# POTENTIAL COST AND EFFICIENCY SAVINGS THROUGH IMPROVED MULTIPHASE APPLICATION IN UK FOSSIL-FIRED POWER GENERATION

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## SUMMARY

ETSU on behalf of the UK Department of Trade and Industry (DTI) has commissioned a study into potential cost and efficiency savings that may be gained through improved multiphase flow (MPF), application in UK fossil-fired power generation. The aims of this review were: -

- to survey MPF application in the UK fossil-fuel energy sector, paying particular reference to power generation.
- to identify key applications of MPF.
- to assess in which of these applications, further developments would lead to a potential overall energy, efficiency and/or cost savings.
- to estimate the potential energy, efficiency and/or cost savings in these applications.
- to identify the further developments which would lead to greater benefits.

To maintain a manageable database, the study has excluded tube-side steam-water flows, and also the oil/gas/water flows associated with oil and gas recovery.

The report contains a review of the current status of the UK fossil-fuelled power industry and how it has developed since privatisation. Important changes in the mix of fuels used to generate electricity since the 1970s have been highlighted and the prospects for the continued use of coal firing for power generation have been discussed.

Questionnaires were submitted to selected organisations within the power generation industry, UK universities and equipment suppliers. Power generators were asked to identify problem areas and any MPF activity with potential for cost and/or efficiency improvements. Universities were asked to identify their relevant past and possible future development projects. Possible applications of new technologies into the fossil-fired generating sector were also solicited. Equipment suppliers were asked for their views on equipment development in the present and future.

The response to and findings from the questionnaire were revealing. Despite the recipients being carefully screened for the study, the response was, with a few exceptions, poor. The opportunity by UK universities to identify and disseminate details of MPF and other relevant expertise was largely ignored. No attempts were made to suggest new applications for developing advanced technologies. Equipment manufacturers and computer software suppliers almost completely ignored the

questionnaire. Power generators were the exception and most provided valuable data, which served to confirm and strengthen existing views regarding their areas of concern.

The report contains sections that identify MPF techniques that occur in the fossil-fired generation business. It then focuses on those areas of particular interest to generators; specifically on how they might make cost and/or efficiency savings and where regulatory pressure for environmental improvement exists, such as the reduction in oxides of nitrogen (NOx). These include pulverised fuel (PF), flow measurement and control, low-NOx burners (LNB's), coal milling and classification, microfine particulate control, gaseous pollutants, improvements in electrostatic precipitator (ESP), performance, controls and instrumentation, air toxics, reduced ash deposition and corrosion and fly ash beneficiation.

Where possible the report attempts to quantify the cost and/or efficiency benefits associated with these topics. Where not possible, the reasons for this are described. Cost/benefit quantification is a particularly difficult topic given the very competitive nature of power generation in the UK at present. Although there are areas where cost and efficiency savings are possible, importantly, in many other areas, there is a regulatory requirement for action to be taken. These areas, where not optional, will incur extra costs for the generators.

The final section contains a series of recommendations for further research and development into MPF based on the findings of this report. It is felt that these are the areas where effort is most likely to be funded in the search for improvements to efficiency and cost reduction and for regulatory compliance.

The areas of expertise within UK universities are also discussed so that the appropriate contacts between the industry and academe can be forged if it does not already exist.

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# 1. INTRODUCTION

## 1.1. Background

The Implementing Agreement for the International Energy Agency's Collaborative Programme of Research on Fossil Fuel Multiphase Flow Sciences - Annex 1 was signed in April 1987 and has been further extended, first to March 1998 and then to March 2003. For the purposes of the Annex, the term 'Multiphase Flow' refers to any mass flow phenomena associated with obtaining energy from fossil fuels where matter is present in more than one phase, eg, solid, liquid, gas.

The programme is task-shared and is administered by an Executive Committee, which comprises a nominated member from each country. ETSU, a division of AEA Technology, is the Contracting Party for the UK.

The objectives of the agreement are as follows:

- to improve understanding of the fundamental behaviour and properties of MPF through theoretical studies as well as experimental data gathering and verification.
- to develop improved research instrumentation for gathering fundamental information on MPF.
- to provide participants with access to advanced research apparatus and research instrumentation not readily available in their own programmes.

The main activities in the aforementioned Annex 1 involved collaborative research work and information exchange on:

- the science dealing with the flow and deformation of matter in multiphase systems;
- development of mathematical models for prediction of transient behaviour, such as sudden changes in flow rate or start-up;
- complex geometry flows;
- steady-state flows;
- development of on-line instrumentation, specifically non-intrusive instrumentation, to determine individual particle velocities and trajectories, solids loading, concentration distributions and wall stresses;
- effects of particle-particle interaction and particle surface.

The expected benefits of this research are in areas such as, reduced wear in pipes, leading to less 'downtime'; improved efficiency in the separation of mineral matter during coal cleaning; and an improved control of flow in pipes, where the ratio of gas to solid is important, such as the flow of PF (pulverised fuel).

### 1.2. Scope of Review

ETSU, on behalf of the UK DTI, has commissioned a study into potential cost and efficiency savings that may be gained through improved MPF application in UK fossil-fired power generation. The aims of this review were:

- to survey MPF application in the UK fossil-fuel energy sector, paying particular reference to power generation;
- to identify key applications of MPF;
- to assess in which of these applications, further developments would lead to a potential overall energy, efficiency and/or cost savings;
- to estimate the potential energy, efficiency and/or cost savings in these applications;
- to identify further developments which would lead to greater benefits.

In order to maintain a manageable database, it was decided that the study should exclude tube-side steam-water flows, and the oil/gas/water flows associated with oil and gas recovery.

## 2. METHODOLOGY

This investigation required the systematic collection and assimilation of data from a wide range of sources that were relevant to the objectives of the project. The information was then supplemented by discussion with certain key organisations such as several of the main UK power generators. The outcome of these discussions formed the basis for the final report

### 2.1. Sources of Information

Information has been gathered from published texts, conference proceedings, scientific journals, Internet web sites and from discussion with appropriate personnel.

### 2.2. Questionnaire- Format and Review

**Background**

As part of the information gathering exercise that was used in the preparation of this report, a series of questionnaires were prepared and circulated to selected bodies. The selection process was made with great care given the tendency of questionnaires to be discarded with little or no regard. The accompanying letter was also aimed at trying to elicit a response from people who, it was recognised, normally have little time to spare.

Three different questionnaires were used, (see Appendix 3). They were designed for universities, power generators and equipment suppliers to the power generation industry.

In the case of universities, the recipients were asked to indicate their major MPF work area(s), from four categories and to rank them in order of what they saw as degree of importance to their department. Details of the MPF systems, with which the recipient worked, and also of specific projects, either completed or ongoing, were also, requested. Some idea of the level of technological maturity of each of the project areas was sought.

Power generators were asked to identify areas involving MPF which would benefit from further work and to try to quantify the level of improvement, either financial or in terms of efficiency gain. Questions were also asked regarding what options would be chosen for new plant and how overseas business affects research and development (R&D), thinking in the UK. An additional document was prepared by the authors of this report which was originally intended for use only by the power generators. Its purpose was to enable them to comment on and assign severity values to a number of potential problem areas in fossil-fired power generation involving MPF. It was later decided to circulate this document to all questionnaire recipients to get their view, as non-power generators, of perceived MPF problem areas.

The questionnaire for the equipment manufacturers asked for comments on their perception of MPF problems in the UK fossil-fired power industry. They were asked where they felt better knowledge was needed and how they would develop new products for the generation industry.

The bulk of the questionnaires were sent to UK bodies but about 25% were sent to European universities and power generators to get a broader picture of MPF activities.

**Analysis of Data**

The following information was obtained from the survey:

| | **UK universities** | **Non-UK universities** | **UK power generators** | **Non-UK power generators** | **Equipment suppliers** | **Total** |
|---|---|---|---|---|---|---|
| Number of forms sent | 33 | 15 | 14 | 8 | 22 | 92 |
| Number of forms returned (as on 07/12/00) | 10 | 8 | 8 | 2 | 3 | 31 |
| Returns, (%) | 30.3 | 53.3 | 57.1 | 25.0 | 13.6 | 33.7 |

A total of 92 questionnaires were circulated of which 31 were returned complete. Of the 62 organisations that did not supply data, 57 did not reply, one organisation had moved premises and one questionnaire was returned as the recipient was no longer with the organisation to which it was sent. Three other organisations, all of them UK universities, returned their questionnaires stating that they did not work in MPF or related fields.

Except for the generators, the response to the questionnaires was, on the whole, disappointing, particularly from the equipment suppliers. No responses were received from any of the large combustion equipment suppliers, and, with the exception of

CINAR Ltd., none of the commercial computational fluid dynamics (CFD), companies made contact. This was particularly disappointing as CFD is recognised as having a significant role in future R&D in this field, and much work has already been done on, for example, improved coal classifiers.

