Abstract

Excessive ash deposits on a coal-fired boiler’s heat transfer surfaces will reduce its efficiency, and in extreme cases a boiler can be shut down by ash-related problems. Ash deposits are known as slagging and fouling deposits according to their location within the boiler, and have the most serious impact on boiler operation in terms of cost. It has been estimated that slagging incidents cost the global utility industry several billion dollars annually in reduced power generation and equipment maintenance.

This report sets out to consider how the understanding of the slagging and fouling process has developed, how changes in the utility sector have impacted on the importance and likelihood of ash deposition incidents, and how problems may be predicted and tackled on a practical level. Some important factors which impact on the topic are considered in this review including:

- Power generation sector deregulation;
- Technological developments;
- Environmental protection technologies;
- New technologies;
- Cofiring with biomass;
- Increased international coal trading.
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1 Introduction

Slagging occurs in the boiler furnace where ash deposits are exposed to the radiant heat of the coal flames, while fouling occurs in the boiler’s convective passes. The propensity of a coal or a blend of coal with other fuels for producing slagging and fouling deposits depends on its ash content and, more importantly, the composition of that ash, and how the ash behaves under the conditions within the boiler during and after the combustion of the accompanying carbonaceous matter. The fact that the propensity for slagging and fouling problems is governed by the complex interaction between a boiler’s operating conditions and the coal ash chemistry makes the prediction of slagging and fouling very difficult.

Excessive ash deposits on a coal-fired boiler’s heat transfer surfaces will reduce its efficiency, and in extreme cases a boiler can be shut down by ash-related problems. Ash deposits are known as slagging and fouling deposits according to their location within the boiler, and have the most serious impact on boiler operation in terms of cost. It has been estimated that slagging incidents cost the global utility industry several billion dollars annually in reduced power generation and equipment maintenance (Devir, 2001).

A previous IEA CCC report entitled *Understanding slagging and fouling during pf combustion* (Couch, 1994), presented a comprehensive review of the topic at that time. The report summarised the ‘state of knowledge’ in respect of boiler design and operation, ash formation and deposition, predictive techniques and remedial measures. A later IEA CCC report, also by Couch (2006) entitled *Ash management in coal-fired power plants*, covering a number of ash-related issues, addressed some of the more recent developments in the field of slagging and fouling but a number of significant changes have continued to reshape the power generation sector which warrant this updated study of the topic. This report sets out to consider how the understanding of the slagging and fouling process has developed, how changes in the utility sector have impacted on the importance and likelihood of ash deposition incidents, and how problems may be predicted and tackled on a practical level. Some important factors which impact on the topic are considered in this review including:

- Power generation sector deregulation;
- Technological developments;
- Environmental protection technologies;
- New technologies;
- Cofiring with biomass and other alternative fuels;
- Increased international coal trading.
2 Ash formation and deposition

This section provides an overview of the current understanding of the formation and subsequent deposition of ash particles during coal combustion.

Ash formation involves a number of complex processes which take place alongside the rapid oxidation and combustion of the organic carbon and other combustible matter in the coal. When the coal particles are injected into the furnace, the heating rate is extremely rapid, and is of the order of $10^4$ to $10^6 \, ^\circ\text{C/s}$. The particles enter a zone of high turbulence and high temperature where they are subjected to shock heating by radiative and convective heat transfer, and by the exothermic reactions taking place on and in the particles themselves. As the ash-forming materials are released from the fuel, they follow different reaction paths. The expulsion of water from the particle pore structure is almost instantaneous, while pyrolysis takes place with the volatile organic species being released and then oxidised where 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.

These processes are summarised in Figure 1.

Figure 1 Ash-forming mechanisms (Couch, 2006)
Within the furnace section of the boiler, the organically-bound components tend to vaporise. 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. Where the ash can receive radiant heat from the combustion process, it can be 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 fouling deposits.

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. Deposition is also strongly influenced by the combustion gas stoichiometry at the waterwall or heat transfer tube surface and ash melting characteristics can vary greatly in sub-stoichiometric environments compared to oxygen-rich environments. The path taken in deposit formation from the fuel particle to a mature deposit is complex and has been summarised by a number of workers including López and others (2004). A schematic diagram showing the significance of different ash deposition mechanisms is given in Figure 2.

**Figure 2  Ash behaviour mechanisms in a PCC boiler** (Couch, 2006)
This chapter considers the changes that have occurred within the power generation sector over the last fifteen years and their impact on the incidence of ash slagging and fouling.

Deregulation and privatisation in the power generating market of many countries has put increasing pressure on plants to reduce the cost of generation. With fuel being by far the largest cost factor, power plants are required more than ever to be able to utilise a wide range of coals of differing quality, often far outside the plant’s original design fuel range. Additionally, there are increasing demands from legislation to increase boiler efficiency and to reduce emissions such as CO₂, NOx and SOx which require operators not only to switch fuel (for instance from high sulphur to low sulphur coals) but to make plant modifications (for instance fitting low NOx burners and overfire air ports). However, combustion modifications beyond the original design limit of the plants frequently change the slagging and fouling characteristics of the generating unit with regard to the tenacity and location of ash deposits, which can result in derates and forced shut-downs of a unit.

### 3.1 Importance of slagging and fouling issues to economic operation

O’Connor and Harding (2006) report a study undertaken by EPRI to survey selected members and determine their major concerns related to coal quality. A coal quality questionnaire was developed and sent to several EPRI-member utilities to obtain first-hand information on specific problems, as well as to solicit their insights on the effects of coal quality at their plants. An equally important part of the survey was to seek guidance on future research and development needs. The questionnaire was sent to thirty-six individuals from thirty different utilities as shown in Table 1. From the list of thirty-six contacts, twenty-one completed questionnaires were received.

Nearly all of the respondents listed slagging and fouling as the main coal quality issue at their plants (18 of 21). In addition to slagging, at least half of the personnel listed fouling and pulverisers as principal areas of concern with fuel quality (see Figure 3). These were closely followed by fuel blending which was noted on nearly half of all respondents’ questionnaires.

In a further study, Harding and O’Connor undertook an assessment of the data on utility plant performance in the NERC GADS database (Harding and O’Connor, 2006). The NERC GADS database is a significant source of utility reliability, availability and maintenance information (NERC, 2005) for US plant. This database is updated annually and contains operating histories on more that 5000 generating units, and according to NERC, represents about 90% of the installed generating capacity in North America. The NERC GADS database receives information from nearly 80% of the coal-fired generating units within the USA.

### Table 1 Utilities receiving questionnaire

<table>
<thead>
<tr>
<th>Utility</th>
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<tbody>
<tr>
<td>Alabama Electric</td>
</tr>
<tr>
<td>Detroit Edison</td>
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<tr>
<td>Cinergy</td>
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<tr>
<td>Constellation Energy</td>
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<tr>
<td>Hoosier</td>
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<tr>
<td>NIPSCO</td>
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<tr>
<td>Omaha Public Power</td>
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<tr>
<td>PNM</td>
</tr>
<tr>
<td>RG&amp;E</td>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>Great River Energy</td>
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<td>Kentucky Utilities</td>
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<td>OGE</td>
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<tr>
<td>Salt River Project</td>
</tr>
<tr>
<td>TXU</td>
</tr>
<tr>
<td>Southern Company</td>
</tr>
</tbody>
</table>

The data for all boilers designed for either lignite or coal and commissioned between 1900 and 2005 with all firing modes and subcritical or supercritical steam pressures were evaluated using both the deposition and coal quality cause codes. The results for the deposition-based cause codes are given in Figures 4 to 6.

Figure 4 shows the number of events reported for the forced outages and derates as well as the planned outages and derates. Ignoring the data for the small boilers listed, this evaluation provided the ability to calculate the total estimated annual cost of slagging and fouling for all boilers using coal or lignite fuel and employing either wall-, tangential or cyclone-firing. The main conclusions of the study with
Developments in the power sector

Slagging and fouling in coal-fired boilers

Figure 3 Number of responses for individual categories (O’Connor and Harding, 2006)

Figure 4 Average MWh lost for all boilers due to deposition cause codes (O’Connor and Harding, 2006)

Figure 5 Distribution of deposition related lost MWh lost for all boilers (O’Connor and Harding, 2006)

Figure 6 Average MWh lost per boiler for all boilers from deposition related cause codes (O’Connor and Harding, 2006)
respect to ash deposition were:

- slagging and fouling continue to be the leading coal quality concerns of utility personnel. Issues with ash chemistry resulting from fuel blending and new coals being utilised continue to be the main area for needed utility support. Nearly all respondents listed slagging as one of the top five problem areas in their respective power plants;
- there were many research needs provided by the utility respondents. Most mentioned the need for applied rather than fundamental studies. General topics suggested for further research included fuel preparation, handling and online analysis; fuel and ash characterisation; boiler optimisation with new fuels; and development of fundamental and cost/performance models of ash deposition phenomena;
- an availability assessment of coal- and lignite-designed boilers showed that slagging and fouling continue to be areas of economic impact in the power industry. Older boilers did not appear to be more problematic than newer boilers, and pulverised coal units (wall and tangential) tended to have less problems per boiler than cyclone units; however because of the larger number of pulverised coal fired units, the economic impact was much greater;
- an estimated annual economic impact of over $1.2 billion was calculated for all coal- and lignite-fired boilers in the USA based on coal quality and deposition causes.

3.2 Effects of deregulation

Since the early 1990s the power generation sector in many parts of the world has undergone, or is undergoing, a process of deregulation. In many cases large organisations, sometimes state-owned, are broken up into smaller companies which then compete to meet the needs of the local market. The deregulated utilities operate under a different set of conditions and assumptions compared to those of the former monopoly suppliers and seek to gain a competitive advantage through effective fuel purchasing and plant operation. These new companies may take advantage of coals available on the ‘spot market’, waste coals and other fuels including biomass that pose technological challenges in their use, but whose price is sufficiently attractive to offset the risks. Power plant may be operated on a more flexible basis, with coal-fired plant previously used for base load operation competing against other fuels (for example gas) depending on the relative fuel price. Coal-fired plant may be required to operate flexibly, for example ‘two-shifting’ where a plant is started and shut down twice a day. These new patterns of operation put pressure on supplier and seek to gain a competitive advantage through effective fuel purchasing and plant operation. These new companies may take advantage of coals available on the ‘spot market’, waste coals and other fuels including biomass that pose technological challenges in their use, but whose price is sufficiently attractive to offset the risks. Power plant may be operated on a more flexible basis, with coal-fired plant previously used for base load operation competing against other fuels (for example gas) depending on the relative fuel price. Coal-fired plant may be required to operate flexibly, for example ‘two-shifting’ where a plant is started and shut down twice a day. These new patterns of operation put pressure on plant components and much work has been undertaken to ensure long, reliable and efficient operation under these conditions. Where the local market is favourable, coal-fired plants may be cofired with additional fuels that pose additional technological challenges. These influences on ash slagging and fouling are discussed further in the sections below.

3.3 Boiler operation practice

Chang reports (Chang and Tilley, 2004) that typical fossil power plants commissioned in past decades were designed for base load operation, burning specific coals, often locally sourced, with limited variations in quality and without stringent emission requirements. These same fossil plants operating in today’s environment are required to operate more efficiently and flexibly and to do this they need to achieve the following:

- cycling operation;
- burning low cost coals with substantial variations in quality;
- operational changes to optimise NOx;
- heat rate improvement initiatives for cost and CO2 reduction;
- variable pressure operation for heat rate improvement and turbine protection;
- reliability and availability improvement;
- outage interval extension and duration reduction;
- capital, production, and maintenance cost reduction.

It is obvious that there are conflicting requirements among these plant operating objectives. In the context of slagging, attention is drawn to the importance of furnace exit gas temperature (FEGT) control. FEGT control is a critical parameter, which can be used to preserve boiler operation and reliability. If FEGT is above the design value, the following undesired conditions could occur:

- reduced heat absorption and increased fouling of superheaters, reheaters, economisers, and air heaters;
- increased boiler slagging;
- increased CO and carbon-in-ash;
- increased high temperature corrosion rates of superheater and reheater tubes;
- increased attemperation and potential of convective pass tube overheating (creep damage);
- altered design conditions which are more difficult to correct by the operator;
- increased boiler exit temperature which increases heat loss.

If FEGT is below the design value, the following undesired conditions could occur:

- high NOx level;
- low superheater and reheater temperatures and reduced efficiency.

Once significant boiler slagging has been initiated, the slag deposits will further lower the heat transfer to the furnace waterwalls, thereby increasing furnace temperatures and increasing the ash deposition rate leading to more slagging. FEGT provides an operational safeguard for proper boiler operation and can also be used to initiate automatic sootblowing, which is discussed later in this report.

In a mixed generation environment where differently fuelled power plants compete to supply power, coal plant, which has historically operated on base load, may be operated on a flexible basis, for example, two-shifting, as outlined previously. Operators of such plant frequently report a reduction in the number and severity of ash-related deposition problems. This has been attributed to the plant running for fewer hours and the rapid cooling/heating cycles that result in thermal stresses which cause deposits to shed from the boiler.
walls (Quick, 2008). However, industry commentators (Lefton and others, 2002) opine that the true life cycle cost of operating and maintaining a power plant includes the penalties incurred during starts, stops, and cycling operation – the ‘wear and tear’ on equipment that degrades efficiencies, increases forced-outage rates, and increases maintenance budgets.

3.4 Summary

Ash-related problems are clearly still of great importance to the operators of power plant. The costs of lost generation through, for example, a slagging incident are very high. Increased competition between utility companies has led to the use of a suite of coals whose properties are often far removed from the coals specified for the original boiler design. The changing electricity market in many areas, where the use of fuels other than coal (for example gas) has become widespread, has led to coal-fired plant being operated in some regions (for example OECD countries) under regimes other than base load. This change in operation has helped to reduce boiler slagging to some degree through the regular shedding of deposits as the boiler is thermally cycled.
This chapter considers the impact of technological changes, both established and in the process of development on ash deposition.

