a few hours, it would be difficult to justify a US$1 million project unless some area of savings could be identified such as blending with cheaper fuel.

According to Thomas (2005), from the late 1990s emphasis has been on the development of a new type of analyser that does not require a radioactive source (such as Californium) but utilises neutron generator tubes to produce neutrons for bombardment of the coal atoms. Such an analyser would have an energy strength of about seven times that of the Californium source, creating a potential for developing a system that can analyse coal constituents (such as sodium) that are difficult to determine with lower strength units. The technique used in the analyser is known as pulsed fast thermal neutron analysis (PFTNA). TVA in cooperation with the Western Kentucky University (WKU) have been working on developing the analyser at the Cumberland coal-fired power plant. The analysis technique and analyser in question are presented in Chapter 5. Belbot and others (2004) present the evaluation and performance of the PFTNA analyser at TVA. Thomas (2005) states that while the results with this analyser have been disappointing, a similar type of analyser is produced by Sodern (France) (see Chapter 5) who have already sold one such analyser in China and is scheduled to install another at the Tennessee Eastman Company in East Tennessee (USA).

TVA is also involved in evaluating and testing laser-based online, in-duct/boiler-outlet, gas measurement and control systems at a number of their coal-fired power plants. The technologies and test sites are discussed in Chapter 5.

PacificCorp (USA) operates seven coal fired power plants and owns 4 more facilities operated by other companies. The 11 plants are comprised of 26 generating units with a combined rated capacity of 6.1 GWe (net). The utility currently utilises 5 PGNAA and several dual-gamma analysers. The dual gamma analysers are used to monitor ash content of the coals on an overland conveyor at the Deer Creek mine (delivered to the Huntington plant) and the ash content of the coal blended at the Cottonwood preparation plant (adjacent to Hunter power plant). A belt PGNAA analyser is also used on the run-of-mine conveyor at the Deer Creek mine, also for ash monitoring. Online analysers installed at the power generating facilities include (Snider, 2005):

- Huntington Canyon plant (2 units totalling net 900 MW)
  - One Thermo Gamma-metrics CQM analyser is used to monitor and aid in coal blending. Blending is for total ash content and to maximise the ash softening temperature. The ash softening temperature is estimated using relationships developed between coal ash chemistry (ash oxides) and fusion temperatures of the available coals. The analyser was installed in 2004 and is currently undergoing precision testing;

- Hunter plant (3 units totalling 1320 net MW)
  - Another CQM analyser is used at Hunter to control coal blending. The objective here is also to maximise the ash softening temperature of the blend of available coals. The analyser has been in operation for the past 2–3 years and has, along with the blending system located nearby, proven very successful in reducing lost generation due to slagging;

- Jim Bridger plant (4 units totalling 2120 net MW)
  - A further Thermo Gamma-metric CQM at this plant is used to monitor the quality of coal entering the units. Plant personnel are in the process of designing upgrades to the coal handling system that will allow greater control over coal blending and use of this analyser in a similar way to the Huntington and Hunter facilities. That is, to maximise ash softening temperatures and reduce forced outages related to slagging. The analyser has been in service for about three years. Installation of a PGNAA belt analyser is currently being considered as part of the upgraded coal system to aid in sorting and blending from new stacking tube stockpiles;

- Dave Johnston plant (4 units totalling 726 net MW)
  - A new CQM analyser has just been installed at this
Better monitoring of the coal blend into the units and reduced coal chemistry-related boiler derates (for example better control of the calcium content of the blend of available coals) are expected to be achieved with the new analyser. The latter is because the units fire PRB coals which are very high in calcium oxide. CaO greater than about 23% content results in reflective ash coatings inside the boiler and excessively high furnace exit gas temperatures (FEGT). Experience at the utility has shown that PGNAA analysis provides reasonably good results when measuring calcium in the coal.

The utility is also contemplating re-starting an older model PGNAA at their Naughton station. This analyser is on the consumed coal stream and would be used to monitor both sulphur (for which it was originally installed) and coal analysis to deal with some slagging problems with certain coal seams.

Snider (2005) states that, at all these PacifiCorp power plants, better understanding has been achieved of the relationships between coal chemistry and boiler performance issues such as slagging and fouling, because of the information provided by online, real time analysis. In general, the utility finds online analysers to be very useful tools when used properly (that is, having the ability to take appropriate action based on the readings the analysers provide). Knowledge of coal quality in real time is of no value if nothing can be done to either modify the quality or change boiler operation to adjust for quality changes.