The response from UK universities was also disappointing. As mentioned earlier, the recipients were carefully selected and the poor level of response is hard to understand. One area in which it was hoped new contacts might arise was where universities who are not currently working with MPF processes would realise that there are opportunities for new applications for hitherto unused techniques. Unfortunately, three of the UK universities that were approached did not appear to recognise the opportunities the questionnaire presented.

Most of the major UK power generators did, however, respond and their views were particularly welcome.

Information was sought towards the end of the project from generators and universities in Europe. The response was quite good with 43% of the questionnaires being returned.

**Response to Potential Problem Areas**

The subsidiary questionnaire on how the recipients perceived the problems of fossil-fuelled power plants was evaluated. The questionnaire was sent to all participants but the responses from the power generators was deemed to be most relevant and was subjected to detailed analysis. The questionnaire identified four main categories, Coal Handling, Coal Combustion, Emissions and Other Issues. These were subdivided into specific topics and the recipients were asked to rank the topic from 0 to 5 where 0 was not a problem to 5 being a severe problem. Ten power generators supplied data with eight being of UK origin. The totals for each topic were calculated and the top 10 issues were as follows, (see also Table 1): -

| | | |
|---|---|---|
| 1. | PF - distribution to burners | 37 |
| 2. | PF - correct fuel/air mixing | 36 |
| 3. | Stack opacity | 29 |
| 4. | $NO_X$ | 25 |
| 5. | PF -elimination of ‘ropes’ | 22.5 |
| 6. | Fine particulate | 18.5 |
| 7. | Sulphur dioxide ($SO_2$) | 16 |
| 8. | Coal blending -adequate mixing | 14 |
| 9. | PFA -deposition | 13 |
| 10. | PFA -fly ash beneficiation and corrosion | 12.5 |

A total of 36 different potential problems were identified in the questionnaire covering all aspects of coal and oil firing. Other issues such as renewables and emulsion fuels were also included in the questionnaire. In addition, there was an opportunity for recipients to identify problems not identified in the questionnaire.

Although the questionnaires were returned from large and small generators in the UK and Europe, there seems to be a clear consensus as to which are the most pressing areas of concern. The main area seems to be the transportation, measurement and control of the flow of pulverised coal from the mill to individual burners. Another area of concern relates to NOx, stack opacity and the need to control fine particulate emissions. Certain generators seem to be concerned over coal milling activities and ash deposition and its effects.

There appeared to be few concerns at present over air toxics and carbon dioxide ($CO_2$), emissions, which was a little surprising. Also regarded as unexpected was the level of concern expressed over $SO_2$. Control of $SO_2$ is a mature technology where there are clear means by which the regulatory limits may be reached. It is possible that the concern expressed relates to the cost of compliance rather than any perceived technical difficulties.

**Identification of Areas of MPF Expertise in Universities**

The questionnaire for universities was designed to allow them to identify in which areas of MPF they worked and which they regarded as most important. The categories were identified as Modelling, Instrumentation, Experimental Studies and Development. They were then asked to indicate in which system or systems they worked, ie gas/liquid etc. Recipients were also asked to identify any relevant projects in which they had participated and the state of development of this work. Of the 17 useful responses, 6 indicated that Instrumentation and 5 that Modelling were their major activities in MPF work. In terms of the systems that they were most interested in 13 of the 17 indicated it was Gas/Solid systems, with 2 identifying Gas/Liquid systems. The range of activities was large spanning the following: -

- heat transfer research in boiler technology,
- froth flotation,
- renewable energy,
- waste/coal co-combustion,
- sawdust and related fuels,
- modelling of coal combustion,
- mineral aspects of PF coal combustion,
- non-intrusive PF flow meters, modelling of PF flow in pipework,
- gasification of solid wastes,
- combustion diagnostics,
- cyclone optimisation,
- pressurised fluidised bed combustion (PFBC),
- fluidised bed (FB), combustion and gasification,
- emission reduction,
- hydraulic conveying of coal,
- gasification of coal,
- hot gas clean up,
- acoustical monitoring of particle flows,
- modelling of turbulent liquid atomisation.

When asked to identify the degree of technological maturity of the projects on which they had been working, 2 of the 18 responses were stated to be ‘ready for use’ and 6 said that the work was ‘between basic and applied research’. The remaining 12 responses were shared equally between ‘basic research’, ‘applied research’ and ‘between applied research and development’.

More specific details of the areas of MPF expertise, including project data, are shown in Appendix 1.

## 3. STATUS OF FOSSIL-FIRED POWER GENERATION IN THE UK

### 3.1. Development of the Privatised Electricity System in the UK

The supply of electricity in the UK was under state ownership until the late 1980s when privatisation was introduced, [1]. The purpose of the liberalisation of the electricity supply system was to create a competitive industry and to encourage the participation of other organisations. In January 1989, the former Central Electricity Generating Board (CEGB), was split into three parts which were called National Power, PowerGen (now Powergen), who were the generators and the National Grid, which was the supply arm. At this time, the nuclear generating capability was retained by the UK government and was known as Nuclear Electric Co. In 1990, 18% of generation output in England and Wales was supplied by nuclear generation.

From March 1990, the generators began trading as plc's. The split had been made on a 60%/40% output basis with National Power being the larger company. The 30GW of plant that National Power operated and the approximately 20GW owned by Powergen were predominantly coal-fired, (60%). There was 30% of heavy fuel oil or dual fired capacity and the remainder was made up of gas turbine, hydroelectric and renewable power.

In 1990, 90% of the generating capacity was owned by just three companies, National Power, Powergen and Nuclear Electric, and there were only ten generating companies in existence. By the end of March 1998 this had risen to 34 companies and a year later 65 companies were supplying electricity to UK users. These new generators included Regional Electricity Companies (REC's), equipment suppliers, gas and oil companies, and overseas companies from the USA and Europe.

In a bid to create more competition, the UK electricity regulator required that National Power and Powergen divest themselves of 6,000MW of coal fired plant. This was acquired by Eastern Generation, which by 1997-98 had 8% of the market share.

Nuclear generation has also increased by this time with the commissioning of Sizewell 'B' and improvements to plant operations. The nuclear market share rose from 17% in 1990-91 to just over 24% by 1997-98.

The increase in competition in the generation industry had seen the fall in market share of the two original generators, Powergen and National Power, from a combined total of around 75% to just over 20%. Further reductions occurred to Powergen when the regulator required that they sell 4,000MW of capacity to purchase the REC, East Midlands Electricity. This was accomplished by the sale of their Fiddler's Ferry and Ferrybridge 'C' units to Edison Mission Energy in June 1999. National Power divested themselves of a similar capacity when they sold Eggborough and Drax power stations to British Energy and AES respectively, in order, it is believed, to concentrate on their overseas business. More recently, November 2000, Powergen sold its Cottam Power Station to London Electric, a unit of Electricité de France.

Since privatisation there has been a major shift from coal fired generation to gas. This resulted partly from increased competition, but mainly from the European Union's decision to allow power generation from gas, which, in turn, enabled the generators to close older, less efficient and uncompetitive coal-fired plant. Gas provided the means by which low capital cost, short build-time, environmentally friendly and, crucially, higher thermally efficient plant could be realised. The build strategy of the original generators has had to change in recent years in order to respond to a different market place. Now the power generators concentrate on smaller units, (in the range 150MW to 300MW), which use advanced technologies and, therefore, produce competitively priced power in what is now a high risk market.

## 3.2. Current UK Fossil-Fired Power Stations

Conventional fossil-fired plant presently in operation in the UK together with current owners is shown in Table 2. What is notable is the small number of units, 23 in total, of which three are oil only and not currently operating. There are 20 coal or coal/oil plants owned by nine different generators.

In 1980 coal and oil accounted for 84% of the electricity produced from all sources in the UK. However, by 1999 it had fallen to just 29.5%, of which coal now accounted for 28.1%.

## 3.3. The Future for Coal-Fired Power Generation in the UK

One of the major issues for this review is to identify the areas within fossil-fired, and this is effectively coal-fired, power generation in the UK involving multiphase flow that may derive cost and efficiency benefits from further development.

This report has sought to identify the areas of relevance and the topics of interest that the power generators regard as important. However, any possible investment in making such savings will be influenced by the future lifetime for the existing coal-fired stations. All of these units are now fairly old and it is unreasonable to expect their owners to carry out expensive and extensive modifications if the life expectancy of the units is unknown but could be short.

Some idea of the forecasts for coal appeared in a recent paper by Tombs, [1], who quoted the UK government white paper, [2], in which it predicted a fall in market share of coal fired generation from 34% in 1997 to 20% at best in 2003. The share of gas-fired generation could be expected to rise from 30% in 1997 to 50% by 2003. The recent relaxation by the UK government on the gas moratorium for power generation could see gas-fired generation rise to 60%. There has been a recognition within the UK government that a diverse mix of generating capability should be maintained and there appears to be some danger that gas will, in the near future, take a disproportionate segment of the total capacity. A 1998 survey by the National Grid Company confirmed these fears and predicted an increase in output from 63GW to 86GW with the increase expected to be entirely due to gas powered generation.