4.1 Environmental Protection Measures

4.1.1 NOx

The continuous drive for low emissions from power plant requires the adoption of technologies for emission reduction or capture. The first generation of NOx abatement technologies, low NOx burners, are now being followed by improved devices such as BOFA (boosted overfire air) and SOFA (secondary overfire air), together with full-boiler staging for reducing NOx through combustion modification. All of these technologies introduce sub-stoichiometric conditions within the boiler, which can increase the probability of slagging incidents and boiler corrosion. Further emissions reductions require post combustion processes such as catalytic conversion and flue-gas scrubbing, and in the longer term, carbon capture for compliance with climate change driven legislation.

The first generation of low NOx burners were designed to give a less intense coal flame, with lower peak flame temperatures and a zone of reducing conditions for the consumption of NOx and NOx precursors (Welford, 2001). It was thought that the longer, more reducing coal flames might give rise to an increase in boiler slagging as certain ash components are sensitive to forming low melting eutectic mixtures under reducing conditions (Gupta and others, 1999). However, operators report that the lower flame temperatures have led, generally, to a reduction in slagging incidents (Richardson and Hall, 1999; Quick, 2008). Lower peak flame temperatures make mineral matter less ‘sticky’ and less likely to agglomerate, producing ash particles that are finer and less prone to deposition. Less of the ash deposits on the boiler walls as slag and is removed as bottom ash. A side effect is that more of the fine ash must be removed by the electrostatic precipitators (Sear, 2008). Because this can present problems of effective precipitator operation, and because boilers are designed to operate with a minimum amount of ash deposition on the waterwalls for controlled heat transfer, Wigley and others (2006) undertook combustion trials to determine whether mineral additions could increase the proportion of coal ash depositing on boiler walls, and whether mineral additions could increase the fly ash particle size distribution.

The combustion trials were carried out with three coals and six additives in various combinations on the entrained flow reactor (EFR) at Imperial College London and on the RWE npower 0.5 MW combustion test facility (CTF). The three coals used were Daw Mill, Kellingley and La Loma. Daw Mill and Kellingley are typical UK power station coals with relatively high ash contents – Kellingley coal ash has a high level of iron oxide, while Daw Mill contains significant lime and magnesia as well as iron oxide. La Loma is a South American coal with a lower ash content that is predominantly aluminosilicate in composition, which is imported for use in UK power stations. The six mineral additives used were: albite (NaAlSi3O8), calcite (CaCO3), dolomite (CaMg(CO3)2), orthoclase (KAlSi3O8), iron blast furnace (BF) slag and pulverised fuel ash (PFA). Ash contents and chemical compositions are listed in Table 2 for the coals and in Table 3 for the minerals.

Mineral addition trials on the EFR indicated that deposition efficiency and the level of deposit sintering were mainly controlled by the coal (Daw Mill or La Loma), rather than the additive. Further EFR trials, using Daw Mill coal with additions of albite or calcite at 5 levels (0–40 wt%), indicated that the mineral additions did not produce a significant increase in deposition efficiency, nor a significant change in ash particle size distribution, although there were changes in the microstructures of the deposits. A more detailed study showed that the mineral additions had interacted with the coal ash in the deposit, to change the deposit microstructure and chemistry (more strongly for calcite than for albite). The addition of minerals to combusting coal did not increase the proportion of ash that deposits as slag or coarsen the fly ash particle size distribution. The researchers concluded that the mineral addition trials on the Imperial College EFR and the RWE npower CTF did not appear to have reversed the changes in ash deposition efficiency and particle size distribution that followed the fitting of low NOx burners to utility boilers.

Current boiler designs optimised for NOx control tend to be larger than existing units, and have fewer mills and burners. Flames have ‘more room’, and past problems of flame impingement with attendant slagging and corrosion have mostly been designed out. Larger furnaces tend towards lower furnace exit temperatures and longer residence times (1.5–2s) allowing more complete carbon burnout (Hough, 2008).

However, care is still needed to ensure that boiler components are designed to minimise ash deposits. For example, Chudnovsky and others (2001) described the effect of the burner replacement on boiler performance in Israel Electric Corporation’s 575 MW tangentially coal-fired units. The boilers were designed for two-shift operation with a turndown ratio in the range 20–100%. To maintain the required turndown ratio, Combustion Engineering designed and supplied coal nozzles of the type referred to as a wide load range nozzle tip (WLRNT), which has a prismatic central body, referred to as a ‘cone’. The cone creates a highly turbulent zone near the nozzle in order to provide a stable ignition of the fuel. The use of WLRNT was accompanied by numerous operational problems such as damage in the outer plates of the cone, tip cracking, deformation and slagging, and high NOx emissions. A programme of study using computer simulations of the combustion process in the boiler was...
undertaken, paying particular attention to the detailed simulation of the flow and ignition in the near-burner zone. Subsequently, the WLRNT nozzles were replaced by new ones without the cone, referred to as aerotip nozzles (ATN).

Both simulation and measurement show that WLRNT enhances the burning process, that is, the maximum heat flux on the walls is situated further down stream with ATN compared to WLRNT, and the maximum temperatures near the WLRNT burner are higher than the temperatures near the ATN burner. Due to the high intensity of the turbulence near the WLRNT burner the ignition of the air-fuel mixture occurs close to the nozzle, while the jet released from ATN nozzle has lower intensity of turbulence that results in a lower combustion rate. These modifications successfully solved the observed slagging and related problems.

An unwelcome side effect of low NOx technologies involving combustion modifications is an increase in the level of unburned carbon in the fly ash. (DTI, 1999; Hower and others, 1999). Consequently, utility operators may pay close attention to the control of coal fineness leaving the pulverising mills to achieve better combustion efficiencies, through the installation of improved classifier systems. After some bad experiences in the 1990s, dynamic classifiers are now a proven technology and are considered as part of all new designs. They are particularly effective in controlling levels of carbon-in-ash. For example, specifications for prospective new UK stations include a limit of 3% for carbon-in-ash, requiring dynamic classification systems to be fitted (Hough, 2008). These modifications can result in a shift in ash composition releasing components which would otherwise be included in larger structures, and this can affect the course of ash deposition.

### Table 2  Coal ash content and chemical composition (wt%)

<table>
<thead>
<tr>
<th></th>
<th>Daw Mill</th>
<th>Kellingley</th>
<th>La Loma</th>
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<tbody>
<tr>
<td>Ash content</td>
<td>11.2</td>
<td>15.0</td>
<td>7.6</td>
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<tr>
<td>SiO₂</td>
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<tr>
<td>Al₂O₃</td>
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<tr>
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### Table 3  Mineral ash content and chemical composition (wt%)

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<th></th>
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<th>BF slag</th>
<th>Calcite</th>
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<td>26.1</td>
<td>100.0</td>
<td>58.2</td>
<td>0.4</td>
<td>5.6</td>
</tr>
<tr>
<td>MgO</td>
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<td>7.3</td>
<td>0.0</td>
<td>41.8</td>
<td>0.0</td>
<td>1.5</td>
</tr>
<tr>
<td>K₂O</td>
<td>3.0</td>
<td>0.9</td>
<td>0.0</td>
<td>0.0</td>
<td>10.8</td>
<td>2.5</td>
</tr>
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<td>Na₂O</td>
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<td>2.7</td>
<td>1.1</td>
</tr>
<tr>
<td>TiO₂</td>
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<td>0.0</td>
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<tr>
<td>P₂O₅</td>
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<td>0.0</td>
<td>0.0</td>
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</tr>
<tr>
<td>MnO</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Another technology reported as being effective in reducing unburnt carbon loss is the rotating overfire air system manufactured by Mobotec and used in several US installations. In this system, the combustion gases in the furnace are set in rotation via special asymmetrically placed air nozzles. These nozzles generates turbulence and rotation in the entire furnace and this rotation prevents laminar flow and allows the whole volume of the furnace to be used more effectively for the combustion process (Mobotec).

### 4.1.2 SOx

Environmental protection legislation covering emissions of sulphur has driven many utilities to switch to low sulphur coals to achieve compliance with the law. One of the largest changes in coal utilisation that results from this driver is the increase in the use of coals from the Powder River Basin; a region in southeast Montana and northeast Wyoming. Powder River Basin (PRB) coalfield seams are expansive, rich with low sulphur coal and covered by little overburden. Wyoming PRB coals are characterised by a relatively high calcium content, while Montana PRB coals are high in sodium. The low cost of production, combined with US Clean Air Act regulations that favour low sulphur coal, and the deregulation of the railway industry that lower transportation costs, have made PRB coal an attractive consideration for power generation, although the significant and expensive modifications required to enable power plant systems to use the coal have limited the number of conversions. Unlike most bituminous coal, PRB varieties, contain high level of calcium within the coal structure. The calcium present in bituminous coal is in the form of calcite and dolomite. Table 4 shows the significant difference in the calcium levels and their distribution between bituminous and low rank coal and mineral types.

Wyoming Powder River coals are known to give rise to ash deposition problems owing to the inclusion of components such as calcium that lower the softening temperature of the ash (Zhuang and Parikh, 2006). During the early use of this coal in boilers designed for bituminous coals there were a number of slagging problems. However, operators now report that better control over boiler operating conditions and the use of computer management systems for control and automated sootblowing have significantly reduced these incidents (Harding, 2008).

A characteristic of Powder River coals that is shared by other high calcium subbituminous coals concerns the affect of fine particles on heat transfer in the boiler. The organic coal bound calcium on entry into the boiler furnace is rapidly released forming fine particles of mainly calcium oxide and calcium silicate (Benetech, 2002). Coal that is high in calcium and/or magnesium produces an ash that is reflective at temperatures common on the side walls of the furnace. The significance of this is that instead of allowing a high percentage of incident heat flux to be absorbed into the furnace walls, this ‘reflective ash’ reflects a much larger portion of the incident heat flux away from the furnace walls, reducing radiation heat transfer. The following simplified equation illustrates the furnace radiation heat transfer:

\[
Q = \alpha \varepsilon A (T_f^4 - T_w^4)
\]

where \( \alpha \) is a constant (Stefan-Boltzman constant), \( \varepsilon \) is the wall emissivity, \( T_f \) is the local flame (flue gas) temperature, and \( T_w \) is the wall temperature. The emissivity for clean carbon steel tubes at furnace temperatures is about 0.7 to 0.8. When the tubes become coated with a light amount of non-reflective ash (insignificant amounts of calcium and magnesium), the emissivity does not drop significantly, and radiation heat transfer is not reduced. However, coal ash containing high percentages of calcium and magnesium cause the emissivity to drop to 0.45–0.55 even when the deposits are only a few millimetres thick. Thus, because radiation heat transfer is directly proportional to emissivity, these deposits reduce radiation heat transfer by around 33%. If allowed to accumulate beyond a few millimetres thick, the heat transfer reduction in the radiant zones can be as much as 50% or more.

Therefore, when a furnace which is not designed for reflective ash becomes coated with these deposits, and especially when the sootblowers are ineffective, overall furnace heat transfer will drop well below design levels. This can cause one or all of the following problems:

- elevated steam attemperation spray flows, which can reach maximum levels leading to a boiler load reduction;
- elevated furnace exit gas temperature (FEGT) causing increased slagging and fouling in the convection passes of the boiler;
- elevated back-end (economiser and air heater) gas temperatures causing a reduction in boiler efficiency and sometimes exceeding metal temperature allowable levels;
- excessive (often near-continuous) use of the ineffective wallblowers leading to high rates of tube wall erosion and wallblower maintenance.

When a fuel to be burned has a combination of increased calcium percentage, increased sodium percentage, and reduced ash fusion temperature, the likely strategy for boiler cleaning will be as follows. First, clean the furnace effectively to remove the reflective ash and restore furnace heat transfer.

| Table 4 Significant differences between US bituminous and subbituminous coals |
|----------------------------------|----------------|----------------|
| Ash, % (dry)                     | 8.6            | 6.8            |
| CaO, %                           | 2.7            | 28.3           |
| Coal bound calcium               | 30.0           | 70.0           |
| Calcium in mineral matter        | 70.0           | 97.0           |
| Coal bound calcium               | 8.6            | 28.3           |
| Calcium in mineral matter        | 30.0           | 70.0           |
as close to design level as possible. This may require water lances or water cannons to be installed. However, regardless of whether the furnace sootblower complement consists of wallblowers, water lances, or both, it is critical to identify the correct operational interval which sustains a high level of heat transfer benefit from the equipment. Effective furnace cleaning reduces the attemperation spray flows thereby improving boiler efficiency, and reduces flue gas temperatures throughout the unit. This allows the convection pass sootblowers to clean more effectively. Recent developments in ‘intelligent sootblowing’ are noteworthy here and are discussed later in this report.

Subbituminous coals such as Powder River Basin have also been associated with the production of ‘large particle ash’ (LPA), also known as ‘popcorn ash’ from its resemblance to cooked and expanded corn. The mechanism for the formation of popcorn ash is not clear, but it has been suggested that the deposits form on waterwall surfaces and then detach and become entrained in the flue gas stream (O’Connor, 2008). The particles of popcorn ash are relatively large and, unlike normal pulverised coal ash, cannot pass easily through the matrix of pollution control equipment such as SCR. In units not fitted with SCR, popcorn ash can cause serious blockages in airheaters. Craig and others (2008), describe SCR plugging problems at Georgia Power’s Bowen plant where the SCR had to be removed from service after only 69 days. The SCR was inspected and while there was no significant ash build-up on the ash screens, the removal of the screens showed that the catalyst channels were extensively plugged with popcorn ash and fly ash. There was a gradient of blockage, with the worst being on the south wall (boiler side) of the reactor and the least on the north side of the reactor. A new set of baffles designed to protect the SCR channels were installed but only succeeded in slowing the rate of blockage. More recent developments have seen a refinement of the screen design and these components are now being fitted to units likely to suffer from LPA issues (Tillman, 2008).