**Eskom** is the state owned utility that generates 95% of the electricity used in South Africa. Its involvement in online elemental analysis began in 1993, when a joint venture was established between Eskom and Ingwe (SA subsidiary of Billiton) to test the Scantech Coalscan PGNAA analyser at the interface between the Hendrina power plant and Optimum Colliery (multi-product Ingwe mine supplying Eskom and the export market). After extensive testing/validation/calibration, Coalscan was accepted in December 1999 as the tariff reference for payment against a contract. Procedures governing the use and testing of the analyser have been further refined since. According to Cumming (2005), there has been a huge challenge in acceptance of the technology against the traditional laboratory based systems. However, it seems that the local industry is becoming more accepting due to greater exposure and understanding of the technology mainly through the efforts of plant personnel.

Eskom (South Africa) have also been involved at two power plant sites with microwave moisture analysis and dual gamma technology. Dual gamma was not favoured due to the variability in the coal with regard to iron and calcium which interfered with the signal. Two Coalscan moisture analysers were installed at the interface between another Eskom power plant and the supplying colliery in 1996 as part of a moisture peak management process. The analysers were not successful due to the bed depth/tonnage rates and measurement of moisture above levels of 12%. Eskom are currently considering installing the new generation moisture analysers, which are capable of handling these volumes.

In 2004, a project was initiated to review the use of online analysis within Eskom. A report of the findings will be issued shortly to management. A workgroup has been established with representatives from each power plant. Initially meetings were undertaken to expose key players to the technology and has progressed to discussion sessions with the major online analysis system suppliers including those offering PFTNA technology. Two stations have already budgeted in the current financial year to purchase and install online analysers and are awaiting the closure of the report. Eskom are focusing on the over-belt models for coal management/plant optimisation purposes. A research project will also be launched shortly looking at the use of the online information for combustion control purposes. Much work has already been done on slagging models. Anglocoal (South African) have recently installed two over-belt Coalscan analysers at two of their operations and are currently in the process of commissioning these. Cumming (2005) believes that more application of online analysers in the Eskom fleet will follow.
13 Cost justification for analyser installation

Justification for installing an online analyser simply put, by Evans (2004b), is that it must lower coal production costs or generated electricity costs, increase the capacity of the facilities in tonnes or megawatts, guarantee or increase the value of the products sold, eliminate contract or environmental penalties or, all the above. Table 12 summarises the ways coal analysers have been used to generate additional revenues. Some of the items in the table are difficult to evaluate before an analyser is installed, but are included because of the additional benefits that have been observed following the installation. In this section, only justification for power generators will be discussed.

According to Mazzone (2003) the following are some of the questions that should be considered to determine if an online analysis system is suitable for a particular installation:

- do the economics of the process control at the site justify the cost of an online analyser?
- what are the parameters that can be controlled? For example, ash, sulphur, moisture?
- if blending is a goal, are the feeders responsive and scale installed for each blend source, as well as the final product stream?
- which parameters are for contract purposes but do not have to be analysed in real time?
- what degree of accuracy is needed for the process control?

Corollaries to the process control accuracy include:
- is it well known that the calorific/heat value, volatile matter and sulphur dioxide are not directly measured but calculated from other elements?
- are the limitations of microwave technology for moisture determination understood, particularly regarding inherent moisture changes or differences?

These issues among others must be considered and evaluated in order to provide necessary information for decision making to take that step and invest in online analysis systems in any facility for coal quality management.

Actual capital cost depends on site specific requirements. An analyser installation capital cost ranges from about US$400,000 to US$1.2 million depending on the type of analyser and the amount of required support work. Evans (2004b) used the payback period as an indication of whether the analyser investment rate-of-return will be sufficient to justify the investment. Table 13 shows the relationship of payback period for a US$800,000 investment on project

Table 13 Internal rate of return (IRR) to payback period on an US$800,000 investment (Evans, 2004b)

<table>
<thead>
<tr>
<th>Payback period in years</th>
<th>IRR for US$0.8 million project, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>200</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>1.5</td>
<td>66</td>
</tr>
<tr>
<td>2.0</td>
<td>49</td>
</tr>
<tr>
<td>2.5</td>
<td>38</td>
</tr>
<tr>
<td>3.0</td>
<td>31</td>
</tr>
<tr>
<td>3.5</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 12 Ways coal analysers have been used to generate additional revenue (Evans, 2004b)