Uncertainties remain, however, and the future growth of gas may be influenced by factors such as availability and price of gas, new EU regulations or possible political changes in UK government.

Currently, coal-fired generation is produced by around fifty 500MW units with some smaller units of 200MW, 300MW and 350MW all of which are now around 30 years of age. They have been upgraded in that they are fitted with LNB's, improved electrostatic precipitators (ESP's), and some have flue gas desulphurisation (FGD), plants fitted. They are all sub-critical units and have efficiencies in the range 38% to 40%. Although old, the units can be operated for a further 20 years by the use of a planned life extension programme. Since they are no longer base load units, these boilers have to operate in a rapid response and flexible manner which includes load following and two-shifting modes. The increased number of start-ups and shutdowns, which flexible operation brings, causes accelerated damage to boiler components by rapid expansion and contraction. The philosophy is to estimate residual life of the boiler parts and by close monitoring to ensure that the life of the components can be optimised by developing maintenance strategies.

In light of this approach it seems that the extent of future expenditure on existing coal-fired plant could be low. Whilst some development work continues in certain areas, and is identified in other parts of this report, a close and careful cost/benefit analysis for each activity needs to be carried out.

A recent move, which could signify a more optimistic outlook for the future of coal-fired generation in the UK, is the number of applications and commitments which have been made to fit FGD to existing UK stations. In February, Mission Energy announced plans to spend £100M on FGD plant for its Ferrybridge station. This was followed by Edison First Energy's announcement to spend £60M at its Fiddlers Ferry plant. In March 2000, Mitsubishi disclosed of an order from TXU Europe to retrofit their 2000MW West Burton plant with a wet limestone/gypsum FGD system. It is clear that the level of investment in these plants would not have been sanctioned unless there was a belief and expectation that these stations will continue to operate for some time to come. It is also believed that the new owners of Eggborough and Cottam are investigating the retrofitting of FGD plant.

### 3.4. Overseas Fossil-Fired Power Stations with UK Interests

The two original power generators, formed at the break-up of the CEGB have expanded their interests into overseas power generation schemes and now have a considerable stake in these ventures. In many cases this involves newer technologies such as combined cycle gas turbine (CCGT), and co-generation. The plants listed in Table 3, however, are confined to conventional coal- and oil-fired plant, as it is these categories which are of relevance to this project.

In October 2000, National Power demerged its business into Innogy Holdings plc and International Power plc. The former is responsible for its UK generating interests and the latter those which are overseas. International Power plc is one of the largest independent electricity generating companies with 6,400MW (net) in operation, 4,500MW (net) under construction and approximately 8,000MW (net) in advanced development. Among the countries where it has operating facilities are Australia, the

United States, the Czech Republic, Portugal, Spain, Turkey, Malaysia, Pakistan, and Thailand.

International Power announced in November 2000 an increase in its interest in the 1,600MW Hazelwood power station in Victoria, Australia. Hazelwood is a mine-mouth, coal-fired generator, comprising eight 200MW units, located in the Latrobe Valley, Victoria and was commissioned progressively between 1969 and 1971. The Hazelwood Power Partnership, in which International Power will hold a 91.8% interest, owns the station and the mine. Hazelwood operates as a base load generator. Other conventional International Power thermal power plants include EOP in the Czech Republic, Pego in Portugal and Hub River in Pakistan.

Powergen has recently acquired Louisville Gas and Electric, a company which owns around 40 coal-fired units in the USA. This purchase provides them with a significant presence in the US power generation business. Powergen also has interests in Leipzig, Germany where they own one third of MIBRAG, a company operating two large lignite mines and three power plants. These mines supply the 900MW state-of-the-art Schkopau Power Station, in which Powergen has a 22 per cent stake.

In addition, Powergen has a stake in the Australian electricity industry with a 49.9% stake in Yallourn Energy, which they acquired when the state of Victoria decided to privatise its electricity generation industry. Yallourn comprises a 1,450MW power plant and a mining operation. They have also invested £90 million in the development of a major 1,220MW coal-fired power plant at Paiton on Java. The units are scheduled to be fully commissioned in the second half of 2000. Powergen owns 35% of this project. A number of projects are being developed in India, of which the most advanced is a 578MW project at Bina in which they have a 49.9% stake. Powergen also has a 35% stake in a consortium developing a 1,400MW power station at Map Ta Phut in Thailand which is expected to be operational in 2006.

Whilst Powergen and National Power evolved from the English and Welsh parts of the old CEGB, the Scottish segment became Scottish Power. This organisation rapidly expended its interests and now owns PacifiCorp, the utility which unsuccessfully tried to buy Eastern Generation, (now TXU Europe). In addition it has acquired the REC Manweb and Southern Water.

The level of involvement by UK companies in overseas purchases is subject to regular change and the status of the ownership as identified in Table 3 may be expected to alter. However, the high level of UK involvement in overseas power generation projects should provide the incentive for a vigorous programme of technical development and support.

Powergen appears to have undergone a recent, (January 2001), change of strategy as it now appears to have sold or is about to sell all of its interests in the far east and appears to be concentrating mainly on it’s USA and UK activities. It has also disclosed that discussions regarding a possible takeover by the large German energy producer, E.on, and others have taken place.

## 4. DESCRIPTION OF UK FOSSIL-FIRED POWER GENERATION WITH REFERENCE TO MPF SYSTEMS

MPF processes are those which involve substances which are present in more than one phase. These include systems containing a solid and a gas, (for example, pulverised coal and air), a solid and a liquid, (for example, a water-quenched ash hopper), a liquid and a gas, (for example, atomised fuel oil and steam) or combinations of all three. When one considers the generation of electricity from the combustion of fossil fuels, these processes are found to appear with surprising regularity.

This section of the report is concerned with the identification of those areas of the fossil-fired power sector where, within the objectives of this report, MPF processes occur. These activities are described and have been used to formulate a questionnaire which has been circulated, primarily, to power generators within the UK. The responses to the questionnaire lead to the identification of areas of MPF where:

- problems were believed to exist;
- further development would lead to improvements in costs and plant efficiency;
- regulatory pressures for action exist.

Information on these items was gathered and they are discussed in the following sections of the report.

### 4.1. Coal Handling

**Transport**

Most of the coals used in UK power stations are transported by rail. Merry-go-round (MGT), trains carrying from 1,000 to 1,300 tonnes of coal are used. Bulk coal deliveries can be made by sea if the power station is located on the coast, for example, Kingsnorth or Kilroot. In addition, large terminals for the receipt of imported coal at places such as Gladstone and Immingham facilitate the handling and delivery of bulk coals by rail to power stations. Small quantities, (10% to 20%), of opencast and deep mined coals are also delivered by road. One power station, Ferrybridge, is supplied by canal. The coal barges, which are pushed up the canal from the coast by tugs, are lifted out of the water for discharge.

**Discharge**

Coal handleability is of prime importance since the plant can be brought to a standstill by a train which cannot unload. The blinding of trash screens is a serious problem which can be caused by excessive moisture or incorrect size distributions. Oversize coal can cause problems with the automatic devices used for on-line sampling and analysis. Opencast coals are often dry and flow very well. The optimum size for coal is less than 50mm with not more than 40% less than 3mm.

Rail hoppers are specially designed to facilitate rapid automated discharge as the coal train transits a discharge station within the power station site. Coal handleability may be an issue as it is a difficult property to measure and quantify. Work has been carried out which has lead to the successful development of a coal handleability monitor, [3]. Discharge may be assisted by specially designed freight wagons but severe frost, (not normally a serious problem in the UK), can be troublesome.

**Stockpiling**

The stockpile is usually made horseshoe-shaped and the outer edges of the pile remain intact for the life of the station under normal circumstances. The coal is laid down in 6-inch layers by the use of bowl scrapers. The coal is compacted so that air is excluded and moisture is not absorbed, hence it will not heat up spontaneously. Deterioration of the coal is difficult to measure but if the stockpile is kept intact, the heat loss is less than 0.5% during the first year with no further loss.

In the UK, power station coal is normally received and used without stockpiling. The stockpiles consist of strategic reserves. Short term coal stockpiling is also potentially of concern as it is unlikely that the same degree of care will go in to their preparation. Loose, unsealed stockpiles can result in a dust nuisance as fines blow away or, if subject to heavy rainfall, can become segregated into ‘difficult-to-handle’ fines at the base and coarse material at the top of the stockpile. Spontaneous ignition is also possible if the necessary conditions prevail.

**Blending**

Coal blending has assumed much greater importance with the decline of the UK coal industry and the increased importation of competitively priced overseas coals. Most of the imported coals are low in sulphur and contain less ash than conventional UK power station coals. Coal blending is used to lower the overall sulphur content of the coal and thus the sulphur oxides (SOx), emissions. It is very important to ensure good mixing of the component coals in order to achieve the desired effects in terms of consistent boiler performance and emissions quality.

It is recognised, however, that the effects of blending on the combustion performance of multi-component fuels cannot be predicted in all cases. Certain properties such as SOx emissions may be predicted but others, such as ash fusion characteristics and NOx emissions cannot, and this topic needs to be studied in greater depth.