4.2 Technological developments

A number of utility companies worldwide are considering the introduction of new coal-fired power plants. These new installations are likely to be of the ultra super critical type with steam temperatures above 610°C and steam pressures above 25 MPa. These new boilers will have to meet very stringent emission targets, including near-zero CO₂ emissions whilst simultaneously being able to utilise a wide range of coals and secondary fuels such as biomass and possibly wastes. Along with the enhanced steam conditions and higher efficiency, further gains can be achieved through oxy-firing, to be discussed in more detail in a later section. In oxy-firing a modified conventional boiler is fed with pure oxygen or oxygen-enriched air rather than normal combustion air, and a proportion of the flue gases are recycled through the combustion chamber. This has the effect of significantly raising the concentration of CO₂ in the flue gases. The low concentration of CO₂ in the flue gases from conventional boilers is a major barrier to CO₂ capture since separation of CO₂ from the other gases, principally nitrogen, is a very expensive process.

4.3 Alternative technologies

The following section looks at the most popular alternative combustion technology to pulverised coal firing – circulating...
Fluidised bed combustion, and at oxyfuel combustion, designed to facilitate carbon capture and storage.

4.3.1 CFBC

Pulverised coal firing remains the dominant technology for power generation, but the newer cleaner coal technologies have been steadily gaining ground, particular circulating fluidised bed technology installation in the developing economies. These plants are very fuel flexible and can be optimised for fuels including low-grade, high-ash coals, biomass, petroleum coke and coal wastes. Considerations of slagging and fouling are different in these systems, but plant operation is still governed by factors previously outlined. Consequently, the development of appropriate strategies is important for the continued acceptance of these technologies, against competing systems. The most successful of these technologies is circulating fluidised bed combustion (CFBC), which currently accounts for a small amount of installed capacity worldwide.

In CFBC, combustion takes place at temperatures from 800–900°C resulting in reduced NOx formation compared with pulverised coal combustion. NO₂ formation may, however, be increased in systems fitted with SNCR where ammonia or urea injected into the boiler converts some of the NOx into NO₂. SO₂ emissions can be reduced by the injection of limestone into the bed offering ash-based glassy layer forms on the grid and eventually enough to fall down on the fluidising grid. What then tends to any of the ash components soften, particles can agglomerate and fouling in the same way as it does in a PCC unit. There is a great deal of mixing, and residence time during one pass is very short.

Circulating beds use a higher fluidising velocity, so the particles are constantly held in the flue gases, and pass through the main combustion chamber and into a cyclone, from which the larger particles are extracted and returned to the combustion chamber. Individual particles may recycle anything from 10 to 50 times, depending on their size, and how quickly the char burns away. Combustion conditions are relatively uniform through the combustor, although the bed is somewhat denser near the bottom of the combustion chamber. There is a great deal of mixing, and residence time during one pass is very short.

CFBC units are designed for the particular coal to be used. The method is principally of value for low-grade, high-ash coals which are difficult to pulverise, and which may have variable combustion characteristics. It is also suitable for cofiring coal with low-grade fuels, including some waste materials. The direct injection of limestone into the bed offers the possibility of economic SO₂ removal without the need for flue gas desulphurisation. The advantage of fuel flexibility often mentioned in connection with FBC units can be misleading. Once the unit is built, it will operate most efficiently with whatever design fuel has been specified.

For a bed burning a bituminous coal, the carbon content of the bed is around 1%, with the rest of the bed consisting of ash, together with sand (if needed), and/or lime and calcium sulphate. Overall carbon conversion efficiencies should be over 98%, leaving only a small proportion of unburnt char in the residues.

Larger boilers will have several cyclones in parallel to remove the solids for recirculation. One design characteristic is the need for heat recovery from the bottom ash, some of which is removed. This is part of the basic design in some units. Ash coolers are prone to plugging, hence the use of some fluidising air, and the heat transfer tubes in them are prone to erosion, which may be exacerbated by the air flow.

Various CFBC designs are used. One design variant consists of wall heating tubes, and then a heat exchanger for the flue gases in an external chamber. In a second design, there are platen heat exchangers in the combustion chamber in addition to the wall tubes, although further heat exchange is also needed for efficient operation. In a third arrangement, the upper part of the furnace has a considerable number of heat exchange tubes, such that the exit flue gases are substantially cooled before leaving for the cyclone. The returning ash cools the base of the combustor. Where there are heat exchange tubes in the path of the recirculating solids the possibilities of erosion are considerably increased. In all cases, the finest fly ash leaves the cyclone with the flue gases, and is normally separated by using an ESP or a baghouse. The ash may contain quite high proportions of carbon, possibly up to 15%. Coals used in the larger CFBC units worldwide include:
- Chinese and South Korean high-ash anthracites;
- Polish brown coals;
- high sulphur coals where the ash has a high calcium content as at Gardanne in France;
- Gujarat lignite, India.

The largest CFBC unit currently operating is at Jacksonville in the USA, with 300 MWe capacity. A larger supercritical unit 460 MWe capacity is under construction at Lagisza, Poland with, 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 grinding 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 the process suitable for many brown coals. The combustion temperature in CFBC is generally in the range from 800°C to 900°C and 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. In tests undertaken recently in South Africa, it has been found that, under certain
conditions, once the fluidised bed has dropped during a period of downtime, strong agglomeration and slagging occurs – despite the combustion operating temperatures in the bed having been kept below 900°C. This has been attributed in part to the continuation of combustion of the coals still in the bed (and specifically inertinite chars) which would lead once again to much higher temperatures in the body of the slump. This would be exacerbated by the gradually increasing pressure of overburden over time. Such conditions would also lead to increasing reducing conditions which would induce a lowering of the melting temperatures in the minerals (Falcon, 2008).

Future developments in CFBC include the construction of large (600 MWe) units operating with supercritical steam cycles where the increased tube temperatures may require careful attention to avoid the development of ash deposits.

4.3.2 Oxyfuel combustion

Oxyfuel combustion technology is being developed for pulverised coal plants, fluidised bed plants and advanced power cycles (for example IGCC) to facilitate carbon capture. The products of oxyfuel combustion are carbon dioxide, the other pollutants normally associated with coal combustion (NOx and SOx, etc) and water – and since the water is easily separated, a stream of CO₂ ready for sequestration is obtained. Oxyfuel combustion has significant advantages over traditional air-fired plants. These include:

- an approximately 75% reduction in the mass and volume of the flue gas;
- because the flue gas volume is reduced, less heat is lost in the flue gas;
- the size of the flue gas treatment equipment can be reduced by 75%;
- the flue gas is primarily CO₂ suitable for sequestration;
- the concentration of pollutants in the flue gas is higher making separation easier;
- most of the flue gases are condensable, making compression separation possible;

- heat of condensation can be captured and reused, rather than lost in the flue gas;
- since pure oxygen, rather than air is used for the combustion process nitrogen oxide production is greatly reduced.

Temperatures in an oxyfuel system are controlled by recycled flue gas in a complete power system. In both pulverised coal and power cycle applications, the current state of art is such that a greenfield oxy-combustion plant could be built or an existing boilers retrofitted using current technologies. However, such plants would not be optimised due to a lack of data or proven computer models of oxyfuel combustors, boiler systems or carbon dioxide recovery. Multiple oxy-combustion facilities at various scales are being constructed or are in operation in a number of countries (see Figure 8).

Sheng and others (2008) studied mineral matter transformations and ash formation during the simulated oxyfuel combustion of pulverised coal. Five typical Chinese thermal coals were burned in a drop tube furnace to generate ashes under various combustion conditions. The ash samples were characterised by XRD analysis and Mössbauer spectroscopy to study the transformations of the main minerals in the coals. Fine ash particles were collected by a low-pressure impactor and their size distribution and elemental composition were analysed to study the fine ash formation. The impacts of O₂+CO₂ combustion on the mineral transformation and fine ash formation were explored through extensive comparisons between O₂+CO₂ combustion and O₂+N₂ combustion. They found that, O₂+CO₂ combustion does not significantly change the phases formed in the residue ash, but does affect the relative proportions of the mineral phases. Moreover, it was found that O₂+CO₂ combustion significantly affects fine ash formation behaviour, including reducing the mass fraction of sub-micron particles in ash and significantly changing the elemental composition of these sub-micron particles as compared to O₂+N₂ combustion.

Figure 8  Schematic diagram showing oxyfuel combustion (Vattenfall, 2007)
In a more detailed investigation Zulfiqar and others (2006) undertook the evaluation of the combustion performance on a pilot-scale furnace (fired at a nominal 0.8 MWth) at the IHI-test facility in Japan. Three Australian coals were selected for study under two different combustion conditions, air-firing and oxy/recirculated flue gas (RFG) firing, with measurements made on ash character and particle size distribution. Ash and deposit samples were collected from several locations for each combustion condition. These locations included deposit samples from panels in the radiant and convection sections, ash from the furnace bottom, two gas coolers, air heater and the bag filter hopper (see Figure 9).

Differences were observed in tests involving combustion of the three coals in air and oxyfuel conditions, as follows:

- the dust concentration measured in the pilot-scale experiments was typically 1.5 times greater in oxyfuel combustion due to the reduced gas volume but no significant difference in the dust particle size distribution was observed;
- the chemical compositions and the size distribution of the fly ash did not differ significantly when produced in oxyfuel and air combustion;
- for Coal A, oxy-firing increased the extent of deposition, as indicated by the deposit mass collected for both slagging and fouling, but no difference was found in the chemistry of the deposits. For Coal B, an increase in the extent of fouling was observed, with an increase in calcium and sulphur levels. For Coal C, no changes in deposit mass were found. The rankings for slagging severity were, from measured deposit mass; Coal A >Coal B > Coal C, and from TMA melting behaviour: Coals A and C > Coal B. The rankings for fouling severity from measured deposit mass were; Coal C > Coal B > Coal A;
- impacts due to the differences in gas volumetric flows – giving greater ash drop out in the furnace, and higher concentrations of the sulphur containing gases – giving higher sulphur levels in deposits – were observed. Trends in the sintering and melting behaviour of the deposits varied with Fe₂O₃ in ash.

In another pilot-scale based study of the affects of oxy-firing on ash deposition, a comprehensive suite of ash deposits was collected during oxyfuel combustion trials on the 1 MW combustion test facility (CTF) at E.ON UK. Combustion parameters that were investigated included firing mode (air or oxyfuel), excess oxygen level, proportion of air staging and degree of oxygen enrichment. The deposit samples were characterised by scanning electron microscopy and X-ray diffraction (Wigley and Goh, 2008). The study concluded that for oxy-firing, compared to air-firing:

- coal minerals showed similar transformations, but to a lesser extent because of lower flame temperatures (see Figure 10);
- deposits were smaller and showed less sintering, because lower flame temperatures and gas temperatures meant that the ash particles were less ‘sticky’;
- deposit structures were affected by the different gas velocities and densities;
- deposits appeared to become more like air-fired deposits as the level of oxygen enrichment increased;
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Indiustry professionals opine that oxy-firing represents largely unknown territory in respect of the impact of the modified combustion environment on ash slagging and fouling and associated effects such as tube corrosion (Hough, 2008; O’Connor, 2008; Tillman, 2008; Harding, 2008; Wall, 2008).

4.4 Summary

The increasing pressure on coal-fired power stations to reduce emissions has led to the development of technologies for the abatement of specific pollutants that impact on ash slagging. Combustion modifications for NOx reduction are considered the most significant and have, through a trend towards larger furnaces and cooler flames, generally reduced slagging propensity. Where coal switching has taken place for sulphur control, low-sulphur coals have been used in boilers not designed for them, with consequent problems. The best example of this is the increasing use of Powder River Basin coal in US plant, where the low-cost, low sulphur characteristics provide a powerful imperative for solutions to any problems arising from its use.

CFBC plants continue to make inroads into the power generation market and are particularly effective with very low-grade coals. The different combustion environment, as compared to pulverised coal fired plant, gives rise to unique ash-related problems such as bed agglomeration.

The latest generation of pulverised coal fired plant, designed for high efficiency through the use of high steam temperatures and pressures, present the greatest challenge with respect to ash slagging and fouling. These new plant are almost certain to be required to operate under conditions that allow carbon capture and storage, for compliance with climate change driven requirements. The leading technology for this is oxy-firing and represents a very substantial change to combustion conditions within the boiler. It is regarded by boiler manufacturers, users and academic researchers as warranting significant study to identify and ameliorate any issues arising from the new combustion environment.

Figure 10 Typical particles within CTF deposits (air-fired, left; oxy-fired, right) (Wigley and Goh, 2008)
This chapter considers the impact of the cocombustion of other fuels, in particular biomass, in coal-fired power plant.

Power plants cofiring two and sometimes more fuels (usually oil and gas) have been in operation for many years. However, recent changes in the energy marketplace have made the practice of cofiring more common. A major area of growth is the cofiring of biomass with coal. This is being undertaken in many countries as a way of reducing the carbon dioxide emissions, and where local regulatory practices encourage biofuel use, often with financial subsidies as a financial imperative. The cofiring of biomass has an impact on plant operation and performance, including issues of slagging and fouling. Other materials that are being successfully cofired include waste-derived materials such as sewage sludge, automotive tyres, refuse-derived fuel, and meat and bone meal products. These fuels may be mixed with the coal, fired through dedicated burners, or processed externally – for example by external gasification prior to combustion and energy recovery. The additional ash components that may be introduced into the boiler (for example high concentrations of alkali metals) can contribute to increased problems of ash deposition.

When biomass is cofired with coal in an existing coal-fired installation, the biomass offers a number of benefits. Since growing biomass removes carbon dioxide during its growth cycle, the use of biomass as a fuel can significantly reduce the greenhouse gas emissions per unit of electricity generated. It can lead to reductions in the emissions of the oxides of sulphur and nitrogen, and it can assist with the disposal of solid waste avoiding of landfill and the associated costs. The biomass fuel itself may be available as a lower cost fuel compared to coal. However, all potential benefits are site-specific and cost savings, in particular, need to be evaluated carefully as the costs of biomass feedstock can vary over a wide range, and transportation and handling costs can make even zero cost wastes expensive at the power station gate. Other reasons for using biomass as a fuel source include: a diversified primary fuel mix, reduced dependence on imported fuel resources, and security of fuel supplies. However, the energy density of biomass is low compared to coal and other fossil fuels. Even when dry, biomass has a heating value much less than a bituminous coal and is somewhat closer to a lignitic coal. The moisture content of biomass can be high and thus the biomass may require drying before combustion, otherwise efficiencies of the energy conversion processes will be reduced. Drying is an energy-intensive process and from a sustainability viewpoint is best done using the natural drying agents of wind and sun. However, this may not be feasible when the biomass is being used at high rates of consumption or in wet, humid climates.

