Abstract

The presence of troublesome impurities in coal affect its behaviour during combustion and hence the performance of coal-fired boilers. The report discusses how the quantity and composition of the ash varies in the world’s major coals. Ways of minimising the amount of mineral matter in the coal are outlined.

The mineral transformations which take place in a pulverised coal fired boiler are described together with the behaviour of various ash-forming components which can cause slagging or fouling deposits. Various management methods can be used to minimise and/or control the adverse effects of deposition. These include modelling coal quality impacts and using advanced measurement devices and control systems. Intelligent sootblowing where the boiler cleaning blowers are actuated when required is being increasingly used.

Ash management in circulating fluidised bed boilers is also discussed, together with various aspects of ash use. There is increasing pressure to make use of the ash formed in boilers to reduce the need for disposal sites.
# Acronyms and abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ACARP</td>
<td>Australian Coal Association Research Programme</td>
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<tr>
<td>af</td>
<td>ash free</td>
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<tr>
<td>AI</td>
<td>abrasion index</td>
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<td>ar</td>
<td>as received</td>
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<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
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<tr>
<td>BFBC</td>
<td>bubbling fluidised bed combustion</td>
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<td>BS</td>
<td>British Standard</td>
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<td>CCB</td>
<td>coal combustion by-products</td>
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<td>CCSEM</td>
<td>computer controlled scanning electron microscopy</td>
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<td>CFBC</td>
<td>circulating fluidised bed combustion</td>
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<tr>
<td>CFD</td>
<td>computational fluid dynamics</td>
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<td>CPP</td>
<td>coal preparation plant</td>
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<td>CQETM</td>
<td>Coal Quality Expert</td>
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<td>CQIM</td>
<td>Coal Quality Impact Model</td>
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<tr>
<td>daf</td>
<td>dry ash free</td>
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<td>dmmf</td>
<td>dry mineral matter free</td>
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<tr>
<td>DOE</td>
<td>Department of Energy (in the USA)</td>
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<td>DTI</td>
<td>Department of Trade and Industry (in the UK)</td>
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<tr>
<td>ECOBA</td>
<td>European Coal Combustion Products Association</td>
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<td>EERC</td>
<td>Energy and Environmental Research Centre (in Grand Forks, ND, USA)</td>
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<tr>
<td>EGC</td>
<td>equivalent generation capacity</td>
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<tr>
<td>EPRI</td>
<td>Electric Power Research Institute (in Palo Alto, CA, USA)</td>
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<tr>
<td>ESP</td>
<td>electrostatic precipitator</td>
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<td>FBC</td>
<td>fluidised bed combustion</td>
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<td>FEGT</td>
<td>furnace exit gas temperature</td>
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<td>FGD</td>
<td>flue gas desulphurisation</td>
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<td>FSU</td>
<td>Former Soviet Union</td>
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<tr>
<td>HGI</td>
<td>Hardgrove Index</td>
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<td>HHV</td>
<td>higher heating value</td>
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<td>HTM</td>
<td>Heat Transfer Manager</td>
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<td>IDT</td>
<td>initial deformation temperature</td>
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<td>IEA</td>
<td>International Energy Agency</td>
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<tr>
<td>IGCC</td>
<td>integrated gasification combined cycle</td>
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<td>ISB</td>
<td>intelligent sootblowing</td>
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<td>LHV</td>
<td>lower heat value</td>
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<tr>
<td>LOI</td>
<td>loss-on-ignition</td>
</tr>
<tr>
<td>mmmf</td>
<td>moist mineral matter free</td>
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<tr>
<td>NETL</td>
<td>National Energy Technology Laboratory (Morgantown, PA, USA)</td>
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<tr>
<td>OECD</td>
<td>Organisation for Economic Cooperation and Development</td>
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<tr>
<td>PCC</td>
<td>pulverised coal combustion</td>
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<tr>
<td>PCI</td>
<td>pulverised coal injection</td>
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<tr>
<td>PGNAA</td>
<td>prompt gamma neutron activation analysis</td>
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<tr>
<td>PLC</td>
<td>programmable logic controller</td>
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<tr>
<td>PRB</td>
<td>Powder River Basin</td>
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<tr>
<td>SCR</td>
<td>selective catalytic reduction</td>
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<tr>
<td>SEMPC</td>
<td>scanning electron microscopy point count</td>
</tr>
<tr>
<td>TVE</td>
<td>township and village enterprise</td>
</tr>
<tr>
<td>UHV</td>
<td>useful heat value</td>
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<tr>
<td>WEC</td>
<td>World Energy Council</td>
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</tbody>
</table>

### Units used

- ha: hectares
- GWe: gigawatts (electrical)
- km: kilometres, MJ/kg: megajoules per kilogramme
- m: metres
- MPa: megaPascals
- MWe: megawatts (electrical)
- My: million years
- Mya: million years ago
- s: seconds
- t: tonnes
- µm: micron (m x 10⁻⁶)
- y: year
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Ash management in coal-fired power plants
Coals contain both organically-bound inorganic components and inorganic mineral matter, in widely varying amounts. During combustion, these constituents undergo various transformations to form both ash and gaseous products. It is the management of these processes and transformations (insofar as they can be managed) which is the subject of this report.

The presence of troublesome impurities, particularly of the ash-forming minerals and sulphur, affect the behaviour of coal during combustion and hence the performance of a coal-fired boiler. They may absorb heat as they change in phase, they may catalyse the oxidation taking place, and may cause particles to have a sticky surface. There is a wide range of behaviours, depending on the mineral matter present and on the time-temperature cycle which the particles experience. Some mineral impurities are interspersed through the coal and some may arise from adjacent rock which is disturbed by the mining operation getting mixed up with the coal. Impurities such as the organic sulphur, organic nitrogen and some mineral salts, are an integral part of the structure of the organic macerals.

The impurities present contribute to the nature and composition of the flue gases arising from the combustion process. These gases may need cleaning before they are emitted via the stack. The impurities also contribute to surface deposition in various parts of the boiler which interferes with heat transfer, and may, in some situations lead to large-scale build-up of solids in parts of the boiler. They may also contribute to erosion and corrosion within the boiler, and may affect gas cleaning processes.

The report is structured to address ash management issues by discussing:
- where the ash comes from and how its quantity and composition varies in the world’s major coals. These are discussed in Chapters 2 and 3;
- coal pre-treatment, and in particular coal washing, which can affect both the quantity and nature of the ash-forming constituents present in a boiler, is discussed in Chapter 4, together with milling conditions which affect the particle size of the feed;
- the potential reactions in the coal particles during the time-temperature cycle and conditions they are likely to encounter in the combustion chamber, and then during the flue gas cooling stages in the convection section of the boiler. Combustion conditions are affected by the burner and boiler design, by the air and fuel distribution (for example they are different if low NOx burners are being used). The conditions have a direct impact on the formation of both fly ash and bottom ash. New boiler conditions using higher steam temperatures and pressures may affect the coal specification required, as well as the behaviour of the ash once formed. All these topics are discussed in Chapter 5;
- the temperature reduction and flow of the flue gases carrying ash particles through the superheater, reheater and economiser sections of the boiler. These affect both the formation and deposition of the ash. The heavier particles with a sticky surface are more likely to deposit, and then to catch other passing particles, resulting in fouling. These mechanisms affect the heat transfer performance of the various boiler sections and hence its thermal efficiency;
- the nature, composition and quantity of the fly ash. These have a crucial effect on the performance of the electrostatic precipitators (ESPs) or baghouse filters which are used to remove particulates from the stack gases before discharge. The presence of ash may have an effect on post-combustion clean-up of the flue gas using, for example, selective catalytic reduction (SCR) to reduce the levels of NOx, and on the operation of flue gas desulphurisation (FGD) units. These issues are discussed in Chapter 6.

Previous experience in other boilers provides an invaluable empirical and practical basis for making management decisions, and for predicting and minimising slagging and fouling. The various management tools which are available to supplement operational experience and help with ash management are reviewed in Chapter 7. Ash management in CFBC systems is discussed in Chapter 8.

Coal combustion by-products (CCBs) arising from power generation are described by Punshon and others (2003) as being the largest waste streams worldwide from any process. Legislation aimed at reducing the environmental impacts arising from its disposal is increasing the need to develop safe and appropriate uses for these materials. While the production of CCBs continues to rise, so do the costs associated with disposal and landfilling. As a result, there are an increasing number of commercial applications for the materials, and the language used is tending to change from referring to the materials as residues or wastes to referring to them as by-products.

The nature of the fly ash in particular, and to a lesser extent of bottom ash, affects its potential for constructive use. Currently very large quantities of ash are dumped after combustion. Environmental awareness and regulatory pressure in many countries is making this increasingly costly, so that operators are looking for markets and uses for the material. This means that there is more attention paid to the composition of the ash formed. The issues connected with the use of CCBs are explored in Chapter 9. Some aspects of this have been covered in other IEA Clean Coal Centre reports Cement and concrete – benefits and barriers in coal ash utilisation, and, Land uses of coal fly ash – benefits and barriers (Smith, 2005a,b).
Ash is the material which is formed as a residue during and after coal combustion or gasification. Strictly, coal does not ‘contain’ ash, but it includes ash-forming materials which consist of both included and extraneous minerals, together with organically bound components. Most either melt or vaporise in the combustion zone of the boiler, and then solidify or condense when the flue gases are cooled. The solid materials formed are the coal ash.

Coals are thought to have originated from degraded vegetable matter which was growing on the earth’s surface, and later formed very thick peat-like deposits. It is a sedimentary rock which is, in effect, a compacted and stratified mass of decayed plants converted into a mineral deposit. During peatification, which typically lasted for 10,000–15,000 years, biochemical activities were predominant. The biological activity was determined by whether or not the deposit was under water. If the vegetable matter was under water, this would exclude oxygen/air based reactions, as in the formation of the world’s current peat deposits (Couch, 1993).

Plants and trees contain a rich variety of materials, including:

- structural components contributing to the plant’s rigidity and form, including cellulose, hemicellulose, lignin and calcium pectate;
- stored food for the promotion of future growth including carbohydrates, starch, fats, oils and proteins;
- protective materials including resin, cutin, waxes and sporopollenin (Malvadkar and others, 2004).

With geological change, the layers of vegetable matter including all these complex materials were buried, and subjected to pressure, temperature and movement over periods of millions of years. The process called coalification has taken tens and even hundreds of millions of years, and resulted in the formation of coals which have widely differing properties from place to place, from seam to seam, and even within individual seams.

Some seams lie in horizontal or only gently inclined strata, while others have been folded over by geological action, or lie at a steep angle. Seam thickness can vary from just a few centimetres up to amounts of more than 100 metres, and only some of the coal which has been formed can be mined economically. In the deeper bituminous coal deposits, the extracted seams commonly have a thickness of between 1 m and 4 m. The coal seams frequently lie in a sequence representing successive periods when the peat-like deposits were formed. There can be as many as twenty or thirty different seams in a sequence. Of these seams, two or three are likely to be mineable by conventional methods, and the normal pattern is to extract the shallower seams first wherever possible to avoid geological disturbance. There are substantial deposits at depths below 1000 m which cannot generally be extracted by conventional mining methods as the temperatures and pressures in the seam would be too high.

The different environments during deposition

Carboniferous coals were deposited 350–270 million years ago (Mya) in a broadly tropical environment where there were probably no marked seasons. There was moderate to heavy rainfall in many places and forests covered huge areas of the globe. Deposition and burial rates were higher in the warmer Carboniferous mires. The dominant flora in Carboniferous times were giant clubmosses, a conifer precursor together with a variety of ferns and fern-like plants. By contrast, the Permian coals (270–225 Mya) were formed under temperate to cool conditions with marked seasonal differences. In the Permian period, the dominant flora in the peat bogs were deciduous trees and shrubs, with lesser amounts of ferns. Except in China, deposition leading to the formation of coal, declined in what became the northern hemisphere. In what subsequently lay generally to the south, important deposits were laid down in India, South Africa and Australia.

In the Cretaceous period (150–65 Mya), the climate was so mild that vegetation grew even in the polar regions, leading to the formation of subbituminous coals in many places. In the Tertiary period (from 65 Mya), the deposition of plant materials continued, and ashes, willows and maples were common plants. Deposits from this period tend to be of lignite or brown coal as the coalification process has not gone very far. Just a few of the coals used, like those in Turkey, were formed at the very end of the Tertiary in a period called the Quaternary, which just covers the last two million years.

Coalification involves the cumulative effects of both temperature and pressure, and deeper seams have experienced higher temperatures due to the heat coming from the earth’s core. The pressure experienced affects the coal’s physical properties, including hardness, strength and porosity. The environment during which coal formation took place had a strong influence on the nature of the ash-forming materials present.

During the period from around 400 Mya, when coal formation started, there have been major movements in the shape and location of the world’s continents. This is because the Earth’s crust and the upper part of the mantle, consist of a number of mobile plates that have undergone amalgamation and fragmentation in response to convection effects in the magma underneath. This is discussed in more detail in another IEA Clean Coal Centre report, Major coalfields of the world (Walker, 2000). The main geological periods are defined in Table 1. There was some coal formation during the Devonian period, but at this time the vegetation fell mainly into shallow lagoons, so most of the coal formed was in thin coal sequences rather than in mineable and identifiable seams (Williams and others, 2000). It was during the period between 400 and 200 Mya that some of the oldest coalfields were initiated with their anthracites and higher rank bituminous coals.
Until around 200 Mya it is thought that all the worlds continents were joined together into one single supercontinent called Pangea (all the earth). There were three main blocks, Gondwana, Euramerica and Siberia. Around 130 Mya the supercontinent known as Gondwana drifted away and broke up to form Australia, India, Africa, South America and Antarctica. Since many of the coals in Gondwanaland had much the same origins, and the conditions for their formation were broadly similar, the older coals in these places have many similar characteristics including those associated with the ash-forming minerals present.

It was not until the early Tertiary period from 65 Mya, that the continents approached their current global positions and the world’s land masses were shaped roughly as we see them today. The younger coals formed during the Tertiary are highly variable, and consist mainly of the lignites, brown coals and some subbituminous coal. Their formation was dependent on even more variable conditions than existed earlier, and most have been subjected to much less coalification. The composition of the different coals affects their combustion characteristics, and therefore what time-temperature cycle the various impurities experience. The younger coals are more reactive with a higher volatiles content, and they contain more water in a well developed pore structure. The need to evaporate considerable amounts of water tends to result in a lower combustion temperature in a boiler.

### The origin of the ash-forming materials

As outlined above, coals include a wide range of inorganic materials which were deposited into the strata, and these were introduced as:

- constituents of the vegetation from which the coal is derived. Woody tissue contains 1–2% of inorganic material, while leaves and bark contain 10–20%. Much of this remains in the coal, possibly after reaction with the changing organics. In the low rank coals, many of the inorganics remain chemically attached to the carbon structure;
- detrital matter which was blown on to or washed into the deposits. The discrete solids may have came from volcanos or from fires, and the fine particulates were carried around by the wind, dropping into the peat bogs in which the coal was forming;
- crystalline deposits which originate from either groundwater or seawater. The material described as mineral matter may well include the dissolved salts in water held in the pores. Dissolved salts may have crystallised out when the environment changed, and the inorganics deposited then stay in the coal (Ward, 2002). These contain mainly iron, calcium, magnesium and chloride minerals.

### Table 1 The geological age of different coals, and where the main coalfields were formed

(modified from Williams and others, 2000; Walker, 2000)

<table>
<thead>
<tr>
<th>Geological period (Mya)</th>
<th>Million years ago</th>
<th>Main coalfields formed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Devonian</td>
<td>400–350</td>
<td>Most central European bituminous deposits, including European Russia; Canada (Nova Scotia); USA (eastern and central states)</td>
</tr>
<tr>
<td>Carboniferous</td>
<td>350–270 (Upper Carboniferous 350–310) (Lower Carboniferous 310–270)</td>
<td>Part of Asiatic Russia, including Kusnetz; East India (Raniganj/Jharia basins); East China; South Africa (Karoo basin) and part of Australia (the Bowen and Sydney basins)</td>
</tr>
<tr>
<td>Permian</td>
<td>270–225</td>
<td>India (NW frontier); West China; New Zealand (south); part of Australia; most of Asiatic FSU, and Georgia</td>
</tr>
<tr>
<td>Triassic</td>
<td>225–180</td>
<td>USA (Great Plains); Canada (BC, Saskatchewan and Alberta)</td>
</tr>
<tr>
<td>Jurassic</td>
<td>180–135</td>
<td></td>
</tr>
<tr>
<td>Cretaceous</td>
<td>135–65</td>
<td></td>
</tr>
<tr>
<td>Tertiary subdivided into:</td>
<td>65–2</td>
<td>Most European brown coals; Australian and New Zealand brown coals; India (NW frontier and Tamil Nadu); USA (western coals and northern Great Plains); parts of Canada; Indonesia</td>
</tr>
<tr>
<td>– Paleocene (65–55)</td>
<td></td>
<td></td>
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<tr>
<td>– Eocene (55–37)</td>
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<td></td>
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<tr>
<td>– Oligocene (37–22.5)</td>
<td></td>
<td></td>
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<tr>
<td>– Miocene (22.5–5)</td>
<td></td>
<td></td>
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<tr>
<td>– Pliocene (5–2) Mya</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quaternary subdivided into:</td>
<td>2 to present</td>
<td></td>
</tr>
<tr>
<td>– Pleistocene (2–0.01)</td>
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<td></td>
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<tr>
<td>– Holocene (0.01 to present)</td>
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</tbody>
</table>

Various commentators use slightly different dates to define the geological periods

Note that 0.01 My = 10,000 years
The differences between the conditions under which Carboniferous, Permian and the younger Tertiary coals were deposited, affected the formation of macerals which are the degraded remains of plants, and thus organically based. There is great variety, even within the coals formed at similar times. The inclusion of foreign mineral matter may be triggered by volcanic action, it can arise because of the inclusion of salts from a marine environment or it may be the deposition of small wind-borne solid particles resulting from erosion. The mineral matter consists mainly of compounds with a defined composition, many of which are in a crystalline form. There are also some chemically combined inorganics held within the organic material, particularly in the younger coals.

In general, Permian coals contain a higher proportion of clay minerals, significantly higher semifusinite, lower vitrinite and liptinite and less sulphur than Carboniferous coals. Coals with a high inertinite content are generally slower to burn. The dominantly marine Carboniferous coals tend to have a higher sulphur content than the more terrestrial Permian deposits (Relfenstein and others, 1993).

The mineral matter in coals has been studied principally in order to understand its behaviour during combustion or other processing. The various analytical techniques used, including computer controlled scanning electron microscopy are discussed by Carpenter and Skorupska (1993), and Couch (1994). The solid inorganics in coal are mainly present in crystalline form, either as single compounds or as interwoven mixtures, although some exist as amorphous phases. The major groupings of mineral matter in coals include silicates, oxides, carbonates, sulphides, sulphates and phosphates. Organically-bound elements such as Na, K and Ca are more commonly found in lower rank coals.

Northern hemisphere researchers developed coal classification and terminology in the early part of the last century, largely based on Carboniferous coals. Many of the coals originating in Europe and north America are Carboniferous, although there are deposits of most ages spread widely around the world. More recently, younger coals from the Gondwana continent have been widely exploited, particularly in Australia, India and South Africa.

In relation to coal combustion, it is the mineral matter present which forms most of the ash, and it may be present in quantities which can range from just 1% (in a few coals in Indonesia and New Zealand) to over 50%, at which level the coal becomes unattractive and is generally uneconomic to use.
As discussed in the previous chapter, coals do not ‘contain’ ash, but they include ash-forming materials. Deposits have been formed in almost every geological period since the Carboniferous, 350–270 Mya, and some even started during the Devonian, up to 400 Mya. The post-Carboniferous coals are found mainly in the southern hemisphere; in the western USA and in parts of Europe, see Figure 1. The deposits of interest which can be mined by conventional methods are mainly those lying less than 1000 m deep, and under a land mass or very close to the coastline. Coal seams need to be thick enough to justify the costs of extraction and it is easier and cheaper to extract those that lie more or less horizontally. The **world’s major coalfields** are described and discussed in an IEA Clean Coal Centre report by Walker (2000).

One of the issues which makes it difficult to discuss and compare coal behaviour and that of the ash formed, is the lack of a unified coal classification system. One attempt to present a comparison between the different systems is shown in Figure 2 which is based on an earlier comparison (Couch, 1988) adding-in the Chinese and Russian coal classification systems.

Because more than 85% of coal is used inside its country of origin, the incentive to agree a common classification system is limited – and is really only necessary in relation to the limited range of coals that are internationally traded. Of the traded coals, a significant proportion are those for coking and use in the steel making industry.

One of the reasons why coal classifications differ is that the requirements and properties which affect thermal use (for combustion) are different from those affecting coking. For coking where the coal is cooked in the absence of air, the crucial properties are the yield of volatiles, and the thickness of the plastic layer formed. During coking the coals used lose their volatiles, soften, swell and then solidify into a strong porous coke structure. The caking properties of a coal are far more specific than those for combustion, as described in an earlier IEA Clean Coal Centre report *Metallurgical coke production* (Couch, 2001). Some aspects of coal classification have concentrated on coking properties – which are largely irrelevant when coal is simply burned. In a boiler the key properties relate to grindability, coal reactivity (largely dependent on rank), moisture content, and ash content together with its composition (hence its behaviour and deposition characteristics in the boiler).

**In 2004 world coal production was 5500 Mt, of which just over 4600 Mt was hard/bituminous coal. Out of this, the internationally traded coals totalled just over 750 Mt, with 540 Mt of steam coal and 215 Mt for coking (IEA, 2005a).**

On a historical basis, the national/regional classification systems arose separately, as the coal use industries initially developed relatively independently. People got used to dealing with the properties of their local/indigenous coals without having to be concerned about the slightly different problems experienced by other coal users. This can still give rise to difficulties when attempting to apply the various predictive indices and computer models which have been developed to assess ash behaviour and its effects. **Coal classification** was discussed in an earlier IEA Clean Coal Centre report (Carpenter, 1988). Systems have two parallel purposes, one is scientific, to enable researchers in different places to compare and discuss results, and the other is commercial, to enable traders and purchasers to define coal properties. Different nomenclatures are applied in different countries leading to significant variations in the terminology used, see Figure 2.

A key difference in coal characteristics from the viewpoint of the user is whether or not a coal has good caking characteristics which would make it suitable for coking, and, generally, enhance its value. The world’s reserves of good coking coals are limited, which much of them being in Australia and China. As a result, coking coals generally attract a premium price, and are more expensive than the steam/thermal coals. Since this study is looking at the behaviour of ash during and after coal combustion, the focus of the discussion is on the steam/thermal coals produced and used.

**Ash analysis, and test methods available**

In earlier Clean Coal Centre reports (Skorupska, 1993; Couch, 1994), the standard methods of coal analysis are discussed. **These can provide useful data for predicting the behaviour of ash in the boiler, but none replicate the actual conditions encountered in the boiler and so the information has to be used in conjunction with operating experience gained over many years and with combustion modelling.**

During the past ten years, more experience has been gained with operating larger boilers using a wide range of different coals, and some of the boilers use supercritical steam conditions. In addition, the power of computers has increased enormously, facilitating the development of more sophisticated models to replicate what happens in the boiler.

One of the basic requirements for laboratory procedures is that they must be carried out under standard conditions and be reproducible in different parts of the world. Most are empirical, and the results obtained need then to be compared and validated against operating experience. This is discussed in detail in another Clean Coal Centre report *Coal quality assessment – the validity of empirical tests* (Carpenter, 2002).

The most common methods used for coal are the:

**Proximate analysis** which assesses the following characteristics/contents:
- total moisture;
- residual moisture after air drying;
The ash in the world's major coals

- volatile matter;
- ash;
- fixed carbon.

**Ultimate analysis** which measures the elemental composition of the organic coal, and determines the following:
- carbon;
- hydrogen
- nitrogen;
- sulphur;
- oxygen (which is determined by difference, subtracting the sum of the other measured elements, and expressing the result as a percentage);
- **ash analysis** is carried out by oxidising the mineral matter in a laboratory furnace at a temperature of 815°C. Note that there will be differences between the amount of ash measured by proximate analysis and that measured by ash analysis. This is because some dehydration, decomposition and oxidation of the mineral

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Figure 1 Comparing the geological age of the world's major hard coal and lignite deposits (modified from Walker, 2000)
There may take place in the furnace, and there may be partial loss of the volatile constituents.

There are also standard procedures for determining the forms in which sulphur occurs in a coal, and for determining the amount of halogens present, and of the large number of trace elements which may be there. These are components which may significantly affect the behaviour of the ash in a boiler, and thus its performance and efficiency.