It is worth recognising, however, that many, if not all, coals supplied to power stations from UK coal mines are blends. Blending is not easy to detect and conventional coal analysis is not helpful in this respect. Although variations in rank for UK power station grades of coal are often rather small, unexpected differences in burnout can occur and efficiency losses may increase unexpectedly.

Blending may be achieved by the use of speed-controlled belt feeders which load coals directly into the bunkers in predetermined amounts from two or more separate supplies. The degree of mixing achieved by this approach is good in so far as the bunkers get filled with the correct amounts of each coal but they may not be well mixed at this stage. The mixing is achieved within the milling circuit. Although this approach should ensure homogenisation of the coals, possible differences in grindability of the coals means that the pulverised coal which leaves the mill may not be in the same proportion as the lump coal which was fed from the belts. Further work needs to be done to investigate such effects.

Other coal blending schemes require the use of large stocking areas and are particularly suited to coastal power stations which received single large consignments on a regular basis. Such a station is Sines in Portugal owned by Electricidade de Portugal (EDP), [4]. The coal consignments are laid down in layers according to the required blend compositions and a ‘sandwich’ of coal is then sliced laterally and fed to the boilers. This technique has enabled the operators to optimise plant performance for NOx and carbon-in-ash whilst using the least cost coal supplies.

Whilst coal handling may not be seen strictly in terms of MPF processes, it, nevertheless, has a significant effect on the feeding of coal into the boiler. Many MPF systems in the power generation sector are solid/gas processes and the properties of the solids can have a profound effect on the way the system as a whole will behave.

## 4.2. Coal Milling

A major application of MPF is seen during the preparation of pulverised coal. It is usual for the coal to be dried and ground during the milling process. It is clear that fracturing of the coal, vaporisation of liquid water in the coal and the aerodynamics of the classification process which leads to the removal of fine, dry PF from the mill represents important areas of MPF which merit further study.

Most large power station boilers are direct fired, that is, the coal is supplied to the mills and is pulverised continuously with direct pneumatic transport of the pulverised coal/air mixture to the burners. Thus the performance of the mills has a direct effect on the performance of the unit. In modern practice, a single mill can supply several burners. In tangentially-fired systems, a single mill typically supplies all four burners on a single elevation. In wall-fired systems, a single mill may supply a complete row or another symmetrical array of burners. A common design practice is to size systems to achieve full load with one or more mills out of service. This allows time for maintenance and enables the spare mill to be brought on-line in the event of a failure occurring in one of the other mills.

### Types of Coal Mill

Milling plant may be divided into three main types, namely low-speed, medium-speed and high-speed mills.

Low-speed mills are commonly known as ‘Tube Ball Mills’, (see Figure 1). They operate at 17 to 20 rpm mostly under suction, although pressurised mills were developed more recently. The slow speed is necessary to allow the ball charge to cascade within the rotating drum and thereby effects grinding. A higher speed would inhibit this effect and reduce grinding efficiency. Although this type of mill produces a very fine grade of pulverised coal, its power requirements are approximately 50% more than the more commonly used medium speed mill. It is particularly useful where a low volatile coal is being burned which requires excellent quality pulverised coal to achieve satisfactory burnout.

UK power generators mostly use the medium speed 'Vertical Spindle Mill', operating at 80rpm to 100rpm. These mills operate under both suction and pressure and the grinding elements are either three rollers rotating on a ring or a series of balls in a bowl. An example of this type of mill is shown in Figure 2.

The 'High Speed Mill', (see Figure 3), is no longer used in the UK where the coals are of high rank. This is because the high maintenance required keeping pace with the rapid wear of the hammer tips and other parts give severe availability problems. They are, however, of use where the coal to be ground is of low rank. This is because their grinding action is favoured for the more 'fibrous' nature of these coals. In addition, the high reactivity of low rank coals means that very fine particle sizes are unnecessary.

**Classification**

In order to obtain high output of sufficiently fine pulverised coal, the mills are fitted with devices known as classifiers. The use of such devices is particularly important where LNB's are fitted to a boiler, as any oversize coal particles will seriously affect the performance of the unit, [5]. The aerodynamics of the flow of coal particles through the classifier of a coal mill is an example of MPF.

In the case of medium speed mills, such as the vertical spindle mill, raw coal is fed into the centre of the revolving bowl of the mill. Centrifugal force throws it to the edge of the mill where it is crushed by the rotating rolls. The partially pulverised coal passes over the edge of the bowl, is picked up by the hot air stream, and flash dried. A device within the classifier returns the larger particles, which comprise 75% to 85% of the feed, to the grinding zone. The rising air current around the bowl carries the intermediate and fine fractions of coal up into the classifier inlet vanes, where a spinning action is imparted. Adjustment of the vane settings determines the degree of spin and thus the fineness of the coal, leaving the classifier. The oversize material, which falls back onto the grinding surfaces, is hot and when mixed with fresh coal feed helps to dry it.

Factors which affect classifier performance include fineness of feed material, grindability of coal, spring pressure on the rolls, degree of wear of grinding elements, inadequate coal drying and air velocity through the mill. In order to allow adjustments to be made to the mill during operation and to provide better product quality, the dynamic classifier has been developed.

As its name suggests, the dynamic classifier has moving parts within it, [6]. The classifier contains a rotor with a hollow shaft and attached inclined blades, (see Figure 4). Coal is fed through the hollow shaft onto the grinding surfaces of the mill. The dried and ground coal dust rises in the air stream and meets the rotating blades of the classifier. It is accelerated to almost the speed of the blades and equilibrium is set up between the drag of the airflow through the mill and centrifugal force imparted by the rotor. The finest particles follow the airflow through the blades and are lead out of the mill whereas the denser particles are thrown against the walls of the mill and fall back onto the grinding surfaces. The fineness of the coal depends upon rotor speed and transport air flow. Adjustment of the rotor speed is normally used to optimise coal fineness. Further development has produced a classifier which contains a preliminary static classifier and a dynamic classifier for the highest size distribution requirements, [6]. Many equipment manufacturers have developed and market their own classification equipment, [7-11].

Mathematical modelling of classifiers appears to be a topic for study which has enjoyed some success, (see Section 5.2. for details).

## 4.3. Coal Combustion

### Distribution of Pulverised Coal to Burners

In order for combustion to be carried out in the most efficient way, it is necessary for the pulverised coal to be delivered to each of the burners with the correct particle size distribution and in the correct quantity for the amount of combustion air supplied. The output from a particular coal mill will feed several burners which will be on different levels and with different pipe runs (length and geometry) from the mill. As an example of the tortuous routes that pulverised coal travel from mill to burner, Figure 5 shows the pipe layout for Kingsnorth Power Station.

It has long been recognised that the distribution of pulverised coal from a single stream to two or three streams in smaller pipes is not easy to control or to measure. The effect of maldistribution of coal is to increase carbon-in-ash and carbon monoxide (CO), levels where the burner is operating substoichiometrically and to increase $NO_x$ levels where the burner is operating with higher than designed excess air.

The division of a MPF into two or more streams is one which has received much attention. Though there is significant literature for division of gas/liquid flows at pipe junctions, [12], work on gas/solids flows are much more limited. Much of these concern themselves with the additional pressure losses across the junction. Work using particles of sizes typical of PF flows reports that the division of solids depends strongly on the division of gas, [13,14]. When the particle sizes were in the millimetre region, there was much less effect, [15]. Given this problem more elaborate dividing devices have been designed and implemented. However, in tackling this problem there are complications which have to be considered. Firstly, there is the matter of metering the two-phase flows. To ensure that the dividing devices work, there is a need to know the gas and solids flow rates emerging from each outlet.

One problem, which exacerbates the flow division, is the distribution of gas and solids about the pipe cross-section. Concentration of solids in particular parts of the cross-section can occur in two particular forms called roping and saltation.

### Coal Ropes - Their Occurrence and Elimination

Roping is the gathering of solids into a coherent ‘rope’ or stream whose cross-section is less than that of the pipe. This has been observed and quantified both in research facilities [16,17] and on plant [18]. It appears to be caused by bends [19,20] and decays thereafter. Factors such as bend radius, conveying velocity, particle size and wall roughness affect the distance required for ropes to decay [16,17]. The direction of gravity relative to the bend and the proximity of bends [21] influence rope behaviour. The large number of variables involved makes correlational approaches inappropriate. CFD methods have been employed to predict roping phenomena but the method still has shortcomings. However, developments in CFD, particularly if validated against carefully performed experiments, will be an important tool for the future. This could lead to understanding and development of methods for breaking up of ropes. A considerable amount of work has been done in the past to develop so-called rope-breakers, [22,23]. These have been successful but, as with other fuel-related transport issues, more development is needed. Current methods are purely empirical [24,25].

Roping has been claimed as a limiting factor in the ability to reduce NOx emissions.