### Types of cofiring

Cofiring of biomass with coal in a pulverised coal fired boiler can be achieved using a variant of one of three technology options:

- direct firing of the biomass with the coal;
- indirect firing of the biomass with the coal;
- firing the biomass in a separate boiler and incorporating the steam raised within the existing turbine-generator infrastructure.

Of these options, only the first two introduce changes in ash composition within the combustion environment and since direct firing is by far the most commonly practised technique, it is therefore the main focus of this review.

### 5.1 Direct cofiring

In direct cofiring the biomass fuel is fed directly into the pulverised coal fired boiler, through one of four options depending on precisely where the biomass is blended with the coal and how it is introduced into the boiler (see Figure 11). These options may be considered as:

- co-pulverising of the biomass with the coal;
- separate pulverising of the biomass and common injection with the coal;
- separate pulverising of the biomass and separate combustion through dedicated burners;
- use of biomass as a reburn fuel.

The composition of some typical biomass and waste fuels that have been utilised for cofiring are summarised in Table 5. It should be noted that these are given by way of example, as compositions can vary significantly depending on where the biomass is grown and on the make-up of the waste-derived materials.

---

**Figure 11 Routes available for direct cofiring (Meijer, 2004)**
van Ree and others (2001) reviewed the operational experiences of utilities undertaking the direct and indirect cocombustion of biomass/waste in European coal and natural gas fired power plants. The operational experiences of (mainly Dutch) direct cocombustion activities in coal-fired power plants were described together with an overview of European indirect cocombustion activities. The authors set out the technical, environmental, and economic feasibility of different indirect cocombustion concepts (that is upstream gasification, pyrolysis, combustion with steam-side integration) and the results were compared with the economically preferable concept of direct cocombustion.

The main technical constraints that limit the cocombustion capacity of biomass/waste in pulverised coal fired power plants were considered to be: the grindability of the biomass/coal blend, the capacity of available unit components, and the danger of severe slagging, fouling, corrosion and erosion.

Following discussions with the operators of several plants, the authors conclude that severe slagging and fouling associated with some types of biomass may occur because of a high alkali content, calcium and potassium and P₂O₅. This has been reported as a potential issue in connection with slagging of the burners, furnace walls and superheaters. A high sodium and potassium content may also result in fouling problems.

Jenkins and others (1998) reviewed the properties of biomass relevant to combustion drawing attention to the variability of compositions of biomass among different fuel types, especially with respect to inorganic constituents important to the critical problems of fouling and slagging. Hughes (1998) set out the overall limits to biomass cofiring. Alkali and alkaline earth metals, in combination with other fuel elements such as silica and sulphur, and facilitated by the presence of chlorine, are responsible for many undesirable reactions in combustion furnaces and power boilers. Reductions in the concentrations of alkali metals and chlorine, created by

---

Table 5 Composition of typical biomass and waste materials and their ashes (Miles and others 1995)

<table>
<thead>
<tr>
<th></th>
<th>Almond shells</th>
<th>Olive stones</th>
<th>Wheat straw</th>
<th>Rice husks</th>
<th>Bagasse</th>
<th>Willow</th>
<th>Poplar</th>
<th>Demolition wood</th>
<th>Mixed paper</th>
<th>RDF (steel-free)</th>
<th>Tyres</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dry basis</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash, %</td>
<td>3.29</td>
<td>1.72</td>
<td>7.02</td>
<td>20.26</td>
<td>2.44</td>
<td>1.71</td>
<td>2.7</td>
<td>13.12</td>
<td>8.33</td>
<td>26.13</td>
<td>8.83</td>
</tr>
<tr>
<td>Volatile matter, %</td>
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<td>82.0</td>
<td>75.27</td>
<td>63.52</td>
<td>85.61</td>
<td>82.22</td>
<td>84.81</td>
<td>74.56</td>
<td>84.25</td>
<td>73.4</td>
<td>68.00</td>
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<tr>
<td>Fixed carbon, %</td>
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<td>16.28</td>
<td>17.71</td>
<td>16.22</td>
<td>11.95</td>
<td>16.07</td>
<td>12.49</td>
<td>12.32</td>
<td>7.42</td>
<td>0.47</td>
<td>23.17</td>
</tr>
<tr>
<td>Carbon, % as C</td>
<td>49.3</td>
<td>52.8</td>
<td>44.92</td>
<td>38.83</td>
<td>48.64</td>
<td>49.9</td>
<td>50.18</td>
<td>46.3</td>
<td>47.99</td>
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<td>Hydrogen, % as H</td>
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<td>5.46</td>
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<td>5.9</td>
<td>6.06</td>
<td>5.39</td>
<td>6.63</td>
<td>5.78</td>
<td>6.81</td>
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<tr>
<td>Nitrogen, % as N</td>
<td>0.76</td>
<td>0.45</td>
<td>0.44</td>
<td>0.52</td>
<td>0.16</td>
<td>0.61</td>
<td>0.6</td>
<td>0.57</td>
<td>0.14</td>
<td>0.8</td>
<td>0.36</td>
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<tr>
<td>Sulphur, % as S</td>
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<td>0.05</td>
<td>0.16</td>
<td>0.05</td>
<td>0.04</td>
<td>0.07</td>
<td>0.02</td>
<td>0.12</td>
<td>0.07</td>
<td>0.35</td>
<td>1.24</td>
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<td>Oxygen, % as O</td>
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<td>41.77</td>
<td>35.47</td>
<td>42.82</td>
<td>41.8</td>
<td>40.43</td>
<td>34.45</td>
<td>36.84</td>
<td>27.24</td>
<td>9.67</td>
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<tr>
<td>Chlorine, % as Cl</td>
<td>&lt;0.01</td>
<td>0.04</td>
<td>0.23</td>
<td>0.12</td>
<td>0.03</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>0.05</td>
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<tr>
<td>GCV, kJ/kg</td>
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<td>21.59</td>
<td>17.94</td>
<td>15.84</td>
<td>18.99</td>
<td>19.59</td>
<td>19.02</td>
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<td>20.78</td>
<td>15.54</td>
<td>32.92</td>
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<tr>
<td><strong>Ash composition</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>8.71</td>
<td>30.82</td>
<td>55.32</td>
<td>91.42</td>
<td>46.61</td>
<td>2.35</td>
<td>5.9</td>
<td>45.91</td>
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<td>Al₂O₃</td>
<td>2.72</td>
<td>8.84</td>
<td>1.88</td>
<td>0.78</td>
<td>17.69</td>
<td>1.41</td>
<td>0.84</td>
<td>15.55</td>
<td>52.56</td>
<td>12.71</td>
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<td>Fe₂O₃</td>
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<td>0.81</td>
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<td>1.45</td>
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<td>CaO</td>
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<td>14.66</td>
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<td>41.2</td>
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<td>13.51</td>
<td>7.49</td>
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<td>10.64</td>
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<tr>
<td>MgO</td>
<td>3.19</td>
<td>4.24</td>
<td>1.06</td>
<td>&lt;0.01</td>
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<td>2.47</td>
<td>18.4</td>
<td>2.55</td>
<td>2.36</td>
<td>5.64</td>
<td>1.35</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.09</td>
<td>0.34</td>
<td>0.08</td>
<td>0.02</td>
<td>2.63</td>
<td>0.05</td>
<td>0.3</td>
<td>2.09</td>
<td>4.29</td>
<td>1.66</td>
<td>2.57</td>
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<tr>
<td>Na₂O</td>
<td>1.6</td>
<td>27.8</td>
<td>1.71</td>
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<td>0.79</td>
<td>0.94</td>
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<td>0.53</td>
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<td>1.10</td>
</tr>
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<td>K₂O</td>
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<td>25.6</td>
<td>3.71</td>
<td>0.15</td>
<td>15</td>
<td>9.64</td>
<td>2.14</td>
<td>0.16</td>
<td>0.2</td>
<td>0.92</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>4.46</td>
<td>2.46</td>
<td>1.26</td>
<td>0.43</td>
<td>2.72</td>
<td>7.4</td>
<td>1.34</td>
<td>0.94</td>
<td>0.2</td>
<td>0.67</td>
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<tr>
<td>SO₃</td>
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<td>0.56</td>
<td>4.4</td>
<td>0.72</td>
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<td>1.83</td>
<td>2.04</td>
<td>2.45</td>
<td>1.7</td>
<td>2.63</td>
<td>15.38</td>
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<td>ZnO</td>
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<td>nd</td>
<td>nd</td>
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<td>34.5</td>
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</table>

References: 44, 44, 44, 44, 44, 44, 44, 44, 44, 44, 44, 80

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Cofiring

Slagging and fouling in coal-fired boilers
leaching the elements from the fuel with water were shown to yield significant improvements in ash fusion temperatures and hence deposition.

### 5.2 Impact of cofiring on slagging and fouling incidents

Due to the compositional differences, ashes formed during coal and biomass combustion behave differently. Compared to coal, biomass-based fuels tend to contain smaller amounts of sulphur but can contain significant quantities of, for example, the alkali metals: straw contains significantly higher amount of chlorine and potassium, compared to coal and wood chips. The significance of the high content of inorganic volatiles, such as chlorine and potassium, in straw is very important for both fly ash formation and ash transport mechanisms.

The large quantities of volatile inorganic species influence the condensation of vapour species, both as submicron particles (homogeneous condensation) and on the surface of ash particles, and result in a more pronounced effect than for pure coal-fired boilers (Nielsen, 1998). According to Andersen (1998), alkali sulphates dominate the composition of the inner layers of hotter deposits, while sulphates and chlorides are the major components in deposits collected at colder sampling points. Chlorine salts, present in biomass ashes, are the major cause of severe corrosion of the superheater tubes. The presence of alkali elements also influences the deposit characteristics, for example melting behaviour, which is important for the ash deposit build-up and shedding.

Potassium forms low-melting compounds with silicon, meaning that the overall melting range of a biomass-derived ash is lowered significantly (Jensen and others, 1997). This is why biomass-derived ash partly melts during thermal conversion and increases the sticking tendency of associated ash to heat transfer surfaces. Jensen reported deposition probe studies from boilers burning eight types of cereal straw. The superheater deposits had a composition very similar to the fly ash, whereas the furnace deposits were enriched in silicon and calcium. The chemical analysis of mature deposits from a boiler (Masneder, Denmark) burning straw, undertaken by Hansen and others (2000), showed that the inner part of the deposit contained high amounts of chlorine and potassium, and only small amount of silicon; the middle part was highly dominated by potassium and chlorine, but increasing amounts of silicon and calcium were observed; the outer part contained almost no chlorine, but consisted mainly of potassium, calcium and silicon. All the deposits had a characteristic layered structure, with a dense K$_2$SO$_4$ layer present next to the metal surface. The presence of a K$_2$SO$_4$ layer was explained by initial deposition of KCl on the superheaters, and its subsequent sulphation. This is supported by the thermodynamic equilibrium calculations, and by the fact that deposition probes, held in the boiler for some hours, did not contain K$_2$SO$_4$. Calculations (Nielsen, 1998), predicted that solid phase and KCl would be thermodynamically stable at the metal surface temperature (approximately 560°C), that is, around this temperature they are likely to be present in the condensed phase. In the matching flue gas, with the higher prevailing temperature (1000–1100°C), the thermodynamically stable species are gaseous KCl, and small fractions of gaseous KOH and K$_2$SO$_4$. Since the condensed K$_2$SO$_4$ is more stable at higher temperatures than condensed KCl, this indicates that KC1 would not condense on top of the K$_2$SO$_4$ layer (since the surface temperature of the subsequent layer is higher), as might be indicated from the deposit structure. The conclusion is that KCl is the initially deposited species, which later reacts with a sulphur-containing species (most likely SO$_2$ or SO$_3$) to form the inner layer of K$_2$SO$_4$.

Further evidence of the importance of alkali metals in governing the melting behaviour of the deposits in biofuel-fired boilers was given by Salmenoya who presented calculated dependencies of the melt fraction with temperature, for biomass deposit samples containing different amounts of K and Cl (5 wt% of potassium, and 3 wt% of chlorine) (Salmenoya, 2000). Using a technique known as the MELTEST method, it was found that the chlorine content influenced the increase of melt fraction at first observed melting temperature (FMT), but not the FMT itself. On the other hand, potassium affects FMT, but not the amount of melt at that temperature. The deposits in biofuel-fired boilers are usually not completely molten, but the amount of melt increases as the temperature rises. The molten phase, present in the deposit, is usually not in a direct contact with the metal surface. Usually the outermost deposit layer may be molten. A molten layer on the top of the deposit may effectively block the inner layer, and decrease the rate of the diffusion of gases through the deposit.

#### 5.2.1 Deposition

When biomass is cofired with coal, the effect on deposition is, firstly, that the rate and extent of slag formation increases. This is principally due to the decrease in fusion temperatures of ashes produced during cofiring since fused or partially fused slag deposits are more likely to incorporate incoming particles and grow. The most dramatic impact of this process is observed when biomass is cofired with a coal which has a particularly refractory ash. In these cases cofiring biomass at even modest cofiring ratios can have a major impact on ash fusion behaviour. The presence of significant levels of alkali and alkaline-earth compounds in the mixed ash acts as a very effective flux on the coal ash, reducing ash fusion temperatures by 100–200°C and dramatically increasing the likelihood of slagging. This effect is less dramatic with coal ashes originally having lower fusion temperatures and already having significant slag formation propensities. Secondly, the volatilisation and condensation of alkali metals and phosphates when cofiring biomass with coal is a major mechanism for the initiation and growth of fouling deposits. Most types of biomass are high fouling fuels and cofiring biomass with coal in almost all cases increases the likelihood of fouling. The level of risk depends not only on the nature of the biomass and coal ashes and the cofiring ratio but also on site specific factors. The sensitivity of individual boilers regarding the tendency to accumulate ash, its subsequent effect on reduced heat transfer and the effectiveness of installed cleaning systems varies from plant to plant. In many cases the appropriate response to problems of slagging and fouling during cofiring, is to reduce the cofiring ratio. Experience in Europe suggests that slagging and fouling are
unlikely to be a problem for cofiring ratios of less than 10% on an energy basis (van Loo and Koppejan, 2003).