<table>
<thead>
<tr>
<th>Sources of additional revenue</th>
<th>For the coal producer</th>
<th>For the power generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower operating costs</td>
<td>control of out of seam dilution</td>
<td>lower fuel cost</td>
</tr>
<tr>
<td></td>
<td>by-pass coal around a preparation plant</td>
<td>lower net heat rates (fewer tonnes fired per MW)</td>
</tr>
<tr>
<td></td>
<td>increased preparation plant efficiency</td>
<td>fewer forced outages</td>
</tr>
<tr>
<td></td>
<td>ability to blend in lower cost coals</td>
<td>identification of non-coal related problems faster</td>
</tr>
<tr>
<td>Increased capacity</td>
<td>control of out of seam dilution</td>
<td>higher unit availability</td>
</tr>
<tr>
<td></td>
<td>preparation plant efficiency improvement</td>
<td>fewer derates</td>
</tr>
<tr>
<td></td>
<td>reduce over washing</td>
<td>fewer forced outages</td>
</tr>
<tr>
<td>Increased product value</td>
<td>consistent coal quality</td>
<td>operating closer to unit design limits</td>
</tr>
<tr>
<td>Avoiding penalties</td>
<td>blend shipped coal to avoid rejects and quality penalties</td>
<td>increased generation availability when rates are high</td>
</tr>
<tr>
<td></td>
<td></td>
<td>increase the value of the fly ash product for sale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>blend to control stack emissions</td>
</tr>
</tbody>
</table>

Online analysis and coal-fired power plants
internal rate-of-return (IRR) assuming a constant income stream.

Typical justification in power plants for online analysers include reducing fuel costs, increasing the average generating capacity of the station, and/or eliminating or reducing station derates and forced outages due to fouling and slagging. In the USA, experience has shown that when the coal feed quality is known finding and dealing with operational issues such as mill or primary or secondary air problems is faster. The timely information on ash, moisture, sulphur, energy content and elemental analysis allows for decision making that maximises the value of the resource and minimises operating costs. In addition, many power plants today increasingly fire coal blends in boilers that were initially designed to burn specific coals. According to Cole and Frank (2004), plants firing design specification coal have equivalent availability factors in the range 85–90%, equivalent forced outage rates in the range 3–5% and net heat rates in the range 9700–9950 Btu/kWh (10234–10497 kJ/kWh) or lower. When switching coals (whether because the original supply is depleted or compliance issues forcing a coal mix change or simply in search of cheaper coals) these plants equivalent availability factor ranges change to 70–75% or lower, equivalent forced outage ranges are 15–20% or higher and net heat rates ranges change to 10,000–12,000 Btu/kWh (10550–12660 kJ/kWh) or greater. When switching coals (whether because the original supply is depleted or compliance issues forcing a coal mix change or simply in search of cheaper coals) these plants equivalent availability factor ranges change to 70–75% or lower, equivalent forced outage ranges are 15–20% or higher and net heat rates ranges change to 10,000–12,000 Btu/kWh (10550–12660 kJ/kWh) or greater. Online coal analysers provide tools that monitor and control the coal quality and feed to achieve optimum performance and therefore improve the financial productivity of a power plant (Evans, 2004b).

Evans (2004b) gives hypothetical examples of fuel cost savings including savings due to fuel blending controls, savings for a plant with different peak and off peak load demands and savings due to reduced fouling, slagging and forced outages. The latter issues, resulting from the ash softening temperature of the coal not matching the boiler design, cause derates or in worse cases a forced outage. These are costly in that less electricity is generated to sell and maintenance efforts have to be undertaken to deal with the fouling and slagging problems. Two steps are needed for justification of an online analyser to control these problems. These are:
- data collection to determine the cost of the derates and forced outages;
- determination of a relationship between the ash softening temperature and the analysis that can be carried out with the analyser.

Table 14 shows the effect on revenues if the forced outages and/or the average derates at a plant are reduced, assuming an average value per MW of US$35.

In conclusion, Evans (2004b) states that when analysers are used to improve an operation, project justification must be based on the additional profits that will result from using the analysers to improve performance. This requires a detailed understanding of the economic factors in the operation that real time, continuous knowledge of the coal quality can affect.