Saltation is the term employed to describe the settling of the conveyed solids when the air velocity becomes too low [18]. Particle image velocimetry (PIV), has been used to study such problems in pneumatic conveying and the data support the proposition that roping leads to settling

*Metering*

A large number of techniques have been applied to the measurement of the mass flow rates of gas and solids in pneumatic conveying. These employ optical [26], capacitance [27-30], correlation of electrostatic charge [27,31], ultrasonics [32], pressure difference [29,33] and nucleonics [34,35]. Some use combinations of methods, eg, correlation of electrostatic charge and capacitance [27] or pressure difference and capacitance [29]. Though most aim to provide mass flow measurements, others, eg [30], employ tomographic techniques to provide cross-sectionally resolved concentration measurements. The majority of the reported work was carried out on small-scale research facilities. However, some report plant measurements. The ultrasonic work [32] is one of these. It employs two separate aspects of measurements. Concentration is determined from attenuation of a pulsed ultrasonic beam transmitted across the conveying fuel pipeline. Flow velocity is measured using the ultrasonic contra-propagation method, ie, the gas velocity is determined from the difference in transit times of a pulsed ultrasonic beams sent upstream and downstream in the pipe.

**Correct Coal/Air Mixing**

The latest advanced wall-fired LNB’s have combustion air split into several discrete layers. This is necessary to stage the combustion process and ensure that the optimum low levels of NOx are produced. For this reason it is necessary for the coal to be fed to the burner in a well-dispersed condition. This may require a form of rope breaker just upstream of the burner. The burner itself may then take the dispersed coal stream and concentrate it into controlled, fuel-rich streams. This is to provide further NOx reduction via a process known as fuel-staging.

## 4.4. Gaseous Emissions and their Control

Gaseous emissions arise from the combustion of fuels. This is the result of interactions between fuel particles and gases, such as oxygen, and as such must be classified as MPF processes. In addition, the emission of gaseous pollutants represents the most serious challenge to the continuing operation of fossil-fired power plants. Emissions of oxides of nitrogen, sulphur and carbon are produced during combustion. The first two are of most concern to the regulatory bodies, and limits exist for their emissions, although environmentalists wish to include the last on their list of harmful substances.

**Nitrogen Oxides (NOx)**

Pulverised coal combustion is the most widely used process for power generation, accounting for about 40% of the electricity produced world-wide. Coal-fired power plants, which are major producers of NOx, became subject to the EC's Large Combustion Plant Directive (LCPD), in 1988. The LCPD restricted the emission of NOx from new, large, coal-fired plant of more than 50MW to 650mg $Nm^{-3}$.

*Occurrence and Formation*

The nitrogen oxides formed during combustion are mainly NO (nitrogen monoxide) and $NO_2$ (nitrogen dioxide), with possible small amounts of $N_2O$ (nitrous oxide or dinitrogen monoxide), depending upon the combustion conditions. In the case of pulverised coal combustion, 90% of the nitrogen oxides emitted are NO and the balance is $NO_2$. These gases are known collectively as NOx.

Three mechanisms by which NOx may be formed in flue gas are recognised. These mechanisms are known as 'thermal NOx', 'prompt NOx' and 'fuel NOx' (see Figure 6).

Thermal NOx is formed according to the Zeldovich mechanism, from molecular nitrogen which is supplied primarily from the combustion air. Conversion starts at temperatures above $1,300^{O}C$ and increases markedly with rising temperature. The degree of conversion is also proportional to the concentration of molecular oxygen.

Prompt NOx as defined by Fenimore, [36], describes a mechanism by which molecular nitrogen is converted, via intermediate products, into NO in an early phase in the flame front with the participation of hydrocarbon fragments. The degree of conversion depends on the stoichiometric conditions and temperature. In practice prompt NOx is of minor importance with regard to the total NOx emissions.

Fuel NOx is formed by oxidation of nitrogen contained in the fuel. The sequence of events culminating in the formation of NO is complex and not completely understood. The nitrogen content of coal varies from about 0.5% to about 2.5% on a dry, ash-free basis. Heavy fuel oils contain around 0.5% although this is rising slowly as refinery changes are introduced. Distillate fuels contain a trace of nitrogen but gas contains virtually no nitrogen.

*Techniques for Reducing NOx Formation*

There are a number of means by which the formation of NO can be reduced during the combustion process, [37], many of which involve MPF processes.

In the case of 'thermal NOx' these include decreasing the flame temperature in all reaction areas to below $1,300^{O}C$ and also reducing the furnace heat release rate. Other effective methods include decreasing the residence time in all high temperature zones and decreasing the excess air by which means the concentration of atomic oxygen will also be reduced in the high temperature zones.

Selecting a fuel with lower nitrogen content can reduce 'fuel NOx' formation, but unlike the sulphur content of the fuel, its oxide, ie NOx in this case, cannot be easily predicted from this value. It may also be significantly reduced if the nitrogen in the fuel can be volatilised in an oxygen-deficient zone. This results in the formation of elemental nitrogen instead of NOx.

*Burner/Boiler Optimisation*

Burner optimisation is usually the first method used to control NOx formation. Optimisation is achieved by modifying boiler operating conditions. Excess air control, boiler fine tuning and balancing the fuel and air flows to the various burners are in use and continue to be investigated to achieve minimum $NO_x$ formation in the burner.

Since NOx formation is directly related to the amount of available oxygen in the combustion air, it may be reduced by limiting the amount of oxygen in the near-burner region. Although effective, there are disadvantages in the technique if it is taken to extremes. For example, as the oxygen level is reduced, combustion efficiency falls and the amount of carbon-in-ash may increase. In addition, the steam temperature may also decrease. Reducing the oxygen in the primary zones to very low amounts (< 1%) can also lead to high levels of CO. The result of these changes can be a reduction in the boiler efficiency, slagging, corrosion and a negative overall impact on boiler performance. However, provided the reduction in excess oxygen is kept to moderate amounts, this technique does offer some limited scope for NOx reduction.

Fine tuning the boiler settings includes mill balancing, adjusting air registers, air and coal flow balancing, tuning firing configuration and improving the plant control system. All of these can be regarded as MPF activities.

*Low NOx Burners (LNB's)*

LNB's, see Figure 7, are designed to reduce NOx by controlling the mixing of fuel and air. Peak flame temperature is thereby reduced, and this results in less NOx formation. The improved flame structure also reduces the amount of oxygen available in the hottest part of the flame thus improving burner efficiency. Combustion, reduction and burnout are achieved in three stages within a conventional LNB. In the initial stage, combustion occurs in a fuel-rich, oxygen-deficient zone where NOx and hydrocarbon fragments are formed. The hydrocarbon fragments then react with the NOx to form elemental nitrogen. In the final stage of combustion, further air is added to complete burnout of the carbonaceous matter. However, this process will result in the formation of NOx which is beyond the scope of LNB's to control. This however can be minimised by completing the combustion in an air-lean environment.

LNB's can be combined with other primary measures such as overfire air, reburning or flue gas recirculation.

*Air Staging*

Air staging or two-stage combustion, is generally described as the introduction of overfire air (OFA), into the boiler or furnace. Staging the air in the burner (internal air staging) is generally one of the design features of LNB's.

Furnace OFA technology requires the combustion air to be introduced as separate primary and secondary flows to achieve complete burnout and to encourage the formation of elemental nitrogen rather than NOx. Primary air is mixed with the fuel producing a relatively low temperature, oxygen-deficient, fuel-rich zone and, as a result, moderate amounts of fuel NOx are formed. Secondary combustion air is injected above the combustion zone through a special wind-box mounted above the burners. Combustion is completed within this increased flame volume. It is the relatively low temperature secondary stage which limits the production of thermal NOx. The location of the injection ports and mixing of OFA are critical to maintain efficient combustion. Retrofitting OFA on an existing boiler involves waterwall tube modifications to create the ports for the secondary air nozzles and the addition of ducts, dampers and the wind-box.

*Fuel Staging*

One method for fuel staged combustion involves fuel biasing. In this process, combustion is staged by diverting fuel from the upper level burners to the lower ones or from the centre to the side burners. The aim is to create a fuel-rich lower or central zone and a fuel-lean upper or side zone in order to achieve complete burnout. The technology lowers flame temperature and improves the balance of the oxygen concentration in the furnace. $NO_x$ emissions may be reduced by up to 30% using this technology.

Another form of fuel staged combustion is the procedure known as ‘Burners-Out-Of-Service' (BOOS). The technique involves shutting off the fuel flow from one or more burner to create fuel-rich and fuel-lean zones. $NO_x$ emission control of around 10% may be achieved, although the technique is not widely used in pulverised coal-fired plants.

*Flue Gas Recirculation (FGR)*

FGR alone in coal-fired boilers achieves a modest NOx reduction efficiency, (<20%). This is because the ratio of thermal NOx to total NOx emissions is relatively low in coal-fired plants. The technique is used on coal-fired units in combination with other primary measures for NOx control.

FGR for NOx control includes gas recirculation into the furnace or into the burner. In this technology 20-30% of the flue gas, (at 350-400°C), is re-circulated and mixed with the combustion air. The resulting dilution in the flame decreases the temperature and availability of oxygen therefore reducing thermal NOx formation. When FGR is used with LNB’s, the flue gas is usually re-circulated subject to the operational constraints of flame stability and impingement, as well as boiler vibration.