### Ash production in different countries

The coals discussed here in relation to their ash content...
Table 2  Approximate ash quantities arising from power production in the world’s largest coal producers in 2002 (World Energy Council, 2004; together with other references detailed in the country by country commentary below)

<table>
<thead>
<tr>
<th>Country</th>
<th>Production bituminous coal</th>
<th>Production brown coal</th>
<th>Coal consumption (net import+ export-) [for coke making]</th>
<th>Used for power production, Mt/y</th>
<th>Ash [Average% in the coal]</th>
<th>Total ash production, Mt/y</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>1343</td>
<td>50</td>
<td>1315 (~78) [240]</td>
<td>700–750</td>
<td>[24%]</td>
<td>160–185</td>
</tr>
<tr>
<td>USA</td>
<td>520</td>
<td>473</td>
<td>992 (~1) [19]</td>
<td>820</td>
<td>[10–15%]</td>
<td>90</td>
</tr>
<tr>
<td>India</td>
<td>335</td>
<td>24</td>
<td>379 (~20) [23]</td>
<td>285–290</td>
<td>[30–40%]</td>
<td>90</td>
</tr>
<tr>
<td>Australia</td>
<td>256</td>
<td>84</td>
<td>133 (~207) [4]</td>
<td>55 &amp; 68</td>
<td>[30% &amp; 4%]</td>
<td>18–23</td>
</tr>
<tr>
<td>Russia</td>
<td>168</td>
<td>85</td>
<td>214 (~39) [40]</td>
<td>165–175</td>
<td>[10–20%]</td>
<td>25–35</td>
</tr>
<tr>
<td>Germany</td>
<td>29</td>
<td>182</td>
<td>242 (+31) [10]</td>
<td>34 &amp; 169</td>
<td>[10% &amp; 8%]</td>
<td>15–20</td>
</tr>
<tr>
<td>Poland</td>
<td>102</td>
<td>85</td>
<td>146 (~41) [14]</td>
<td>40 &amp; 60</td>
<td>[20% &amp; 10%]</td>
<td>10–15</td>
</tr>
<tr>
<td>Indonesia</td>
<td>103</td>
<td>0</td>
<td>29 (~74)</td>
<td>20–22</td>
<td>[10%]</td>
<td>2–3</td>
</tr>
<tr>
<td>Ukraine</td>
<td>82</td>
<td>1</td>
<td>86 (+3) [27]</td>
<td>40</td>
<td>[20–25]</td>
<td>10–20</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>71</td>
<td>3</td>
<td>50 (~24) [3]</td>
<td>25</td>
<td>[40]</td>
<td>8–15</td>
</tr>
<tr>
<td>North Korea</td>
<td>53</td>
<td>15</td>
<td>31</td>
<td>na</td>
<td>na</td>
<td></td>
</tr>
<tr>
<td>Greece</td>
<td>0</td>
<td>70</td>
<td>68 (+2)</td>
<td>65</td>
<td>[10–15%]</td>
<td>8–12</td>
</tr>
<tr>
<td>Canada</td>
<td>30</td>
<td>37</td>
<td>60 (~7) [4]</td>
<td>11 &amp; 44</td>
<td>[10% &amp; 15%]</td>
<td>5–10</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>15</td>
<td>48</td>
<td>58 (~5) [5]</td>
<td>4 &amp; 41</td>
<td>[15%]</td>
<td>4–8</td>
</tr>
<tr>
<td>Turkey</td>
<td>2</td>
<td>51</td>
<td>65 (+12) [4]</td>
<td>1 &amp; 42</td>
<td>[15–20%]</td>
<td>6–10</td>
</tr>
<tr>
<td>Colombia</td>
<td>40</td>
<td>0</td>
<td>3 (~37)</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Serbia &amp; Montenegro</td>
<td>0</td>
<td>34</td>
<td>34</td>
<td>na</td>
<td>na</td>
<td></td>
</tr>
<tr>
<td>UK</td>
<td>30</td>
<td>0</td>
<td>59 (~29) [5]</td>
<td>46</td>
<td>[10%]</td>
<td>4–6</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>0</td>
<td>26</td>
<td>31 (~5) [1]</td>
<td>24</td>
<td>[25–30%]</td>
<td>5–8</td>
</tr>
<tr>
<td>Spain</td>
<td>10</td>
<td>12</td>
<td>44 (~22) [4]</td>
<td>37</td>
<td>[10% &amp; 20%]</td>
<td>5–10</td>
</tr>
<tr>
<td>Thailand</td>
<td>0</td>
<td>20</td>
<td>20</td>
<td>15</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Vietnam</td>
<td>15</td>
<td>0</td>
<td>10 (~5)</td>
<td>8</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Hungary</td>
<td>0</td>
<td>13</td>
<td>14 (~1) [1]</td>
<td>12</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Total</td>
<td>3423</td>
<td>out of 3451</td>
<td>3403</td>
<td>4273 [409]</td>
<td>~2975</td>
<td>[487–595]</td>
</tr>
</tbody>
</table>

Country by country notes – Source explanation and commentary
The data for coal production/consumption in the first three columns comes from the World Energy Council (2004), and refers to the year 2002. The net export/import data is simply deduced by difference from the WEC information, and may need some comment or adjustment for example for Canada and the USA. The coking coal figures are based on coke market survey data and apply to 2003.

In column 4 the amount of coal used for power generation is approximated, and in column 6 there is a broad estimate of the amount of ash produced in each country, expressed as a range.

Where figures are referred to as X & Y Mt/y the first number is for bituminous coal and the second one refers to brown coal.

1 China See Table 4, together with an explanation of changes in coal production and use in the text. The fly ash produced is estimated to be 160 Mt/y by Koukouzas and others (2005), and with bottom ash the total is likely to be around 180–190 Mt/y. Figures relating to China are subject to considerable uncertainty because of the recent very rapid increase in coal production, and the enormous amount of coal-fired capacity being built and commissioned. Data depend on exactly when they were collected as well as on how complete they are.

2 USA Production 993 Mt (2002). Imports are 16 Mt (2 Canada coking; 8 Colombia; 2 Indonesia; 3 Venezuela; 1 others). Exports are 20 Mt coking & 16 Mt steam (Coal information IEA, 2005a). Fly ash production is estimated to be 71 Mt in 2004 together with 17 Mt of bottom ash and 2 Mt of slag. There is just under 1 Mt from FBC boilers (ACAA, 2005).
include those from the main producing and exporting countries (listed in order of their total coal production) namely:

- China;
- the USA;
- India;
- Australia;
- Russia;
- South Africa;
- Germany;
- Poland;
- Indonesia.

Also discussed are Japan, Taiwan and South Korea which are three countries which import and use large amounts of traded coals.

In relation to five of the world’s major coal producers (China, the USA, India, Australia and South Africa), projections are presented relating to what is likely to happen to coal quality during the period up to 2020, and there is a discussion of the factors which will influence this. Changes in the amount or nature of the coal ash will affect its management in coal-fired power plants.

In Table 2, an estimate is presented of the amount of ash produced from coal-fired power plants for nearly all the major coal producing countries. Table 3 presents an estimate of the amount of ash produced from coal-fired plants in the major coal importing countries. Data have been collected from a number of sources, and are not therefore entirely consistent, but the overall figures accord well with the estimate from ECOBA (European Coal Combustion Products...
Association) that the world production of coal ashes in 2000 was 480 Mt (Barnes and Sear, 2004). Since 2000, Chinese coal production and use has risen sharply with a resultant increase in the production of ash. Production there roughly doubled between 2000 and 2004, and the amount of ash produced will have increased in proportion.

In some countries there are no reliable data about the exact amount of coal burned at power plants for the year 2002 specified in the table, nor its average ash content. Thus the amounts are expressed as a range within which the figure should fall, based on some simplifying assumptions.

The presence of mineral matter depends on what is inherently included in the coal, together with extraneous material which is picked up during mining operations. The nature of the mineral matter and of chemically combined impurities is strongly influenced by the age of the coal. The discussion of the implications of the impurities in coal will describe the factors which will govern the behaviour of the ash formed in virtually all the world’s different coals.

In the bituminous coals from the northern hemisphere, such as those in European countries and in north America, the mineral matter tends to be present in a coarse crystalline form. In the Gondwana coals from the south, such as those from Australia, India and South Africa, much of the mineral matter tends to be very finely dispersed through the coal structure, and as a result it is more difficult to ‘clean’ these coals by processes based on the density difference between particles. The substantial differences between the northern and southern hemisphere coals and also the large brown coal deposits in both hemispheres, are discussed in detail by Stach and others (1982). They result in different ash composition and behaviour.

The remaining part of this chapter contains a country-by-country review of the reserves and use of coal and of the factors which will affect how much ash is produced.

### 3.1 China

China has the third largest coal reserves in the world at 115 Gt, after the USA and Russia, but is the world’s largest coal producer (World Energy Council, 2004). Production has increased sharply during the last five years. It is reported to have risen from a little over 1 Gt/y in 2000, to as much as 2 Gt/y by 2005, see Table 4. This increase has been driven largely by a sharp rise in demand from coal-fired power generators, as new capacity has come online. A short time ago, Chinese coal exports were a little under 100 Mt/y, about half the amount being exported from Australia, but making it the world’s second largest coal exporter. As coal demand within China itself rose, the amount which was exported stabilised and even fell slightly as the exports of coking coal dropped by nearly 10 Mt/y between 2003 and 2004. The amount imported increased from 2 Mt in 2000 to 19 Mt in 2004 (IEA, 2005a), probably mainly for use near the coast.

Because of the difficulty in collecting reliable information from the small mining operations, and from other sources, there are uncertainties regarding the accuracy of some production data (Minchener, 2004). Although this comment affects some of the other information quoted, the general trends identified should be valid.
At the end of the 1990s there were efforts to close thousands of small unlicensed mines, and production dipped from an estimated 1.4 Gt/y to near the 1 Gt/y figure. At this time there had also been a build-up in stocks in some areas.

The increase from 999 Mt/y in 2000 to 1989 Mt/y in 2004 represents a huge proportion of world production which will have risen from something like 4600 Mt/y in 2000 to nearer 5400 Mt/y in 2005. One major problem in the mines is that of safety, and it is reported that more than 5000 miners each year are killed in accidents of one kind or another. Explosions resulting from the uncontrolled emissions of methane are all too common. During the coming years, this problem will doubtless be tackled, and may result in some reductions in productivity and in cost increases.

There has been a very sharp increase in coal-fired generation capacity, and the statistics say consistently that just over 50% of China’s coal is used for power generation. Coal is also used for district heating; for chemicals and coke production, and for domestic heating. The 700–750 Mt/y range used in Table 2 is based on that 50% proportion.

In China, some 90–95% of the coal comes from underground pits. This is a far higher proportion than in any of the other large coal producing countries. Additionally, more than 20% of the Chinese reserves consist of low volatile coals and anthracite and this proportion is reflected in the coal which is mined. This affects the nature of the ash formed as low volatile coals are generally burned using higher combustion temperatures.

The coals in China come from almost every geological period, see Figure 1. The main coals are Carboniferous and Permian, but there are also deposits arising from the Triassic, Jurassic and, later, the Tertiary. Current production is concentrated in the northern and central/eastern provinces, particularly Shanxi, Shaanxi, Ningxia, Heilongjigang, Henan and Inner Mongolia. Lignites only comprise a relatively small proportion of the Chinese coal resources, and are located in the far south-west and in the north near the Russian border. There are huge reserves of steam coals in the western provinces which are currently largely unexploited as they are located a long way from the main potential users. Other deposits can currently supply the coal needed at a lower price/cost.

Many of the mines can extract coal from seams lying in relatively undisturbed ground, and up to 10 m thick although seam thicknesses of 3–5 m are more common. This should result in relatively low mining costs, depending on the seam depth, although surface subsidence is likely to be an increasingly important issue.

Internally in China, the price of coal is being increasingly determined by the supply/demand balance, rather than being centrally determined by government, as happened in the past (Minchener, 2004). This should mean that customers can become more selective in the coal that they may purchase, although there will be limitations due to bottlenecks in the transport system. The market for coal has only recently been opened up and consequently it will be some time before the real cost of extraction, treatment and transport is established. Where there is a shortage, the cost of coal is likely to increase, possibly quite sharply.

Although the main thermal coal/s used are relatively high ash content bituminous coals, considerable quantities of low volatile coal/s are mined, together with substantial amounts of lignite in the northeast. Some coals suitable for coking are in fact used for heat generation although as their potential value becomes more readily recognised, this practice is likely to decline.

The ideal combustion conditions for these coals differ widely, and although different boiler designs are used, they are

---

**Table 4** Changes in Chinese coal production and use (based on data from Chen Yafei, 2005)

<table>
<thead>
<tr>
<th>Year</th>
<th>Coal production, Mt/y</th>
<th>Total installed capacity, GWe [coal only]</th>
<th>Coal used for power production, Mt/y</th>
<th>Amount of ash arising (at 25% average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>620</td>
<td></td>
<td>112</td>
<td>25–30</td>
</tr>
<tr>
<td>1985</td>
<td>872</td>
<td></td>
<td>166</td>
<td>40–45</td>
</tr>
<tr>
<td>1990</td>
<td>1079</td>
<td></td>
<td>270</td>
<td>65–72</td>
</tr>
<tr>
<td>1995</td>
<td>1292</td>
<td>217</td>
<td>426</td>
<td>100–115</td>
</tr>
<tr>
<td>1997</td>
<td>1325</td>
<td></td>
<td>517</td>
<td>125–140</td>
</tr>
<tr>
<td>1999</td>
<td>1044</td>
<td></td>
<td>522</td>
<td>125–140</td>
</tr>
<tr>
<td>2000</td>
<td>999</td>
<td>319</td>
<td>609</td>
<td>140–165</td>
</tr>
<tr>
<td>2001</td>
<td>1106</td>
<td></td>
<td>641</td>
<td>150–175</td>
</tr>
<tr>
<td>2002</td>
<td>1415</td>
<td></td>
<td>729</td>
<td>170–195</td>
</tr>
<tr>
<td>2003</td>
<td>1728</td>
<td></td>
<td>881</td>
<td>200–240</td>
</tr>
<tr>
<td>2010</td>
<td>630 [432]</td>
<td></td>
<td>~1250</td>
<td>280–320</td>
</tr>
<tr>
<td>2020</td>
<td>950 [605]</td>
<td></td>
<td>~1500</td>
<td>350–400</td>
</tr>
</tbody>
</table>
probably not optimised. China is developing CFBC units on a considerable scale to burn its low volatile coals, some of which have quite a high ash content (Sculy-Logotheti and Lemasle, 2004; Luo and Cen, 2005, Wu, 2006). As a result of these differences, the ash-forming materials have different characteristics, follow different time-temperature cycles and behave in different ways.

The quality of Chinese thermal coals is reported to be decreasing (Power in Asia, 2005a), and this is almost certainly associated with an increase in the ash content. In view of the shortage of supplies through the period 2000-05, and the sharp rise in production, customers may have been willing to accept lower quality coal. This also suggests that coal washing capacity is limited.

Only some 20–25% of Chinese coal is washed, and much of this is for metallurgical coke production or for export coals. Ash management therefore presents some major challenges to power generators. In the context of the dramatic increase in coal production from 1 Gt/y to 2 Gt/y in just five years, it is difficult to know whether washing capacity has kept pace with the increase. The power generating utilities may try to impose tighter specifications on the coal quality they receive, but until coal washing capacity increases, their ability to do this will be limited.

The ash content of the coal supplied to power generators averages an amount in the 20–25% range (Fu and Bai, 2005). However, there will probably be quite a wide spread in the amount of ash in coal/s supplied from different mines.

Until recently, the policy has been to design, build and operate coal-fired boilers in such a way that the relatively high (and variable) ash content can be accommodated. A similar policy has been pursued in the past in India. This is not necessarily the optimum economic method of using coal see earlier IEA Clean Coal Centre reports, including Couch (1995); Rousaki and Couch (2000); Couch (2002). It is not clear whether the new supercritical PCC plants which are being built and commissioned will be supplied with washed coal. The potential benefits of coal washing are discussed in Chapter 4.

The sulphur content of Chinese coals is highly variable, although the generally accepted average figure is about 1.1%.

Changes in Chinese production up to 2020
Because China is in the middle of radical change, it is difficult to forecast and anticipate the direction of change when considering the ash from Chinese coals. The map in Figure 3, shows the distribution of the reserves of the thermal coals.
There are three different kinds of coal mines in China, namely:

- Key state mines that are under provincial government control. These tend to use relatively advanced extraction techniques, and much of their production goes to other state enterprises;
- Local state mines mainly administered by prefecture and county authorities, which tend to be smaller and less mechanised than the key/main state mines, but which also mainly supply other state enterprises;
- Township and village enterprise (TVE) mines, many of which employ only manual extraction techniques. In the mid-1990s there were reported to be as many as 82,000 such mines, producing nearly half the total Chinese output (Minchener, 2004).

Since then, many thousands of the TVEs have been closed down, partly to eliminate the unacceptable and dangerous working conditions and to promote more efficient extraction. Output from both the key state-owned mines and the local state mines has climbed, and it would seem that this trend is likely to continue. The largest tonnages of coal currently come from the central provinces of Shanxi, Shaanxi and Henan, but there are important mining activities in Inner Mongolia, Heilongjiang and Guizhou. In the northeast, significant amounts of lignite/brown coal are mined. In the centre, production is of both thermal and coking coals. The Guizhou coals tend to have a considerably higher amount of sulphur, and there is also more sulphur in the eastern rather than the western coals.

In terms of development during the period up to 2020, if the current output of 2 Gt/y is maintained and even increased, then there will firstly be a tendency to have to extract deeper reserves in the prime producing areas. This is likely to bring gradual changes from the high ash low sulphur content coals of the upper formations which are generally easy to wash, to medium ash and medium-high sulphur content coals of the lower formations which have poorer washability characteristics.

The main factor which will affect the ash from thermal coal use will be whether or not CPPs are built to treat the coal produced. This will affect both the ash quantity and its nature/composition, and will improve the consistency of the coal quality. There could be substantial benefits arising from the more widespread use of CPPs (Couch, 2000, 2002).

Exploiting the substantial reserves of northwestern coals which generally have lower ash and sulphur contents will be dependent on demand, cost, and on infrastructure development. The coal could either be transported by rail to the big consumption areas in the southwest or long-distance transmission lines would be needed to transport the electricity produced. Such development would take a substantial amount of time, and is unlikely to have made a major impact on coal production quantities by 2020. In the longer term, however, this coal, which is in Xinjiang, may well be needed and exploited.

### 3.2 USA

The USA has the world’s largest reserves of recoverable coal with some 247 Gt, compared with 157 Gt in Russia and China’s 115 Gt. The coals cover the entire spectrum from lignite to anthracite, although the reserves of greatest interest during the next 20–30 years will be those of the subbituminous coals in the west, mainly from the Powder River Basin (PRB). These have a low sulphur content, and there are relatively thick seams near the surface, so that mining costs are low. US bituminous coals have relatively good washability characteristics. Many of the bituminous coals have a high sulphur content, and part of the reason for washing is to reduce the amount of sulphur.

### Changes in US production up to 2020

It is projected that over the next twenty years, the amount of subbituminous coal used will increase sharply, see Figure 4. Most of this will be for power generation, and as a result there will be significant changes in the nature of the ash formed and produced. The Appalachian region to the east covers the states of Pennsylvania, West Virginia, and Alabama together with the east side of Kentucky. It produces something like 350 Mt/y from large underground mines and from some small surface mines. The Interior region includes Iowa, Illinois, Indiana, and bits of Kansas, Oklahoma, Arkansas together with part of the west side of Kentucky. It produces about 160 Mt/y, mainly from mid-size surface mines with some 247 Gt, compared with 157 Gt in Russia and China’s 115 Gt. The coals cover the entire spectrum from lignite to anthracite, although the reserves of greatest interest during the next 20–30 years will be those of the subbituminous coals in the west, mainly from the Powder River Basin (PRB). These have a low sulphur content, and there are relatively thick seams near the surface, so that mining costs are low. US bituminous coals have relatively good washability characteristics. Many of the bituminous coals have a high sulphur content, and part of the reason for washing is to reduce the amount of sulphur.

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### Changes in US production up to 2020

It is projected that over the next twenty years, the amount of subbituminous coal used will increase sharply, see Figure 4. Most of this will be for power generation, and as a result there will be significant changes in the nature of the ash formed and produced. The Appalachian region to the east covers the states of Pennsylvania, West Virginia, and Alabama together with the east side of Kentucky. It produces something like 350 Mt/y from large underground mines and from some small surface mines. The Interior region includes Iowa, Illinois, Indiana, and bits of Kansas, Oklahoma, Arkansas together with part of the west side of Kentucky. It produces about 160 Mt/y, mainly from mid-size surface mines with some 247 Gt, compared with 157 Gt in Russia and China’s 115 Gt. The coals cover the entire spectrum from lignite to anthracite, although the reserves of greatest interest during the next 20–30 years will be those of the subbituminous coals in the west, mainly from the Powder River Basin (PRB). These have a low sulphur content, and there are relatively thick seams near the surface, so that mining costs are low. US bituminous coals have relatively good washability characteristics. Many of the bituminous coals have a high sulphur content, and part of the reason for washing is to reduce the amount of sulphur.
mines. The Western region includes the Dakotas (with lignite deposits), Montana and Wyoming (the centre of the PRB subbituminous deposits), Colorado, Utah and New Mexico. It produces just over 500 Mt/y, mainly from large surface mines which include the world’s biggest. Wyoming alone accounts for some 30% of total US coal production. The principal problem with the western coals is their reactivity and tendency to spontaneously combust, which can pose difficulties during transport, storage and handling. In addition the slagging and fouling characteristics of the ash are very different from those of the Appalachian and Interior coals. The sulphur content of the Western coals is generally low.

In the USA a high proportion of the bituminous coal produced is washed. There are reported to be more than 250 CPPs, and in recent years 10 new ones have been commissioned and 25 have had a significant upgrade. The industry does not, apparently, make extensive use of online analysers, but has adopted the use of programmable logic controllers (PLCs) on most plants. This conclusion is based on data from several sources, and presented in the US Prep Plant Census (Fiscor, 2005). Coal is transported over long distances, principally by rail, but also, where appropriate, by barge, using parts of the extensive river and canal system. As the production of bituminous coal falls, there should therefore be plenty of washing capacity.

There are intensive efforts in the USA to develop new technologies whose use will result in a sharp reduction in the emissions of greenhouse gases, and facilitate the continued use of coal as the principal energy source for power generation. Some of these will have implications relating to the way in which ash is both formed and handled. The FutureGen project was launched in 2003 to demonstrate a near-zero emission 275 MWe coal-fuelled IGCC plus hydrogen production plant, incorporating CO₂ separation together with geological storage. The project is intended to create the world’s first zero-emissions fossil fuel plant which, when operational, will be the cleanest fossil fuel-fired power plant in the world. Cooperation between government, industry and international partners is a key element of the project. The mineral matter will behave in different ways in an IGCC reactor, but as the work will not be completed for some years, its implications will not be addressed in this study.

### 3.3 India

India has coal reserves estimated as being 92 Gt, and production in 2002 was around 360 Mt. It is growing at a rate of some 4–5%/y. About two-thirds of the coal is used for power production. The coal is mainly of low grade and high ash content, so the amount of ash arising from power generation is very substantial, and in quantity, is second only to that in China. There is some production of lignite, which has a lower ash content, but which contains significant amounts of water, and, in some deposits, there are iron-sulphur compounds which cause slagging.

Much of India’s coal comes from opencast mines, which results in serious environmental impact and extensive land degradation (Pachauri, 2005). Production from the underground mines is around 50 Mt/y.

Currently, some power plants have difficulties in obtaining adequate supplies of coal. There are doubts about whether India can continue to expand its production and match it with the necessary improvement in the transport infrastructure in order to fuel new coal-fired power plants. More steam coal is being imported; an increase from 12 to 16 Mt/y between 2004 and 2005 was reported (International Coal Report, 2005b). Expansion plans for new capacity in coastal areas of Gujarat, Maharashtra and Karnataka could mean that coal imports would increase to ~75 Mt/y by 2010 (International Coal Report, 2006a). While these plans are at an early stage, the shortage of power will encourage such development.

Indian thermal coals generally have a low sulphur content (<0.5%) and low chlorine content. Although the ash content is high, the ash fusion temperature is generally high (with an initial deformation temperature (IDT) of >1150°C). The ash generally has a refractory nature, a low iron content, and low concentrations of toxic trace elements (Chowdhary, 1998). The refractory nature of the ash means that it has considerable potential for erosion, but it has a lower slagging tendency than many other coals, such as those from the UK and the USA.

Power station coals in India are not generally washed. As a result, much of the coal is supplied and used with an ash content in the 40–45% range, and because of variability, can sometimes be higher. Because there has been a supply shortage, power plant managers are in a weak position when trying to negotiate on issues related to coal quality.

Government policy is to increase the amount of washed coal used in power plants substantially, and there is a regulation that all coal transported more than 1000 km must have an ash content of less than 34%. This would generally be equivalent to a coal whose coarse fraction has been washed in a jig. One of the difficulties in India is that coal prices do not reflect quality in any meaningful sense. For example, once the 34% ash content has been reached, there is little incentive to clean the coal further.

Another way of meeting the 34% ash requirement is to blend coal with a low ash content imported coal. Depending on the coal used, this could result in more problematic ash behaviour, and an increase in slagging and/or fouling.

There is considerable scope for the application of coal cleaning in India to deshale the coal and to do some further separation. This is in spite of the fact that the coal washability characteristics are fairly poor. Washing to remove loose stone and mineral matter should also provide a more consistent quality feed to power plants and reduce mill wear and other erosion (Couch, 1991, 1995; Selvakumaran and others, 2005). Many Indian coals could be economically washed with yields of 70–80%, reducing the ash content to levels in the 24–32% range. This could reduce both the investment and running costs of the new generation of large coal-fired boilers which are increasingly being deployed in India to meet demand.
Changes in Indian production up to 2020
Several factors have contributed to the current shortage in coal supplies in the country. These include:

- increasing demands from the power generation sector;
- the limiting of coal production to state-owned mines;
- coal price regulation which does not provide an adequate margin to promote new investment;
- the grading of coal with quite wide band-widths representing coal quality (see Table 5) where the concept of the Useful Heat Value (UHV) is used;
- huge surplus manpower in the industry resulting in low labour and machine productivity;
- a low level of mechanisation;
- delays in project approvals, and problems with land acquisition (Power in Asia, 2005b).

There are significant restraints on the development of coal production in India, although the government is encouraging restructuring and the imposition of more rigorous procedures to ensure that electricity is paid for. It is also encouraging investment by private companies. Forecasts suggest that there will be a growth in the coal requirements for power generation ranging from 5 to 8%/y. Because of constraints in the rail system, it is proposed to build new mega power plants having capacities up to 4000 MWe either at pithead sites, or on the coast. Coastal locations would favour the use of imported rather than indigenous coals.

A combination of the extensive use of CPPs and of imported coals would have the effect of reducing the amount of ash in the coals used for power generation which should result in the more efficient operation of coal-fired boilers. Much will depend on the loosening of state control on electricity prices, on the coal pricing mechanisms and on the development of the power distribution grid.