5.3 Cofiring with straw

In 1995 the Danish utility company Elsam converted the 150 MWe pulverised coal fired Studstrup Power Plant, Unit One, for the cofiring of coal and straw for technology demonstration purposes. The conversion consisted of establishing a straw pre-processing plant and modifying the burner system. After plant commissioning in January 1996, a two-year demonstration programme was initiated. The objective of the programme was to evaluate the influence of cofiring on boiler plant performance, combustion chemistry, heat surface deposits and corrosion, residue quality, emissions and SCR systems. Based on the two years of large-scale operation under normal power plant conditions, it was concluded that the cofiring technology was viable up to a straw input of 20%, on an energy basis. The boiler performance was only marginally affected. Corrosion was only slightly increased and fouling could be kept within a controllable level. Based on the demonstration firing on, Elsam has converted a 350 MWe PC unit, for cofiring. The plant was commissioned in early 2002 and is now in commercial operation.

Fuel analyses from the Studstrup trial are given in Table 6.

It is seen that Studstrup coal ash is composed mainly of alumino-silicates and quartz with the other major constituents being compounds of iron, calcium, magnesium, potassium and sodium. The sulphur, chlorine and phosphorous contents of coal ash are low. As this coal contains relatively low levels of fluxing elements such as iron, calcium, potassium, sodium and magnesium, the ash is relatively refractory and has a low propensity for slagging and fouling. Straw ash, like most biomass ashes, is not composed of alumino-silicates but of quartz and salts of potassium, calcium, magnesium and sodium, principally phosphates, sulphates and chlorides. These ashes would have fusion temperatures in the range 750–1000°C compared with fusion temperatures well in excess of 1000°C for coal ash and are hence much more likely to cause slagging and fouling. The properties of the wood ash are similar to those of straw ash. Though the data in Table 6 are not atypical for coal, straw and wood, the levels of these components in other coal and biomass fuels can vary widely. When biomass is cofired with coal in low-to-medium cofiring ratios, the behaviour of the resulting ash will be determined mainly by the behaviour of the coal ash. A key reaction that needs to be considered is the release of volatile species as described in the section above, such as alkali metals and phosphate compounds at flame temperatures and their subsequent deposition on boiler surfaces and on surfaces of ash particles and deposits. During the investigations conducted at the 150 MWe pulverised coal fired boiler at the Studstrup power during straw/coal cofiring trials with up to 20% straw on a thermal basis, the main effects of cofiring on deposition were associated with release of potassium species into the vapour phase and their subsequent condensation. Mineralogical analysis of fly ash and deposit specimens showed a considerable increase in the concentration of potassium aluminosilicates formed by the reaction at high temperatures of condensed potassium species and the aluminosilicate constituents of the ash.

5.4 High level biomass cofiring

In 2005, RWE npower and Imperial College, London began a two-year study into the effects of high level biomass cofiring on slagging and fouling. The project aimed to provide boiler operators with greater confidence in using higher levels of biofuel replacement (50% or more on a thermal basis) with the specific objectives of:

- identification of the main areas of the boiler at risk if biomass is cofired with coal at 50% or more of thermal replacement;
- determination of the nature of deposits likely to form in the radiant and convective passes of the boiler.

Measurement of the physical and mechanical properties of the deposits to determine thermal shock and sootblowing properties;

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Coal ash, %</th>
<th>Straw ash, minimum %</th>
<th>Straw ash, maximum %</th>
<th>Wood ash, typical %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>59.8</td>
<td>19.7</td>
<td>38.9</td>
<td>10</td>
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<tr>
<td>Al₂O₃</td>
<td>19.1</td>
<td>0.24</td>
<td>0.52</td>
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</tr>
<tr>
<td>Fe₂O₃</td>
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</tr>
<tr>
<td>CaO</td>
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<td>35</td>
</tr>
<tr>
<td>MgO</td>
<td>1.7</td>
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</tr>
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<td>Na₂O</td>
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</tr>
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<td>P₂O₅</td>
<td>0.2</td>
<td>2.45</td>
<td>3</td>
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<td>SO₃</td>
<td>2.1</td>
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<td>12</td>
</tr>
<tr>
<td>Cl</td>
<td>&lt;0.1</td>
<td>4.55</td>
<td>7.06</td>
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</table>

Table 6 Ash data from Studstrup cofiring trial (van Loo and Koppejan, 2003)
development of a model to predict the thermal impact of fouling deposits and to optimise sootblowing operations;  
- assessment of the use of low-cost additives to mitigate the effects of alkali metal fouling from biomass residues;  
- a technical and economic assessment of the viability of high levels of biomass cofiring, including recognition of current CO2 abatement levels and other environmental constraints.

One of the key concerns in cofiring high levels of biomass has been the impact that high concentrations of biomass ash would have on the nature of the ashes produced and the effects on boiler operation in particular the impact of the alkali metal species present in the biofuels. UK experience in fouling has essentially been restricted to the impact of sodium.

Laboratory-scale trials were undertaken at Imperial College using an Entrained Flow Reactor (EFR) which has a well proven track record in coal and coal ash characterisation activities. Rig-scale trials were undertaken by RWE npower using the Combustion Test Facility (CTF) located at Didcot and this again has a well proven track record in coal combustion trial activities. The CTF is modelled on the flue gas path of a typical 500/660 MWe boiler and creates with its single horizontal burner a time-temperature history representative of a middle row burner in a full-scale boiler and with peak temperatures similar to a burner surrounded by other burners.

Un-cooled ceramic coupons were inserted into the flue gas stream at positions representing the pendent superheater nose level of a two-pass boiler and these were used to establish the deposition behaviour of the ash in the flue gas steam of each trial.

Analysis and characterisation of ash and deposits was undertaken by Imperial College using a number of techniques including Scanning Electron Microscope (SEM) and X-ray Diffraction (XRD).

Four main categories of biomass fuels were studied during the work, specifically:  
- Short Rotation Coppice (SRC);  
- Miscanthus;  
- Palm Kernel Expeller (PKE);  
- Forest Residues and Wood Pellets.

The ash contents and compositions for the four biomass fuels are given in Table 7.

The ash deposition/slagging tests showed a general increase in the rate of slagging with the use of ‘oily’ types of biomass such as olive residue and PKE. Typically, for 15% olive residue mixed with a South African coal, the deposition rate rose by approximately 20% from 10 kg/h/m² to around 12 kg/h/m². In the case of ‘dry’ biomasses, such as wood, the deposition rate reduced slightly from 10 kg/h/m² to around 9 kg/h/m² when firing 25% biomass in the fuel mix.

Over a range of trials using South African coal with wood, olive residues and PKE, the ash deposits were found to be medium to strongly sintered in the temperature range 1000–1200°C. By comparison, for the same temperature range, the resulting slag from a ‘coal only’ test would be described as light to medium sintering.

The impact of slagging was assessed as a function of temperature and both ‘dry’ and ‘oily’ biomasses were found to increase the level of concern when compared with straight coal firing. In the case of South African coal mixed with 40% wood, slagging appeared to become an issue of concern when flue gas temperature rose above 1180°C. By comparison the same level of concern was reached for a 15% olive residue mix with South African coal at approximately 1150°C.

Figure 12 demonstrates the dramatic effect adding a small amount of biomass can have on deposit morphology where the normally friable ash deposits have sintered and melted to coat the test coupon.

### 5.5 Cofiring with wood and garden waste

Australian workers undertook a series of pilot-scale...
coal/biomass cofiring combustion experiments, funded by CCSD, under pilot-scale conditions in a 150 kW boiler simulation furnace in the ACIRL facility (Zulfiqar and others, 2006) Four types of domestically utilised Australian coals and three types of biomass fuels were used in the tests. The objective of the combustion study was to investigate the impact of coal and biomass types, biomass blending ratios, biomass moisture content and biomass size on boiler operation.

The design of the ACIRL boiler simulation furnace (BSF) (see Figure 13) is such that it can realistically simulate the combustion and heat transfer processes occurring in a full-scale pulverised fuel boiler.

The BSF system consists of:
- a weight belt feeder to give the required coal feed rate;
- electrical air heaters for heating the primary and secondary air;
- a variable swirl burner;
- five view-ports along the furnace wall for visual observation;
- two thermocouples for measuring temperature in the near burner and tunnel exit zone;
- three water-cooled slagging panels (200 mm²) in the furnace zone, for simulating furnace ash deposition (slagging);
- a convective tunnel, fitted with air-cooled probes to simulate superheater tubes, which allow an evaluation of the impact of ash deposition on the convective zone (fouling);
- a flue gas analysis train for measuring CO₂, CO, NO, SOx and O₂
- a pilot-scale electrostatic precipitator system, which consists of four tubular stages with interconnecting ductwork.

Four domestically utilised Australian coals were used as the basis for the study and were fired in combination with three types of biomass: softwood (pine), hardwood (eucalyptus) and urban green waste. Both woody biomass types were obtained as representative of a tree, which includes wood, bark and leaves. All biomass samples were in the form of chips, which had been prepared in a 500 kg/h capacity Raymond-type vertical spindle mill. Urban green waste is basically household garden waste, which contains a lot of dirt (and is therefore high ash). A total of 19 sets of experimental runs were conducted to investigate the variation in biomass (types, blending ratio and moisture contents) and the use of different coals on the boiler operation. The proximate analyses of the coals and biomass are given in Table 8, while the corresponding ultimate analyses are given in Table 9.

Slagging panels in the ACIRL facility were used to simulate ash deposition on the radiant section of a boiler. Overall, the deposits formed on slagging panels were typically thin (less than 6 mm), covered the whole plates and were easily removed. A sintered layer formed in scattered areas on top of a powdery base layer on the top and middle slagging panels. No molten deposits were observed. The ash deposits formed from the combustion of all of the samples were found to be relatively harmless. Although, in the case of Lithgow coal, some deposits formed sintered materials, the ease of removal indicated that these deposits were of little concern. Based on the samples collected and the observations made, the slagging deposits developed during combustion of all coal and samples should easily be removed by standard sootblowing practices.

Fouling probes were introduced only for the last experiment of each day. This approach was adopted to minimise the impact of consecutive experiments on each other as the fouling probes, unlike slagging panels, were not fitted with thermocouples for heat transfer flux measurements. The growth of fouling deposits throughout the duration of the test was recorded digitally by taking photographs through a viewing port adjacent to the first bank of fouling probes. Further analysis of the fouling deposits indicated that for all experiments the deposits were very brittle and could be easily crushed and removed. This in turn indicates that in a full-scale
operation fouling deposits can be removed by standard sootblowing equipment if available.

The following conclusions were drawn from this research:

- the application of cofiring has environmental potential at moderate cofiring levels (10% on a mass basis);
- the application of cofiring has economic potential at low cofiring levels mass basis;
- most problems reported in the literature are usually the result of using inappropriate equipment;
- PF boilers are viable options for low-percentage cofiring (≤10%);
- cofiring of wood-based materials in PF boilers is typically limited by pulveriser performance which depends on the type of biomass;
- cofiring of 7–10% (mass basis) in PF boilers may require a separate feeding system;
- combustion penalties involved in low-level cofiring are relatively slight and can be overcome by careful design.

5.6 Cofiring with switchgrass

In certain parts of the USA, switchgrass, Panicum virgatum (SWG), which is a native Iowa grass that grows well on marginal ground, has been considered a promising biomass fuel for co-combustion. The most important elements with respect to deposit formation and corrosion introduced by cofiring SWG are potassium and chlorine. The content of these elements varies much in SWG, but especially in the early harvest. SWG has a significantly higher content of K and Cl than the Powder River Basin coal used at the plants where switchgrass has been cofired. Chariton Valley Conservation Reserve and Development Inc (CVRCD) plan to grow up to 200,000 tonnes of SWG annually, and by cofiring the biomass at the Alliant Energy’s coal-fired power plant Ottumwa Generating Station (OGS) up to 5% of the annual coal consumption could be replaced. As part of the Chariton Valley Biomass Project (a federally cost-share funded project coordinated by CVRCD) several cofiring tests have been conducted, and the goal is a commercial system with a full design capacity of 22.7 t/h, generating ~35 MWe of power from renewable energy sources (Chariton Valley Biomass Project, 2008).