*Reburn*

Reburn is another form of fuel staged combustion, (see Figure 8). It is a three-stage, (zone), system, which is why it is sometimes referred to as a three-stage combustion process:

- primary combustion zone;
- reburn zone; and

·	burnout zone.

In the primary zone, coal is fired through conventional or LNB’s generally in low excess-air conditions to reduce initial NOx formation. A secondary fuel is injected or blown into the upper section of the furnace. This is a secondary sub-stoichiometric reburn zone without combustion air. Recirculated flue gas is sometimes used as a carrier for the reburn fuel. Currently natural gas is the most widely used secondary fuel although coal and oil are currently being demonstrated. A primary function is to provide effective mixing of the natural gas with the bulk flue gas in the reburn zone. The secondary fuel breaks down at this stage to produce hydrocarbon fragments, which react with the NOx produced in the primary combustion zone and reduce it to atmospheric nitrogen. In the third, burnout zone, the gases exiting the reburn zone undergo additional combustion with OFA. This final combustion stage is necessary to consume the CO and unburnt hydrocarbons leaving the reburn zone. In general, 10-30% of the total heat input can be used as the secondary fuel. The process creates a fuel-rich, oxygen-deficient reducing zone, which decomposes the NOx, formed in the primary combustion zone. The technology, in conjunction with LNB’s, is capable of achieving relatively high NOx reduction (up to 70%). The cost of the secondary fuel influences the operating costs considerably. Hence reburning costs can be higher than other primary measures for NOx control.

Reburning is a technology applicable to all types of coal-fired boilers. In addition, in some boilers such as cyclones, the typical combustion delaying techniques of reducing excess air to optimise combustion cannot be applied as operation necessarily occurs under excess oxygen conditions to avoid problems such as tube corrosion. Reburning is, in this case, an appropriate and reasonably efficient technique which, in the absence of other technologies, can be used on this type of boiler at an acceptable cost.

There are additional advantages in using natural gas with this technology due to the effects of the natural gas burning on other pollutants formed during pulverised coal. Particulate matter, $SO_2$ and $CO_2$ are also reduced in addition to the reduction in NOx emissions combustion. Since natural gas contains no ash, the particulate loading is reduced in direct proportion to the amount of coal displaced. A similar argument leads to the conclusion that $SO_2$ emissions are also reduced, also in direct proportion to the amount of coal displaced. Although $CO_2$ is not normally considered a pollutant it is identified as a greenhouse gas and therefore any reduction in it is also welcome. The $CO_2$ reduction is due to the greater ratio of hydrogen to carbon in natural gas, compared with coal. 15 to 20% of coal substituted by natural gas results in a reduction of 6 to 9% in $CO_2$ emissions. Factors affecting installation of reburning technology are the availability of natural gas in close proximity and the coal/gas cost differential.

A recent workshop held by the DTI, [38] reviewed two reburn demonstration projects. The first was performed on unit #2 at Longannet Power Station in Scotland, using a gas-over-coal reburn system, [39, 40]. The second involved a coal-over-coal reburn system in which unit #4 at Vado Ligure in Italy was converted. Both of the projects were supported by the EU via their THERMIE programme. Both projects demonstrated that the expected NOx reduction of up to 50% could be realised with acceptable carbon-in-ash increases, [41]. Future units will benefit from certain lessons learned in the two demonstration projects. In the case of Longannet, the cost and weight implications of the FGR system and the overall complexity of the plant can now be reviewed, [42].

*Selective Catalytic Reduction (SCR)*

SCR involves the reaction of two gases in the presence of a solid catalytic surface and as such may be regarded as a MPF process. In the catalytic reduction method the NOx concentration in the flue gas is reduced by injection of ammonia in the presence of a catalyst. Plants are in operation where the NOx concentration is reduced by over 80% to 90%. The reaction products are nitrogen and water. The reaction is selective which means that oxidation of ammonia and $SO_2$ should not occur. The temperature of the catalyst is very important for the reactions. The optimum temperature is usually between 300$^O$C and 400$^O$C. Different types of catalyst such as titanium oxide, zeolite, iron oxide or activated carbon have been used and their optimum operating temperatures vary considerably.

The efficiency of NOx reduction is dependent upon several factors such as the NOx concentration at the inlet to the catalyst, the flue gas temperature, the ratio of ammonia injection, oxygen concentration and catalyst properties.

An increase in ammonia injection leads to increased NOx reduction, but the amount of ammonia which reacts with the NOx depends on the catalyst. The unreacted ammonia leaving the stack is called ‘ammonia slip’ and is undesirable and unacceptable as it can contaminate fly ash and render it unsaleable.

The catalyst can be placed in different positions in the flue gas flow, the main factor being that the conditions such as flue gas temperature are right for the catalyst used. The positions that are used are referred to as ‘high dust’, ‘low dust’ and ‘tail end’. The ‘high dust’ location is between the economiser and the air pre-heater. The flue gas passing through the catalyst section contains all of the fly ash and SOx from combustion. This can cause degradation of the catalyst leading to a decrease in NOx reduction capability.

A ‘low dust’ location means that the catalyst is situated after a hot gas ESP and before the air pre-heater. The flue gas reaching the catalyst is almost dust-free but contains SOx. Hot gas precipitators operating at 300$^O$C to 400$^O$C are seldom considered favourably.

‘Tail end’ systems have the catalyst situated in the chain of flue gas cleaning equipment, after the desulphurisation plant. The flue gases reaching the catalyst therefore only contain small amounts of SOx and particulate matter. However, the flue gas temperature after the desulphurisation is too low for most types of catalyst so reheating is needed.

There are a number of benefits in using this systems:

· less risk of catalyst degradation so a longer catalyst lifetime can be expected.

· the optimum flue gas temperature for catalyst operation can be maintained independently of boiler load.

· a smaller catalyst volume and higher catalyst activity can be used.

- there is no contamination of fly ash by ammonia slip.
- in a retrofit situation, there is no need for rebuilding the boiler or other parts of the plant.
- similarly, only a short boiler shutdown time is needed for installation.

The single major disadvantage is the need to reheat the flue gas. The cost can be significant as it has been calculated that to raise the flue gas temperature by about $50^{O}C$ will require 2% to 3% of the boiler capacity.

Catalyst poisoning occurs and may be attributed to those substances which combine chemically with the active catalyst. Such substances are the alkali metals and alkaline earth metals, especially if present as their sulphates, and arsenic. Catalyst deactivation can also occur due to a physical coating or pluggage of the catalyst gas paths. Similarly, high ash coals can under certain conditions, ie uneven gas flow regimes erode away parts of the catalyst.

*Selective Non-Catalytic Reduction (SNCR)*

In this process NOx is reacted with solid, gaseous or solutions of chemical which can react with it to destroy it. NOx emissions can be controlled through thermal reactions by using appropriate reducing chemicals. The process is called selective non-catalytic reduction or SNCR. It is an attractive proposition as it does not require the use of expensive catalysts. However, the removal efficiency of SNCR is much lower than SCR and figures of 50% to 60% at low boiler load probably represent the optimum removal efficiency. One of the reasons for the low removal efficiency is the problem of getting the NOx and reagent well mixed in the shortest possible time so that the reduction reaction can take place.

There are many methods using different chemicals, all needing a specific temperature to allow the reactions to occur. The range of temperature at which the reaction takes place is called the temperature window. This varies for different chemicals and for the most common chemicals it is $900^{O}C$ to $1,100^{O}C$. The commonest used substance, ammonia, will not react below the temperature window and will appear in the flue gas as ammonia slip, but at higher temperatures, it will be oxidised to NOx. The importance of injection at the correct temperature has resulted in the need to install injection points at a number of different locations in a boiler. This is because as the boiler load changes, the position of the temperature window will move.

In addition to ammonia, other chemicals such as urea, amines, other amides and cyanuric acid have been used. The purpose has been to lower and widen the temperature window. There has been some success in this respect and proprietary systems such as NOxOUT™, [43], contain what are known as enhancers to lower the temperature window to around $500^{O}C$.

It has also been found that different conditions in the flue gases influence the reactions and the temperature window. As well as temperature, oxygen content of the flue gas affects the width of the window and removal efficiency of the injected chemical. Other gases such as CO and SOx affect the removal efficiency of the reductants.

**Sulphur Oxides**

The effect of SOx from power station flue gas in producing acid rain is well documented. As a result, much effort has been expended in attempting to overcome or minimise its effects.

*Techniques for Reducing $SO_2$ Emissions*

*Fuel Switching*

The simplest way to reduce the quantity of SOx emitted is to replace, either completely or in part, the existing fuel for one with a lower sulphur content. In the UK, the availability of indigenous low sulphur coal has been poor and the power generators have been obliged to obtain world traded, low sulphur coals from countries such as South Africa, South America, Australia and Indonesia.