3.4 Australia
In Australia has some 79 Gt of recoverable reserves (World Energy Council, 2004). Some 75% of the bituminous coal which is mined comes from open cast pits, mainly in New South Wales and Queensland. This is because there are significant quantities of coal formed during the Permian period (see Figure 1) lying relatively near the surface. Large additional deposits were formed during the Tertiary period, mainly in Victoria. These are of low rank, and hence of relatively low grade, and all the mining of these brown coals is from open cast pits (Walker, 2000; Geoscience Australia, 2003).

Australia is the world’s largest coal exporter. Approximately half the exports are coking coals – which are not discussed in this study. The use of coal for coke and steel-making was discussed in another IEA Clean Coal Centre study *Metallurgical coke production* (Couch, 2001). In 2003, Australia exported some 100 Mt of bituminous thermal/steam coal (IEA, 2004a), with three-quarters of it going to Japan, South Korea and Chinese Taipei (Taiwan). These coals have a typical ash content of 12–13%, and an LHV of 26–27 MJ/kg (International Coal Report, 2005a). Sulphur content is in the range 0.6–0.8%. These coals are burned in conventional PCC boilers, and increasingly, the units using imported coals use supercritical steam conditions. This is because it reduces the cost of electricity when burning coal which has been mined, cleaned and transported, and is therefore costing maybe 50–60 US$/t delivered.

Virtually all the coals exported from Australia are washed, and some are blended before despatch, in order to keep within the tight specifications set for various properties. Because the coals come from a consistent source, and are thoroughly washed/prepared, their quality is high. The ash content is difficult to reduce further, because some of the mineral matter is present as finely divided particles. Much of the higher ash content material from the washery is used in power stations in Australia, where the ash content of the coal feed may commonly be in the 30–35% range. The ash in the Australian hard coals tends to have a high fusion temperature.

A different picture emerges when considering the ash arising from the use of the Australian brown coals. These were mainly formed during the second half of the Tertiary, from around 35 to 10 Mya. Major peat deposits formed in a steadily subsiding landscape, forming some thick deposits which lie quite close to the surface. Mines have been established where the seam thickness is as much as 100 m. The coal (brown coal/lignite) has different characteristics from that of the bituminous coals in Queensland and New South Wales which provide the bulk of Australian exports. The brown coal has a very high moisture content, in the range 55–65%, a low ash content, generally in the range 1–3%, and a LHV which is typically 9–12 MJ/kg. The coal is reactive, and subject to spontaneous combustion. Its main use is for minemouth power generation, and it is neither transported nor stored (for more than a few hours) because of its low energy content, and the risk of spontaneous combustion. Although it has a low ash content, ash management through the boilers causes particular difficulties, often associated with a high sodium content. This commonly causes deposition and fouling problems in the boiler, and the deposits can be difficult to remove, even with regular sootblowing.

During combustion, the behaviour of the ash from the bituminous export coals, from the bituminous coals used...
internally, and from the Victorian brown coals is very different. This is due primarily to differences in the nature of the ash-forming materials present, and in the case of the bituminous coals, to the quantities involved. It is also due to differences in the combustion conditions since temperatures are lower with the low rank coals because of the amount of water being evaporated.

Changes in Australian production up to 2020
Because of the extent of the current reserves, no great changes in the quality or characteristics of Australian coals are expected. This applies to both the black and brown coals. As new mines are opened to supplement or replace others that are becoming mined out there will be variations, but no big changes are expected during the next fifteen years.

3.5 Russia
Russia is exceptionally well-endowed with energy resources, and is the third largest energy consumer in the world after the USA and China. It is also a major energy exporter. There is great interest in exporting as much oil and gas as possible, and international prices for these commodities are expected to rise. Recoverable coals reserves are estimated to be 157 Gt, including more than 100 Gt of low rank coal.

The mining industry is still in poor shape because of mismanagement during the Soviet era and more recent under-investment, but a considerable amount of restructuring has already been undertaken. Coal supplies about 17% of the primary energy used in Russia, and this proportion will probably be maintained. As in many other countries, Russia has its own basis for coal classification, see Figure 2.

The coal industry in Russia has undergone massive changes during the past 15 years. Demand/output dropped sharply during the early 1990s, falling by some 30–40% between 1990 and 1995. The drop in demand was associated with the closure of some of the inefficient and polluting heavy industries which used large amounts of energy. Some 150 unprofitable mines were closed, and employment in the industry fell from 900,000 in 1991 to 400,000 in 2001 (Butrin, 2002).

The demand for coal has largely stabilised, for power generation, metallurgical coke production and for export. During 2000-04 there was continued restructuring (Butrin, 2004) and according to the figures in Coal information (IEA, 2005a), output increased between 2002 and 2003 by some 8%. During the period 1995 to 2003 there has been a steady growth in the amount of coal exported.

Coal production is projected by the IEA to grow slowly from around 240 Mt in 2002 to 276 Mt in 2030 which is well below the peak of 437 Mt/y achieved in 1988. An estimated 86% of Russian coal production now comes from independent privately-owned producers. Approximately two-thirds comes from opencast mines. It is anticipated that the incremental output will go almost entirely into domestic markets, bucking the trend mentioned above relating to increased exports (IEA, 2004b).

Russia’s coal reserves are enormous, but there has been extensive re-evaluation of the total under the new discipline of market-orientated economics, and this process is ongoing (Walker, 2000). In figures relating to 2002, Russia’s recoverable reserves are estimated to be 157 Gt of which 49 Gt are bituminous, 98 Gt are subbituminous and 10 Gt are lignite (World Energy Council, 2004). A great deal of Russian coal comes from the centre of the country. In 2000, 45% came from the Kuzbass/Kuznetsk basin and 16% from the nearby Kansk-Achinsk basin which has low rank coals. Both are in Siberia, in the southern part of central Russia. Of the remainder, those in East Siberia contributed 14%, the Far Eastern mines contributed 12%, Pechora in the far north near the Europe/Asia border, contributed 7% and the Donets area by the Ukrainian border and the Urals region, some 6% (IEA, 2002).

It is difficult to find comprehensive data about the ash content of Russian coals. Data included in the UK DTI report

### Table 6  Typical coal qualities in Russia's principal coal basins (Hird and others, 2003)

<table>
<thead>
<tr>
<th>Coal basin</th>
<th>Ash, %</th>
<th>Moisture, %</th>
<th>Sulphur, %</th>
<th>LHV, MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuzbass (with 65% of hard coal reserves)</td>
<td>18</td>
<td>11</td>
<td>0.4</td>
<td>24</td>
</tr>
<tr>
<td>Kansk-Achinsk (has very large reserves of brown coal)</td>
<td>9</td>
<td>35</td>
<td>0.5</td>
<td>15</td>
</tr>
<tr>
<td>Donbass (mainly anthracite coals)</td>
<td>36</td>
<td>10</td>
<td>2.4</td>
<td>21</td>
</tr>
<tr>
<td>Pechora (with mainly coking coals)</td>
<td>31</td>
<td>10</td>
<td>3.1</td>
<td>14</td>
</tr>
<tr>
<td>Moscow (low grade lignite deposits)</td>
<td>47</td>
<td>32</td>
<td>3.8</td>
<td>9</td>
</tr>
</tbody>
</table>
on opportunities for the application of cleaner coal technologies in Russia is presented in Table 6. The figures represent the inherent ash in the coals mined, and not the post CPP quality when the coals are washed.

With the restructuring of the industry, and the closure of many unprofitable mines, some CPPs would have been, effectively, stranded in the wrong place. Where new mines have been opened, the provision of a CPP will have been considered, and will probably have been built where the coals were intended for export or for coking. Also, some Russian coals have a high sulphur content, giving coal washing a higher priority, while other coals, including some of those of low rank, have relatively low ash and sulphur contents.

As in other countries, the coking coals are all washed, but for internally used thermal coals less priority is given to coal quality. This is partly because most of the coal-fired power plants are old, and relatively inefficient with thermal efficiencies mainly in the 30–35% range (Kakaras and others, 2005). As new units are built, including those using supercritical steam conditions, there is likely to be an increased demand for higher quality steam coals, and greater use of CPPs. There is insufficient information to support any forecast about the coal which will be being mined in 2020 and its ash behaviour.

### 3.6 South Africa

South Africa is a major coal producer, and a significant player in the international market. It has recoverable reserves estimated as being just under 50 Gt. The coals are of relatively low grade, but most are washed, with the result that coal for export has an ash content of around 15%. That which is used internally for power production commonly has an ash content in the 30–35% range. The coals generally have a fairly low sulphur content. South Africa has no low rank coals.

Most of the coal reserves are in the northern part of the country, and many large power plants have been built near the mines. The power is distributed using the high voltage transmission system. Because the coalfields such as those around Witbank have been heavily exploited, mining in the future is likely to have to move further north to exploit reserves near the Botswana and Zimbabwe borders. This coalfield is called the Waterburg, and one large mine is already established there, supplying the Matimba power plant.

Mining in the Waterburg area will involve some changes in the nature and quality of the coal. In addition, the areas which have these reserves are particularly arid, and issues which are connected with water availability will need to be addressed. These are discussed further in another IEA Clean Coal Centre study, Coal use in areas of water shortage (Couch, 2005).

It seems likely that after 2010, new power generation capacity will be needed, and after a few more years, many of the existing coal-fired generation units will need to be replaced. Coal-fired boilers together with air-cooled condensers are likely to be a cost competitive option when these decisions are made.

### 3.7 Germany

German coal reserves are estimated to be 6.7 Gt of which some 97% consist of brown coals. Coal production is still around 30 Mt/y bituminous (much of it for coking and from underground mines) plus some 170 Mt of lignite/brown coal which is nearly all used for power production and comes from open pits (World Energy Council, 2004). Imports are of just over 30 Mt/y, mainly steam coal for power generation. The bituminous coals used in power plants will therefore be mainly traded and hence of relatively low ash content. These coals will nearly all have been washed, be of consistent quality, and high grade. The lignite/brown coal used also has a low ash content, but will be more variable, and the coal is of lower grade because of the high water content.

The ash arising in German coal-fired power plants will therefore be fairly consistent in both quantity and composition, although it will differ between the bituminous coals and those using brown coal. The ash content of the bituminous coals would be typically around 10–12% on average while that in the brown coal would be perhaps only around 8%.

### 3.8 Poland

Poland has recoverable reserves of 14 Gt of bituminous coal, and 2 Gt of brown coal (World Energy Council, 2001, 2004). In 2004, production was of 100 Mt of bituminous coal (83 of steam coal and 17 for coking), together with 61 Mt of brown coal (IEA, 2005a). 16 Mt was exported (13 of steam coal and 3 for coking). Of the 70 Mt of steam coal used internally, some 50 Mt is used for power generation, together with all the brown coal.

The Polish coal industry is undergoing extensive restructuring (Feller, 2004). This may involve a reduction of some 15% in the number of people employed in the industry to about 100,000, the introduction of some privatisation, and possibly some small further reduction in the amount of hard coal produced. Production had previously dropped from over 200 Mt/y in the years around 1980 when the mines employed 400,000 people (Jureczka and Krieger, 2004). As world coal prices have hardened in recent years, the prospects for Polish exports remain good.

The Polish hard coals, like others in Europe, have fairly good washability characteristics. With the reduction in output, there is likely to be spare washing capacity, although its location may preclude its application. In 2004 there were just over 40 state-owned underground mines together with eight independent mines. There are more than 40 CPPs.

The in-seam quality of Polish coals is high. 80% of the reserves have an LHV of >25 MJ/kg, while some 50% have an ash content below 10%. Sulphur content is also low, and
in two-thirds of the reserves it is below 1%. However, the mined coal is of much lower quality, and the LHV ranges from 15 MJ/kg to 24 MJ/kg, and the ash content from 17 to 42%. The high ash coal is nearly always washed, as is all the coking coal and that which is traded.

As in some other countries, the majority of the coal-fired boilers in Poland are designed for relatively low quality coal, and are resistant to paying a higher price for washed higher grade coal (Blaschke and Gawlik, 2004). As older and less efficient boilers are replaced, then there will be an increased demand for coals with more consistent properties and higher grade.

3.9 Indonesia

Indonesia has recoverable reserves of 5 Gt of mainly low rank coals. 0.75 Gt is of hard coal (World Energy Council, 2004). Production was more than 100 Mt/y in 2002, and is rising rapidly. Almost all the production comes from opencast mines.

In 2002, exports were of 67 Mt of steam coal and 7 Mt of coking coal, while 28 Mt was used internally. By 2004, exports were up to 90 Mt of steam coal plus 17 Mt of coking coal (IEA, 2005a). The potential for growth in Indonesia’s coal industry is discussed by Sunardi (2004). Domestic consumption is set to rise since current generating capacity of around 7500 MWe (which accounts for nearly 30 Mt/y of coal consumption) is set to rise by 2000 MWe when units currently being constructed are commissioned and then a further 4300 MWe is planned by 2015 (Ewart, 2004).

The coals are nearly all young coals from the Tertiary period, see Figure 1, and are mainly of lower rank with higher moisture content. This has implications for the nature of the ash, as with the western subbituminous coals in the USA. Most of the coal which outcrops and can therefore be extracted by opencast mining methods is of low rank. Most has a low sulphur content, and some is exceptionally low with a sulphur content of less then 0.1%. The slightly older coals (Eocene, from 55 Mya to 37 Mya) have a higher mineral matter content than those from the Oligocene (37 to 22.5 Mya) or Miocene (22.5 to 5 Mya). Some of the Miocene coals occur in very thick seams and have a low ash content.

Most Indonesian coal is used for heat generation, and some of the coals have a high enough moisture content to affect the economics of transportation. This makes them more suitable for domestic, local, power production. Some of the coals can be used for pulverised coal injection (PCI) into blast furnaces, even though their rank is below the optimum level for this purpose. Their low rank and low ash content might make them suitable as a feedstock for conversion to a synthetic natural gas or for the production of liquid products when the economics of these processes become more favourable (Cook and Daulay, 1999).

The emergence of Indonesian coals on the international market has introduced a new dimension into the equation relating to coal choice. Not only is there price and supply security, but the ash from Indonesian coals may behave quite differently from that from Australian, Colombian, Polish, Russian, South African coals, or from those from the USA. Thus particular care must be taken in assessing ash management in coal-fired plants using Indonesian coals.

3.10 Coals used by the big coal importers

The biggest coal importers are Japan, South Korea and Taiwan. All import significant amounts of both coking and thermal coals, from a variety of sources, see Table 7. The principal suppliers are China, Australia and Indonesia.

Overview

The summary above discusses only the largest coal producers and users. However the discussion covers about 90% of the world’s coal ash. In Tables 2 and 3 the quantities of ash arising from coal-fired power generation are estimated based on data from the World Energy Council, and from the IEA publication Coal Information together with several country specific sources. The data are not always entirely consistent, and in relation to the average ash content may be missing altogether. It is also not always possible to derive the exact amount of coal used in power plants. Consequently ash quantities generated are expressed as a range, and the intention is to highlight the contrast between large coal consumers who use lower ash content coals, and possibly smaller consumers who use high ash content coals.

| Table 7 Coal imports to Japan, South Korea and Taiwan, 2004 (IEA, 2005a) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Total imports, Mt | Coking coal, Mt | Steam coal, Mt | Principal steam coal sources, Mt |
| Japan           | 183             | 86              | 97             | Australia 59, China 20.5, Indonesia 8, Russia 5.5, Venezuela 3 |
| South Korea     | 79              | 21              | 58             | China 21, Australia 18, Indonesia 13.5, Russia 4 |
| Taiwan (Chinese Taipei) | 60           | 7               | 53             | China 20, Australia 12, Indonesia 19, South Africa 1, Russia 1 |
The options for minimising and removing the ash-forming materials from coal prior to combustion are shown in Figure 5. The focus of the discussion here is on the methods which will reduce the amount of ash-forming material present in the boiler feed, and/or will improve its consistency.

In addition, the form in which the coal is fed into the boiler, and the particle size distribution has a significant impact on its subsequent behaviour. Coal pulverising is discussed in Section 4.3.

4.1 Minimising the amount of ash-forming material during mining

The depth, thickness and slope of the coal seams determine the method used for extraction. Shallow, flat coal deposits are generally mined from the surface. Strip mining is one of the most economical methods, where the removal of overburden and of coal proceeds in parallel strips. The spoil for a new strip is deposited into the area from which coal has just been extracted. Underground mining is used for deeper seams.

Avoidance of the inclusion of extraneous rock when mining is the first stage in the management of ash, by reducing the amount of ash-forming material. There are different issues, depending on whether the mining is on the surface or underground and on the machinery used. Much depends on the exact lie of the coal seam; the nature of the surrounding rock and on dirt bands within the seam itself.

While size reduction of the coal is largely avoided, because of the difficulties of dewatering finer material, some is needed in order to facilitate handling. Very large (hard) lumps which arise during mining, may be removed in a breaker, or...
may even be taken out by hand. Smaller pieces of rock – which can cause considerable problems in a power plant boiler – will, however, slip through the breaker.

Either before or after coal preparation, coal homogenising or blending may be beneficial in terms of supplying a power generation unit a consistent feedstock. This will not reduce the amount of ash-forming material, but may mitigate some of the undesirable effects, particularly in terms of deposition in the boiler and of maintaining the performance of the ESP at the end of the process. A uniform feed makes it easier to operate the boiler consistently and efficiently. Homogenisation involves ironing out the variations in the coal from a single source while blending is carried out to provide a consistent material from a feed of two or more coals. The techniques are discussed in an earlier IEA Clean Coal Centre report, *Coal blending for power stations* (Carpenter, 1995). Both homogenising and/or blending are carried out at a cost. The costs need to be balanced against an assessment of the benefits in terms of reduced CPP or power plant operating costs.

### 4.2 The effects of coal cleaning

The distribution of minerals between the coarse rejects from a washing plant and the fines depends largely on the size and distribution of the mineral matter. If the minerals are sufficiently large, and crystalline, some will be liberated during preliminary crushing, and can be readily separated. Most of the coal passing through a washing unit will be a mixture of particles high in mineral matter content and others low in mineral matter content. The separations carried out essentially involve sorting one from the other. Both coarse and fine wastes are therefore high in mineral matter content. The minerals in coals are generally inextricably mixed together in solid matrices, so that separation and recovery of any one component is impracticable and/or would be very costly.

Coal cleaning/preparation involves the partial separation of some (or much) of these impurities, primarily by exploiting the differences in density between mineral matter and organic coal, and with the smallest particles, the differences in surface wetting properties. The degree of separation achievable depends on the nature of the coal, and thus the properties of the individual particles fed to the CPP. It is generally only possible to remove the inorganic impurities and not those which are organically bound in the coal structure. *Advanced coal cleaning technology* is discussed in Couch (1991) and by Leonard (1991) and Osborne (1988a,b).

From the point of view of the use of coal for power generation, if the coal is not washed, there are various costs to set against those incurred by cleaning, including:

- the increased cost of coal transport and handling, since the mineral matter present increases the bulk and weight being carried;
- a considerably increased capital cost for the boiler and its associated equipment, as it needs to cope with a larger mass flow of material for a given thermal output related to the power output required;
- increased operating costs related to boiler operation, such as those arising from;
  - pulveriser wear;
  - burner wear;
- a reduction in the heat released in the boiler for a given amount of coal feed;
- different reactions between the ash-forming components, and an increased amount of material which may form slag, and/or may form fouling deposits (both of which should be removed on a regular basis, which involves increased cost). In addition, the increased solids load is likely to result in increased erosion in various parts of the boiler;
- the effects of a high ash content commonly include an increase in the number of unplanned outages, and reduced boiler availability;
- the presence of increased amounts of ash mean that the ESPs or bag filters must be proportionately larger, and to be designed to deal with the maximum ash content material;
- similarly, the increased amount of sulphur may mean that a larger FGD unit is needed;
- there are larger volumes of ash which may need to be disposed of near the power plant site.

There are inherent difficulties in making assessments about whether the costs associated with coal preparation result in sufficient reductions in the capital and operating costs of the power generation unit. Most of the major design decisions taken before it is commissioned, effectively determine the main parameters for the entire life of the unit. The costs will be deduced from experience on other units, but during the 30–50 year life of the plant, many of the assumed external parameters may change. In practice, when it becomes necessary (or economically preferable) to burn coals with a different ash content from the design coal, it is possible to change some of the operating conditions in order to accommodate the different properties and behaviour of the ash. Modifications can be made to the pulverisers, to the burners, and to the distribution of air through the boiler. All will affect the behaviour of the ash in some way or another. The fundamental ratios between the heat transfer areas in different parts of the boiler are more difficult to change.

Depending on the plant location, it may well be possible to fire different coals, but the boiler size and configuration will place some limits on what is practical. The fuel price and/or power price may change, significantly, while the regulations governing emissions may be tightened, involving changes in operational patterns, and possibly the addition of new gas clean-up equipment. Plant instrumentation and control equipment will almost certainly be upgraded at least twice during the life of the unit, offering the possibility of reduced operating costs. The local availability and cost of water may vary during 30–50 years, and this too will have implications for the cost of electricity, and might have implications relating to the practicality of coal preparation/washing. The limits on the different kinds of coal which can be used will be associated with the properties of the ash formed and with the coal rank.

It is noteworthy that virtually all the thermal coal traded on
the international market is washed before sale. While transport costs for the traded coals are likely to be proportionally higher, because of the distances involved, most other factors are the same for the coals used inside the country of origin. Also, in a number of countries, notably China, India, Russia and the USA, coals are transported over long distances overland, mainly by rail. The alternative in these countries is to generate the power near the mines, and to have high capacity long-distance cables to take the power to its point of use.

The other great advantage offered by coal preparation/cleaning is that a much more consistent product is produced, and tight specifications can be set on parameters such as hardness, ash, sulphur and moisture content, and heating value.

The classic study on the impact of coal washing was carried out in the 1980s at the Cumberland and Keystone plants in the USA, where in both cases, rom coal was replaced when a CPP was built. The detailed results from this study are presented in Couch (2000) and even though the prime objective at Cumberland was to reduce the amount of sulphur, the ash content of the coal was reduced from some 15% to less than 10% resulting in an increase in boiler efficiency from 88% to 89.5%. The improvements were reflected in a reduction in the annual maintenance costs from some US$16–18 million to around US$6–7 million. At Keystone, both the plant availability and the net power generated increased significantly when the CPP was commissioned in 1982, see Figure 6.

4.2.1 Managing coal cleaning wastes

CPPs produce large volumes of tailings and of solid wastes. In addition, the storage and handling of coal generates dust. Early planning and careful design of the operations can minimise any pollution arising from the mining activities. In most places, new mines will have a mine closure and restoration plan incorporated into the application for planning permission.

Using coal cleaning wastes

The production of waste materials involves a cost in terms of their disposal, which have to be offset against the benefits which arise from the use of the cleaner coal in the boiler. If some of the wastes can be used, then the overall cost of cleaning is reduced. Uses include:

- incorporating coarse wastes as a construction material for dam walls and as a base for building roads;
- incorporating waste materials into cement;
- using the wastes as a low grade fuel. The possibility of burning the residual carbon present in waste material in a fluidised bed combustor, thus recovering usable energy, has the attraction that virtually all the mined carbonaceous material can be burned. The subject is discussed in another IEA Clean Coal Centre report, Adding value to coal cleaning wastes (Couch, 1998).

The ideal arrangement under which energy recovery can be maximised by burning the cleaned coal from a CPP in a PCC boiler (or an IGCC unit) and then putting the low grade wastes through FBC units is shown in Figure 7.

Figure 6 Yearly average of the hourly net generation, and plant availability at Keystone, PA, USA (Harrison and others, 1997)
4.3 Coal pulverising

The pulveriser or mill is at the heart of the coal preparation system for its use in a PCC boiler. Pulverising the coal to reduce the particle size allows for very high combustion rates which are a function of the total particle surface area available and of coal reactivity. After pulverisation, the coal particles can be burned completely in just one or two seconds, at the temperatures found in the boiler combustion chamber, and in an oxygen-rich environment.

The key coal properties relating to comminution are ‘grindability’ and ‘abrasiveness’ which will affect mill throughput and wear. Grindability is a measure of the relative effect of a coal on the maximum grinding capacity of a mill when producing a product of specified fineness. Abrasiveness is a measure of the potential wear on mill components during operation.

The HGI is the standard indicator of the grindability of a coal. This depends both on the mineral matter content together with its grain size, and on the coal volatile matter content. The test results in values which generally lie between about 30 and 100. A high value indicates that a mill using the coal will have a high output, so lower values indicate a reduced/lower mill capacity. The test is non-linear, so a change in the HGI from 90 to 80 indicates only a relatively small decrease in mill capacity while a change from 50 to 40 indicates a much greater decrease in capacity. Coal moisture content plays an important part both in the HGI test and in full-scale mill operation. This is particularly significant with the lower rank coals for which it is more difficult to derive a meaningful grindability number.

In parallel with the HGI, the Abrasion Index (AI) provides a comparative measure of the tendency of a coal to cause wear. It is expressed in the standard test as milligrams of metal lost per kilogramme of coal used (Carpenter, 2002).

The fineness of the mill output can be controlled by using a suitable particle classifying device to separate and recycle any oversize. However, if the recycle is too high, the mill capacity will decrease. The coal abrasiveness, which may be strongly influenced by the mineral matter present, will affect the mill availability as it affects mill wear. Mill performance and behaviour are also dependent on the design and the materials of construction used.