Finally, for an online analyser of any type to be considered useful for power plant operation the following must be considered (Thomas, 2005):
- online analyser units are quite large and would be too expensive for multiple analysers to be mounted between the bunkers and the power plant. Therefore these units would more likely be mounted between the coal yard and the bunkers. This would also require the need for a good bunker modelling programme to predict when the coal that has been analysed would actually be fired in the boiler; such programmes are available but are not discussed in this review;
- currently coal samples represent a large amount of coal, or coal that has been sampled over many hours. Sometimes issues can be masked in a sample taken over many hours versus what could be seen in a continuous analyses. TVA, for example, experienced such issues with moisture meters;
- the ability to compare online analysis to actual power plant performance will reveal correlations that are currently not possible with conventional coal sampling.

| Table 14 The effect of reducing forced outages and derates on a 750 MW power plant revenue (Evans, 2004b) |
|-------------------------------------------------|-----------------|-----------------|
| Number of forced outages                      | 9               | 4.5             | 9               |
| Average hours a forced outage lasts           | 48              | 48              | 48              |
| Unit derate in MW/h                           | 30              | 30              | 15              |
| Rated generation capacity MW/h                | 750             | 750             | 750             |
| Scheduled service h/y                         | 100             | 100             | 100             |
| Equivalent forced outages rates               | 8.79%           | 6.39%           | 6.89%           |
| US$/MW                                         | 35              | 35              | 35              |
| Lost revenue US$/y                            | 19,979,400      | 14,536,200      | 15,659,700      |
| Revenue increase, US$/y                       | 5,443,200       | 4,319,700       |

IEA CLEAN COAL CENTRE
These correlations, at this time, are speculative, not proven and may not actually occur. However, the possibility of these correlations occurring is what drives the interest in the area of online analysis in coal-fired power plant.

If a power plant operator knew what problem coal and/or flue gas constituents were to cause next, this would allow him/her to explore their options to deal with the problem. They would know that they may have to, for example reduce load to avoid slagging or feed combustion chemicals to the unit or, change the coal source to the unit to another silo or reclaim.
Online analysis can play a major role in minimising not only generation costs (for example, fuel cost) but also operational issues at a coal-fired power plant. The technology is accepted in the coal producing sector but its application remains somewhat sporadic in power generating plants. Coal quality and constituents from the same mine can vary enormously. At the mine, online analysis can provide the opportunity to control the ash content of the coal and thus match production to contract specifications. Once stockpiled on the plant site, obtaining representative samples of the many thousands of tonnes of coal in a consignment is difficult. On site as well as off-site conventional laboratory analyses can be time consuming and hence do not necessarily reflect current plant operating conditions. Online analysers in power plants, can provide real time data on parameters such as ash and moisture content as well as elemental composition of the coal, thus showing variations in coal quality as they occur. Non-destructive and direct measurement of either parameter is not possible. Instead, values are inferred from measurements of the amount of mineral matter (primarily Si, Al, Ca and Fe). The calorific value of coal is not measured directly either but determined through algorithms that use organic matter elements such as C, H and O.

Online analysis techniques today use nuclear (X-ray, gamma ray, neutron), microwave, ultrasonic and optical technology. Significant advances are being made in a range of associated technologies including lasers, electronics, computers, software, detectors and digital signal processing. These advances enable the development of measurement and control systems that were not feasible just a few years ago.

To date, the major benefit of online analysis has been to provide real time, coal quality information for use in sorting and blending: thus, optimising the use of resources while delivering a consistent product that meets contract specifications. Coal-fired power plants make up about a third of online analysis applications for ash and moisture content but constitute a much smaller percentage in the use of elemental analysers. However, the demand for electricity at the lowest possible cost while meeting environmental compliance (minimising emissions) has led more utilities to the lowest possible cost while meeting environmental constraints on particle size, they are easier to relocate should the conveyors be moved or the preferred location changed and they are relatively easy to maintain. However, cross-belt analyser performance is not as good as that of sample-stream analysers as obtaining physical coal samples to compare to the analyser data is challenging in many cases. Cross-belt analysers are not recommended for steel cable belts because of the high and varying iron content in the belt.

A number of pulverised coal flow measurement instruments are now commercially available. Some have already been installed at demonstration and/or at commercial scale at a number of pulverised coal-fired power plants in several countries including Australia, Canada, Denmark, Finland, Germany, Japan, Republic of Korea, Portugal, Spain, South Africa, the UK and the USA. These operate mainly on acoustic, electrostatic and microwave sensing principles. The majority of these instruments achieve coal velocity measurement by applying cross-correlation signal processing algorithms. Absolute measurement of coal concentration and hence coal mass flow rate remains an area where work continues and further development is still required. There are also no commercially proven devices currently available for the split control of coal flow although coal flow balancing systems are being demonstrated at coal-fired power plants. The split control of particles is recognised as an inherently complex subject especially in large-scale power plant pipes. Work also continues to develop such devices.