It is preferable that the low sulphur replacement coals are of a similar rank to the high sulphur coals, as this should minimise any boiler operational changes that may otherwise be needed. An example where this has not been the case involved certain low sulphur coals, which are widely and cheaply available in the US, from coal fields in states such as Wyoming and Montana. These coals are of much lower rank than the original power station design fuels. This has meant that boiler outputs have had to be reduced due to the lower calorific value of the new fuel and the greater difficulty in their pulverisation. Other problems include the worsening of boiler slagging and fouling; effect on fly ash sales and safety issues due to the increased reactivity of the low rank coals also need to be addressed as well as precipitator performance, [44].

The cost/benefits of replacing existing coals with lower sulphur versions is a topic which lends itself to study by a software package such as Coal Quality Impact Model (CQIM), (see Section 5.5.). This would enable a determination of the cost of using the replacement coal in plant operation and maintenance terms as well as the coal costs and the emission levels. From this data, the optimum replacement coal in the correct blend ratio could be determined.

*Gas Co-firing*

The presence of an economical, readily available supply of natural gas would encourage a power generator to consider investigating the use of co-firing gas and coal in order to reduce pollutant emissions. There would clearly be a cost involved in the installation of gas piping but if light-up burners for gas were already in place, they could be used for co-firing. The benefits in SOx reduction would accrue from the gas simply being a sulphur-free replacement fuel.

Another benefit from this technology is that the lower carbon to hydrogen ratio of natural gas reduces $CO_2$ emissions to about 60% of those from coal for the same thermal input.

There are other, arguably more valuable, benefits from co-firing natural gas with coal, which involve reductions in NOx and $CO_2$ levels. These are discussed in more detail in

Section 4.4. Further details on this topic can be obtained from an IEA review entitled 'The use of natural gas in coal-fired boilers' [45].

*Flue Gas Desulphurisation (FGD)*

The most effective way to remove SOx from flue gas is to use FGD. In simple terms, the $SO_2$ in the flue gas is reacted with a sorbent which enables it to be removed from the gas stream. The sorbent may be a solid or an aqueous slurry and its reaction with the gaseous SOx is another example of a MPF process. Removal efficiencies in the high 90%'s are possible with some of these systems.

There are many variations in the type of technology used, [46-49]. The first categorisation is whether the system is regenerable or non-regenerable. The regenerable system allows the sorbent to be reused and the $SO_2$ is then processed into elemental sulphur or sulphuric acid. The non-regenerable systems require fresh sorbent to be continuously used to trap out the $SO_2$. The commonest system of this type uses calcium, (either as oxide or hydroxide as the sorbent), and produces gypsum as the final product. To reduce overall costs, the gypsum is of a suitable quality to be saleable for use in plasterboard manufacture. However, the production rate is continuous whilst the FGD plant operates and, as a result, the price obtained for the gypsum is not high.

*Wet Scrubber Systems*

Reactions between $SO_2$ and sorbents, in both regenerable and non-regenerable processes, may take place as gas/liquid, gas/solid or gas/gas reactions. For non-regenerable processes, gas/liquid reactions are the most common. Where such processes produce a wet product they are known as wet scrubbers. This is the most widely used type of FGD installation. The sorbent slurry, generally lime or limestone, is sprayed into the flue gas, generally in an open tower although a packed tower may sometimes be used. Originally a waste product was formed of incompletely oxidised calcium sulphite but design improvement have lead to a saleable product being produced, namely gypsum. Other alkaline liquids such as ammonia, caustic soda, sodium carbonate, potassium and magnesium hydroxide are currently used in some commercial applications.

A variation on this process has been used whereby seawater is used as the sorbent. The collection efficiency is around 80% to 90% and the chemically-bound sulphur oxides are disposed of in the sea. This is a rapidly expanding technology, particularly in tropical countries, [49]. Its main advantage is that it requires no solid sorbent nor has waste by-products to dispose of. Although capable of high sulphur removal, it obviously can only be applied to coastal power stations and also one with sulphur contents no higher than 3%.

*Spray Dry Scrubber Systems*

Spray dry scrubbers have been developed as an alternative to wet scrubbers and require the use of an efficient particulate control device such as an ESP or fabric filter. In this process, which involves gas/liquid reactions, the sorbent slurry or solution is sprayed into the reactor vessel, drying as it reacts with the $SO_2$ in the hot flue gas. Lime slurry is commonly used as a sorbent, resulting in a dry product of mixed calcium sulphite/sulphate. When sodium carbonate solution is used as sorbent, the by-product is a mixture of sodium sulphite and sulphate. With both reagents there will be some unreacted sorbent present.

Spray dry scrubbers are the second most widely used FGD technology. However, their application is limited to smaller sized units, ie 200MW, or units burning low sulphur coals. $SO_2$ removal efficiencies of greater than 90% have been achieved and some equipment suppliers will guarantee greater than 95% removal.

*Sorbent Injection Systems*

Sorbent injection systems involve gas/solid reactions. There are four such systems as follows:

- furnace sorbent injection
- economiser sorbent injection
- duct sorbent injection
- hybrid sorbent injection

The simplest technology is 'furnace sorbent injection' where a dry sorbent is injected into the upper part of the furnace to react with the $SO_2$ in the flue gas. The finely-divided sorbent must be distributed quickly and evenly over the entire cross section of the upper part of the furnace for the process to be successful. It has been found that the reaction between sorbent and $SO_2$ occurs in the temperature range $750^{O}C$ to $1{,}250^{O}C$. Higher temperatures will cause loss of reactivity in the sorbent due to sintering and at lower temperatures the reaction practically ceases. To maintain optimum efficiency of $SO_2$ removal, typically up to 50%, there must be a number of different injection points to deal with boiler part-load conditions. The preferred sorbent is calcium hydroxide although calcium carbonate has also been used. Calcium to sulphur ratios of 2 are needed to obtain optimum SO2 removal.

The spent and unreacted sorbent is removed in the boiler dust collection system together with fly ash. The effect of these additional substances with the fly ash needs to be recognised in respect of the sale and/or disposal of the ash stream.

In an 'economiser sorbent injection' process, calcium hydroxide is injected into the gas stream near the economiser where the gas temperature is in the range $300^{O}C$ to $650^{O}C$. It has been found that the sorbent is able to react directly with $SO_2$ at a much lower temperature than when used in furnace injection. The main product from this system is calcium sulphite.

In 'duct sorbent injection', the aim is to distribute the sorbent evenly in the flue gas duct after the pre-heater where the temperature is about $150^{O}C$. At the same time, the flue gas is humidified with water if necessary. Reaction with the $SO_2$ occurs in the ductwork and the by-product is captured in a downstream filter. Removal efficiencies of up to 80% have been reported and there is a wide range of process variations including the use of the sorbent, (calcium- or sodium-based, dry or slurried) and recirculation/reactivation of the by-product. A pre-filter, if installed, has the advantage that fly ash and desulphurisation products are separated. This makes recirculation of unreacted sorbent easier, resulting in improved sorbent utilisation.

There are many factors which influence the performance of a duct sorbent injection process. These include sorbent reactivity, quantity of injected sorbent, relative humidity of the flue gas, gas and solids residence time in the duct, and quantity of recycled, unreacted sorbent from the particulate control device.

The ‘hybrid sorbent injection’ process is usually a combination of the furnace and duct sorbent injection systems aiming to achieve higher sorbent utilisation and greater $SO_2$ removal. Various types of post-furnace treatments are practised in hybrid systems, such as injection of a second sorbent, (for example, a sodium compound), into the duct and humidification in a specially designed vessel. Humidification reactivates unreacted calcium oxide and can boost the removal efficiency up to around 90% depending on the process. The advantages of this system are that it is of low capital and operating costs; it is easy to retrofit with easy operation and maintenance. The space requirements are small and there is no slurry handling or waste water treatment required.

*Dry Scrubber Systems*

Circulating fluid bed and moving bed technologies, which utilise a dry sorbent to reduce emissions in a flue gas in a dedicated reaction chamber are categorised as dry scrubbers.

In the circulating fluid bed dry scrubber process, hydrated lime is injected directly into the reactor. Water is also injected into the bed to produce a condition close to the adiabatic saturation temperature. The process achieves $SO_2$ removal efficiencies of 93% to 97% at a calcium-to-sulphur molar ratio of 1.2 to 1.5.

In the moving bed dry scrubber a dry absorbent, made of coal ash and lime, is injected into the absorber. There is currently one plant using this technology and achieving 90% $SO_2$ removal efficiency.

*Regenerable Systems*

A range of regenerable FGD systems is in use, although the total number of installations on coal-fired plant is small. Regenerable systems tend to be more complex than non-regenerable processes, and hence have higher capital costs. Their overall economics are highly dependent upon the price obtained for the end product. The most widely used regenerable FGD system is the Wellman-Lord process, [49], which uses a gas/liquid reaction with sodium sulphite solution as the sorbent. The reaction product is regenerated by heat treatment to produce an $SO_2$-rich gas that can be further processed to give sulphuric acid or elemental sulphur. Regenerable processes generally produce no wastes for disposal, little waste water and have low sorbent make-up requirements. However, in most systems, a pre-scrubber is essential to control chlorides. Although these processes can achieve high $SO_2$ removal, (>95%), they have, in general, high capital costs and power consumption.