The first test campaign was performed from November 2000 to January 2001 with non-commercial SWG handling equipment. The aim of the first test was to observe the effects on the boiler operation and emissions and to study the handling of the SWG. It was shown that cofiring of up to 15.2 t/h – corresponding to a heat input of about 3% – is feasible without adverse operational problems. From November to December 2003, the project’s Interim Cofiring Test was completed. The purpose was to test and improve the processing equipment, to verify the emissions and performance information obtained during the first test campaign and to collect and characterise coal, SWG and ash samples. The paper described the findings with respect to corrosion and deposition during the project’s third and final test burn, a 2000 consecutive hour continuous test burn of SWG cofired with coal in the OGS boiler. The test burn was conducted from February to May 2006, and 1675 hours of operation were achieved burning around 15,650 tonnes of

### Table 8 Proximate analysis of coal and biomass samples (Zulfiqar and others, 2006)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Proximate analyses (wt% air-dried)</th>
<th>Moisture</th>
<th>Ash</th>
<th>Volatile matter</th>
<th>Fixed carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal A (Lithgow)</td>
<td></td>
<td>2.1</td>
<td>22.8</td>
<td>29.5</td>
<td>45.6</td>
</tr>
<tr>
<td>Coal B (Acland)</td>
<td></td>
<td>2.8</td>
<td>23.6</td>
<td>38.4</td>
<td>35.2</td>
</tr>
<tr>
<td>Coal C (Tarong)</td>
<td></td>
<td>3.1</td>
<td>29.8</td>
<td>26.0</td>
<td>41.1</td>
</tr>
<tr>
<td>Coal D (Collie)</td>
<td></td>
<td>18.9</td>
<td>5.4</td>
<td>30.5</td>
<td>45.2</td>
</tr>
<tr>
<td>Softwood</td>
<td></td>
<td>7.6</td>
<td>5.5</td>
<td>66.9</td>
<td>20.0</td>
</tr>
</tbody>
</table>

### Table 9 Ultimate analysis of coal and biomass samples (Zulfiqar and others, 2006)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Ultimate analysis (wt% dry ash free)</th>
<th>C</th>
<th>H</th>
<th>N</th>
<th>S</th>
<th>O (difference)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal A (Lithgow)</td>
<td></td>
<td>84.0</td>
<td>5.85</td>
<td>1.90</td>
<td>0.84</td>
<td>7.4</td>
</tr>
<tr>
<td>Coal B (Acland)</td>
<td></td>
<td>82.2</td>
<td>7.1 6</td>
<td>1.13</td>
<td>0.58</td>
<td>8.9</td>
</tr>
<tr>
<td>Coal C (Tarong)</td>
<td></td>
<td>83.0</td>
<td>5.52</td>
<td>1.51</td>
<td>0.39</td>
<td>9.6</td>
</tr>
<tr>
<td>Coal D (Collie)</td>
<td></td>
<td>75.8</td>
<td>4.75</td>
<td>1.37</td>
<td>0.45</td>
<td>17.6</td>
</tr>
<tr>
<td>Softwood</td>
<td></td>
<td>52.8</td>
<td>6.03</td>
<td>0.54</td>
<td>0.07</td>
<td>40.6</td>
</tr>
<tr>
<td>Hardwood</td>
<td></td>
<td>50.9</td>
<td>6.01</td>
<td>0.22</td>
<td>0.03</td>
<td>42.8</td>
</tr>
<tr>
<td>Urban green waste</td>
<td></td>
<td>53.0</td>
<td>6.1 6</td>
<td>0.76</td>
<td>0.09</td>
<td>40.0</td>
</tr>
</tbody>
</table>

These tables provide the proximate and ultimate analysis of coal and biomass samples.
In addition, a coal only reference test was carried out in July 2006. The third test burn was intended primarily to assess long-term impacts of burning SWG in the OGS boiler.

As part of the Chariton Valley Biomass Project, measurements were conducted at a 725 MWe coal-fired power plant in order to assess the long-term influence of switchgrass cofiring on deposition and superheater corrosion. Altogether, the investigation revealed that cofiring with up to 5 wt% switchgrass only influenced the deposition behaviour and the corrosion mechanisms marginally. Tests with deposit probes indicated that the deposition fluxes and the deposit chemistry in the superheater region were virtually unchanged by switchgrass cofiring. No indications of increased contents of alkali chlorides in the deposits were found. Samples of fly ash collected during cofiring tests also showed no increase in the chlorine content compared to coal reference ash. However, a minor increase in the potassium content was observed.

Analysis of corrosion test tubes exposed for 1675 hours of switchgrass cofiring further revealed that the corrosion behaviour was largely unaffected by the increased chlorine and potassium inputs. No chloride was present in the inner deposit or the corrosion products. On the contrary, sulphur was found to play a dominant role in the corrosion mechanism. The input of sulphur with the switchgrass compared to that of the coals is negligible. During discussions with industry commentators, the observation was made that biofuels which pose potential risks of increased deposition through their higher alkali contents are generally those where the concentration of trace elements has been enhanced through the use of fertilisers (Tillman, 2008).

### 5.7 Summary

The cofiring of other fuels with coal, especially biomass represents the one of the biggest challenges to power plant operation in the last fifteen years. A large number of fuels have been studied at laboratory, pilot and full scale and are now in regular use in operating plants. The ash chemistry of these alternative fuels is often very different to that of the coals routinely used and has given rise to serious problems, particularly in the early days of cocombustion. The alkali metals are particularly important in deposit initiation and growth and care has to be taken when selecting biofuels and establishing the appropriate levels of cocombustion. However, the widespread practice of cofiring has demonstrated that these problems can be overcome, with minimum ash-related impact on plant operation.
The quantity and quality of internationally traded coals has changed markedly over the last fifteen years. By 2006, seaborne coal trade reached an estimated 765 Mt (SSY, 2007), roughly 15% of the world supply. Australia was the largest exporter of hard coal (steam and coking), although in the steam coal market alone Indonesia was the largest (see Figure 14). The total split of seaborne trade comprised 563 Mt of steam coal and 202 Mt of coking coal.

In addition to the prime steam coals that have long been traded, a significant quantity of the so-called ‘battle coals’ became available in the mid-to-late 1990s. They have properties that would previously have made them unattractive to utilities, but have a commercially attractive price. These coals may have high sulphur contents and be rich in the ash components that increase the likelihood of slagging and fouling problems. Nevertheless, many utility operators have developed strategies to use these coals, while minimising their plant impacts.

### 6.1 Dutch experience

Increasing competition in electricity markets, and the need to reduce costs, inspired changes in the coal purchasing policies of European utilities earlier in the 1990s. The case of the Dutch utility GKE, reported in the IEA’s report International Coal Trade – The Evolution of a Global Market (IEA, 1998), is a good example. GKE coined the term ‘battle coals’ to express the programme of procuring a wider range of lower cost coal types and developing the capability in Dutch power stations to use these coals acceptably. Flexibility was considered to be the key to this strategy and was facilitated by the establishment of large stockpiling and blending capacity and, as necessary, last minute coal purchasing. As the IEA report observed, this strategy involved risk-taking and GKE itself accepts that stocks may run low and problems may be encountered with the quality of the blend, including problems of slagging and fouling. Dutch workers carried out a programme of work on ways of utilising ‘battle coals’ on an economic basis. ECN undertook a study on the ash behaviour of selected low quality battle coals for pulverised fuel fired boilers (Korbee and others, 1999). The study was run in parallel to a test programme supported within the International Energy Agency Coal Combustion Sciences Programme, annex 2 part 4, addressing the combustion behaviour of these coals. A suite of coals and blends, varying in rank from medium-volatile bituminous to subbituminous, was selected in consultation with the Dutch electricity producers and extensively analysed, focusing on ash composition. Relatively high levels of the elements Ca, Mg, Fe, Na and K were found in these coals. The speciation of the inorganic constituents in terms of mineral composition and size distribution was determined by means of Computer Controlled Scanning Electron Microscopy (CCSEM). Single coals as well as binary blends were fired in a 2.5 MWth boiler furnace simulator, and ash and deposit samples were collected for offline analysis and evaluation. The results were expressed and ranked in terms of slagging and fouling propensity for each coal, and have been compared with the outcome of a considerable number of commonly used predictive ash deposition indices. Observations of significant slagging or fouling were in many cases related to the presence of alkali and alkaline earth metals, which were often ill-predicted due to the occurrence of mineral interactions. Selected tests were also undertaken in a laboratory-scale combustion simulator under well-defined (low NOx) conditions to elaborate further on the prevailing ash deposition mechanisms. The observed mechanisms were generalised into three classes in order to allow a certain extension of the conclusions towards new, similar fuels. From these mechanisms, guidelines were derived for coal blending aiming to reduce ash deposition problems. The methodology of laboratory-scale fuel testing to evaluate in advance their potential to induce or enhance typical ash-related problems – here slagging and fouling –...
The international coal market

Slagging and fouling in coal-fired boilers

was extended to an integral assessment of ash behaviour and ash quality for utilisation options.

In a supporting study, KEMA undertook an evaluation of several coals and coal blends in a drop tube furnace where the fuel particles are burned and the ash particles travelled with the resulting flue gases through zones of progressively lower temperatures (Gast, 2003). Under these conditions the moderately volatile elements in the flue gas are able to condense on the surface of the ash particles. Chemical analysis of these ash samples was performed and the bulk composition of the ash was determined as well as the composition of the surface layer of the ash particles. These analytical results were evaluated and these samples showed a marked difference between bulk composition and the composition of the surface layer of the particles (see Table 10).

The surface layer of the deposit was enriched in alkali metals and sulphur and depleted in silicon content. From these results it was clear that this preparation method delivered ash samples comparable to the ash produced in a full-scale boiler and therefore suitable for the evaluation of the slagging and fouling behaviour. Subsequently, coal blends were prepared by using blend percentages of 100/0; 75/25; 50/50; 25/75 and 0/100. These fuel blends were fed to the drop tube furnace and the resulting ash was collected. For the determination of the slagging and fouling propensity of the ash samples a simple experimental method was chosen. The procedure consisted of sintering the ash samples at 1100°C in alumina cups. Thereafter the hardness of the sintered ash samples was determined using a EquoTip hardness measurement. With this method a small steel marble is projected onto the surface of the sintered sample and the degree to which the marble recoils from the surface is registered. As the method is only comparative way, the measurements are given in (arbitrary) units produced by the EquoTip equipment.

The results of these sintering experiments are shown in Figures 15 to 18.

<table>
<thead>
<tr>
<th></th>
<th>El Cerrejón</th>
<th>Eagle Butte</th>
<th>Ulan</th>
<th>Polish coal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>surface</td>
<td>bulk</td>
<td>surface</td>
<td>bulk</td>
</tr>
<tr>
<td>MgO</td>
<td>1.5</td>
<td>2.2</td>
<td>2.8</td>
<td>5.7</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.2</td>
<td>0.85</td>
<td>2.7</td>
<td>1.8</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>7.3</td>
<td>9.6</td>
<td>5.6</td>
<td>5.0</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.3</td>
<td>0.85</td>
<td>2.2</td>
<td>1.0</td>
</tr>
<tr>
<td>CaO</td>
<td>4.6</td>
<td>3.7</td>
<td>13.9</td>
<td>24.2</td>
</tr>
<tr>
<td>K₂O</td>
<td>2.7</td>
<td>1.85</td>
<td>2.5</td>
<td>0.2</td>
</tr>
<tr>
<td>SO₃</td>
<td>5.2</td>
<td>3.5</td>
<td>8.6</td>
<td>16.1</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>3.2</td>
<td>0.20</td>
<td>3.1</td>
<td>0.7</td>
</tr>
<tr>
<td>SiO₂</td>
<td>51.0</td>
<td>59.2</td>
<td>42.2</td>
<td>29.6</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>21.2</td>
<td>18.0</td>
<td>16.4</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Table 10 Chemical composition of the surface layer and of the bulk of four ash samples prepared in the KEMA drop tube furnace (wt%) (Gast, 2003)

![Figure 15 Sintering strength of ash samples originating from blends of El Cerrejón and Eagle Butte (Gast, 2003)](image)

![Figure 16 Sintering strength of ash samples originating from blends of Eagle Butte and Ulan (Gast, 2003)](image)
It appeared that for two of the four series blend compositions, a marked non-linear sintering behaviour was found. Figure 16 shows the blends of Eagle Butte and Ulan. The blend with only 25% of Eagle Butte with 75% Ulan has a sintering strength equal to that of 100% Eagle Butte. In Figures 15 and 17 (blends that also contain Eagle Butte) the trend of changes in sintering behaviour with blend ratio is almost linear. In Figure 18 a mixture of 75% El Cerrejón with 25% Polish coal appears to have a minimum sintering strength. In this case the interaction between the ash constituents appear to have a positive effect with respect to slagging and fouling propensity.

These examples are a good demonstration of the non-linear behaviour of coal blends with respect to slagging and fouling. The availability of a test method to reveal this type of behaviour for blends of different fuels is very important as it will provide plant operators with an early warning of possible concerns that might manifest when new low-grade fuels have to be utilised.

Despite the promising premise of the ‘battle coals’ initiative, by the start of the new century many of the utility companies had moved away from these fuels and back towards more routinely traded steam coals.

6.2 Summary

The huge growth in demand for internationally traded coals for the power generation and steel-making markets over the last fifteen years has led many coal exporting countries to concentrate on providing the best quality indigenous coals for export. This has led to a steady reduction in the quality of coals used internally for power generation with consequential increases in coal quality-related incidents such as slagging (Falcon, 2008; Wall, 2008). Even countries with large coal reserves such as China are experiencing a decline in coal quality as the premium coals are steered towards the steel making market (Hough, 2008).

Huge growth in the international coal trade and an increase in the price of traded coal has led to changes in coal procurement. An initiative by the Dutch utilities to define a strategy for using very low quality coals (‘battle coals’) generated a great deal of know-how on using these fuels. A trend in the major coal-exporting countries towards high quality coal for export has led to the increased use of low-grade domestic coals for power generation, and this has sometimes been accompanied by an increase in ash problems.
This chapter looks at the role of computer controlled scanning electron microscopy (CCSEM) and computer modelling in understanding slagging and fouling.

### 7.1 CCSEM

An important step in the understanding of the mechanisms of slagging and fouling has been the development of computer controlled scanning electron microscopy (CCSEM). CCSEM enables a researcher to acquire knowledge of the mineral forms present and the distribution of inorganic species responsible for a coal’s ash deposition behaviour. CCSEM provides data on the size, association, composition and abundance of mineral components in coal. It can also be used to study the inorganic constituents in chars, fly ash and deposits. Thus CCSEM can follow the changes in the size, chemistry and shape of the mineral grains through the various stages of combustion to fly ash formation. One advantage of the CCSEM technique over the more conventional methods of coal mineral analysis, such as those described by ASTM and other standards organisations, is that it avoids the need for the separation of the mineral matter from the coal by low temperature ashing. Therefore the inherent problems of transformation and reaction of mineral matter are eliminated. Many complete CCSEM systems are commercially available, incorporating all the necessary computer hardware and software and the technique has become an established tool in understanding ash deposition issues.