One of the main factors in optimising boiler combustion, efficiency and minimising emissions is to have the overall oxygen level (air to fuel ratio) as low as possible while maintaining acceptable boiler operation. Oxygen analysis in flue gas made major advances in the 1980s with the introduction of reliable in situ measurement tools. Extractive, mainly paramagnetic devices were widely used as the only source of continuous measurement until the introduction of the zirconium oxide in situ measurement techniques. Today, the real time, continuous, in situ zirconium oxide analyser is the standard for measuring oxygen at coal-fired boiler outlets. Cross-duct laser spectrometry appears to be increasingly attractive in aggressive environments such as coal-fired boilers. Also zirconia sensors are emerging for CO measurement.

Online analysers are used for monitoring carbon in ash at numerous coal-fired power plants. Their application is mainly driven by the need to guarantee the marketability of the fly ash. Online carbon in fly ash analysers may be considered an ideal tool to monitor the quality of fly ash on a continuous basis to maximise not only its sales potential but also minimise disposal as well as laboratory analysis costs. Where
possible, by using the data in a signal feedback system, a
plant operator may be able to boost combustion performance,
achieve less NOx emission and improve boiler efficiency.

The performance and accuracy of online analysers depend
strongly on initial installation, calibration, subsequent
maintenance and application environment. Of prime
importance is initial calibration. Reference samples that
represent the range of coals fired at a plant must be used
during the initial calibration process. Analysis of coals
beyond the range of the initial calibration, will not have the
same accuracy. Therefore, changes in coal supply can
necessitate re-calibration. Re-calibration may also be
necessary due to drift over time.

Not all online analysis applications have been successful.
Some have resulted in disputes between vendor and user
regarding performance. In some cases, the online analysis
projects were considered a failure and consequent economic
losses were incurred by all parties involved. When deciding
to invest in an online analyser, as with any other technology,
important factors must be considered at the outset to achieve
successful installation. For example, there should be a clear
understanding of what the project must accomplish to be
judged successful, such as reducing annual generating unit
derates by a specified percentage or reducing monthly quality
penalties on coal shipments by a set amount.

In general, online analysers can be very useful tools when
used properly – that is, combined with the capability/ability
to take appropriate action based on the readings the analysers
provide. Knowledge of coal quality, flue gas constituents,
carbon in ash content, or any other data in real time is of no
value if nothing can be done to either alter the quality of the
coal feed, its flow and distribution or modify boiler operation
to adjust for changes. Suppliers maintain that online analysis
is designed for process control, to optimise the use of the
carbon and pro-actively control the boiler operation; it is not
designed to replace laboratories. Acceptance of online
analysers and their uptake in coal-fired power plants has been
increasing since the late 1990s. Over the next few
months/year the performance of these installations will
determine whether investment in them is worthwhile. Initial
indication is that online analysers are capable of improving
the operation of a power generating plant and payback is
usually in a relatively short period of time, thus justifying the
incentive expenditure. Many of the power plants supplied
with elemental analysers use the analyser ability to measure
sulphur as the key justification for acquiring these systems.

An overview of online systems application in IEA CCC
member countries indicates that online analysis techniques
although widely used in mines and coal preparation plants
are not as widely used in existing coal-fired power plants.
Especially where the sole purpose is measuring ash, moisture
and elemental analysis to improve power plant performance
and therefore reduce emissions. Although online analysers
(mainly for carbon in ash) are in use or are being tested at a
number of facilities in Europe, these are not considered as
operating at commercial level but only for research purposes.
However, it appears that online analysers for ash and
moisture measurement are being used in Australia, Canada,
South Africa and in the USA. Elemental analysers have also
been installed in a small number of coal-fired facilities in
some countries such as Australia and South Africa but are
mainly used in the USA. The installation of most of these
online analysers has been in the last 4–5 years. The
successful and beneficial application of real time, online
analysers once proven, should result in a larger number of
installations. The ability of such analysers to provide precise
and reliable data on the quality of the coal fired in real time
can assist in maximising boiler efficiency and performance
thus reducing all emissions. Furthermore, online analysers
can be used to optimise coal blend to keep within emission
limits and without using excess amounts of premium priced,
low sulphur coals or, in some cases, fitting FGD.

Applying online analysis in a coal-fired power plant involves
extensive planning, preparation and evaluation prior to the
installation and, continued monitoring and maintenance after
installation. Repeatability combined with speed, ease of
integration and reliability are most important specifications in
any online analyser. Each potential application has unique
characteristics and requirements that must be considered in
order to achieve the desired outcome.

Online analysis and coal-fired power plants
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