The mill types most commonly used are:

- **tube mills/ball mills** which are low speed machines which rely on the grinding action of a charge of tubes or balls contained in a slowly rotating horizontal chamber. They can cope with coals containing hard components, and contain enough coal for several minutes of boiler operation. They have been used for a wide range of coals including anthracites and bituminous coals;

- **vertical spindle mills** which are medium speed machines, including bowl mills, ring roll mills and ring and ball mills. These are also known as contact mills since they contain both stationary and power driven elements which are arranged to have a rolling action with respect to each other. The grinding elements may consist of balls rolling in a race, or of rollers running over a surface. A stream of air (the primary combustion air) passes through the grinding compartment. A classifier on the mill exit allows fine particles to pass through into the boiler, while those oversize are rejected and recirculated. The various different designs are suited to different coals;

- **impact mills** where high speed impact is used for pulverising in beater wheel mills, used commonly for the more fibrous low rank coals. In an impact mill, the coal remains in suspension during the entire process. These mills operate with a small inventory of coal in the mill and hence provide fast response rates. They commonly operate as a crusher-dryer since the lower rank coals being milled have a high moisture content, and hot flue gases from the upper part of the boiler are recirculated through the mill (Woodruff and others, 2005).

The impact of the mineral matter in a coal on pulverisation can be considerable. Coals with a high content of pyrite or of quartz or of other hard mineral components will cause considerably more wear in the mill, especially if the minerals consist of coarse particles. These are generally identified by the tests which measure the AI for a coal, although like most other tests, this is derived empirically.

Size reduction is energy intensive, and the power consumed is a significant part of the auxiliary consumption (for fans, pumps and other motors). There is also a considerable variation in the fineness requirement for coal, depending on its volatile content. Coals with a low volatile content, such as the anthracites and low-volatile bituminous coals need to be pulverised to a greater degree of fineness than those with a higher volatile content.

Boilers are normally designed with excess mill capacity, so that at any one time the boiler can maintain full throughput even though one or two of the mills are taken out for maintenance. After the mill the coal/air mixture may be fed to a number of different burners, and there are issues about the evenness of the split achieved.
The main discussion here relates to the behaviour of coal in PCC boilers where the combustion temperature is broadly within the range 1300–1700°C, depending mainly on the rank of the coal being burned. In cyclone-fired boilers, the combustion temperature in the burner can be as high as 2200°C, and most of the ash forms a slag which is removed from the boiler base. This method is not commonly used in new boilers because of the formation of much greater quantities of NOx.

There is also consideration in Section 5.6 of the behaviour of coal in CFBC boilers where the combustion temperature is in the range 800–900°C. The CFBC-fired capacity represents only about 2% of the world’s total, although it is likely to make an increased contribution in the coming years, firing both low-volatile high ash coals, particularly in China, and low rank coals in a number of countries.

Many of the operational issues relating to boiler performance are the result of the behaviour of the ash-forming materials. These can form deposits which affect heat transfer, and may cause serious corrosion and erosion in the boiler. These can result in boiler derating, and in unplanned shut-downs.

What happens to the carbon, and its resultant char is discussed in the IEA Clean Coal Centre report Fundamentals of pulverised coal combustion (Wu, 2005). This describes the initial drying and heating of the coal particles and the process of devolatilisation. This leaves a char which itself is oxidised and contributes the majority of the heat released. The mechanisms involved are complex, and are still not wholly understood.

The various effects are coal specific, since they depend on the amount and nature of the ash-forming components. Thus there are issues which arise when different coals are burned in a boiler, as happens at many of the units which are not at the minemouth or with a secure and tied supply. Boilers using internationally traded coals may, for example, be required to burn Australian, Chinese, Colombian, Indonesian, and/or South African coals among others. In Germany and the UK, and other countries where there is both mining activity and the import of coal, boilers may also be required to burn coals from local mines. Even minemouth plants can experience difficulties as the deposit being mined may not have uniform properties and characteristics. The deposit needs to be well explored and then an appropriate mining plan can minimise the variations.

In a typical subcritical 500 MWe PCC unit, the coal feed will be about 5000 t/d for a UK bituminous coal or a high grade traded coal. Just under 50,000 t/d of air will be supplied to the boiler. If the ash content is 15%, then some 750 t/d passes through the boiler, and much of this will be removed from the stack gas using an ESP or baghouse. Some 10–20% of the ash will be removed as bottom ash from the base of the boiler chamber. If the ash content is 40%, as might be the case in India, with a coal which has a lower calorific value than the UK coal, then the ash formed can be as high as 2500–3000 t/d from the same capacity unit.

The coal feed consists of a range of particle sizes, including liberated mineral matter which results from the milling process. A generalised time-temperature cycle seen by individual particles is shown in Figure 8.

The mineral matter and other inorganics present in the coal particles which form ash during and after the combustion process can cause:

- wear in the pulverisers and in the pipes feeding the burners;
- slag in the burners, on the boiler walls and on the superheater pendant tubes;
- fouling deposits on heat transfer surfaces in the later parts of the boiler;
- corrosion;
- erosion, especially where the local gas velocity is high.

These factors affect boiler performance either in terms of the heat transfer taking place between the hot combustion products and the water/steam in the tubes, or in terms of the boiler availability, and the life of various components. They thus directly affect the boiler efficiency, and its maintenance costs.

![Figure 8 Generalised time-temperature cycle for the coal particles in a PCC boiler](based on Wibberley and Wall, 1983; Raask, 1986a,b; Couch, 1994)
The coal combustion by-products (CCBs) which are formed are:

- **fly ash**, which is a fine powdered ferroaluminosilicate material made up of hollow glassy particles, enriched with Ca, K and Na, and with various trace elements condensed on the surface. Various types of particles are found, including cenospheres (hollow particles), plerospheres, filled with smaller aggregations known as microspheres and opaque magnetite spheres related to the pyrite content of the original coal;
- **bottom ash**, which is partially uncombusted material that settles in the bottom of the boiler. It is often granular and is similar to concrete sand;
- **boiler slag**, which is molten ash formed in the hottest part of the boiler which is drained from the boiler base. This is a shiny black granular material which has abrasive properties, and is often used as the grit for snow and ice control, structural embankments, aggregate and as a road base material;
- **FGD residues**, which, although they are increasing in volume, worldwide, are not discussed in this study except in connection with mercury partitioning, as they are not directly related to the combustion process. By far the largest proportion is fly ash, representing something like 75–85% of the total. Different classification systems have been applied to CCBs in the USA, in the UK and in other parts of Europe. In the USA there are several ASTM (American Society for Testing and Materials) specifications. In the UK there is BS 3892 covering fly ash, and in Europe there is EN 450. There are doubtless equivalent systems in countries like China, India and Russia, and the classifications, like those for coal itself, tend to be specific to each country of origin. CCBs that cannot be used are disposed of in lagoons, disposal mounds or in landfill sites. Where there is a minemouth power plant, some are put back in the mine from which the coal was extracted. Research has shown that in many places landfill is not environmentally safe in the long term. The main hazards arise from the potentially toxic trace metals and metalloids present, and excessive concentrations of soluble salts that can be leached out (Punshon and others, 2003). In most places, due to the diminishing space and increasing cost associated with disposal, potential uses for the CCBs are being actively sought. There is great variability in the nature of the ash-forming materials in coals of different rank and origin. Lower rank coals contain more organically bound impurities such as Na, K, Ca and Mg. Higher rank coals will have more aluminosilicate clays, silicates, carbonates and disulphides as major components with, commonly, sulphates, sulphotites, feldspars and oxides as minor components. In the higher rank coals it is the mineral matter which represents the major part of the ash-forming material, and it is present either in crystalline form (as single compounds, and/or as interwoven mixtures) or as an amorphous phase (Wu, 2005).

Ash formation involves a number of complex processes which take place alongside the rapid oxidation and combustion of the organic carbon in the coal. When the coal particles are injected into the furnace, the heating rate is extremely rapid, and is of the order of 10⁴ to 10⁶ °C/s. The particles enter a zone of high turbulence and high temperature. They receive shock heating by both radiative and convective transfer, and are heated by the exothermic reactions taking place on and in the particles themselves. The environment is an extraordinary ‘witches brew’. As the ash-forming materials are released from the fuel, they undergo different reaction paths. The expulsion of water from the particle pore structure is almost instantaneous. Pyrolysis takes place with the volatile organic species being released and then oxidised – so that the coal particles can be seen to burn with a visible flame. During this time, some of the reactive ash-forming elements will be released into the surrounding gas. The remaining char starts burning and shrinking so that the included minerals fuse and coalesce, and the pore structure collapses. Individual char particles may fragment during this process. The minerals often appear as molten particles on a receding char surface, or alternatively as a lattice network left within a rapidly shrinking particle, see Figure 9.

In an overview of ash related issues, Benson and Sondreal (1999) discuss both the detrimental effects of the fuel-associated inorganic components and the prediction of ash behaviour in the boiler and in subsequent gas clean-up units. The paper is based on work carried out at the Energy and Environment Research Centre (EERC) in North Dakota, USA over several decades. It focuses on the influence of ash constituents on the fireside performance of various conversion systems, including, prominently, PCC boilers. The report suggests that because the conventional ASTM methods of coal/ash analysis do not determine the way in which the inorganic components are distributed, such methods have severe limitations in connection with the prediction of ash behaviour. The effects of the minerals can be predicted with a much higher degree of certainty by the use of computer controlled scanning electron microscopy (CCSEM) and other advanced methods of analysis. These reveal the particle size range of the minerals and their relative proximity, so that mineral interactions can be more readily understood and forecast. In lower-ranked coals, chemical fractionation can be used to determine the abundance of the organically associated cations that affect ash behaviour, thus improving the performance of predictive indices which are used to assess the impacts of deposition.

A great deal of detailed work has been undertaken to clarify the complex mechanisms involved in ash formation. This was reviewed in an earlier IEA Coal Research report (Couch, 1994) and more recently by Bryers (1999) and Benson and Sondreal (1999). The organically-bound components tend to vapourise. Some mineral matter which is liberated when the coal is pulverised may fragment due to thermal shock. Then, after the rapid temperature increase to peaks where surface temperatures may exceed 2000°C there is rapid cooling of the ash-forming materials, as the flue gas exchanges its heat with the steam in the superheater and reheater, and with water in the economiser. During this cooling, some components will condense, possibly forming very tiny particles.

In Figure 9, three mechanisms which describe ash formation...
in the combustion chamber are illustrated. In one mechanism, the char burns away, and the included minerals – which are physically close to each other – react together easily and form a single molten ash particle. A second mechanism involves the generation of volatiles inside the particle, so that as the char burns, the particle grows, and the mineral matter particles are spread out. Some of them may break away, and as the char recedes further, the mineral particles form molten droplets of different sizes. In the third mechanism, as the char burns, and volatiles are released inside, the particle becomes a shell, commonly called a cenosphere. Some of the minerals may fuse together to form a glassy shell, others may break away to form a cloud of even smaller ash particles.

Char fragmentation dominates the ash formation processes, and the included minerals undergo some degree of coalescence before the formation of molten ash particles. Excluded minerals which result from stray rock particles present, or which have broken away when the coal particles passed through a breaker, are present as molten particles, or in a few instances are still present as a solid.

In the combustion zone, most of the mineral matter forms molten particles. Some components such as quartz, may remain as a solid, even in the combustion area. As the ash is carried into the upper part of the boiler, and then through the superheater and reheater zones, the flue gas cools down, and some of the ash-forming particles will solidify. If they have a sticky surface, the particles may deposit on the walls and tubes, reducing heat transfer between the flue gases and the steam. The deposition processes are called slagging and fouling, which take place in the radiant and convective sections of the boiler respectively.

Where the ash can receive radiant heat from the combustion process, it is molten, and forms a mobile liquid layer on the waterwalls and superheater tubes. It is then called ‘slag’. Past the furnace exit at the top of the combustion chamber, the
Flue gases are progressively cooled by heat transfer to the steam in superheater and reheater tubes, and deposits in these areas, and in the economiser are referred to as being due to fouling.

### 5.1 Coal mineral transformations

In a study by the UK DTI the mineral transformations during PCC in a wide range of coals, mainly from exporting countries, are assessed. The work was carried out using the combustion test facility at the Ratcliffe Power Technology Centre, and by Imperial College, both in the UK, using a high temperature Entrained Flow Reactor. The combustion facilities generated a range of samples for analysis and characterisation, including combustion ash and unburned char, cyclone ashes and deposits collected on ceramic probes, and a slag panel. Characterisation of the samples enabled the

<table>
<thead>
<tr>
<th>Table 8</th>
<th>Proximate, ultimate and ash analyses of the coals assessed in the UK DTI study (Wigley and Williamson, 2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>Harworth</td>
</tr>
<tr>
<td>Origin</td>
<td>UK</td>
</tr>
<tr>
<td>H₂O, %</td>
<td>2.5</td>
</tr>
<tr>
<td>ash, % (ar)</td>
<td>14.4</td>
</tr>
<tr>
<td>VM, % (ar)</td>
<td>31.4</td>
</tr>
<tr>
<td>GCV, MJ/kg (ar)</td>
<td>28.9</td>
</tr>
<tr>
<td>NCV, MJ/kg (ar)</td>
<td>27.8</td>
</tr>
<tr>
<td>S, % (ar)</td>
<td>2.3</td>
</tr>
<tr>
<td>Cl, % (ar)</td>
<td>0.20</td>
</tr>
<tr>
<td>C, % (daf)</td>
<td>82.4</td>
</tr>
<tr>
<td>H, % (daf)</td>
<td>5.5</td>
</tr>
<tr>
<td>N, % (daf)</td>
<td>1.78</td>
</tr>
<tr>
<td>O, % (daf)</td>
<td>7.4</td>
</tr>
<tr>
<td>VM, % (daf)</td>
<td>37.8</td>
</tr>
<tr>
<td>Fuel ratio</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Normalised ash compositions, wt%

| SiO₂ | 50.8 | 56.4 | 36.3 | 39.2 | 61.5 | 81.6 | 63.4 | 43.1 | 67.2 | 38.6 | 48.5 |
| Al₂O₃ | 26.1 | 25.4 | 19.7 | 20.9 | 31.0 | 13.2 | 20.0 | 33.3 | 24.3 | 19.1 | 24.9 |
| Fe₂O₃ | 14.5 | 10.7 | 6.2 | 6.8 | 4.1 | 2.8 | 7.2 | 4.8 | 2.9 | 6.4 | 9.7 |
| CaO | 1.2 | 2.1 | 20.9 | 23.0 | 0.5 | 0.3 | 2.5 | 10.9 | 1.1 | 22.6 | 7.6 |
| MgO | 1.2 | 0.9 | 5.6 | 4.6 | 0.2 | 0.3 | 2.4 | 2.6 | 0.8 | 5.4 | 2.4 |
| K₂O | 3.9 | 2.3 | 0.7 | 0.5 | 0.3 | 0.9 | 2.4 | 0.5 | 1.8 | 0.5 | 2.0 |
| Na₂O | 0.8 | 0.5 | 7.6 | 1.5 | 0.1 | 0.1 | 0.8 | 0.3 | 0.1 | 4.0 | 3.0 |
| TiO₂ | 1.0 | 1.6 | 1.8 | 1.8 | 1.9 | 0.7 | 1.0 | 1.7 | 1.3 | 1.8 | 1.5 |
| BaO | 0.1 | 0.1 | 0.9 | 0.7 | 0.1 | 0.03 | 0.2 | 0.4 | 0.1 | 0.8 | 0.3 |
| Mn₃O₄ | 0.05 | 0.03 | 0.06 | 0.03 | 0.01 | 0.03 | 0.07 | 0.08 | 0.03 | 0.05 | 0.02 |
| P₂O₅ | 0.3 | 0.15 | 0.21 | 1.1 | 0.39 | 0.07 | 0.16 | 2.4 | 0.46 | 0.68 | 0.16 |
| SiO₂/Al₂O₃ | 1.94 | 2.22 | 1.84 | 1.87 | 1.99 | 0.20 | 3.18 | 1.29 | 2.76 | 2.02 | 1.95 |
| Base/acid ratio | 0.26 | 0.20 | 0.71 | 0.59 | 0.05 | 0.05 | 0.18 | 0.24 | 0.07 | 0.66 | 0.33 |
combustion performance and slagging propensity of the coals to be assessed and compared with that of a typical UK bituminous coal. The coal analyses are given in Table 8, and these provide a useful ‘snapshot’ of the properties of different coals, and in particular of the properties which affect ash behaviour. Two subbituminous PRB coals from the USA were included in the study.

The impact of the coal minerals on aspects of plant operation can be described in terms of the decomposition of the key mineral groups listed in Table 9. Their transformations are described below.

The two main types of clay found in bituminous coals are kaolinite and illite. They entered the coal formation process as a deposit in the form of a river-borne product of rock weathering. The proportion of kaolinite to illite is generally higher in the southern hemisphere coals where the minerals are generally more widely dispersed through the organic matrix and in individual coal particles. Unlike kaolinite, which has a consistent chemical composition, the illites have a wide range of compositions, all based on muscovite KAl_3SiO_10(OH)_2. The proportions of K, Al and Si may vary, and these elements can be partially replaced by Na, Ca, Mg and Fe. Montmorillonite is more often found in lower rank coals.

Quartz entered the coal in a similar way to the clays. Its composition is very similar to pure SiO_2. Larger quartz grains tend to form discrete particles when the coal is pulverised while the smaller grains may be intimately mixed with the clay minerals.

Pyrite usually forms in coal after deposition as clusters of crystals called ‘framboids’. These are formed under anaerobic conditions during coalification. Framboids typically 10–20 µm in diameter consist of spherical clusters of 1 µm pyrite crystals. Alternatively the pyrite may form as veins, infilling any cracks formed as the coal moves. Individual pyrite crystals may be released by the milling process.

Calcite is the main carbonate in northern hemisphere bituminous coal although dolomite and ankerite are often associated with it. Siderite is more common in southern hemisphere coals although other carbonates may be present. Carbonates can form solid solutions in each other, resulting in a variation in composition. They are formed in the coal later on in the coalification process and are typically found in veins. After milling, they tend to form excluded particles in the pulverised feed to the burners.

Clay mineral transformations

The clays melt to give an aluminosilicate liquid that usually contains small crystals of mullite Al₆Si₂O₁₃. Pure kaolinite melts more slowly than other clay minerals because of the more restricted chemistry, and the absence of cations such as K, Na and Ca. In a coal containing mixed clay minerals, the combustion behaviour will be controlled by the average chemical composition rather than by the properties of individual grains. On cooling, liquid ash particles derived from clay minerals supercool to form an aluminosilicate glass with the crystallisation of some of the mullite.

Table 9 The key mineral groups found in coals (Wigley and Williamson, 2005)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clays</td>
<td></td>
</tr>
<tr>
<td>kaolinite</td>
<td>Al₂Si₂O₅(OH)₄</td>
</tr>
<tr>
<td>illite</td>
<td>Based on muscovite [KAl₃SiO₁₀(OH)₂], but the proportions of K, Al and Si may vary, and these elements may be partially replaced by Na, Ca, Mg and Fe</td>
</tr>
<tr>
<td>montmorillonite</td>
<td>Like illite, but with Ca and Na more abundant than K</td>
</tr>
<tr>
<td>Quartz</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Pyrite</td>
<td>FeS₂</td>
</tr>
<tr>
<td>Carbonates</td>
<td></td>
</tr>
<tr>
<td>calcite</td>
<td>CaCO₃</td>
</tr>
<tr>
<td>dolomite</td>
<td>CaMg(CO₃)₂</td>
</tr>
<tr>
<td>ankerite</td>
<td>Ca(Mg,Fe,Mn)(CO₃)₂</td>
</tr>
<tr>
<td>siderite</td>
<td>FeCO₃</td>
</tr>
<tr>
<td>Minor components</td>
<td></td>
</tr>
<tr>
<td>apatite</td>
<td>CaAl₃(PO₄)₃(OH)</td>
</tr>
<tr>
<td>crandallite</td>
<td>CaAl₂(PO₄)(SO₄)(OH)</td>
</tr>
<tr>
<td>feldspar</td>
<td>Compositions between NaAlSi₂O₈ and CaAl₂Si₂O₈</td>
</tr>
<tr>
<td>garnet</td>
<td>(Mg,Fe)₃Al₂Si₂O₁₂</td>
</tr>
<tr>
<td>rutile</td>
<td>TiO₂</td>
</tr>
</tbody>
</table>
combustion zone with evidence of only minor surface melting as the melting point of pure SiO₂ is in excess of 1700°C.

**Pyrite transformations**
During combustion, pyrite readily loses sulphur to form pyrrotite Fe₃S₈, which then oxidises. It passes through a molten oxy-sulphide stage before forming magnetite Fe₃O₄ or haematite Fe₂O₃ and sulphur dioxide SO₂.

**Carbonate transformations**
All the carbonates lose CO₂ during combustion. They tend to form agglomerates of small oxide particles which reflect the composition of the parent material.

**Particle interactions and ash behaviour when particles form deposits**
In a coal-fired boiler, coal minerals transform and react in response to the high temperatures reached. Clay minerals and quartz fully or partially fuse to form a viscous melt. At the temperatures at which slagging deposits form crystalline phases will usually grow from the aluminosilicate melt. Mullite is frequently the stable phase in these melts. If the CaO amount in the bulk coal ash is high, or if the deposition processes have preferentially selected lime-rich particles, then anorthite CaAl₂Si₂O₈ may crystallise. Where there is even more Ca present, gehlenite CaAl₂SiO₇ may also form.

Pyrite loses sulphur, and oxidises through a liquid Fe-S-O stage to form iron oxide solid. Carbonate minerals lose CO₂ to form mainly solid oxide products.

Where the ash deposits, mineral matter particles interact with each other by processes involving viscous flow and diffusion. A sintering process leads, locally, to a more uniform chemical composition in the ash formed that is related to that of the original composition in the coal. The rate of sintering will be strongly dependent on the local temperature as well as on composition. The sintering and consolidation of deposits determines both their effect on heat transfer and the ease of removal by sootblowing.

The chemical homogenisation of a deposit by sintering, diffusion, dissolution and the growth of locally stable crystalline phases involves complex mechanisms. When magnetite dissolves, for example, the surrounding aluminosilicate melt becomes enriched in iron, and hercynite may crystallise around the dissolving magnetite particles. Given the various obstacles to deposit homogenisation, it is not surprising that it is only the hottest boiler deposits that approach phase equilibrium on a macro scale. Unstable crystalline phases and incomplete chemical homogenisation usually persist in slags from the upper part of the boiler and from those on the pendant tubes. Deposits in the cooler regions of the boiler may show little transformation beyond the first stages of sintering.

Organically-bound alkalis will volatilise, so another important ash-forming mechanism is condensation, as these components cool down. The surfaces of slagging deposits are usually too hot for components to condense and combine with the slag, but there may be significant interactions with fouling deposits in the convective zone. The condensation of alkali sulphates and/or chlorides can bind on to existing ash deposits. The deposit can then grow in such a way that it obstructs the gas flow, and becomes dense and difficult to remove. Under certain conditions, lime and unreacted calcite may form a strong and well bonded fouling deposit.

**The complexities of ash behaviour**
The discussion above illustrates some of the complexities involved in the behaviour of ash in a coal-fired boiler. The mechanisms are, however, much better understood, based both on test and development work such as that reported, and on long experience in operating boilers. New factors which are coming into play include the greater use of imported coals, particularly in parts of Europe, the wider use of western subbituminous coals in the USA and the higher steam temperatures being used in supercritical boilers in order to increase the overall thermal efficiency of the cycle. Changes in coal characteristics and boiler operating conditions both have implications in terms of ash behaviour.

### 5.1.1 The significance of the presence of trace elements

The significance of the trace elements in coals relates to the potential environmental impact of the CCBs formed, both in the form of solid residues, and in the flue gas discharged (Dale, 2005). Trace elements can have adverse health and ecological effects under certain circumstances. The major concerns about these are associated with ore smelting plants and other heavy industry where the elements of concern may be present in quite large quantities. Nonetheless coal-fired combustors are of concern because of the large quantities of coal processed, and the nature and form of the CCBs and stack gas.

The environmental awareness of the trace elements in coal was first highlighted in a classification system devised by the US National Research Council in 1981. They were classified as follows:

- **major concern**, arsenic, boron, cadmium, lead, molybdenum and selenium;
- **moderate concern**, chromium, vanadium, copper, zinc, nickel and fluorine;
- **minor concern**, barium, strontium, sodium, manganese, cobalt, antimony, lithium, chlorine, bromine, and germanium;
- **elements with negligible concentrations**, beryllium, thallium, silver, and tellurium;
- **radioactive elements**, uranium and thorium, and the products of their decay.

The range of concentration of the main trace elements in coal is set out in Table 10. Many are difficult to quantify in such small amounts, and accurate determination is difficult. Considerable advances have been made during the past 20 years in the application of modern analytical techniques, but some uncertainties remain.

During combustion, trace elements which are present in the coal are distributed between the different by-product/waste
streams – bottom ash, fly ash, stack particulates and stack gas. The distribution mechanism is strongly affected by the volatility of the species originally present in the coal. Trace element behaviour is discussed in the IEA Clean Coal Centre report on *Trace element emissions* (Sloss, 2000).

The presence of trace elements in the flue gases can be of concern, and in the US Clean Air Act 1990, a range of elements were identified as hazardous air pollutants, and power plant operators were required to monitor mercury emissions. Additionally, fly ash disposal behind ash dams can result in the release of trace elements such as arsenic, boron, cadmium, chromium, copper, mercury, molybdenum, nickel, lead, selenium, vanadium and zinc. Leach tests are therefore required where this might cause an environmental problem.

There has been increased scrutiny of the levels of trace elements in coal, and of there behaviour and partitioning – and this is driven by increasingly stringent regulations relating to emissions to both air and water (Dale, 2005).