Gibb and others (1994) reported the findings from a British collaborative research programme addressing all aspects of slagging in bituminous coal fired boilers. He advanced a new slagging index that was designed to take into account the distribution of mineral matter in a coal sample, and hence the likely degree of assimilation of the fluxing oxides CaO and Fe₂O₃ into an aluminosilicate glass. The proposed index was based on CCSEM analysis of the coal to provide data on the composition and size distribution of the mineral-matter particles present. On the assumption that all of the calcium in the coal was assimilated into the glass, it was assigned an effectiveness of 1.0 as a fluxing agent. For iron it has been shown that the proportions of the iron minerals present that are involved in coalescence is variable, and will depend on the size and distribution of the minerals within the coal. The predominant form of iron in the coals studied was pyrite. It was assumed that iron in pure pyrite particles has an effectiveness of 0.5, and any iron in a clay/pyrite mix has an effectiveness of 0.5–1.0 depending on the amount of clay present in the mix. The CCSEM index was thus defined as follows:

\[
\text{CCSEM index} = S \frac{\text{all mineral occurrences}}{(\text{Mass fraction} \times (\text{CaO} + \text{Fe}_2\text{O}_3 \times (1-0.5 \times (\text{Fe}_2\text{O}_3 / (\text{Fe}_2\text{O}_3 + A\text{l}_2\text{O}_3 + Si\text{O}_2)))))}
\]

Since the key basic oxides in calculating the base/acid ratio are CaO and Fe₂O₃, the CCSEM index is similar in concept.

A plot of base:acid ratio against CCSEM index (see Figure 19) gave fair correlation, with interesting discrepancies that highlight the differences between the indices. The outlying values are ascribed to differences in Ca:Fe ratio and the proportion of pyrite present in the coal as mixed pyrite/clay occurrences. For example the CCSEM-based index predicts that the high calcium-content and high-Ca:Fe coals (Asfordby and Daw Mill) have higher slagging propensities than indicated by the base/acid ratio. Conversely the CCSEM index for Oxcroft is lower than that indicated by the base:acid ratio, due to the low Ca:Fe ratio and relatively small proportion of pyrite present as mixed pyrite/clay occurrences. The CCSEM index placed the three main test coals in the following order of slagging severity: Bentinck (9.6) < Silverdale (15.2) < Daw Mill (17.3). This prediction agreed well with the nature of the slagging observed during the trials at the Ratcliffe power station, where Daw Mill coal gave the most fluid deposits and Bentinck coal gave the least (see Figure 19).

In another study Liu and others (2006) used a CCSEM-based system, called QEMSCAN to study ash formation from the excluded minerals (outside the carbonaceous material) in three Australian black coals selected to represent a wide range of mineralogical composition (Liu and others, 2006). Excluded minerals behave differently from included minerals and at the time of publication little work had been reported on the mineral associations in an excluded mineral grain; that is, an excluded mineral grain consisting of more than one mineral phase. Liu and others (2006) have attempted to study the transformations of excluded minerals with considerations of mineral-mineral associations. Three Australian coals with various mineral compositions were burned in a laboratory furnace at a temperature of 1400°C. Ash particles were collected by a cyclone located at the outlet of a quench probe and the mineral matter in coals and ash collected were analysed by QEMSCAN. Mineral association of quartz with

![Figure 19 The relationship between the base/acid ratio and the CCSEM derived index (Gibb and others, 1994)](image-url)
kaolinite has been positively identified in excluded minerals in coals, and ash particles also support such association. However, mineral association of quartz with carbonates is not a common occurrence in the coals investigated.

Although a very useful analytical tool, CCSEM produces a huge amount of data. It has proved a challenge to find an informative way to present that data, and to use it in more accurate predictions of ash behaviour. Graphical representation of CCSEM data often unveils trends and correlations in a user-friendly manner and the information, which usually is difficult to extract from tables, can be easily displayed and understood. CCSEM analyses are also very expensive and are not therefore routinely used by utility personnel.

### 7.2 Modelling

One of the major developments that has occurred since the last full IEA review of slagging and fouling has been the growth of powerful, low-cost computing facilities. These have impacted on many areas of the science, from laboratory modelling of deposition processes, through complete modelling of fuel-related boiler impacts to ‘intelligent’ automatic cleaning systems.

Previous modelling packages used by utility companies to assess fuel-related impacts include the Coal Quality Impact Model (CQIM) and Coal Quality Expert (CQE). The Coal Quality Impact Model (CQIM), was developed by Black & Veatch for the Electric Power Research Institute (EPRI). The company has recently announced a new coal quality impact model based on CQIM but developed to meet the changing needs of the electric generation industry. This new model, Vista, expands the capability of CQIM and uses equipment-specific engineering models rather than generic correlations to evaluate performance impacts. Predictions are based on equipment configuration and component information coupled with detailed calibration data supplied by the user. Vista incorporates detailed predictive performance models for all equipment affected by coal quality, including a detailed steam generator heat transfer model. Maintenance and availability costs are determined with a detailed component/failure model sensitive to coal quality effects on performance and failure rates. Derates are analysed using a Monte Carlo simulation. All models employ calculations based on empirical formulas and include the impacts of changes in performance of one system or component on another.

The primary benefit of Vista evaluations is to provide the user with total fuel-related costs for alternative coals, on a system-by-system basis, via a summary of projected with total fuel-related costs for alternative coals, on a system-by-system basis, via a summary of projected.

RMT SmartBurn and the University of North Dakota Energy and Environmental Research Centre (EERC) have developed an ash behaviour prediction tool to assess slagging and fouling in coal-fired boilers called AshPro. The development of this tool combines EERC’s coal ash behaviour expertise and RMT SmartBurn’s expertise in combustion, CFD modeling and boiler operation. AshPro claims to integrate ash behaviour models including ash formation, transport, deposition, and growth with boiler CFD simulations (Vásquez and others, 2004). A claimed advantage of AshPro is that it can be used to evaluate the localised slagging and fouling problems that are related to actual operating conditions. Therefore, it can be used to identify the major causes of ash deposition so that measures to reduce the problem can be implemented.

The EERC developed an ash transformation (ATRAN) computer model, which is a sub-module of AshPro, to predict the PSCD (particle-size and composition distribution) of ash produced during the combustion of coal (Steadman and others, 1990; Zygarlicke and others, 1999; Yan and others, 2001). This technique uses advanced analytical characterisation data, boiler parameters, and a detailed knowledge of the chemical and physical transformations of inorganic components during combustion to predict the PSCD of the resulting ash. The PSCD of the ash directly impacts deposit growth, deposit strength development, and ash collectability. The transport of intermediate ash species (that is inorganic vapours, liquids, and solids) is a function of the state and size of the ash species and system conditions such as gas flow patterns, gas velocity, and temperature. The primary mode of particle transport to heat-transfer surfaces is inertial impaction. The PSCD of ash predicted by ATRAN sub-module of AshPro is incorporated with a boiler CFD model to simulate ash particle transport behaviour and to estimate ash impaction rates on boiler heat transfer surfaces.

The combination of the CFD and ATRAN models provide predictions of ash impacting on the furnace walls, the particle temperature and velocity, and PSCD. AshPro was applied to a 512 MW tangentially-fired boiler at Wisconsin Power & Light’s Columbia Energy Center to evaluate the localised slagging on furnace walls and fouling in convective pass (Ma and others, 2006). The predicted boiler ash deposition pattern is reasonably consistent with that observed on the furnace walls and super heater division panels. The prediction of slag state transition (solid/liquid) through deposit viscosity was verified by the observation in the plant (see Figure 20).

In 2003 a consortium of workers headed by the University of Stuttgart reported on the development of a predictive model ‘SLAGMOD’ for ash deposits (University Stuttgart, 2005). The model is based on thermodynamic principles and monitors the heat transfer in a boiler. The modular structure of the model makes it useful as a tool for detecting and analysing local slagging and fouling deposits and is also claimed to have value as a ‘soft sensor’ to analyse varying fuel quality. Parallel
fuel and ash measurements can be correlated and compared to the model simulation and give an insight into the deposition mechanism. During the development of SLAGMOD, a number of sub-models and gross plant models were developed: Dynamic boiler model (Fortran based) for the Uppsala boiler (USTUTT); Dynamic boiler model (ACM) for the Nyköping and the Uppsala boiler (TUD); Steady state boiler model (Fortran based) for the monitoring of Uppsala and Nyköping (IST); NTUA sub-models (radiation model, conduction model, deposit properties model and heat transfer model). During the winter of 2000-01 an extensive measurement campaign at two Swedish power plants was carried out to provide the necessary input data for the offline development and validation of the models. During this campaign the combustion temperature in the plants was measured continuously by acoustic pyrometry.

The use of CFD modelling for tracking and evaluating effects in boilers continues to grow and Reaction Engineering report a number of case studies where codes have been developed for investigating a number of plant impacts (Reaction Engineering, 2008). In addition to the examples cited above there seems to have been a significant increase in the number of proprietary modelling solutions, often closely tied to one utility company, or a specific boiler. These are developed in concert with a local academic institute, such as a university. Being proprietary, however, few details are published in the open literature and information is generally limited to a few lines in the appropriate trade publications.

### 7.3 Summary

CCSEM techniques have been developed for the detailed analysis of the mineralogical matter in coal. However, although undeniably a very useful analytical tool CCSEM analysis produces a huge amount of data. It has proved a challenge to find an informative way to present this data and to use it for more accurate prediction of ash behaviour. Graphical representation of CCSEM data often unveils trends and correlations in a user-friendly manner and the information which may be difficult to extract from tables can be easily displayed and readily understood.
This chapter looks at recent developments in remedial techniques for slagging and fouling issues. It covers coal cleaning, furnace configuration modifications, online boiler cleaning and other measures.

### 8.1 Coal cleaning

The preparation of run-of-mine coal for the power generation market concentrates principally on the reduction of associated mineral matter that gives rise to ash. However, the increasing pressure to reduce the environmental impact of coal use has focused attention on ways of removing the hetero species from coal that contribute to pollution. Sulphur is a prime concern and a considerable body of work has been carried out on its removal from coal. Sulphur removal techniques range from selective ‘washing’ to remove high concentrations of pyrite – the major source of sulphur in UK coals – to more advanced chemical and biological cleaning techniques. However, for all coal beneficiation techniques the reduction of one component inevitably means an increase in concentration for other components that are unaffected by the cleaning process. In ash reduction, it has been shown that the removal of ash often concentrates the elements iron, calcium and sodium and this can lead to an increased risk of slagging and fouling incidents, contrary to expectations (Suydam and Duzy, 1997).

For subbituminous coals where many of the hetero atoms are associated with the organic fraction of the coal, coal cleaning may be ineffective at reducing these species. The effects of coal cleaning on the performance of lignite coals have been studied by Durant and others (1989) and by Borio and others (1989) in a pilot-scale combustion test facility. Four Texas lignites (Big Brown, Sabine, South Hallsville, and Pirkey) and three eastern bituminous coals were also included in the second study. Coal cleaning was performed using wet separation methods, and the fireside performance of the cleaned coals compared with that of run-of-mine coal. Fuel and ash analyses indicated an overall 10% increase in the heating value of the cleaned lignite coals. There was a substantial reduction in ash content in the range of 25% to 50%, along with a small reduction in sulphur content due to the removal of pyrite.

Cleaning primarily removed extraneous silica and clay particles with a reduction in the alumina and silica content of the ash. Organically bound alkali and alkaline-earth elements such as sodium and calcium and fine clays were not removed by the cleaning process, nor was organic sulphur. The ash composition thus showed a relative enrichment of iron, calcium, sodium, and magnesium.

Coal cleaning may reduce the propensity of a coal to produce slagging or fouling deposits, but the effects of cleaning on the elements important in ash deposition must be considered carefully.

### 8.2 Furnace configuration modifications

The experience gained by the makers and operators of coal-fired power plant over many years of operation has been fed back into boiler design as part of a gradual evolution of more efficient plant with increased availability. Availability is of primary importance to a power utility as the costs of lost generation can be extremely high, as discussed earlier. A number of design modifications have been incorporated into the latest designs of plant, which are aimed at eliminating or minimising the production of slagging deposits.

Refractory surfaces in the furnace section of a boiler have long been known to be sites for the development of tenacious ash deposits. Recent developments in eliminating refractory surfaces include tighter tube bends around burner openings, thus reducing the amount of refractory cement needed to give an airtight seal (Hough, 2008). The ultimate aim is the complete elimination of refractory with a full membrane burner throat.

The platen, or pendant superheater tubes in a Benson boiler are perfectly suited for high gas temperatures but have always been a potential site for slagging owing to their position in the flue gas stream and the high tube and ash temperatures involved (see Figure 21). Ash deposits on the hot tube surface if the conditions are right begins to grow. As the ash bridges the space between the individual superheater tubes the deposits become consolidated and very difficult to remove. In extreme cases, explosive charges have been employed to remove such deposits.

As an example of attempts to reduce or eliminate these deposits, Doosan Babcock have developed superheater platens where the individual tubes are joined and held in line by a metal membrane of proprietary design that is capable of flexing to accommodate the stresses and strains as a boiler is cycled during normal operation. Since ash cannot bridge between the tubes, it remains on the surface where it is
amenable to removal by appropriate placed sootblowers. Figure 22 shows three central (hottest) superheater elements modified to include the membranes, after one week’s firing of a high ash, highly slagging South African coal. Following the success of this trial, all the elements were modified and the design is now a standard practice for new plants and retrofits.

8.3 Online boiler cleaning

Most coal-fired boilers have online cleaning devices, called sootblowers from the days when carbon deposits accumulated within boiler gas pathways and required cleaning. Sootblowers use a high pressure jet to remove ash deposits. The fluid used may be superheated steam, saturated steam, water or compressed air (Stultz and Kitto, 1992). Sootblowing systems require primary energy and resources and where steam is used as the cleaning medium, can impact on overall cycle efficiency.

Deposits are removed by a combination of thermal shock to induce fracture and high pressure to dislodge the ash deposit.