### 5.2 Understanding deposition mechanisms

In a coal-fired boiler, the main ash related problems can be defined as being due to one or more of the following phenomena, which have been introduced earlier in the discussion:

- **slagging**, which refers to the deposition taking place in parts of the boiler where radiant heat transfer is dominant;
- **fouling**, which takes place in the cooler boiler sections where convective heat transfer is the main mechanism, as the flue gases are cooling down;
- **corrosion**, which takes place when metal from the tube

| Table 10 Trace elements in International thermal coals compared with Australian coals, mg/kg (Dale, 2005) |
|---|---|---|---|---|---|---|
| Element | International coals | | | Australian coals | | |
| | Average | Low | High | Average | Low | High |
| As | 3.3 | 0.32 | 26 | 0.93 | 0.1 | 2.7 |
| B | 59 | 6 | 143 | 21 | 4 | 36 |
| Be | 0.95 | 0.1 | 3.2 | 0.82 | 0.2 | 2.1 |
| Br | 7 | 2 | 38 | 5 | 2 | 17 |
| Cd | 0.07 | 0.01 | 0.19 | 0.09 | 0.01 | 0.28 |
| Cl | 310 | 10 | 1470 | 320 | 10 | 1500 |
| Co | 4.7 | 1 | 13 | 3.7 | 1.2 | 12 |
| Cr | 12 | 2 | 34 | 9 | 2.9 | 24 |
| Cu | 9 | 1 | 28 | 14 | 6.2 | 32 |
| F | 100 | 15 | 305 | 98 | 35 | 340 |
| Hg | 0.066 | 0.01 | 0.19 | 0.021 | 0.006 | 0.08 |
| I | 3 | 2 | 7 | 6 | 2 | 14 |
| Mn | 44 | 8 | 123 | 99 | 4 | 700 |
| Mo | 1.1 | 0.07 | 4.2 | 0.85 | 0.1 | 2.7 |
| Ni | 9 | 1 | 22 | 8.6 | 1.4 | 31 |
| Pb | 7.2 | 0.5 | 22 | 5.8 | 2.2 | 14 |
| S, % | 0.65 | 0.115 | 3.0 | 0.6 | 0.21 | 0.95 |
| Sb | 0.037 | 0.02 | 1.4 | 0.46 | 0.05 | 1.2 |
| Se | 1.4 | 0.1 | 5.3 | 0.47 | 0.12 | 1.1 |
| Th | 3.1 | 0.1 | 12.2 | 2.6 | 0.5 | 6.9 |
| U | 1.2 | 0.02 | 5.5 | 0.93 | 0.27 | 2.5 |
| V | 20 | 1.5 | 54 | 23 | 7 | 62 |
| Zn | 12 | 4 | 55 | 14 | 4 | 51 |
wall or from joints, reacts with a component from an ash deposit, or from one in the flue gas;
- **erosion** due to the impact of hard particles on tube surfaces and elsewhere, particularly in the high velocity sections of the convective sections and where the gas flow is restricted due to blockages. Slagging and fouling are the main reasons for unscheduled plant shut-down while corrosion and erosion are responsible for long-term material deterioration, which reduces the working life of various plant components.

The deposition of ash particles on the heat exchange surfaces and refractory walls in a boiler, together with the formation of molten layers, depends on the ash composition, the local temperature and flue gas turbulence. The path taken in deposit formation from the fuel particle to a mature deposit is complex. It includes a great many variables which are represented in the series of stages which need to be investigated and assessed, shown in Figure 10. A locational diagram showing where in the boiler the various mechanisms apply is shown in Figure 11.

The zones in a typical boiler where ash deposition takes place, and the symptoms that indicate problems are shown in Table 11.

**Deposit characterisation**
Key properties of a deposit which may be measured or observed include:
- the deposition rate which is directly related to the amount of ash deposited, and hence any efficiency reduction;
- its porosity. A thin but porous layer can reduce heat transfer to a greater extent than a thicker but molten one. Investigations have shown that the thermal properties of ash deposits depend on their structure;
- the strength with which the ashes are bonded together, since this largely determines the potential effectiveness of sootblowers in removing a deposit;
- its viscosity and fusion behaviour. It is difficult to determine a real figure for the temperature at which ash deforms, becomes hemispherical and finally becomes fluid, as the laboratory tests are not carried out on quite the same material as that found locally in a boiler. Taking the Ash Fusion Test figures in conjunction with Differential Thermal Analysis which involves measuring weight loss with time against temperature rise provides a fuller picture;
- the ash particle size. Due to the irregularities in particle shape, it is difficult to determine the particle size distribution of a deposit;
- its thermal behaviour. Figure 12 illustrates the effects of radiative and convective transfer to the fluid in the boiler tubes, and the temperature drops due to the presence of ash deposit layers;
- its chemical composition and properties which can be assessed by removing samples and carrying out CCSEM analysis which also shows the association of different components (López and others, 2004).

5.3 Predicting and minimising slagging, fouling, corrosion and erosion in PCC boilers

In the boiler, the individual particles are in an oxidising environment. Overall, there is excess oxygen, although on a local basis, for example close to the surface of the particles, all the oxygen may have been used up, and the conditions may be reducing. This effect may be reinforced by the efforts made to reduce NOx formation based on reducing the
amount of excess oxygen present at each stage, which is discussed in Section 5.2.

The particles consist of reacting carbon-based compounds which are being rapidly oxidised to CO$_2$, and possibly to CO. Also present is the mineral matter which may have melted. There may have been chemical reactions between the minerals, and some components may already have vaporised. The exact mechanisms are complex and undefined. The surrounding gas consists of nitrogen, water vapour, oxygen, and carbon oxides, together with the various ions, radicals and volatilised species. These include hydrogen chloride, sulphur, sulphur oxides, sodium and potassium compounds, trace element radicals, mercury compounds, together with sulphides, chlorides and oxides.

Because the coal particles are so complex and variable (in composition), and experience a widely differing environment, it is impossible to define the exact condition around individual particles. The overall effects can be best understood via averaged results and through modelling, although the ultimate assessment is against measured parameters such as the local temperature in particular parts of the boiler.

Figure 11 Ash behaviour mechanisms in a PCC boiler (Benson and Sondreal, 1999)
The *Fundamentals of pulverised coal combustion* are discussed by Wu (2005). The report looks at:
- the initial heating and drying of the coal particles;
- devolatilisation;
- combustion of the volatiles;
- char combustion;
- pollutant formation.

In the chapter on pollutant formation, the report considers the ash-forming materials, the formation mechanisms – and the predictions derived from models.

Benson and Sondreal (1999) discuss high-temperature ash chemistry, particle-size distributions and mass transport mechanisms. These control the rate of deposition and deposit strength development in both the slagging and fouling areas of a boiler. The analysis of the mineral grains together with the organically associated cations in low rank coals can be used to predict the patterns of fusion, vapourisation, heterogeneous and homogeneous condensation, and coalescence or fragmentation. The products of these transformations are a wide combination of fused mineral fragments, inorganic vapour species, condensed surface coatings and fine particulates.

Ash deposition depends on the transport of these intermediates/products to the cooler heat transfer surfaces in the boiler by a combination of diffusion, thermophoresis, electrophoresis and large-particle impaction. In the turbulent conditions in the upper sections of a coal-fired boiler, these mechanisms are difficult to define and predict. The cohesion in a deposit is a combination of van der Walls forces, the surface tension of molten particles, electrostatic forces and surface stickiness. The growth and strength development of a deposit are dependent on the formation of low-viscosity melt phases at a microscopic level, and this can be predicted from CCSEM (computer controlled scanning electron microscopy) and SEMPC (scanning electron microscopy point count).

### Table 11  Boiler zones where ash deposition takes place, and the symptoms that indicate a potential problem (modified from López and others, 2004)

<table>
<thead>
<tr>
<th>Boiler zone</th>
<th>Temperature range, °C</th>
<th>Specific boiler components</th>
<th>Boiler symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower furnace (radiant heat transfer dominates)</td>
<td>1400–1600</td>
<td>burners, sloping wall and slag hopper</td>
<td>slag tap plugging; hopper clogs up; tube leaks; lowered steam temperature</td>
</tr>
<tr>
<td>Upper furnace (radiant heat transfer dominates)</td>
<td>1250–1400</td>
<td>nose region, suspended surface pendants</td>
<td>lowered steam temperature; increased attemperation</td>
</tr>
<tr>
<td>High temperature convective zone</td>
<td>1000–1250</td>
<td>superheater and reheater tubes</td>
<td>lowered steam temperature; pressure drops</td>
</tr>
<tr>
<td>Low temperature convective zone</td>
<td>600–1000</td>
<td>backend of the reheater tubes; economiser</td>
<td>lowered steam temperature; pressure drops</td>
</tr>
<tr>
<td>Air heater and SCR regions</td>
<td>300–600°C</td>
<td>air pre-heater; SCR unit (where fitted)</td>
<td>corrosion; lowered steam temperature; blinding in the SCR</td>
</tr>
</tbody>
</table>

![Figure 12 Heat transfer across furnace walls, and the temperature profile through the various barriers (López and others, 2004)](image_url)
analyses of both the precursors and products. Another technology which is making an increasing contribution to the prediction and control of ash slagging is modelling. With the dramatic increase in the power of computers, and with increasing experience with modelling of the combustion processes, together with validation based on experience, CFD (computational fluid dynamics) is proving to be of increasing value (Smyrniotis, 2005). In the examples quoted, CFD is said to have had a substantial impact on the prediction of the optimum operating conditions of boilers in the USA who have switched from bituminous coals to burning PRB subbituminous coals. The use of PRB coals with their high sodium contents can result in uncontrolled slag formation and unpredictable behaviour in terms of the possible build-up of large chunks of slag. One approach to handling the slagging and fouling has been to target areas of the radiant and convection sections of the boiler with chemical additives which reduce or eliminate the deposition. CFD modelling together with virtual reality visualisation, can depict the dynamics of the boiler internal operations in such a way that the complex phenomena associated with eddy currents and flow imbalances can be understood. This provides the opportunity for the modification and control of the various flows.

Zygarlicke (1999) describes a 425 MWe unit burning a North Dakota lignite which experienced severe slagging and fouling problems. The lignite came from three different coal seams. A plan was implemented to use mine-planning, coal-blending and boiler operation strategies to mitigate the difficulties.

Predictive modelling was used to assess coal quality impacts. At the same time, a historical review of the lignite mine and of the boiler operation revealed several areas in the mine where the coal was associated with severe slagging- and fouling-related deratings and outages. Samples of coal from these potential problem areas were analysed in detail alongside samples from other areas in the mine. A boiler inspection and evaluation programme was initiated to provide up-to-date information on deposition severity and the impacts of boiler operating conditions. Indices covering slagging, and both high- and low-temperature fouling for these coals had been developed at the EERC. These were used for assessing coal quality and developing coal blending strategies.

For economic reasons, it was necessary to relate the indices to the results from standard ASTM analysis results rather than to rely on CCSEM data which are much more expensive to acquire. Daily coal analyses coming into the plant were used to calculate fouling indices which were then compared to boiler performance. This was related directly to the severity of boiler tube fouling and of the cyclone burner operation. A shift-by-shift record was kept of the cleanliness of the furnace walls, secondary superheat and reheat regions. Ash deposits were collected from the reheater and analysed.

The plant benefited from the ability to correlate operational parameters such as:
- quantified boiler ash deposition predictions (from the indices used);
- sootblower control;
- gas attemperation;
- flue gas recirculation;
- fuel/oxygen ratios.

As a result, it was possible to extend the period between cleaning shut-downs by some 2–3 weeks, with significant savings in costs. In addition, it was possible to develop a mining strategy which would facilitate the forewarning of the plant when a known high-fouling stream of coal was being fed to the boiler.

### 5.3.1 Australian experience with prediction and trouble-shooting

In an extensive report State-of-the-art review of ash behaviour in coal-fired furnaces (Wall and others, 2001), both the ability to predict slagging and fouling, and the ability to trouble-shoot problems associated with the use of Australian coals are discussed.

The capability for predicting slagging and fouling has improved a great deal in recent years due to the development of novel coal analysis and ash characterisation techniques – and because of a better understanding of deposition mechanisms. The current status of both prediction and trouble-shooting in relation to slagging is summarised in Table 12. This provides the basis for general recommendations in the report related to progressing the science relating to boiler slagging.

The application of sophisticated microanalytical techniques

| Table 12 | The status and applicability of predictive techniques and of trouble-shooting in connection with slagging in Australian coals (Wall and others, 2001) |
|---|---|---|---|---|
| | Prediction | Trouble-shooting |
| Technique | Application | Technique | Application |
| Characterisation | adequate | adequate | good | adequate |
| Mechanisms | good* | poor | adequate | adequate |
| Indices | poor | adequate | poor | poor |
| Predictors | adequate | poor | adequate | poor |

* understanding the mechanisms for strength development in deposits is, however, poor
in conjunction with computer-based methods in CCSEM has made it possible to characterise coals and their impurities in greater detail. Models have been developed using these techniques, alongside engineering design and boiler configuration to reflect many aspects of ash deposition behaviour. Software by the name of Ash Predictor can be used to predict the severity of slagging and fouling, and is at the stage of proving its applicability.

Wall and others (2001) emphasise that even with collaboration with boiler manufacturers and with the power generation industry, progress will be slow. The factors to take into account are the coal, the boiler/furnace design and the operating conditions. Currently, the traditional indices mainly focus on the coal characteristics. The way forward is to progress the applicability of the various predictors by using case histories to validate (and extend) them.

A survey of the experience at Australian black coal-fired power stations indicated that there are episodes when ash behaviour causes operating problems but in general these are sporadic, and do not impact the overall operating costs significantly. However, there are some stations where the impact on costs is excessive, and this is in a situation where the coal characteristics do not, generally, vary a great deal.

Typical locations which are prone to the formation of bonded deposits are shown in Figure 13.

Location 1 is in the superheated tube banks at the furnace exit. Particle impact will be principally by inertial forces, with the larger/heavier particles dominating. Gas temperatures can exceed the ash melting point while low alloy steels provide a surface layer which readily reacts with some ash components. Stainless steel tubes appear to be less likely to collect deposits. These deposits can restrict unit output by limiting gas flow, upsetting the heat balance, and large formations can distort the tubes or fall off and damage the bottom hopper.

Location 2 is the hottest part of the furnace just above the top burner zone. At this point, combustion products are expanding while moving towards the exit. Entrainment by the burners causes some gases to curl back and flow back down the wall placing high temperature gas close to the wall where ash particles can impact and deposit. Deposits here reduce heat transfer which is causing and promoting evaporation, which in turn tends to increase both steam temperature and the external gas temperature, thus increasing the tendency for deposits to form on the superheater tubes.

At Location 3, the gas flow is dominated by the burner jets, directed away from the burner wall. There are also secondary flows parallel to the wall due to gas flowing into the burner region. Deposits tend to form adjacent to the burners, or on burner quars, and may develop from small ash particles deposited from slow recirculating gas flows. The deposits can cause operational problems due to disturbance of the burner flow patterns and the need to clear the clinker formed during maintenance.

The deposits formed in the upper parts of the boiler drop on to Locations 4 and 5 when they get too heavy. Ash hopper blockages are potentially serious and can result in a unit being taken out of service, and can be difficult to clear if not detected early enough.

Two other ash behaviour effects need to be considered:

- furnace heat transfer is predominantly by radiation, so the wall emissivity has a significant effect on furnace performance. In the absence of bonded deposits, a layer of dust will cover all surfaces, which can reduce emissivity with a consequent reduction in evaporation and increase in the gas temperature in the upper part of the boiler;

- certain ashes can form a weak deposit that breaks up when it falls into the furnace hopper. This results in cascades of hot finely divided material entering the ash pit. The rapid quenching of the ash releases large amounts of steam which can cause operational problems.

There has been emphasis on understanding the formation of deposits. In practice, the important issue may be the bond strengths within the deposit, and between the deposit and tube surface. This affects the ease of removal by sootblowing.
Ash management in coal-fired power plants

– and hence on heat transfer from the flue gases to the water/steam in the tubes.

Comprehensive furnace models that can provide detailed information about the gas temperature and composition, and about particle trajectories have been developed. However, there is not yet a parallel mechanistic model available to quantify ash deposit build-up.

5.4 The effects of NOx reduction methods

NOx control for PCC power plants is discussed in another Clean Coal Centre report (Wu, 2002). This covers both the combustion modifications which are relatively simple to install and operate, as well as flue gas treatment methods which can provide higher levels of NOx reduction. Flue gas treatment is discussed in Chapter 6.

Many coal-fired boilers which have been retrofitted with low NOx firing systems are experiencing significant operational difficulties due to:

- increased amounts of carbon in the fly ash;
- increased waterwall wastage.

In one example a 500 MWe opposed wall-fired unit was retrofitted with Foster Wheeler controlled-flow/split-flame burners together with an advanced overfire air system. NOx emissions were reduced from 800 to 300 ppm, but the carbon-in-ash increased from 4% to 8% when using a 10% ash content coal. Low NOx burners and the use of overfire air mean that individual coal particles emerging from the burners have less oxygen available to them, and the peak burning rates pre-retrofit are orders of magnitude greater than they are in the post-retrofit situation.

There are various changes that the plant operator can make in order to decrease carbon-in-ash levels, but these all include much more control of process variables. These include the following:

- biasing the outer/inner burner column secondary air;
- improving the consistency of the grind;
- replacing the burners;
- modifying the angular orientation of the burners to improve the placement of streams with heavy particle loadings;
- adjustment of the flowrate and location of the overfire and underfire air ports.

It is necessary to ensure that the coal particles are as uniformly milled as possible, so that burn-out times are uniform, although the effects of this are dependent on the boiler configuration. Similarly the air/oxygen flows need to be controlled so that oxidising conditions are maintained throughout most of the combustion zone. Using the computational simulations, it should be possible in many situations, to decrease the carbon-in-ash level without any significant increase in NOx emissions. Comparing the results of simulations with the available data from a range of boilers can validate the model assumptions and provide confidence in the methods proposed for reducing carbon-in-ash (Davis and others, 1999). The use of dynamic modelling like this can significantly reduce the time taken to achieve results and reduce the amount of empirical trial-and-error based work.

The experience at the Cumberland plant in TN, USA is illustrative of some of the problems associated with the installation of a low NOx combustion system. Units 1 and 2 are identical, using supercritical steam at 25 MPa pressure and with 1300 MWe capacity. As they used the cell-fired arrangement, with tight burner spacing and high burner zone heat release rates, their NOx emissions were amongst the highest for wall-fired once-through boilers. The units fire a high sulphur eastern bituminous coal with some 3.2% sulphur.

In order to reduce NOx levels, the burner vertical spacings were spread out as much as is practical and the zone height was increased from 11.6 to 15.8 m. A Foster Wheeler low NOx burner system was used, retrofitting the eighty-eight original burners. It was necessary to replace all the waterwall panels in the burner belt. In addition, boundary air ports were installed in each corner, at the level of the previous second burner row. These introduce combustion air from the windbox between the outermost burner columns and the sidewalls to reduce the potential for accelerated waterwall corrosion. The boundary air effectively increases the local oxygen level along the waterwalls preventing the formation of gas constituents like hydrogen sulphide and carbon monoxide which can cause corrosion (Laux and others, 2000). After the retrofit, the loss-on-ignition (LOI) levels in the ash increased for a baseline of approximately 1% to a level of 1.2–1.7%. The retrofit meant that increased attention had to be paid to slag control, but lower furnace slagging was generally reduced.

The effects of controlling the coal particle size

To meet increasingly stringent emissions regulations and particularly those relating to NOx and to particulates, the particle size fed to the boiler from the mills is of considerable importance. Generally the carbon burnout achieved in a particular furnace is directly related to the size distribution of the pulverised coal supplied to the burners.

In the UK DTI study most of the size distributions after milling were similar, except for the Australian Bowen Basin and the Indian Talcher coals. The Bowen Basin coal has a HGI value of around 60, while the Talcher coal contains a considerable amount of very fine quartz particles which are well dispersed (Wigley and Williamson, 2005).

The grindability and density of the minerals in coal determines their ultimate size in the pulverised coal after milling. Their distribution through the original coal determines what proportion are effectively ‘liberated’ during the milling and classification process. Aluminoisilicate clay minerals appear to concentrate in the finest fractions, below 20 µm size. Quartz tends to appear in the size range 20–75 µm, while pyrite tends to concentrate in the size range 10–45 µm. This is in spite of the fact that it is difficult to grind. The reason is that the air flow for the classifiers commonly used on coal mills is unable to remove the dense pyrite particles from the grinding table until they become more finely divided and therefore lighter.
It is to be expected that the particulate (liberated) mineral matter in a typical pulverised coal would have a distribution spectrum weighted towards the smaller sizes compared to the coal particles. This is because many coals contain a proportion of very fine clay sediment particles which are sized from 0.1 to 10 µm. It is also related to the fact that the density of coal is significantly less than that of the mineral matter, so the mineral matter is preferentially retained longer in the mill.

The use of a dynamic classifier – a case study

Experience at the Ratcliffe-on-Soar power plant in the UK with four 35-year old 500 MWe units illustrates the potential benefits of upgrading the classification system. It also demonstrates how important the consistent fineness of the grind is to good combustion performance, and achieving low carbon-in-ash values (Landers and others, 2004).

Changes in the external regulatory environment meant that there was considerable pressure to reduce the levels of NOx emissions. This can be achieved mainly by redistribution of the combustion air so that locally, there is less excess oxygen. This reduces local combustion temperatures and results in the formation of significantly less NOx.

Unfortunately, at the same time, carbon burn-out tends to drop, resulting in increased carbon-in-ash levels which reduces combustion efficiency, and may mean that the fly ash is unsaleable.

If the fineness of the pulverised coal is increased, then these effects can be reduced or even eliminated. Thus Ratcliffe was selected as a test site to demonstrate the operational gains from fitting dynamic classifiers. The eight mills on each boiler are of the ring and ball type, capable of a nominal coal throughput of 38 t/h. During normal operation, six mills are required to achieve full boiler output. The problem with the original mills was the proportion of particles of >200 µm which slipped through, and these are the ones which make the greatest contribution to the unburnt carbon.

The dynamic classifier fitted to one of the mills achieved the virtual elimination of particles of >200 µm, thus providing the basis for maintaining the saleability of the fly ash when the other mills are also fitted with new classifiers. The design is inevitably more complicated than the standard method, and involves two stages. Guide flaps integrated into the classifier redirect the upward flow of air and milled coal dust from an upward direction into tangential flow. A bladed rotor above turns in this same tangential direction. In the gap between the static guides and the blades of the rotor, a region is created where centrifugal forces are generated, promoting classification. Larger/heavier particles are thrown outwards, and drop down under gravity where they are collected and returned to the mill for further grinding. The fineness of the finished material depends on the rotational speed of the rotor. To produce a finer material, the rotor speed is simply increased.

5.5 The effects of cycling

In order to meet the demands of the market, an increasing number of coal-fired boilers are being operated in load-following mode, or are ‘two-shifted’, meaning, effectively, that they are operated during the daytime when demand is high and put offline at night.

These patterns can result in locally unstable conditions in the boiler, and particularly in the convective sections where ash deposition can interfere with heat transfer. When a boiler is operated on base load, as was more common in the past, the conditions relating to temperature, gas velocity and the amount of excess oxygen present are relatively stable. This resulted in relatively well-established patterns of ash formation and of deposition, and corrective action (such as sootblowing) could be taken.

When the boiler is subject to fast start-ups, load following possibly in automatic mode, or operation at a level above the maximum continuous rating, then there are metallurgical effects on various components and effects on the formation and deposition of ash. There will also be some interaction between ash formation and deposition and consequently on corrosion and erosion in various parts of the boiler.

Most knowledge of the long-term effects of ash behaviour are based, effectively, on a basic understanding of the ash chemistry and the time-temperature cycle that the materials experience – and then on empirical experience and observation. Boiler operators get to know what the effects are, and under stable conditions can develop predictive indices which enable them to operate the boiler in the best possible way.

In an article about The real cost of cycling power plants (Lefton and others, 2002), it is concluded that cycling can involve substantial long-term costs. Some upgrading of components where fatigue, creep failure or corrosion may cause premature failure is essential. In addition, while the control of boiler water and feedwater chemistry is of critical importance, the behaviour of the ash-forming materials in the flue gases also has an influence. The effect is quite difficult to quantify in financial terms, see Figure 14 where forced outage rates are assessed for a typical 600 MWe unit. It is only with records that cover several years of operation and with detailed analysis of the kinds of failure related to the coals being used, and their mineral matter content that an understanding of the effects of cycling will be achieved.

It is inevitable that when units are started-up, shut-down or experience rapid changes in the load required, there will be unpredictable changes in ash behaviour. While the period of time involved is relatively short in most situations, the transient conditions could result in ash deposit build-ups in certain circumstances or of excessive erosion, and operators need to be aware of the possibility.

5.5.1 Generation system optimisation

An increasing number of coal-fired boilers are operating and selling power into grids at a price which is determined by the market. Hence the increasing need for units to be cycled, as discussed above.
In a recent review, it was estimated that about 40% of power production in the USA was subject to wholesale competition. Thus to bid intelligently into these markets, real-time prices (hence the return to the plant) must be aligned with real-time costs (Makansi, 2005).

The parameters to be optimised are complex. They include:
- fuel cost (which in many places has been rising). Both coal and gas prices affect the choice of fuel for generation at a particular time;
- coal quality, which has its effects (discussed in this report) on boiler performance, with possible adverse effects from ash deposition, corrosion and erosion. There are engineering and maintenance costs which arise as a result of the slow long-term deterioration in various boiler components, which is affected by temperature cycling, and by the effects of ash deposition (Ambrosini, 2005);
- in addition, coal quality and combustion conditions can affect the emissions of SO₂ and of NOₓ, both of which are traded as credits or allowances. Although these markets are as yet quite crude instruments, nonetheless each tonne of emissions from a plant’s stack has a cost implication;
- fly ash from the plant may either need disposal, or may be sold into the reuse market. Low NOₓ combustion requirements may render the ash unsaleable, and the use of SCR and FGD further complicates the generation process making overall optimisation difficult. The interactions are shown in Figure 15. In the review, the arrival of CO₂ trading is regarded as being inevitable at some stage, so the stage has been set for the application of unified, advanced process optimisation and control programmes (Makansi, 2005).

5.6 Ash behaviour in CFBC boilers

CFBC is generally the preferred method of combustion for certain coals which:
- are difficult to burn because of their low volatiles content;
- difficult to mill because of high mineral matter content, including hard minerals such as quartz;
- have a high sulphur content, best removed by in-bed capture; and/or
- of low and variable grade.

Coals used in the larger CFBC units worldwide include:
- both Chinese and South Korean high-ash anthracites;
- Polish brown coals;
- a high sulphur coal where the ash has a high calcium content at Gardanne in France;
- the lignite in Gujarat, India.

The largest unit currently operating is at Jacksonville in the USA, with 300 MWe capacity, but a larger supercritical unit is under construction at Lagisza, Poland with 460 MWe capacity, due to be commissioned in 2009.

For CFBC the coal only needs grinding down to 3–6 mm size, much less than the feed for a PCC unit. This reduces the cost and facilitates the use of high ash coals which would be difficult to mill. The combustion conditions are more forgiving of variations in the coal feed quality, which makes it suitable for many brown coals. The combustion temperature in CFBC is generally in the range from 800°C to 900°C which means that NOₓ formation is much less than in PCC, although more N₂O is formed.

Because of the lower combustion temperatures, most of the mineral matter present retains its original shape and chemical composition. As the carbon progressively burns away, it can be erosive, but the ash does not result in slagging and fouling in the same way as it does in a PCC unit. There can be fouling in the heat exchanger under the cyclone, and if any of the ash components soften, particles can agglomerate which may interfere with fluidisation if they become heavy enough to fall down on the fluidising grid. What then tends to happen...
is that the remaining carbon burns away, and an ash-based glassy layer forms on the grid and eventually blocks the flow of the fluidising air.

The residues from CFBC units require special consideration as in most cases they are combined with an in-bed sorbent which captures the sulphur in the coal immediately after it has been oxidised.

**Figure 15 The integration of advanced sensors and control devices into plant control** (Makansi, 2005)
With older coal-fired power plant flowsheets, the only action taken to clean-up the flue gases was to remove particulates. This is most commonly done using ESPs. Now, with increased awareness of the adverse environmental effects of emissions there are increasingly stringent regulations in many countries. These govern either the allowable emissions from power plant stacks (the most common form of control) and/or air quality standards, particularly in big cities, which relate to pollution levels from many different sources and in particular that which arises from motor vehicles.

The addition of post-combustion clean-up equipment can affect both the properties and behaviour of the fly ash in the stack gases, and these issues are discussed in the following paragraphs.

6.1 In Selective Catalytic Reduction (SCR) units

The addition of an SCR unit is one of the most common ways of achieving further reductions in NOx emission levels beyond those achievable by the low NOx combustion methods discussed in Section 5.2. As a number of different methods are used for NOx reduction (see Wu, 2002), each with distinctive effects from and on the properties of the fly ash, it is beyond the scope of this study to assess all the impacts. It is the intention here only to highlight the principal issues which relate to catalyst life in SCR units and fly ash contamination.

SCR is generally only applicable when the coal sulphur content is below 2%. In the unit, vaporised ammonia (NH₃) is injected into the gas stream at about 300–400°C. The flue gas is then passed over a catalyst which promotes reactions between NOx and NH₃ to form molecular nitrogen and water vapour. However, there are then traces of NH₃ left in the exhaust gas, together with some SO₃ formed from the oxidation of SO₂.

A number of issues arise in the design and operation of SCR systems. These include the coal characteristics (particularly its mineral matter content), catalyst and reagent selections, process conditions, ammonia injection, catalyst cleaning and regeneration, low load operation and load following.

Coals with a higher sulphur content in combination with significant amounts of alkalis, alkaline earths, arsenic or phosphorus in the ash can deactivate the catalyst, significantly reducing its service life. Catalyst poisoning can be caused by components of the fly ash itself, by As₂O₃ or by acid gases.

The dust load passing through the catalyst plates or the honeycomb is also a factor affecting both performance and service life, and high ash content coals can cause problems including plugging (particularly if the ash is slightly sticky) and/or erosion. Erosion may also be the result of the presence of hard particles.

Another aspect of SCR operation is that residual NH₃ can deposit on the fly ash. Adsorption takes place at temperatures below roughly 260°C. High levels of NH₃ slip can contaminate the fly ash and reduce its sale potential/value as it will restrict its end use. The NH₃ slip is typically maintained at a level of less than 5 ppm, and often the design is for a slip of below 2 ppm.

The contrasting experience in the USA with eastern high-sulphur bituminous coals and western PRB subbituminous coals which have different ash properties is illustrated in Table 13.

6.2 In ESPs

The final stage of ash management in the power plant is the removal of the fly ash from the flue gases. This is done primarily in a dust collection device, and on a power plant,

| Table 13 The influence of ash properties and boiler type on the risk of operational damage to the SCR catalyst (Crowe and Masayoshi, 2002; Hitachi Zosen, 2002) |
|---|---|---|
| Coal | PRB | Bituminous high sulphur |
| Boiler type | dry bottom | dry bottom | wet bottom with fly ash recirculation |
| Poisoning | by fly ash | Ca | A | B | B |
| | | Na, K | B | B | B |
| | by As₂O₃ | C | B | A |
| | by acid gas | C | B | B |
| Erosion by fly ash | B | B | B |
| Cell plugging by fly ash | A | B | B |

degree of risk/consideration: A (high); B (middle); C (low)
this is usually either an ESP or a fabric filter. All plants have a fly ash removal unit, and the vast majority now remove more than 99% of the fly ash, with the most modern units achieving 99.99% removal efficiency. Some very fine particulates may be removed later during FGD.

Particulate control in the stack gas from coal-fired plants is discussed in more detail in other IEA Clean Coal Centre reports, Wu (2000) and Zhu (2003). ESPs are the most common particulate control device used and it is the operation of ESPs which forms the basis of the discussion here. ESPs consist of very large volume boxes in which the flue gas flow velocity is low enough for virtually all the ash particles to be affected by the electric fields present. Gas velocities are kept in the order of 1.5 m/s (Woodruff and others, 2005). The flue gas and its solids load should to be evenly distributed throughout the unit.

In practice, ESPs have to cope with variations in operating conditions including:

- changes in the coal quality and ash content. This includes the inherent variability of a feedstock coming from a consistent source, and the use in a power plant of different coals. These may be used for various reasons, one of which may be that a cheaper fuel is available, and another is that a coal with a lower sulphur content is needed to meet new emissions requirements;
- the effects of load changes;
- start-ups and shut-downs of the unit;
- changes in the flue gas composition and temperature.

In a typical arrangement, precipitation and collection take place in three stages:

- the particles are ionised/charged using a high voltage electric discharge. The flue gas carrying the particles passes through a very strong (negative) electric field, using 50–70 kV, around thin vertical electrodes evenly spaced between earthed collection plates;
- collection takes place on the oppositely charged electrode. The applied voltage is high enough to maintain the field strength, and cause sparking which in turn causes the collapse of the field. The average sparkover rate for optimum precipitator operation is some 50–100 sparks per minute;
- the collected material is discharged when the collected layer is thick enough (0.1 to 1.25 cm) by rapping both the collecting plates and the discharge electrode. The released fly ash falls into a hopper underneath and is removed. The flue gas flow is maintained and the applied voltage remains constant. Particles which are re-entrained in the flue gas flow need to be removed in the next section of the unit. In practice the solids loading is probably skewed towards the lower parts of the unit, and fluid dynamic modelling to quantify this is a useful tool in quantifying the effects of control devices intended to achieve optimum flow distribution (Zhu, 2003).

ESP s generally operate at temperatures in the 120–200°C range. The optimum temperature for a particular installation will depend on the coal used, and combustion and other process conditions. Bibbo (1994) reported that most fly ashes reach a peak resistivity at temperatures between 140°C and 190°C.

Fly ash resistivity is one of the most important factors affecting ESP performance (Wu, 2000).

This depends on the nature of the ash, and on the sulphur content of the coal. This is because most of the coal sulphur becomes sulphur oxides (SO2 and SO3) in the flue gas. The SO3 reacts with the water vapour present and condenses on the fly ash surface. The amount which deposits on the fly ash particles depends on the amount of SO3, and their absorptive capacity.

Other devices are used for particulate collection, including fabric filters. These can be more appropriate for low sulphur content coals, and possibly where there is particular sensitivity to the discharge of the finest particles, referred to as PM 10 and PM 2.5 (particles of less than 10 or 2.5 µm size). Both fabric filters, and the use of wet ESPs are described by Wu (2000) and Zhu (2003).

The choices that have to be made in relation to ash removal are increasingly influenced by the mix of emissions regulations which apply, covering sulphur, NOx and particulates. In the future, in some countries, limits on mercury emissions may place further restrictions. What this means in practice is that plants have fewer and fewer degrees of freedom in their operational patterns. Instead of a single unit operation (the boiler/combustion chamber) being involved, with one flue-gas clean-up device (the ESP) on the end, there is now a whole sequence of unit operations, and each one influences the others, making optimisation more complex. Fortunately this trend is partly balanced by the increased availability of computer-based control systems which can collect large amounts of data, and contribute meaningfully to the optimisation process for the series of unit operations involved (Nalbandian, 2004).

Unit operation variations when different control systems are used

The pressure drop through an ESP is low, at about 12 mm of water gauge, as the gas flow is slow. This compares with a pressure drop of approximately 150 mm which is more typical when a fabric filter is used, as the flue gas has to pass through the layer of solids building up on the fabric.

In certain situations, hot side ESPs are preferred. These operate at temperatures around 300–350°C, and can remove more of the fly ash present as collection efficiency is higher at the higher temperature. However, the unit size needed for a given duty is much larger than for a ‘cold’ side ESP operating at around 150°C. This is because the flue gas volume is much greater at the elevated temperature.

In terms of ash management, the most efficient and...
appropriate device will be selected in order to meet the prevailing emissions regulations. Most of the process problems that will be encountered on plants are connected either with a change in the coal used, and hence in the fly ash amounts and properties, or with the need to meet tighter emissions regulations imposed after the plant was designed and built – and in particular with the need to reduce NOx emissions.

### 6.3 FGD scrubbers

Flue gas desulphurisation is carried out on an increasing number of coal-fired units. As with particulate control, there are a number of methods used, but wet scrubbing with a suitable sorbent is by far the most common. There are reviews of the various processes for FGD in Takeshita and Soud (1993); Soud (2000); DTI (2000); and Blankinship (2005).

Sulphur removal is not required on all plants. Some use a low sulphur content coal which enables the plant to meet current emissions regulations. The increasing use of PRB subbituminous coal in the USA is an example of coal switching to comply with SO₂ emissions requirements. In some other big coal producers such as India and South Africa, the coals used have lower sulphur contents than most of the bituminous coals in Europe or the USA, and FGD has not been required. There is, however, increasing pressure to reduce the emissions of sulphur in a range of countries, and particularly in China, where air pollution is a significant issue, and where new coal-fired power plants are being commissioned.

Where FGD units are operated, there are issues relating to the by-products produced, and their use or disposal. Since the sulphur removed originates in the coal used, it forms a part of the discussion of the subject of this study, even though the by-products are not formed in the boiler itself. This is partly because the issues related to use or disposal are much the same. For example, in the USA, some 30% of the CCBs are used in commercial applications (including the proportion arising from FGD units). The US DOE wants this proportion to grow to 50% by 2010, so the contribution made by FGD by-products may be significant.

In both Germany and Japan, the landfilling of by-products is not allowed, so in both countries the FGD units produce wallboard-grade gypsum which can be sold on the market. In other countries the decision as to whether or not to make this depends on the proximity of the plant to a market for the wallboard. Some systems are designed to produce a lesser quality gypsum, which is suitable for use in the cement industry, or possibly for landfill stabilisation.

The systems use forced oxidation that adds oxygen to make SO₃. Cement industry grade gypsum is easier to produce than wallboard and goes directly to the cement plant. To achieve the whiteness and purity required for wallboard grade requires some purification along with washing and separation (Blankinship, 2005).

### 6.4 Mercury removal

There is a wide range in the mercury contents of different coals, but there is no large supply of ‘low mercury’ coal (Lindau and others, 2003).

In the USA, the Environmental Protection Agency has set limits on mercury emissions from new plants, and the rules envisage placing an eventual cap on emissions from all plants (Sanford, 2005; Offen and others, 2005). However, no technology designed specifically for mercury control is currently being used or has been tested thoroughly enough to ensure that it will work at a given plant. An IEA Clean Coal Centre report on *Mercury – emissions and control* (Sloss, 2002) reviews the available technologies.

The ideal control technology will deliver regulatory compliance at least cost with the smallest footprint in a manner responsive to plant cycling and fuel changes. The point in relation to ash management is that almost all the mercury in the coal is vaporised during combustion, and its speciation in the flue gas, and association with other components depends on the conditions. Because mercury and many of its compounds are still volatile at the temperature of the stack gases from a power plant, there is the risk of substantial slippage.

Various commentators suggest that the chloride content of the coal can alter the speciation of the mercury. Coals high in chloride are reported to be more likely to result in greater concentrations of the oxidised forms of mercury which are water soluble and can therefore be captured by wet scrubbers. Low chloride coals will produce more elemental mercury, which is not water soluble. In addition, the concentration of gas-phase HCl in the flue gas is a direct result of the chloride in the coal and has been shown to be a key parameter in the reaction between vapour phase mercury species and solid sorbents. The distribution of both mercury content and chloride content in the three main coal types in the USA is shown in Figure 16.

In an IEA Clean Coal Centre report *Chlorine in coal combustion and cofiring* (Davidson, 2005) one of the conclusions is that while the presence of chlorine is one of the factors which affects mercury oxidation, it does not seem to be the determining factor. This is based on an extensive examination of the available information.

In a conventional power plant, mercury capture depends on the chemistry of the flue gas and especially on the form of the mercury – elemental, oxidised, or particulate – as it passes though each stage. ESPs and fabric filters capture particles that have absorbed some of the mercury. Wet FGD scrubbers capture most of the soluble, oxidised mercury. Where SCR is used to reduce NOx emissions, much of the elemental mercury is converted to its soluble oxidised form.

In addition to the mechanisms associated with conventional flue gas cleaning techniques as discussed above, it may be necessary to inject a mercury oxidising additive into the flue gas to improve oxidation, together with some active carbon to
adsorb much of the remaining mercury. The oxidised mercury is removed in the wet FGD scrubber, and the active carbon in the particulate control unit. In both cases, the mercury content of the by-product is increased. In the case of FGD the wallboard gypsum will contain more mercury while in the case of the collected fly ash, it will contain the active carbon and thus a higher concentration of mercury. This may well affect the possible use/s of the products.

Figure 16 The distribution of mercury and chloride contents in the three main types of coal in the USA (Lindau and others, 2003)
A number of management tools are available to assist with minimising the deleterious effects of ash behaviour. The first strategy is to minimise the amount of mineral matter entering the plant. New instrumentation enables the power plant manager to measure relevant parameters more accurately, and also in real time. With the use of increasingly sophisticated models it is possible to assess the impact of certain changes with greater certainty, and to include a wider range of variables in the assessment.

### 7.1 Coal preparation and fuel specification

The overall effects of coal cleaning were discussed in Chapter 4. Since on a worldwide basis more than 85% of coal is used in its country of origin, there is scope for a considerable amount of optimisation, especially amongst the largest users such as China, India, and, probably Russia. In a number of other countries, such as Australia, South Africa and the USA, much of the coal produced is already optimally prepared, and there is a better understanding of the overall benefits within the coal-to-electricity chain of pre-cleaning.

From an ash management perspective, particularly for a minemouth power plant, it is important to optimise the amount of washing carried out. The question is whether it is more cost-effective to separate more of the higher-ash material and either dispose of it, or burn it in a FBC unit, or whether it is better simply to accept the ash in the coal and deal with it in the boiler. For ashes with fairly benign properties, in modest quantities, this may be the better option. If the ash in the system results in the need for a bigger and more expensive boiler, and in significantly increased operational costs, then pre-cleaning is the preferred option.

While the overall objective is to make the optimum use of the combustible carbon which is extracted from the mine, there are various practical and economic factors that have to be considered.

Where a plant relies on traded coal, either from an internal market inside the country, or from the coals available on the international market, then a series of different choices are possible.

Where the plant management has the freedom to buy coal on the market the main tool available is to set the specification for the coal to be burned, and that involves a judgement, assessing what might be available and whether higher quality is worth extra cost. There are also issues around the security and consistency of any supply. Plant running costs can often be reduced if the coal quality is consistent, since the operators get to optimise the necessary boiler cleaning routines more readily and there is a reduced risk of unplanned outages. The assessment is a combination of information which is based on coal analysis, and on previous operational experience on the plant.

The impact of coal specification and quality on power station performance is discussed in another IEA Clean Coal Centre report (Skorup ska, 1993). The sulphur content of a coal has become of greater importance in many situations, except, possibly, where a plant has FGD equipment with excess capacity. In the USA in particular, the use of lower sulphur content western coals has enabled operators to meet emissions requirements although often at the cost of increased and less controllable ash deposition in the boiler. The other main areas where there may be a choice is in the ash content of a coal, and possibly in the nature of the ash. Limits may be set, for example, on the amounts of the components associated with boiler slagging and fouling as well as on the coal hardness – which affects the performance of the mills. Ash quantity affects the amount of solids to be handled through the particulate removal system, and the amount that may have to be disposed of.

There is greater analysis and assessment of the cost implications of changes in the coal used for generation. When designing new installations, there are difficult judgements to be made in relation to how much over-capacity to build in, to cope with variations in the coal such as a higher sulphur content and/or a higher ash content. In the USA, mercury content, and even its speciation is becoming of greater interest when coal specifications are being agreed.

It is becoming increasingly common for plants to use coals from a number of sources, as a means of minimising the fuel cost – which often represents some 50–60% of the total operating cost. As a result, blending programmes need to take the different coal properties into account, and the monitoring of plant conditions becomes even more important.

In recent times, two factors have impacted strongly on power plant operators approach to coal specification. In many places, the power plant product, electricity, has been sold into a more flexible market. Its value depends not only on the amount generated, but increasingly on what time of day it is produced. Among other things, the result of the competitive market has been that generators have sought lower cost coals wherever possible, although it remains essential to assess the effects of any change on overall long-term operating costs and on plant availability. Also, changes in the regulatory control of emissions have had a considerable impact on plant operating conditions, and hence on the specifications applied to the coals used.

### 7.1.1 A case study in India

The potential impact of coal washing on power station economics is discussed by Selvakumaran and Reddy (2005). The analysis relates to the situation in India, but the findings would be more widely applicable in other countries, particularly in China, and possibly in Russia. In all these countries, coal is transported long distances, mainly by rail, and there are capacity constraints which are made worse by the weight and volume of dirt/mineral matter which is carried.
The paper reports on one of the relatively few studies where a power station unit is monitored for several months before and after using a washed coal. The benefits of coal washing include improved handling, since:
- both oversize coal and extraneous materials are excluded;
- the presence of fines is controlled;
- clays from the overburden from opencast mines are eliminated. This is particularly important during the rainy season in India.

In addition, the amount of mineral matter fed into the boiler is reduced, its heating value is increased and the cleaned coal is much more consistent in composition.

All of this makes a significant contribution to the efficient operation of coal-fired boilers. Where new units are being designed, it would be possible to make substantial reductions in both capital and operating costs if cleaned coals were used. In a recent study in India at the Dahanu plant, the potential operating cost savings were quantified, see Table 14. The Dahanu plant consists of two 250 MWe units, both commissioned in 1995.

Broadly, the raw grade F coal had an ash content of 40% before washing, and 30% afterwards. Its heating value increased from 14.7 MJ/kg to 18.2 MJ/kg, and the maximum coal size dropped from 300 mm to 50 mm.

With the washed coal, overall thermal efficiency was increased usefully, and outage time reduced dramatically. This meant that the plant load factor increased from 57% to 89%, and the amount of fuel-oil support was reduced to almost nothing.

As presented in Table 14, there were significant improvements in boiler performance.

### 7.2 Using advanced measurement devices and control systems

Today’s power plants are expected to achieve a number of competing objectives, for example:
- providing capacity when it is needed;
- operating efficiently in every way;
- meeting emissions regulations;
- operating safely and reliably;
- minimising overall costs, both short- and long-term.

Various process control systems are available to assist operators. On the boiler, these principally cover:
- feedwater;
- combustion;
- steam temperature.

The presence and behaviour of the ash-forming components in the coal can have a major impact on combustion and heat transfer conditions, thus affecting the steam temperature, thermal efficiency and possibly long-term damage and deterioration.

An increasing number of coal-fired units are required to achieve the following:
- cycling operation;
- burning low/lower cost coals, possibly with substantial variations in quality;
- combustion conditions which minimise the formation of NOx;
- heat rate improvement initiatives to reduce both overall costs and CO₂ emissions;
- variable pressure operation;
- reliability and availability improvement;
- increasing the interval between outages and making them shorter;
- reducing costs relating to all aspects of the operation and maintenance of the plant (Chang and Tilley, 2004).

It is obvious that there are conflicting requirements and objectives within this list, so that plant managers have to make judgements about how to achieve the optimum outcome. Some of the advanced measuring techniques and sophisticated modelling can help with balancing the different objectives, and the discussion here concentrates on the aspects connected with the behaviour of coal ash.

### 7.2.1 Online coal analysis

Online analysis of the coal could make a major contribution

| Table 14 The impact of coal cleaning on the operation of the Dahanu plant in India (Selvakumaran and Reddy, 2005) |
|--------------------------------------------------|--------------------------------------------------|--------------------------------------------------|
| Test period | Raw coal | Blended coal | Washed coal |
| Jun-Oct 1996 | 35.3 | 36.8 | 37.2 |
| Apr-Sep 1997 | 56.7 | 82.5 | 88.9 |
| Dec 1999-May 2000 | 212 | 150 | 14 |
| Overall thermal efficiency, % | 10.2 | 9.8 | 9.7 |
| Plant load factor (monthly average) | 5.3 | 0.8 | 0.2 |
| Outage time (monthly average), h | 0.71 | 0.55 | 0.55 |
| Heat rate, MJ/kWh | 0.71 | 0.55 | 0.55 |
| Fuel-oil support, ml/kWh | 0.71 | 0.55 | 0.55 |
| Specific coal consumption, kg/kWh | 0.71 | 0.55 | 0.55 |
to the management of the ash in coal-fired plants. Its application is quite widespread in the coal production sector, where it is used to control blending operations and in conjunction with CPPs. Its use on coal-fired power plants, however, has been somewhat sporadic, although it has useful applications where emissions limits have to be met by blending low and high sulphur coals. With the increasing pressure on minimising power generation costs, more utilities are looking at and assessing the potential benefits of using online analysis. The subject is discussed in a recent Clean Coal Centre report *Online analysis and coal-fired power plants* (Nalbandian, 2005).

Coal quality and in particular its content of ash-forming materials, is normally monitored by physical sampling and laboratory analysis. The procedures are well established, and were discussed in Section 3.1. They do not provide real-time information to the power plant operator although in many situations where coal quality only changes very gradually, this is not necessarily a serious problem.

For the operator, however, bunker feed monitoring of the coal between the stockpile and the bunkers feeding the pulverisers and hence the burners, could provide early warning of changes and possible problems with the behaviour of the ash. In addition, the online monitoring of the amount of unburnt carbon in the coal ash can give an early warning that combustion conditions are suboptimal.

Online analysis of the ash content of a coal is a reasonably well established technology (Kirchner, 1991; Kirchner and Maude, 1994; Woodward, 2005). However, it involves a considerable amount of technical and management effort to maintain the calibration and accuracy of any individual instrument especially if different coals are being monitored. Some gauges can be used over a conveyor belt, while others involve taking a side-sample, thus introducing another area for error. The method involving prompt gamma neutron activation analysis (PGNAA) provides online elemental analysis. While earlier versions analysed sample streams rather than the full flow on a conveyor, more recently, through- or cross-belt analysers have been developed to try to reduce the cost and complexity of the system.

In three examples quoted by Woodward (2005), power plants have been able to control a coal blend using online analysers. Most analysers used by utilities are for blending to ensure compliance with emissions regulations (Blankinship, 2004).

In one case, the Pacificorp Hunter power plant, in Utah, USA, which has three 440 MWe units, was suffering from an increase in outages and derates caused by a change in coal supply. A nearby mine had been closed, forcing the plant to seek some alternative supplies. The lost generation was traced to increased slagging which was in turn, related to the supply. A nearby mine had been closed, forcing the plant to increase in outages and derates caused by a change in coal source. A Gamma-Metrics CQM analyser was installed on a conveyor supplying a storage barn whose coal served as the bunker feed for the plant (Woodward, 2005).

In this case, ash fusion was closely correlated with the iron and calcium in the coal/mineral matter, and the CQM as an elemental analyser was able to estimate the ash fusion temperature online. Consequently the plant was able to adjust the blend of two different coals to ensure that the ash softening temperature remained above the ‘danger’ point of 1200°C. The online analyser enabled the plant to recover its lost generation capacity, and the investment was reported to have been paid for in a relatively short time (Snider and others, 2004).

### 7.2.2 Online pulverised coal flow measurement

An area where online measurement in a different context might become usable is in the control of the flow of pulverised coal to the individual burners in a coal-fired boiler. There are, however, formidable problems to be overcome before it becomes possible to measure mass flow rates, velocities and particle size distribution, and there is no fully commercial combination of instruments available (DTI, 2001). The particle size distribution is particularly difficult to measure online, although various methods have been investigated. At the moment, the instrumentation available is mainly used to measure the conditions on test rigs, to help clarify some of the mechanisms involved in both char and ash formation. In addition, a number of utilities are attempting to use pulverised coal flow meters to optimise combustion performance. With the introduction of low NOx burners, achieving an even distribution of pulverised coal to the burners has become more important, and development work is continuing (Nalbandian, 2005). The methods of flow splitting after the coal pulverisers where the output from a mill may go to as many as eight burners do not lend themselves to easy measurement and control options. It is more difficult to maintain an even split under conditions of low (or variable) load.