These considerations make it important to clean only as much as necessary. However, since fouling and slagging in the furnace as well as in the convective heat exchanger zone lead to a reduction in boiler efficiency and reduction in availability a balance must be struck between sootblowing too little and too much. Historically, sootblowers 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 (see Figure 23).

System inputs that can be used to determine sootblowing practice can include:
- an increase of furnace exit gas temperature;
- an increase of attemperator spray rate;
- an increase of boiler exit gas temperature.

Figure 22 Superheater platens at Matla power station, South Africa (Hough, 2008)

Figure 23 Intelligent sootblowing control structure and the location of blowers and sensors (Clark and others, 2005; Wicker, 2005)
Developments in remedial techniques

Damages in the hopper area and the wet/dry bottom ash system can result from large slag formations falling down from the furnace walls and superheaters and precipitate an unplanned boiler outage.

However, over-cleaning causes tube erosion/corrosion damage, induced high stress levels in tubes, shortening tube life, and may cause abrupt changes in localised heat transfer affecting thermal performance. It is therefore important for a modern on-load boiler cleaning solution to act flexibly but selectively. This means to clean:
- as early as necessary;
- as little as necessary;
- only in required areas;
- as effectively as required.

Case Study – Big Bend Power Station Neural Network-Sootblower Optimisation

In September 2001 a demonstration project for Neural Network Intelligent Sootblowing was selected for support by the US Department of Energy and was implemented on Unit Two at Tampa Electric Co’s (TECO) Big Bend Power Station. The demonstration project was administrated by the National Energy Technology Laboratory (NETL) and reported in September 2005 (US DOE, 2005).

The primary objective of the study was the demonstration of the Pegasus Technologies Neural Network-Intelligent Sootblowing System (NN-ISB), along with advanced instrumentation and water cannons, in optimising sootblowing on a 445 MW boiler, reducing nitrogen oxide (NOx) emissions by up to 30%, improving heat transfer rate by 2%, and reducing particulate matter (PM) emissions by up to 5%.

Heat flux sensors, slag sensors, and temperature profiling instrumentation were applied at key locations to provide real-time data to the NN-ISB, which interpreted the data through optimisation software developed to send appropriate signals to existing sootblower controls. Signals were sent only to the sootblowers in the specific section(s) of the boiler that required cleaning. The NN-ISB operated in a closed loop mode; that is the online system responded to real-time data and adjusted controls without the need of manual intervention from the plant operator (see Figure 24).

The sootblowers were activated by signals indicating that the heat transfer from the combustion process to the heat-absorbing surfaces in the boiler was being compromised to the point where NOx emissions and heat loss could rise to unacceptable levels. Activation was also influenced by opacity readings where ‘spikes’ in opacity measurements indicated that the PM control system was being overloaded, requiring earlier or sequential activation of sootblowers.

The specific conclusions from the demonstration were reported by the US DOE as follows:
- Unit efficiency contribution was calculated by means of the total Performance Efficiency Index, revealing an improvement of 10 kJ/kWh at high load to 50 kJ/ kWh at low load, when comparing the open loop to closed loop NN-ISB tests.
- When the closed loop NN-ISB was compared to the 2002 baseline year, improvements of 20 kJ/kWh at high load points to as much as 420 kJ/kWh at low load were observed. The project participant acknowledged, however, that several other operational conditions may have contributed to this success.
- NOx reductions recorded by the NN-ISB ranged from no measurable difference to 8.5% NOx reduction, compared to baseline conditions when using a variety of coal and unit operating conditions.
- Opacity measurements during the same period of NOx data acquisition indicated no measurable difference, while examination of the opacity trends during open loop

Figure 24 Configuration of Unit Two, Big Bend power station for optimised sootblowing (US DOE, 2005)
and closed loop operation indicated an improvement ranging from 1% to 1.5% during sootblowing activities.

An economic analysis of the project outcome suggested that there were two major potential savings from the installation of a NN-ISB system. The first was a reduction in coal usage as a result of an efficiency gain. The coal burned in Unit Two is estimated at one million tonnes per year, at a cost of 40 $/t. If an efficiency improvement of 1% could be achieved, this would decrease coal consumption by 10,000 t/y with a saving of 400,000 $/y. Furthermore, this efficiency improvement would result in a reduction of SO₂ and CO₂ emissions in direct proportion to the reduction in fuel consumption. The other potential saving was in the area of NOx reduction, which can be quantified by using the value of a NOx allowance on the emissions trading market. At an assumed heat rate of 10,000 kJ/kWh and a capacity factor of 60%, the NOx emitted from Big Bend Unit Two is estimated to be 7000 t/y. A 5% reduction in NOx emissions would eliminate 350 t/y of NOx. Assuming that the NOx cap and trade programme is available at the plant installing the NN-ISB system, and that the value of one NOx allowance is $2000, this would amount to an annual revenue for the plant of $700,000.

Case Study – Optimised furnace cleaning at the 600 MWe unit ‘G’ of RWE Rheinbraun power station at Niederaussem

The lignite-based utility power plants in the German Rhenish region were faced with a significant change in coal properties when the Hambach opencast mine became a major source of fuel. Lignite from the Hambach mine is characterised by a high calorific value with high iron and sodium contents which are known to be important components governing a coal’s slagging behaviour (Glaser and others, 2002). Additionally, the higher calorific value leads to higher combustion temperatures and, as a result, to increased furnace exit gas temperatures. The increased iron and alkali contents combined with silica lead to a reduction of the ash fusion temperatures. These two processes, especially in combination, caused considerable and heavy slagging on the evaporator walls and molten deposits on the first superheater banks of the convection section of the boiler. This development could be only partially countered by the adjustment of the coal feeding strategy, so that intensive formation of deposits was still observed in the radiant as well as the convection heating surfaces.

Unit ‘G’ at the Niederaussem power station was fitted with an extensive set of water cannons for the online removal of the deposits. Water cannon technology uses a concentrated water jet which impinges onto the opposite furnace wall heat transfer surfaces surface in the form of a meandering cleaning pattern which may be adjusted. However, it is usually pre-programmed with a specific pattern based on operational experience.

The cleaning mechanism for water cannon differs from that of sootblowers, which work with steam as the cleaning medium. Water cannons project a stream of water droplets, which penetrate the pores of the ash deposits. Sudden evaporation and expansion of the water takes place and, as a result the deposits are “exploded” from the heat transfer surface.

Figure 25 FACOS™ (Furnace Analysing and Cleaning Optimisation System)
(Seifried, 2005)

The success of the cleaning process depends on the optimum water penetration of the deposits. This is primarily influenced by parameters such as:

- jet progression speed on the opposite wall;
- impinging water quantity;
- impact angle of the water jet on the opposite wall;
- characteristics of fouling deposits, ie porous or slagged deposits.

As described above, the Water Cannon Technology constitutes the selected instrument for precise and defined cleaning of the evaporator walls. The non-homogeneous fouling conditions caused by the variable coal qualities make it necessary to control the use and the cleaning parameters of the Water Cannons in line with the boiler requirements. Clyde Bergemann has developed a sensor-based system, to detect the fouling in the furnace, which selectively determines the cleaning strategy. The related computer optimisation program initiates the necessary cleaning actions of the Water Cannons in line with the actual operating conditions and the individual fouling situation of the boiler. At the same time the system checks the cleaning success and automatically adjusts the relevant cleaning parameters.

The system works with real time heat transfer measurement collected by SMART Flux Sensors and thus clearly differs from other known optimisation systems for the convective part, which work with calculated thermodynamic parameters. The sensor-based optimisation system for the radiant heating surfaces is protected by patents of Clyde Bergemann and it is offered in Germany under the brand name FACOS™ (Furnace Analysing and Cleaning Optimisation System) (see Figure 25).

8.4 Other measures

In boilers where slagging is a marginal risk, benefits can be gained from setting limits on the boiler control settings (eg economiser oxygen level, burner tilt angle on a tangentially-fired boiler) to satisfy slagging constraints. However this can require a compromise in other operating
parameters such as NOx levels and heat rate and so changes are best carried out in a systematic study to establish the appropriate setting without compromising overall boiler performance.

Coating technologies may offer a cost-effective method to extend boiler tube longevity, improve heat transfer rate, reduce fireside corrosion, minimise slagging propensity, and avoid circumferential cracking in the new generation of supercritical coal-fired power plants. Full-scale demonstration projects, in which waterwall sections will be coated using various technologies and independently tested and evaluated, have recently commenced under the auspices of EPRI to assess these potential benefits (EPRI, 2008). Two or more waterwall sections in a candidate plant will be coated with selected materials to evaluate the potential for corrosion prevention and slag reduction. In addition, reduced sootblower operation and increased slag shedding occurrences will be evaluated to potentially reduce or mitigate circumferential cracking. Coatings technologies may include thermal sprays, ceramic, or other types with the potential to combat corrosion, erosion, and slagging. An inspection will be conducted every one to two years to assess the integrity of the coating. Samples will be removed and analysed in the laboratory by optical and photomicrographs, scanning electron microscopy (SEM), and energy dispersive spectroscopy analysis (EDAX).

8.5 Summary

Coal cleaning continues to be practised to improve coal quality, but care is still needed to consider the detailed impacts on coal chemistry. The gradual evolution of boiler designs has led to the identification of many modifications to the furnace configuration that make serious ash deposits less likely to form. Where ash is unavoidable, the previous generation of sootblowers operated manually according to local and sometimes variable practise has been replaced by units that clean based on the data from a sophisticated set of sensors through effective computer modelling of the effect of ash impacts.
Ash-related problems are clearly still of great importance to the operators of power plant. The costs of lost generation through, for example, a slagging and fouling incident are very high. This fact has continued to drive efforts to better understand the ash deposition process and to find effective remedial techniques.

Developments in the global coal-fired power generation sector continue to influence the subject in a number of ways. Increased competition between utility companies has led to the use of coals whose properties are often far removed from the coals specified for the original boiler design. The changing electricity market in many areas where the use of fuels other than coal (for example gas) has become widespread, has led to coal-fired plant being operated in some regions (for example OECD countries) under regimes other than base load. This change in operation has helped to reduce boiler slagging to some degree through the regular shedding of deposits as the boiler is thermally cycled.

The increasing pressure on coal-fired power stations to reduce emissions has led to the development of technologies for the abatement of specific pollutants that impact on ash slagging. Combustion modifications for NOx reduction are considered the most significant and have, through a trend towards larger furnaces and cooler flames, generally reduced slagging propensity. Where coal switching has taken place for sulphur control, low-sulphur coals have been used in boilers not designed for them, with consequent problems. The best example of this is the increased use of Powder River Basin coal in US plant, where the low cost, low sulphur characteristics provide a powerful imperative for solutions to any problems arising from their use.

An increased use of CFBC plants in the power generation market and are particularly effective with very low grade coals. The different combustion environment, compared to pulverised coal fired plant, gives rise to unique ash-related problems such as bed agglomeration.

The new generation of pulverised coal fired plant, designed for high efficiency through the use of high steam temperatures and pressures, present the greatest challenge with respect to ash slagging and fouling. These new plant are almost certain to be required to operate under conditions that allow carbon capture and storage, for compliance with climate change driven requirements. The leading technology for this is oxy-firing and represents a very substantial change to combustion conditions within the boiler. It is regarded by boiler manufacturers, users and academic researchers as warranting significant study to identify and ameliorate any issues arising from the new combustion environment.

The cofiring of other fuels with coal, especially biomass represents the one of the biggest challenges to power plant operation in the last fifteen years. A large number of fuels have been studied at laboratory, pilot and full scale and many are now in regular use in operating plants. The ash chemistry of these alternative fuels is often very different to that of the coals and has given rise to serious problems, particularly in the early days of cocombustion. The alkali metals are particularly important in deposit initiation and growth and care has to be taken when selecting biofuels and establishing the appropriate coal replacement levels for cocombustion. However, the widespread practice of cofiring has demonstrated that these problems can be overcome, with minimum ash-related impact on plant operation.

The huge growth in demand for internationally traded coals for the power generation and steel-making markets over the last fifteen years has led many coal exporting countries to concentrate on providing the best quality coals for export. This has led to a steady reduction in the quality of coals used internally for power generation with consequent increases in coal quality related incidents such as slagging. Even countries with large coal reserves such as South Africa and China are experiencing a decline in coal quality as the premium coals are steered towards export and the steel making market.

Huge growth in the international coal trade and an increase in the price of traded coal has led to changes in coal procurement. An initiative by the Dutch utilities to define a strategy for using very low quality coals (‘battle coals’) generated a great deal of know-how on using these fuels. A trend in the major coal-exporting countries towards high quality coal for export has led to the increased use of low grade domestic coals for power generation, and this has sometimes been accompanied by an increase in ash problems.

Coal cleaning continues to be practised to improve coal quality, but care is still needed to consider the detailed impacts on coal chemistry. The gradual evolution of boiler designs has led to the identification of many modifications to the furnace configuration that make serious ash deposits less likely to form. Where ash is unavoidable, the previous generation of sootblowers operated manually according to local and sometimes variable practice has been replaced by units that clean based on the data from a sophisticated set of sensors through effective computer modelling of the effect of ash impacts.

CCSEM techniques have been developed for the detailed analysis of the mineralogical matter in coal. However, although undeniably a very useful analytical tool CCSEM analysis produces a huge amount of data. It has proved a challenge to find an informative way to present this data and to use it for more accurate prediction of ash behaviour. Graphical representation of CCSEM data often unveils trends and correlations in a user-friendly manner and the information which may be difficult to extract from tables can be easily displayed and readily understood.

Although predictive models for slagging and fouling are now in wide use, they are not thought to be capable of predicting ash impacts with sufficient reliability in all cases. The
sub-models are thought to be at an advanced stage of development, but overall, model integration is still thought to require development. The prediction of ash impacts is generally thought to be more reliably achieved through a combination of predictive indices, models, historical information on coal and boiler performance and experience.
Slagging and fouling in coal-fired boilers

10 References


Benetech Inc 1851 Albright Rd. Montgomery, IL 60538, personal communication


Chariton Valley Biomass Project (2008) Several papers describing this work are available from:
http://www.iowaswitchgrass.com