### 7.2.3 Combustion diagnostics

The complete combustion of coal in a utility boiler is a function of three parameters, oxygen amount, temperature and time. If there is sufficient oxygen present, a high enough temperature and long enough time, then the amount of unburnt carbon in the ash will be very small. In a paper by Johnson and Lockert (2005) the role of combustion diagnostics in increasing ash value is discussed. The main thrust of the paper is to highlight what operators can do to maximise profit by controlling combustion conditions in such a way as to maintain the quality of a salable ash product.

This can be facilitated in three different ways:

- by developing an ash specification which allows some changes related to the coal source;
- careful attention to mill maintenance and performance which affects the fineness of the fuel being burned;
- by monitoring and controlling the combustion system performance. Burners that are not performing well need to be identified. This can be done by some of the following methods including measuring NOx and O2 concentrations in the economiser outlet duct. Measuring the fuel flow, primary and secondary airflows, and...
overfire airflow to individual burners and to other ports. Measuring flame quality based on processing flame scanner signals for each burner. Each different approach has its advantages and disadvantages.

Combustion tuning can make an important contribution to the production of a consistently saleable fly ash product. Online analysers that measure flame quality and ash LOI can provide the feedback necessary to coordinate multiple burners and overfire air ports into a well-coordinated combustion system.

Other strategies for maintaining a saleable ash include the separation of higher carbon content particles from those with lower carbon content, possibly by air-based classification. This has been successfully used in Europe. The carbon-rich stream can be sold, landfilled or possibly re-injected into the boiler. Re-injection is a method being investigated and developed, but it is necessary to do it in such a way that the unreacted carbon does actually burn when it is reintroduced.

The majority of coal-fired boilers around the world were built before NOx emissions were regulated. In recent years the emissions limits applied to boilers have moved steadily downwards, forcing, in many cases, major burner modification and changes in the pattern of air distribution. This results in an increased need for a detailed understanding of the combustion process.

### 7.3 Boiler cleaning

The principal method for controlling ash deposition in boilers is to use sootblowers. These apply a thermal shock to the deposit, which may cause it to shrink or crack, or otherwise dislodge – and/or physical force from the jet of air, water or deposit, which may cause it to shrink or crack, or otherwise dislodge. Sootblowers are normally provided, based on previous experience with the coal being used, and may be designed to address specific problems in different parts of the boiler. Traditionally they have been used on the basis of some fixed pattern, such as blowing once (or even twice) during a shift – or with cleaner coals, perhaps just once each day. More efficient and ‘intelligent’ systems are increasingly being used to determine when to operate the sootblowers.

The slagging and fouling characteristics of a coal depend primarily on the mineral constituents of the ash and its tendency to adhere to boiler/tube surfaces. There are many different types of sootblower, and apart from the waterlance described below can use either steam or compressed air. They can generally be described as belonging to one of the following categories:

- **wallblowers**, which are designed to remove slag from the furnace walls. A high-pressure flow is applied through a single nozzle on a short retracting lance inserted just inside the face of the tube wall and rotated once to blow across the wall surface. A typical blower can clean an area which is about 3 m in diameter;

- **waterlances**, which can be used to remove the more tenacious slag that tends to form when firing lower rank coals. The lance tube has two nozzles to direct a concentrated water jet back onto the wall when the lance is inserted. The jets can trace out a spiral cleaning pattern covering a circle that can be as much as 6 m in diameter. The lance will be designed to crack the deposits (using thermal shock) but to do minimal damage to the boiler tube material. The lances have a small nozzle area and require high purity water. They can be damaged if hit by falling slag while inserted inside the boiler;

- **long retractable sootblowers**, which are designed to dislodge fouling deposits in the boiler convective section. They consist of long lances containing two or four nozzles. Between operations, which might be typically once a shift, the lance rests outside the boiler. The lance can reach up to 17 m into the boiler and operate in flue gas temperatures up to 1400°C. Most coal-fired units use these at the entrance to each tube bank in the superheater, reheater and economiser regions. Where the coal has serious fouling potential, many such lances may be installed;

- **rotary sootblowers** are suitable for use at temperatures below 1000°C, and are mainly used in the boiler economiser. They consist of a tubular element with multiple nozzles which remains inside the boiler, and are suitable for removing light ash accumulations (Michael and others, 1997);

- a recent development is the **water canon** which in some cases have replaced water lances, as the water jets can be targeted at specific areas requiring cleaning. These are used in the main boiler combustion chamber and can clean the waterwalls up to the boiler nose arch, and down to the sloped hopper in the base. Four canons, one on each wall, can be directed so that they can clean an entire furnace. A special nozzle produces a water jet which crosses to the opposite furnace wall and impacts on any accumulated slag. The water penetrates the outermost layer of the slag, expands into steam and breaks up the slag, thus detaching it from the surface. Water canons can use (cheaper) filtered water while other devices require demineralised water. Cannons can also clean areas which are not easily fitted with wallblowers or water lances (Breeding, 2002). The key operational issues connected with sootblower use are their location, and the amount that they are used. The main benefit from their use is that the boiler surfaces can remain clean, and heat transfer in each region maximised. However, there is an efficiency penalty when they are used, and as a result, sootblowers should only be used when needed. They can also cause tube erosion and metallurgical deterioration because of repeated heat shock.

Multiple waterlances and retractable sootblowers take up a significant amount of space outside and around the boiler, and require regular maintenance.

Increasingly, sootblower use is being controlled using a combination of heat flux measurements, pendant tube weight measurements and modelling based on boiler parameters and
fuel characteristics (Davidson, 2003; Power Engineering, 2004). These applications have been particularly in the USA, spurred on by the switching from Eastern bituminous coals to Western subbituminous for a number of units, but there were earlier applications in European countries.

The pressures arising from the competitive market in electricity have encouraged generators to look at a variety of approaches for achieving cost reductions. Two relevant methods are:

- to use a lower grade coal which is likely to bring with it increased deposition and erosion, associated with the presence of increased amounts of possibly more problematic ash. The removal of deposits in the boiler then becomes even more important;
- increasing boiler efficiency and reducing metallurgical damage (hence increasing boiler availability) which can be achieved by optimising the use of the sootblowers. A principal advantage of using an ‘intelligent’ cleaning system is a reduction in over-use of the sootblowers.

Optimum boiler operation and performance in supercritical universal pressure boilers is discussed by Piboontum and others (2005). The control of slagging and fouling is often more problematic and complicated in supercritical boilers which are operated in a different way from subcritical natural circulation drum units.

The ‘intelligent’ cleaning system described is based on modelling the behaviour of the heat transfer surfaces, while taking the fuel characteristics and its combustion behaviour into account. It is necessary to model the heating surfaces using real-time cleanliness indexes in order to determine the cleaning cycle. The performance of individual convection pass tube banks is interrelated, so determining the optimum sootblowing programme is based on the overall boiler operating parameters.

At the core of the sootblower optimisation system is the Heat Transfer Manager™ programme. The computer model covers all the main heat transfer areas. Fuel input is calculated from measured boiler output and efficiency. Flue gas weight is calculated stoichiometrically from fuel input and excess air (determined from the measured oxygen in the flue gas). The furnace model calculates the expected Furnace Exit Gas Temperature (FEGT) which can then be compared with the measured value. In the convective section of the boiler the tube banks are modelled in detail, and measured steam/water flows and temperatures can be used in conjunction with the gas temperatures to determine an optimum cleaning pattern.

The experience gained with an ‘intelligent’ sootblowing installation at Homer City, PA, USA is described by Clark and others (2005). The system and its application is shown in Figure 17. This shows the interface between the measurements made of heat flux, of pendant weight and of the boiler parameters, and the boiler model with the Intelligent Soot Blowing (ISB) algorithm. It also shows which areas of the boiler are affected and controlled by different parts of the system, and by the different sootblowers.

**Case study Louisa unit 1**

The unit at Louisa, Iowa, USA has a subcritical boiler supplied by Babcock and Wilcox, with a capacity of 680 MWe. It burns western subbituminous coal, and was commissioned in 1983. In general, the unit has had a satisfactory operating history, with good availability. No major upgrades or equipment replacements have been needed so far.

In 1999 a unit performance and heating surface cleanliness study was carried out to determine the cause of an increasing FEGT. Based on the results, changes in the sootblowing regime were implemented, including more frequent blowing of the vertical surfaces and less blowing on horizontal surfaces. An upgrade to install some waterlances to clean the lower side of the upper nose arch was carried out in 2003. This was based on a unit evaluation using Diamond Power’s thermography technology.

The Babcock Powerclean system is based on boiler modelling. The Heat Transfer Manager™ (HTM) programme is derived from historic operating data and draws on the experience of operators. It includes the information needed for calculating total boiler output as well as the heat absorption of each boiler section. In a typical installation, the HTM model consists of the:

- furnace;
- furnace platens;
- primary superheater;
- secondary superheater;
- reheater;
- economiser.

Fuel input is calculated from measured boiler output and efficiency. Flue gas weight is calculated stoichiometrically from fuel input and excess air, which is determined from the measured oxygen content in the flue gas. The HTM model results provides the critical boiler performance and heating surface data used by the Powerclean module in determining the strategies which guide sootblowing.

When the system had been fully implemented, better targeting resulted in less total blowing, the economiser gas exit temperature has trended downwards, and the reheate spray flow has been reduced. These are reflected in improved overall efficiency and reduced heat rate, and it is estimated that the intelligent sootblowing has resulted in operational savings of about 250,000 US$/y (Narkoneczny and others, 2004).

**Case study Neideraussem 600 MWe lignite-fired unit in Germany**

Unit G at Neideraussem is a tower boiler which was commissioned in 1974. A number of modifications have been carried out to optimise combustion and to reduce emissions. One of these was in 1998 with the installation of 14 water canons to replace 72 wall deslaggers.

To cope with variations in the lignite fuel, the operation of the water canons is controlled using the data from a series of heat flux sensors. These are located in the boiler wall tubes.
where a short section of approximately 400 mm is replaced as shown in Figure 18. Steam/water flows through the sensor tube section, and it is inserted to ensure that there is a controlled low pressure drop through it. The measuring element is arranged in such a way that there are no protruding edges on which deposits might form preferentially.

Operation of the optimised cleaning system means that more heat transfer takes place in the main part of the boiler, resulting in:
- a reduction in the FEGT which may then ensure that the ash remains below its fusion temperature;
- a reduction in the fouling of the convective sections of the boiler associated with the lower FEGT;
- a reduction in the attemporator spray rates for the reheater;
- a reduced boiler exit temperature, and increased boiler efficiency.

Case study – quantifying increased profitability
Such control systems involve significant capital and operating cost, as well as staff retraining. They are also dependent on how effective the heat flux measurements are, which will be affected by the specific ash properties in the areas where the heat flux sensors are sited. There is the potential for considerable operating cost savings, and it seems likely that these systems will be more widely used in the future. In an example quoted in Power Engineering (2004) for a 25-year old tangentially-fired 800 MWe boiler, it was reported that while the potential profit from the unit was US$47 million per year, it was netting only some US$29 million per year. Using an ‘intelligent’ boiler cleaning programme, enabled the unit to achieve an increase in its operating profit by nearly US$10 million per year. This was split between:
- NOx credits, 29%, as it was easier to maintain NOx compliance. Improved furnace heat transfer reduces NOx formation;
- this resulted in SCR O&M cost savings, 6%;
- maintaining a lower FEGT because with a cleaner furnace, more of the heat is transferred in the main combustion zone before the furnace exit, 29%;
- the need for less attempetration, meaning that less water treatment is needed, 5%;

Figure 17 Intelligent Sootblowing control structure and the location of blowers and sensors (Clark and others, 2005; Wicker, 2005)
7.4 Modelling coal quality impacts

Data from coal-fired power plants in the USA have demonstrated that burning a fuel that is consistently within the design specification translates into better plant reliability, efficiency and capability for meeting the day to day load requirements (Cole and Frank, 2004).

Many of the larger generating companies and organisations have their own in-house programmes and procedures for assessing the economic impact of coal quality variations on their operations. Traditionally and historically, there has always been a specification set for the quality of the coal to be used in an individual boiler. When the use of a new coal has been considered, pilot scale testing has been carried out to assess whether or not there is a significant risk of increased slagging, fouling, erosion or corrosion. Sometimes, if there is a need or a considerable price advantage, the ‘testing’ has been carried out in the boiler itself. Occasionally, this has resulted in significant operational problems and loss of output.

Logistical issues

Coal switching has led to the need for upgrading the coal stockyard in a number of plants. It may involve the need for new stockpiles and stacker-reclaimer systems. Older conveyors and equipment have needed rehabilitation, to become more efficient and reliable. Existing coal handling facilities have also needed upgrading to accommodate blending schemes. For example in the USA, belt conveyor capacity needs differ for eastern bituminous coal and for western PRB subbituminous coal. Eastern bituminous coal, for example, has a density of about 800 kg/m³ and an angle of repose of 25° while western PRB coal has a density of about 720 kg/m³ and an angle of repose of only 20°.

While these differences may seem quite modest, the fuel change may result in increased horsepower requirements as not only is the coal density different, but because of its lower heating value, a significantly higher tonnage is needed for a given unit output. The changes needed are discussed by McCartney (2005) in an article which includes four case studies.

7.4.1 Coal Quality Expert

During the 1990s, the US DOE supported the development of a versatile software tool called the Coal Quality Expert CQE™. This was to enable utilities, coal producers and equipment manufacturers to analyse the impacts of coal quality, operational changes and/or environmental compliance alternatives on power plant production costs, performance, and emissions. The model facilitated the assessment of possible capital expenditures to improve performance, and of different strategies to meet emissions requirements (NETL, 2000).

The project scope included the collection and analysis of data to form the basis of the CQE™ algorithms, methodologies and submodels – and to verify the accuracy and integrity of the software. The boiler field tests were correlated with the EPRI Coal Quality Impact Model (CQIM) predictions. The CQE™ was distributed to about twenty-five utilities. It can predict power plant performance with a minimum number of bench-scale tests which means that assessments can be made at lower cost than using traditional approaches. Users have to balance these savings against the cost of the software license. While EPRI members received the model as part of their dues, outside firms have to pay a relatively high purchase price. In addition, the software is written for the OS/2 operating system, which creates a barrier if people are not familiar with its use.

The CQE™ undoubtedly demonstrated the viability of the use of models in conjunction with coal analysis and small-scale testing, and as a result, many of the larger companies have developed their own in-house methods and procedures.
The CQIM was assessed for use in connection with Australian coals by the Australian Coal Association Research Programme (ACARP). In a report on its application, it was concluded that its use could reduce the possible errors arising from other empirical correlations by using the known performance when using one coal to predict that of other coals fired in the same unit. Some detailed limitations were described, such as a failure to predict the heat absorption by the waterwall at the Earing plant because of the unusually low ash absorptivity. Care needs to be taken in the choice of the evaluation/base-line coal. The model was, however, able to usefully relate coal quality to fuel costs, maintenance costs and availability of a power station, and ACARP was recommended to maintain a ‘watching brief’ on the performance of later versions (Bennett and Conroy, 1997).

### 7.4.2 Benchmarking indices

The operating cost profile of a coal-fired power plant reflects, among other things, the quality of the fuel it burns. Across a fleet of units operated by a power generation utility, ways of assessing which unit can most profitably be used at any one time are needed.

Aside from wear-related replacements, most changes today are motivated by:

- the value of the power produced at different times of the day, and by the incentives provided by the wholesale market;
- environmental compliance requirements;
- potential new sources of revenue from generating emission credits.

Some utilities will be able to choose between generating the power using different fuels, although the flexibility of the transmission network and plant availability may restrict the choice. Within the coal-fired units in the fleet, the costs associated with meeting demand need to be minimised by selecting the lowest-cost option. With so many variables affecting the overall costs, this has become an increasingly difficult exercise – and most utilities have developed models which provide appropriate guidance for decision making. The coal properties, and in particular the behaviour of the ash will have a considerable impact on these costs although in some situations, other factors will dominate.

Benchmarking studies reported by Solomon Associates in *Power Engineering* are based on industry data collected over a number of years. This covers a wide range of unit sizes, locations, coal qualities, technologies and operational patterns. A proprietary performance measurement methodology called Equivalent Generation Complexity (EGC) is used. The data reflect changes in controllable costs, unit configuration, fuel cost and operating pattern (Jones and Patefield, 2005).

Using the EGC data, the operating expenses less the fuel cost are calculated for a 700 MWe unit firing coals with different ash contents, see Figure 19. While the costs associated with using coals of different qualities are generally reasonably well known, the inflection point on the graph illustrates the level of operation where plant utilisation becomes increasingly cost-ineffective. The overall cost of using a higher ash coal increases because although the cost/tonne will be lower, so is the heating value, and any cost reduction is outweighed by the increased operating costs (both short and long-term) associated with slagging, fouling, corrosion and erosion in the boiler, and of solids handling and removal associated with the greater ash volume.

### 7.4.3 The integrated model used at the Didcot power plant, UK

The kind of operational flexibility required in a competitive market is illustrated by the experience gained by RWEnpower at the Didcot power station in the UK. The Didcot A plant has four 500 MWe coal-fired units dating from the 1970s. They were designed to operate on base load, with a fairly inflexible coal specification relating to coals supplied from the UK Coal Board’s Midlands area.

After the country’s nuclear plants came online supplying much of the baseload, the Didcot units were aggressively cycled, to meet fluctuating loads. Three of the units were converted for dual-firing with natural gas, to meet increasingly stringent environmental regulations. Before privatisation, there were some 750 staff at Didcot A.

In order to cope with coals supplied from all over the world, Didcot now has a combustion test facility, which is particularly important now that the units all have low NOx burners. It can also assess the slagging and fouling potential of any new coal before it is used, and various factors associated with ash management. The coals come from South Africa, the USA, Poland, Russia and Australia. Most have a
Ash management in coal-fired power plants

The Didcot station has averaged over 600 starts per year; both fly ash and bottom-ash recovery systems were installed to reduce stacking/stocking costs; vacuum retention in the condenser; steam turbines were enhanced with new low-pressure blading and upgraded diaphragms, along with better vacuum retention in the condenser; the boiler start-up fuel was changed from light oil to heavy fuel oil and burner capacity was increased – to reduce costs; boiler steam headers were modified to improve the flexibility of the steam system; the direct feeding of coal from rail to bunker was installed to reduce stacking/stocking costs; both fly ash and bottom-ash recovery systems were upgraded. The materials were assessed and marketed, turning a costly residue into a revenue-making stream.

The outcome is that plant operators are able to make decisions based not only on technical data, but on real-time financial data. The decision to generate is based on the income stream calculated and the costs involved in ‘flexing’ the plant to meet demand. The system is intended to enable the company to produce the maximum amount of power when it is most profitable to do so.

Didcot’s integrated load-management software maintains performance in real-time. Electronic dispatch and logging software allow staff to accept or reject dispatch instructions for real and reactive power, along with ancillary services – such as automated control, voltage support and frequency response. Many equipment modifications went towards increasing operating flexibility and profit-making potential, without sacrificing other goals – such as emissions limitations.

For example:
- SO\(_3\)-injection systems are used;
- high performance classifiers and fixed-speed primary air fans were installed on the pulverisers. The mill grinding geometry was modified to maintain boiler performance under strict NO\(_x\) emission rules, and using a variety of coals;
- steam turbines were enhanced with new low-pressure blading and upgraded diaphragms, along with better vacuum retention in the condenser;
- the boiler start-up fuel was changed from light oil to heavy fuel oil and burner capacity was increased – to reduce costs;
- boiler steam headers were modified to improve the flexibility of the steam system;
- the direct feeding of coal from rail to bunker was installed to reduce stacking/stocking costs;
- both fly ash and bottom-ash recovery systems were upgraded. The materials were assessed and marketed, turning a costly residue into a revenue-making stream.

The Didcot station has averaged over 600 starts per year since 1980, and the staffing level has been reduced to around 250. Investments in the plant are based on a comprehensive business risk assessment. All equipment modifications requested by plant engineers are evaluated using a one to ten ranking, determined by market considerations. This is intended to keep the plant from being ‘gold-plated’ while fulfilling the investment needs that result from residual life expenditure, basic repair work, and modifications and upgrades (Power, 2002).

### 7.5 Data interpretation and use

One interesting approach to data analysis is described in a paper by Kusiak and Burns (2005). They present a case study which looked at a commercial 750 MW\(_e\) coal-fired boiler with tangential burners. The unit suffered from a fouling problem which led to pluggage in the reheater section, causing unscheduled shut-downs several times a year after a period of enforced derating. Boiler cleaning took 1–3 days. There was no obvious single parameter causing the blockages, and with a superficial analysis, all the parameters seemed to be within specification.

To investigate the problem, data were collected on 173 different boiler parameters. These included flows, pressures, temperatures, controls, and demands. They were collected at one minute intervals during a three month period following a shut-down and clean-up. Mathematical and statistical approaches such as correlation and multivariate analysis were used to reduce the list of parameters thought to be having an impact to 26.

Time windows which were set to be approximately a week long were established. The initial step was to determine the approximate date for the failure event which was defined as when the boiler was derated due to the pluggage. Over the whole three-month period, the data set contained more than 168,000 observations, and the time window of a week provided over 10,000 observations for the data extraction algorithms.

As a result of the analysis, using statistics, data partitioning, parameter reduction and data extraction, the ‘rare-event detection approach’ identified several critical time-based segments that are indicative of ash pluggage. As a result an intelligent advance warning system is being developed which should reduce the number of boiler shut-downs, and thus reduce costs – although an overall assessment must also take into account the cost of making the measurements and their analysis.

The method involves what is described as ‘data-mining’, but because of the potential confusion with the mining/extraction of coal, the term ‘data extraction’ is used here.

### 7.6 Ash refining

Detailed work has been undertaken in the UK in an assessment of ash refining (Riley and others, 2005). The background to the project was that tighter emissions standards have meant fitting low NO\(_x\) burners to coal-fired plants and using lower sulphur content coals. In addition there have been changes in the electricity market, requiring generating plants to operate more flexibly.

The use of low NO\(_x\) burners has resulted in a reduced low sulphur content, so that FGD is not needed. The coal ash formed will be markedly different.

In addition, there is a comprehensive control and information system which is intimately tied-in with optimising the benefit to the company from electricity trading. Modules on the controlling computer include:
- online data gathering on all the main plant parameters, and their analysis;
- integrated load control;
- a start-up manager;
- a boiler fouling manager;
- chemical diagnostics;
- analysis of the cost of losses;
- electronic data loggers.

When it is most profitable to do so, the company to produce the maximum amount of power for real and reactive power, along with ancillary services – such as automated control, voltage support and frequency response. Many equipment modifications went towards increasing operating flexibility and profit-making potential, without sacrificing other goals – such as emissions limitations.

For example:
- SO\(_3\)-injection systems are used;
- high performance classifiers and fixed-speed primary air fans were installed on the pulverisers. The mill grinding geometry was modified to maintain boiler performance under strict NO\(_x\) emission rules, and using a variety of coals;
- steam turbines were enhanced with new low-pressure blading and upgraded diaphragms, along with better vacuum retention in the condenser;
- the boiler start-up fuel was changed from light oil to heavy fuel oil and burner capacity was increased – to reduce costs;
- boiler steam headers were modified to improve the flexibility of the steam system;
- the direct feeding of coal from rail to bunker was installed to reduce stacking/stocking costs;
- both fly ash and bottom-ash recovery systems were upgraded. The materials were assessed and marketed, turning a costly residue into a revenue-making stream.

The Didcot station has averaged over 600 starts per year since 1980, and the staffing level has been reduced to around 250. Investments in the plant are based on a comprehensive business risk assessment. All equipment modifications requested by plant engineers are evaluated using a one to ten ranking, determined by market considerations. This is intended to keep the plant from being ‘gold-plated’ while fulfilling the investment needs that result from residual life expenditure, basic repair work, and modifications and upgrades (Power, 2002).
amount of bottom ash and an equivalent increase in the amount of fly ash going through the ESP. In addition, low NOx combustion has resulted in higher levels of carbon-in-ash which adversely affects ESP performance as well as making the ash less saleable. These effects are thought to be the result of the lower flame temperatures associated with low NOx burners, and the wider prevalence of reducing conditions.

Large-scale trials have been carried out at the Didcot power plant in the UK, owned by RWEnpower. The unit used has a capacity of 500 MWe. Ash addition to the coal feed was carried out at levels of 5% and 10%. Neither addition rate caused any operational problems. Using South African coal at the 5% addition rate meant that seven mills were required to maintain full load output compared with only six when operating on coal only.

The refiring of ash at an addition rate of 5% appears from the study to be both technically and financially viable. Addition rates of over 10% had a significant adverse effect on NOx levels; and at the 10% addition rate, emissions were higher and it was necessary to reduce the overall plant output by 2%. Because of the additional carbon fed to the boiler, coal usage is reduced.

7.7 The effect of ash variation

Economic pressures, market liberalisation and increasingly stringent emissions regulations have forced many power plant operators to diversify their fuel sources (ie to use different coals) and to modify the combustion conditions. This can result in sharp changes in the ash characteristics, possibly making the product unsaleable. This could be because of unacceptable amounts of unburnt carbon and/or the presence of other undesirable contaminants. The financial difference to the plant’s accounts between selling the ash and having to dispose of it could be several million dollars per year. For inner-city generating stations the cost of landfill for the ash can become a major market driver. Fortunately, as discussed in Chapter 9, fly ash is a desirable component in the manufacture of ready mix concrete, as a soil stabilisation additive and as a flowable fill component. From the ash users viewpoint, a vital characteristic of the product is consistency. Ash needs to be the same, chemically and physically, each and every day.

When the coal feed to a boiler has variable characteristics, and its ash content and composition changes with time it is much more difficult to optimise the boiler operating conditions and to achieve optimum efficiency.

7.7.1 On an existing plant – case study

In recent years, a significant change in the characteristics of the lignite used in the power plants in the Rhenish region of Germany took place when the Hambach pit opened. The supply from Hambach is gradually replacing that from other worked-out deposits. There is some 10,000 MWe of installed lignite-fired capacity in the area, with units of 150,300 and 600 MWe capacity, most of which went into service between the mid-1950s and mid-70s.

The Hambach coal has a higher LHV than the lignites from the older pits, and a low ash content at around 3–3.5%. The ash has higher iron and alkaline content, resulting in a lower ash fusion temperature. As a direct result of the increased heating value, when the new coal was used, the combustion temperature increased with the result that the FEGT rose. The combination of higher temperatures and the change in ash fusion temperature resulted in the deposition of a tenacious slag on the superheater, and increased fouling in the convective section. The boiler outlet gas temperature rose, and these effects caused a loss of overall thermal efficiency (Tippkötter and others, 2003).

7.7.2 On new build

In a paper which discusses future requirements in the USA for clean and efficient supercritical PCC plants, a comparison is made relating to the use of different coals (Baumgartner and others, 2005).

The three most commonly used coal types in the USA are PRB subbituminous, and Illinois and Eastern/Appalachian bituminous, some of which is high in sulphur content. It is said that US coals do not present significantly greater challenges in the design of the furnace for a once-through ultra-supercritical boiler than for a conventional natural circulation drum boiler.

Low carbon-in-ash values should be readily obtained. Slagging, however, is an issue with all the coals owing to their potentially high iron and/or calcium content, and this is a major factor affecting furnace sizing. Adequate burner-to-sidewall clearance is needed, with enough depth for flame development, to prevent flame impingement and excessive slag deposition on the furnace walls. The provision of sufficient radiant heat transfer surface in the boiler ensures that the temperature of the flue gas entering the convective sections in the rear pass is below the Initial Deformation Temperature of the ash.

A furnace designed to fire PRB coals needs to be somewhat larger, to account for the reflective nature of the ash which reduces the effectiveness of heat transfer to the walls.

Other measures to minimise the effects of slag formation include the provision of membraned tips on the superheater platen to minimise distortion and help prevent large slag build-ups. Water cannons, discussed in Section 7.4, are recommended in each wall to control build-up, and these can even deal with the glassy deposits formed when using PRB coal. The cannons also provide more homogeneous cleaning, resulting in more even temperatures and heat transfer while the potential for tube erosion is reduced.
FBC is used in two formats, BFBC, generally for smaller applications, and CFBC for larger ones. The differences are discussed in the IEA Clean Coal Centre report *Understanding fluidised bed combustion* (Wu, 2003).

CFBC is often the most appropriate technology for using coals with properties which make them unattractive for use in large PCC boilers. They include in particular:

- low rank (and other) coals with variable properties as-mined;
- low volatile coals with a high ash content;
- some high sulphur content coals;
- some coals with a high ash content which is difficult to mill.

CFBC can also be appropriate where it is required to cofire coal with other fuels, including petcoke, sewage sludge and biomass. The low combustion temperature and relatively forgiving conditions mean that co combustion can be easier in an FBC unit than in a PCC one. *Fuels for biomass cofiring* is an IEA Clean Coal Centre report (Fernando, 2005) in which some of the issues are discussed. Cocombustion affects the ash properties and behaviour as well as the uses that can be found for it.

CFBC boilers have been successfully built and operated to burn:

- Polish brown coal at Turów;
- low volatile, high ash content coals in China and South Korea;
- previously discarded coal washery wastes in the USA;
- a high sulphur low grade coal in France.

Currently the biggest CFBC boilers are in the 250–300 MWe size range, although a 460 MWe supercritical unit is under construction in Poland. While there are designs for larger CFBC boilers, up to 600 MWe size, none have been built or operated as yet.

The three key advantages of FBC in both its formats are:

- the facility for injecting limestone directly into the bed for sulphur capture which eliminates the need for a costly FGD unit;
- low NOx formation because of the low combustion temperature, which eliminates the need for NOx removal in many places;
- the virtual elimination of ash deposition problems during operation.

With high-ash coals there may be problems with erosion. Sulphur capture in the bed can be more than 80%. While this is considerably less than that in wet FGD, it can nonetheless be perfectly adequate to meet local emissions regulations. In the bed, the limestone particles calcine from a low porosity solid to form CaO which has a porous structure. As the CaO comes into contact with the SO$_2$ present, CaSO$_4$ is formed which blocks the pores. As a result, utilisation of the limestone is only some 20–40%, and the ash has a significant CaO content.

Since for FBC the feed coal is only ground to a size between 6 and 3 mm size, larger mineral matter particles or agglomerations remain intact, and are largely unaffected by the combustion process. The FBC ash is therefore likely to include more coarser particles. In a BFBC unit, there is an identifiable bed of fluidised particles, with a freeboard space above it. Because many of the volatiles burn in the freeboard, its temperature is often higher than that in the bed itself (Oka, 2004), and this will affect ash behaviour, particularly if there is a tendency for ash agglomeration. At the higher temperatures in the freeboard, ash components may soften and become sticky causing operational problems if particle agglomeration takes place.

Since FBC is often the preferred technology for use with coals which have a high ash content, there is sometimes a problem with the residual carbon-in-ash content which is too high for some uses. One solution to this problem for smaller BFBC boilers is presented in the example below.

**Example – reducing the carbon-in-ash when using high ash Indian coals**

The level of carbon-in-ash in the fly ash from small BFBC boilers firing high ash Indian coals is commonly in the range of 6–15%. For application in the cement industry, many producers prefer an ash with less than 5% unburnt carbon since this improves the cement quality.

Low levels of unburnt carbon in the ash has been achieved by:

- having a taller freeboard to increase residence time;
- refractory lining the waterwall tubes to retain a higher flue gas temperature in the freeboard zone;
- providing overfire air;
- improving the burner design; and,
- reinjecting some of the fly ash (Selvakumaran and others, 2004).
As discussed in the earlier chapters of this report, ash production is increasing worldwide, particularly in China and India. There are increasing pressures to reduce the amount of combustion residues which are dumped in landfill. In some countries, either ponding or landfill are becoming increasingly expensive, and in a few places, like the Netherlands, legislation has forced power generators to ensure the utilisation of all the ash.

In the past, a great deal of ash was disposed of in ponds where it would settle, and the water used to transport it would decant off the top of the pond, possibly for reuse. Now it is more common for the ash collected in ESPs or fabric filters to be transported pneumatically to a holding silo. Bottom ash and slag may still be quenched in a water tank under the boiler, since it is at very high temperature compared with the fly ash collected. It may then be crushed and dried.

### The desirable properties for ash use

The highly variable chemical and physical nature of the ashes arising from coal combustion are a major barrier to their use (Rostam-Abadi and others, 1996). While this study is focused on the ashes arising from PCC, there are significant differences between bottom ash and fly ash, and between the ashes formed from low rank and high rank coals. In the USA there are different ASTM specifications for Class C fly ash normally produced from lignite or subbituminous coal and Class F fly ash normally produced from anthracite or bituminous coal.

Care must be taken in relation to ash use when using different coals in a PCC boiler. Some units, of course, are supplied from local mines where the nature of the coal can become well understood. Others may use coals that are traded, and depending on the market, may burn a range of coals. Perhaps the most prominent example of a change in coal properties is the increase in the use of western subbituminous coals in the USA. This is based primarily on its low sulphur content, although it is also competitively priced, and widely available. The amount and possible value of the ash is one factor to be taken into account when assessing the overall cost/benefit of using a different coal in a PCC boiler, although it will probably only make a marginal difference to any costings. It becomes more significant when a market for any ash has been established – with certain quality parameters to meet.

While a great deal of the world’s coal ash is dumped as land fill or in settling ponds, there is increasing pressure to make constructive use of this material. This is because significant land areas are needed to store/hold the ash, and because of the risks associated with the possible leaching of unwanted ash components into the surrounding groundwaters.

High volume markets include use for:
- cement and concrete;
- soil stabilisation;
- structural fill;
- backfill in mines;
- agriculture.

Fly ash is commonly a pozzolana, which is a material that reacts with lime to form a hardened mass. The use of ash in cement and concrete is discussed in the IEA Clean Coal Centre report *Cement and concrete – benefits and barriers in coal ash utilisation* (Smith, 2005a). Other uses are assessed in *Land uses of coal fly ash – benefits and barriers* (Smith, 2005b).

One of the key parameters which affects many of the applications is the amount of residual carbon left in the fly ash. This is measured by the Loss On Ignition (LOI) value. For many grades of cement, the maximum allowable LOI is 5%, while for some markets, the maximum is 3% (Ciccu and others, 1999). A factor which is having an impact on LOI values is the increasing emphasis on reducing NOx levels in the flue gases by controlling the amount of excess air locally available. This tends to result in higher residual carbon amounts in the fly ashes formed.

The principal component of many/most fly ashes is clays which have melted and become glassy, reflecting the dominance of clays amongst the minerals in coal. In the UK, the predominant elements are silicon, aluminium and iron (Barnes and Sear, 2004). The chemical and mineralogical composition of the resultant fly ashes are the key fundamental properties which determine whether and how they may be processed to provide useful products.

For possible agricultural use, fly ash is poor in both nitrogen, and available phosphorous. It is, however, rich in some valuable elements. Most fly ashes have high salinity and alkalinity (pH 8.5–12.5) with water, but high sulphur coals or those low in alkalis can be acidic (with a pH 6.0–6.7). The properties depend on the parent coal, combustion conditions and final handling method.

In the IEA Clean Coal Centre report *Trends in the use of coal ash* (Sloss, 1999), barriers to use are discussed. In particular, the classification systems used in many countries are not ideal. Also, a lack of understanding of the fly ash characteristics means that problems relating ash chemistry to performance will remain for some time. This is likely to be exacerbated where different coals or blends are used in a boiler, and where cocombustion with biomass is practised.

Some specifications have been set to ensure the suitability of ash for individual applications, but these tend to have been set too strictly, and sometimes limit ash use unnecessarily.

Probably the most successful step to enhance ash marketability at any plant is to provide storage facilities for dry ash. Dry facilities avoid the wastage of ash in lagoons or ponds while facilitating a consistent supply through the year despite seasonal variation in ash production. It is also possible to provide different storages for ashes segregated by...
size and/or other parameters, allowing the sale of ash for more specialised and profitable applications. This has been done successfully in countries such as Denmark, Germany and the Netherlands.

Beneficiation
The ash produced from coal combustion systems which is not suitable for construction applications can be processed to enhance its marketability. Various beneficiation methods are available such as blending, sieving, grinding, carbon burn-out (possibly by recycling through the boiler), electrostatic separation and various chemical treatments. All, of course, involve a cost, and some beneficiation methods would only be justified if the product had quite a high value. However, as disposal costs more and more, as it will tend to do, beneficiation and usage will increasingly be the better option.

A review of practice in the USA by Groppo and others (2004) concluded that the amount of ash utilised could be significantly increased. Beneficiation has the objective of improving the raw material properties to increase their usefulness.

The most common market for bottom ash is as a lightweight aggregate in concrete masonry units. The first commercial-scale bottom ash beneficiation system was at the Winyah power plant in South Carolina, and has the capacity to produce 200,000 t/y of lightweight aggregate. Since then, several other plants have been installed. A limiting quality issue is the presence of pyrite in the bottom ash, and there can be a significant amount particularly where the pulveriser rejects (high in pyrite) are co-disposed of with the bottom ash.

For beneficiation, bottom ash can be screened, either wet or dry to select the sizes most appropriate to a particular application. After wet screening there is then the possibility of further separation based on particle density using either spirals or jigs (similar to those used on CPPs). For dry separations, air classification is perhaps the simplest option, and is used for removing the coarser particles.

Some ash separation and beneficiation can be achieved using electrostatic forces, similar to those used in ESPs. This may be used to prepare higher value products suitable for ceramic or refractory applications.

Thermal processing can be used to reduce the level of unburnt carbon. In a fluidised bed unit, once the bed temperature has reached the auto-ignition temperature of the residual carbon (at around 450–460°C), little or no additional fuel will be needed.

The most significant use for fly ash is as a mineral admixture in Portland cement concrete, and this accounted for 56% of the fly ash utilised in the USA in 2001.

9.1 Ash use in Australia
In the early 1990s, the Ash Development Association of Australia was formed to conduct research, to promote technology transfer and to develop market opportunities. In 2002, some 12.5 Mt of ash was produced in Australasia (Australia and New Zealand). From that total, some 4.1 Mt was effectively utilised. The main applications were:
- for cementitious applications, 1.35 Mt;
- for non-cementitious applications 0.47 Mt; and,
- the balance of 2.28 Mt in projects such as mine site remediation and road construction (Heidrich, 2003).

A wide range of ashes is produced, depending on the coal type and source, and the boiler type and age. For example, the brown coals fired in the Latrobe Valley power plants in Victoria produce ashes with very different characteristics from those from the black coals in Queensland or New South Wales. The brown coals generally have a low ash content, whereas the black coal used is generally the lower grade material from the CPP from which the high quality coal is exported. It can therefore have an ash content of 25–35%.

What this means is that something like 90% of the ash comes from hard/black coal combustion and consists mainly of silica and alumina. The fly ashes are light to mid-grey in colour, are irregular to spherical in shape, and particle sizes range from less than 1 to 200 µm.

9.2 Fly ash use in China
The mineralogy and geochemistry of Chinese fly ashes is discussed by Koukouzas and others (2005). The sample used for test came from Hebei Province. The Chinese fly ash is said to be rich in mullite and can be used for brick making. Fly ashes are widely used when blended into concrete and sand slurry in the construction industry, and as a base material for road construction.

There are considerable social, environmental and economic benefits from the utilisation of fly ash in China, not least because the quantities involved are huge. Substantial quantities are used when building new roads. Around 15 Mt of fly ash has been used in the construction of the Three Gorges dam.

It is said that as much as 50% of the fly ash produced is used. However, in 2002 when the amount was about 160 Mt, that means that 80 Mt/y was being held in ponds or dumped on the land. With the sharp increase in coal production and use in China during the past five years, this is likely to result in increasing problems. Since the range of coals used in China is very wide, fly ash properties are likely to vary, depending both on the coal and the boiler combustion conditions.

9.3 Fly ash use in Greece
In the same paper, cited above (Koukouzas and others, 2005) the use of the ashes arising from the use of Greek lignite is
also described. These are mainly used in the cement industry replacing cement clinker, and supporting the production of several types of Portland cements. They have also been used in dam construction at the Planatorvryssi dam which acts as the lower reservoir for a pumped storage scheme.

9.4 Fly ash use in India

Because of the high ash content of Indian coals, the production of fly ash is enormous – and is a similar amount to that produced in the USA who produce three times as much coal (see Table 2). In order to find an environmentally safe method for its use and disposal, work has been undertaken to investigate its use as a soil additive for to support agriculture. The movement and effects of trace elements under these conditions has been discussed by Twardowska and others (2003).

Although fly ash is not regarded as a hazardous waste in India, the sheer volume of material generated makes the future highly problematic in this regard. The tests carried out indicated a significant potential increase in crop yield after the application of up to 500 t/ha. However, it is recognised that agricultural use may bring about irreversible water or soil contamination in the long-term. In many countries, including those of the EU, such soil amendment is banned.

As most test work has been carried out with freshly generated fly ash which is alkaline and non-weathered vitrified material. For fly ash which has been stored, its properties are different. Some of the unwanted elements have already been washed out — and the material may be more benign in terms of its agricultural use. Further extensive studies are needed to establish the conditions for safe application, but there is a strong incentive to undertake this work.

9.5 Fly ash use in the USA

Just over 70 Mt/y of fly ash is produced each year in the USA. Much of this is either cementitious (referred to as Class C) or pozzolanic (referred to as Class F) when meeting the appropriate ASTM C618 specifications. A minimum of 50% is set for the content of SiO₂, Al₂O₃ and Fe₂O₃ in Class C, and 70% for Class F.

Generally, pozzolanic ash results from burning bituminous coal and cementitious ash from burning subbituminous coal. However, lignite and/or brown coals, can produce an ash that may range from cementitious to pozzolanic. In most cases, the fly ashes from lower rank coals contain greater quantities of CaO, MgO and SO₃. In recent times, many utilities have switched from using higher sulphur eastern coals to burning low sulphur western coals, creating several marketing challenges in connection with the by-products.

When Class F ash has been widely used, Class C ash can difficult to introduce as a substitute. In some cases end-users and specifiers require that applications be studied and proven. Concerns over alkali-silica-reactivity (ASR) may hamper the use of Class C ash in settings where this is a concern. Class F ash is becoming harder to find in some places, occasionally forcing distributors to allocate their supplies during the construction season. When in scarce supply, Class F ash can command higher prices allowing it to be used and transported long distances away from the plant where it is produced.

The primary uses for fly ash meeting ASTM standards are in concrete, concrete products and in grout. Significant quantities of fly ash not meeting ASTM requirements are used as raw feed in cement production, in soil amendments, for waste stabilisation, mine backfills, land reclamation, and in structural fills and embankments. Lesser quantities are used in specialty applications. As larger quantities of non-concrete quality ash are produced in the future, industry must find alternative uses. The greatest opportunities are reclamation, mine backfills, structural fills and embankments (Goss, 2006).

Figure 20 shows the growth in ash production from 1966 onwards. It grew quickly up to about 1980, but since that time has increased by only a relatively small amount. By contrast, Figure 21 which shows the change in CCB use shows that this has nearly doubled since 1990. It also shows (by difference) that a substantial amount of fly ash still needs to be dumped.

In terms of restoration, the combination of fly ashes with other industrial by-products such as sewage sludge and biosolids can result in a restorative material which can be applied to eroding soils that require stabilisation. The application of fly ash to soils has been shown to improve its physical quality by introducing different size particles which can enhance the water-holding capacity of sandy soils and improve the drainage in clay soils. However, the presence of various potentially toxic trace elements can limit the amounts which can safely be used. Between 1966 and 2000 the proportion of fly ash reused increased from 6 to 29% which represents an increase of approximately 0.5 Mt/y (Punshon and others, 2003).

With the Clean Air Interstate Rule and Clean Air Mercury Rule, both promulgated in 2005, US utilities will be required to add emission control systems within the next 12 years that could impact fly ash quality. Wet or dry scrubbing systems and various mercury capture technologies have potential to render current ASTM quality fly ash unsuitable for concrete. The decision as to which types of control systems will be added will be made by each individual plant owner based on factors such as boiler design, fuel type, cost, commitment to maintaining ash sales, availability of land for disposal, and general operating conditions for each unit. Changes to the nature of the ash formed need to be taken into account. No one decision will apply to all facilities. A number of organisations are engaged in technology development and research to restore ash quality by mitigating the potential impact of new control systems. Additives to mask the impact of carbon added to flue gases for mercury capture or the use of pre-combustion processes could lessen the negative impact on fly ash. Beneficiation systems to process fly ash are gaining favour with many companies.

At the same time as these new systems are planned, many
utilities have announced the intent to construct or are currently constructing new coal-fired units. The majority are expected to be PCC plants, though some utilities are looking at FBC or IGCC applications. The increase in the overall quantity of fly ash produced will create both challenges and opportunities for fly ash utilisation. Technologies are being studied by the Department of Energy, universities, industry, and other researchers to determine beneficial ways to manage the by-products. The environmental impact of these changes as well as of the fly ashes to be used in land applications is being studied extensively. The regulatory community and CCB industry do not want to create adverse impact through poor or improper management practices. In some cases, fly ash will continue to be disposed of until technically sound, environmentally responsible and economically viable beneficial uses are found (Goss, 2006).

Figure 20  Ash production in the USA 1996-2004 (ACAA, 2005)

Figure 21  Ash use in the USA 1996-2006 (ACAA, 2005)
9.6 CCB use in the construction industry in Europe

Most of the CCBs produced in Europe are used in the construction industry and in underground mining, see Figure 22. The first chart represents the overall production of CCBs in the fifteen countries of the EU. The second shows the usage of CCBs, of which 68% is fly ash (44 Mt). Only some 4% is disposed of, together with 8% which is temporarily stockpiled. The third chart shows the utilisation of fly ash in the construction industry (Berg and Feuerborn, 2005).

Approximately half the fly ash in Europe comes from power plants using brown coals. Most is used as an additive to concrete, in road construction and as a raw material for cement clinker production.

9.7 CFBC ashes

Because CFBC units use different kinds of coal, and the ash/residue most commonly contains both CaO and CaSO4, the ash characteristics are quite variable. This variability has obvious effects on the applicability of existing standards relating to the marketing and utilisation of the ash, or of its disposal.

The FBC ashes normally comprise a mixture of the coal mineral matter (largely unaltered), unreacted lime and limestone, together with the sulphate arising from the sulphation reaction. Since the coal is not pulverised before combustion, the minerals in the ash are often much more granular than they are in PCC ash. In addition, ash disposal presents more of a problem for a CFBC ash than for PCC fly ash, as it contains water soluble components, in particular the CaO and CaSO4. There is a danger of material leaching from an ash dump which might contaminate local ground waters if proper precautions are not taken.

If SO2 removal is not required, then the ash formed is more benign, and disposal is much less of a problem. In terms of ash use, because of its variability, uses have to be sought on a local basis.

In the fifteen countries of the EU, the amount of FBC ash produced in 2003 was about 1 Mt. Out of this, 0.5 Mt were used in the construction industry and for mining purposes. A breakdown of the utilisation of these ashes is shown in Figure 23.
10 Conclusions

Today’s power plants are expected to achieve a number of competing objectives, for example:

- providing capacity when it is needed;
- operating efficiently in every way;
- meeting emissions regulations;
- operating safely and reliably;
- minimising overall costs, both short- and long-term.

Many of the operational issues relating to boiler performance are the result of the behaviour of the ash-forming materials. These can form slagging or fouling deposits which affect heat transfer, and may cause serious corrosion and erosion in the boiler. These mechanisms can result in boiler derating, and in unplanned shut-downs.

Coals which are used as power plant fuel contain both organically-combined and inorganic components in widely varying amounts. These are the components which contribute to ash formation during combustion although ash properties and behaviour also depend on the boiler operating conditions.

Worldwide ash production in 2002 was something over 500 Mt with more than half of it in China and India, and just under 20% of it in the USA. During the period up to 2020, the main changes in the ash produced will result from the increased use of subbituminous coals from the western states in the USA, and the increased use, internationally, of the subbituminous coal from Indonesia. Apart from these changes, the nature of the ash produced is likely to remain substantially the same. The amount of ash produced has already risen sharply in China, and between 2002 and 2005 coal production rose from 1400 Mt/y to around 2000 Mt/y with a proportional increase in the ash formed during use.

The amount of ash-forming material in bituminous coals can be minimised by coal washing although this will result in the production of more coal washery wastes. There are significant opportunities for the increased use of coal washing in both China and India. For the optimum use of the carbonaceous material mined, the cleanest, lowest-ash coal should be used in a PCC or IGCC unit. The lower grades and even the wastes from the washery may be burned at minemouth FBC units. At the minemouth, wastes can often be dumped back in the mine where the mining is open-cast.

Many coal-fired boilers which have been retrofitted with low NOx firing systems are experiencing significant difficulties due to increased amounts of carbon in the fly ash. There are various changes that the plant operator can make in order to decrease carbon-in-ash levels, but these all include much more control of process variables. These include the following:

- biasing the outer/inner burner column secondary air;
- improving the consistency of the grind;
- replacing the burners;
- modifying the angular orientation of the burners to improve the placement of streams with heavy particle loadings;
- adjustment of the flowrate and location of the overfire and underfire air ports.

It is necessary to ensure that the coal particles are as uniformly milled as possible, so that burn-out times are uniform, although the effects of this are dependent on the boiler configuration. Similarly the air/oxygen flows need to be controlled so that oxidising conditions are maintained throughout most of the combustion zone.

The behaviour of the ash-forming constituents in a coal is one of the most difficult to forecast with confidence. Some effects can be readily foreseen, but there are often unexpected impacts due to the interaction between the ash and the boiler operating conditions. If a blend of coals is used, it becomes even more difficult to predict behaviour accurately.

During the 1990s, the US DOE supported the development of a versatile software tool called the Coal Quality Expert CQE™. This was to enable utilities, coal producers and equipment manufacturers to analyse the impacts of coal quality, operational changes and/or environmental compliance alternatives on power plant production costs, performance, and emissions. The model facilitated the assessment of possible capital expenditures to improve performance, and of different strategies to meet emissions requirements. Methods for predicting deposition have become more sophisticated in recent years, and most large utilities have their own predictive indices. These are based on a combination of:

- detailed coal analysis;
- experience;
- combustion and fluid dynamics modelling – and with the increased power of computers, this can play a more important role.

There are a range of other management tools which can be used to minimise the adverse effects of ash formation on boiler operation. These include:

- online coal analysis, although there are still difficulties in calibrating analysers when different coals are being used;
- ‘intelligent’ sootblowing, where sensors measure the build-up of deposits so that sootblowing can be carried out only when necessary.

The mechanisms of ash formation and its behaviour are very different in FBC units compared to PCC. The temperature of combustion is much lower at around 800–900°C compared with 1300–1700°C. The coal particles are only ground to 3–6 mm size, so the original mineral matter may well keep its shape in the coal particle, and much of it will not be liberated. The ash from FBC units thus retain much of the mineral matter in its original form, and most commonly will also have substantial amounts of limestone and CaO where in-bed sulphur removal is practised.

In terms of ash disposal and use, the regulations covering disposal have become much tighter in many countries. While a great deal of the world’s coal ash is dumped as land fill or...
in settling ponds, there is increasing pressure to make constructive use of this material. This is because significant land areas are needed to store/hold the ash, and because of the risks associated with the possible leaching of unwanted ash components into the surrounding groundwaters. Fly ash is commonly a pozzolana, which is a material that reacts with lime to form a hardened mass. The highly variable chemical and physical nature of the ashes arising from coal combustion are a major barrier to their use.

High volume markets include use for:
- cement and concrete;
- soil stabilisation;
- structural fill;
- backfill in mines;
- agriculture.

With modern diagnostic and analytical tools, and a much greater understanding of the implications of ash behaviour in boilers it is possible, now, to operate most coal-fired units effectively and efficiently. Similarly, new uses are being developed for the ash formed, so that less of it has to be dumped in landfill or ponds.
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