**Carbon Dioxide**

‘Greenhouse’ gases are capable of causing global warming by acting as an atmospheric insulator and trapping heat produced on earth. The commonest gas and one which elicits most discussion is $CO_2$. Global $CO_2$ emissions are generally accepted as rising but their likely effect and ways of combating these increases, (if one accepts that they can be affected), is a topic on which a consensus view is difficult if not impossible.

The depth and complexity of the subject means that it cannot be discussed in detail within the scope of this report. However, the formation of $CO_2$ and also its disposal is recognised as involving MPF processes, therefore it was felt relevant to include it in this report. This section includes a review of some of the known facts and comments on what future $CO_2$ control measures might be implemented by the power generators if they were required by legislation to do so.

The link between a fuel and its gaseous emissions can be described by emission factors relating the mass of the gas emitted to the useful energy of the fuel, [50]. The relative value for the three commonest fossil fuels, (in gC $MJ^{-1}$), are as follows: coal ~25, oil ~20 and natural gas ~15. These figures explain why the use of coal for power generation has been under pressure from the environmental lobby and is one of the reasons why gas-fired power generation has become so popular. If one also considers the other gaseous pollutants from coal, such as SOx and NOx, then $CO_2$ is a further potential issue which a coal user may have to address in the future.

The total global emissions of $CO_2$ for 1994 were about 6.2 billion tons of which the USA was the major producer at 22.4%. The UK emitted around 2.4% of the global total, (150 million tons), of which around 45 million tons, (30%), were emitted by power stations. Emissions from power stations have fallen sharply in recent years in the UK with the switch from coal to gas, whereas transport generated $CO_2$ levels have risen, [51].

The Kyoto Agreement of 1997 sought to reach an agreement on limiting global emission of greenhouse gases, primarily $CO_2$, from the combustion of fossil fuels. The latest rounds of talks aimed at implementing agreement on limiting greenhouse gases have been concluded, (November 2000), in The Hague. The outcome has once again been disappointing with delegates from the US, Japan, Canada and Australia being unable or unwilling to sign up to any binding agreement.

There is a view, [52], that even if energy efficient measures and renewable usage will flourish, it would be prudent to investigate large-scale disposal options for $CO_2$. There are three main options, namely:

- disposal in the deep ocean
- disposal in deep aquifers
- disposal in exhausted gas and oil reservoirs

All of the proposals are technically viable. The present view is that long term environmental and safety aspects of disposal require the greatest emphasis in future R&D. Disposal of $CO_2$ in the ocean, in aquifers or in depleted hydrocarbon reservoirs is low in cost relative to capture and compression costs. Unless long distances are involved, transportation of $CO_2$ is also low in cost if carried out on a sufficiently large scale.

None of the storage options has an unacceptable environmental impact in terms of the overall global environment, but much more R&D work is required to provide the information to support the various options. On the assumption that current lack of environmental impact data relates to a greater requirement for research and a greater time to practical implementation of the disposal option, storage of $CO_2$ in depleted gas reservoirs, or possibly in aquifers, represents the most immediately available disposal option. Ocean disposal is a longer-term option but has the greatest potential and represents the most scientifically elegant solution.

The overall aim of future R&D work on $CO_2$ disposal should be to provide data which will allow pilot-scale disposal experiments to take place at carefully selected sites. This means initiating work programmes designed, in the first place, to provide data which is much more specific to the interactions of $CO_2$ with the proposed storage environment, whether this is the ocean or a rock structure. Programmes of work need to be defined which will lead to the selection of experimental sites for detailed assessment. In terms of information that is already available, a depleted gas reservoir would seem to offer an earlier opportunity for a pilot-scale study than an ocean site or an aquifer site. The immense potential of the deep ocean for storage of $CO_2$ and the inherent scientific logic and safety of the disposal route, does however, mean that this option should be pursued as vigorously as possible. It is a longer-term option, because the lack of specific experimental data and the international nature of the disposal route. A review of $CO_2$ capture and storage options has been recently published by the DTI, [53].

## 4.5. Coal Ash

### Deposition

The deposition of coal ash particles onto boiler surfaces is inevitable during pulverised coal combustion. It only becomes a problem when the rate of deposition cannot be controlled or if the residual ash on tube surfaces becomes immovable and heat transfer and/or gas flow rates are unacceptably reduced. A distinction is usually made between deposition within the furnace and radiant sections of the superheater, which is known as slagging, [54], and that which occurs in the convective section, known as fouling. In addition, the mechanisms for initiation and deposition of substances are different, [55].

The process of ash deposition is recognised as a MPF phenomenon. It follows that any reduction in boiler heat transfer due to the insulating effect of the deposit will result in a loss of efficiency. Therefore, any methods by which deposit removal may be improved or techniques from which the elimination of highly slagging and fouling coals may result, are appropriate and should be considered further.

*Slagging*

Mineral matter in the commonest coals used for power generation, ie high volatile bituminous coal, consists mainly of clays (aluminosilicates), quartz (silica) and pyrite (iron sulphide), with a wide variety of other minor mineralogical constituents. During combustion the clays dehydrate and fuse and form a silicate glass whilst the quartz, if large enough, may pass through the boiler unchanged. The pyrite is potentially capable of initiating slagging problems as it passes through a low melting state known as pyrrhotite (FeS), during combustion. The extent and distribution of iron sulphide in the coal, and the furnace gaseous atmosphere will determine whether or not slag build-up will begin. One other fluxing agent is calcium and this is capable of forming low-melting calcium silicate glasses if present in sufficient amounts in the coal ash.

*Fouling*

Fouling is the phenomenon which occurs when the deposition of material onto boiler tubes in the convective section of the boiler happens. These tubes are at a higher surface temperature than furnace tubes and provide a suitable substrate for the deposition of molten or semi-molten alkali metal sulphates, in particular, sodium sulphate. This material remains in the molten state on the tube and is able to trap other particulate material from the gas stream. The deposit builds up and the surface is maintained in the molten state thereby attracting more and more material from the flue gas stream.

**Abrasion and Erosion**

It is more difficult to assess the abrasive characteristics of flame-heated ash than pulverised coal minerals. The latter can be considered to consist of a mixture of soft clay mineral particles, (2-2.5 Mohs) and of hard quartz, (7 Mohs), and pyrite particles, (6-7 Mohs). Thus, the abrasive property of pulverised coal depends largely on the amount of quartz and pyrite in the fuel. In contrast, the glassy spherical particles, which constitute pulverised fuel ash (PFA), are much harder having Moh hardnesses in the range 5 to 7.

The erosion wear experience in coal-fired plant has until recent years been characterised by ash of moderate abrasivity, [55]. Tube failures as a result of ash erosion wear have not therefore constituted a major problem in the first ten years of operation. The design flue gas velocity is between 15 and 18 $ms^{-1}$ and with coals of less than 20% ash and less than 15% quartz in ash there are few erosion wear tube failures during the first 50,000 hours of operation. However, the tube failures become more frequent in the operation period of 50,000 to 75,000 hours, corresponding to an erosion wear rate of 75 to 100nm $h^{-1}$. The tube failures occur frequently at the bends near the duct wall and the tubes situated underneath the flue-gas bypass, [55].

The change to the use of exclusively non-UK coal or as blends has the potential for altering the incidence of tube wall erosion. In most cases the silica in ash content of foreign coals is much higher than for UK power station grades. This is likely to result in a higher quartz content in the ash of non-UK coals, making them more erosive. However, in almost all cases the imported coals contain much lower ash contents, often 10% or less compared with 18% for a typical UK power station coal. This means that the overall ash burden of the imported coal is lower and though it may be more abrasive, there is less of it in the flue gas stream. So far no increased incidence of abrasion has been noted, although it may still be too early to detect any changes.

The severity of erosion wear in the pneumatic transport lines depends largely on the amount of gritty material in the ash, for example, material from the economiser hoppers. Severe abrasive wear also occurs in the hydraulic pipes transporting the abrasive furnace bottom ash to disposal sites. The erosion wear of dry ash pipelines occurs at bends and elbows and can be reduced by the incorporation of wear-resistant refractory such as high purity alumina inside the bends. Special cast iron inserts made of materials such as Ni-hard have also been used with some success.

Research projects are in progress to enable the prediction of pipe bend lifetimes, [56].

**Fly Ash Collection**

*Electrostatic Precipitators*

The most popular device fitted to large power generation boilers for the collection of fly ash is the ESP. The basic theory of operation is that the gas-borne particles are passed through a corona or charging field where they receive an electric charge and then as charged particles are deflected by the electric field producing the charging regime. The charged particles then move across the gas stream from the negative electrode to the positive electrode, which for convenience is normally earthed. From the collectors, the particles are removed into receiving hoppers by mechanical shock impulse rapping.

These devices have been developed over the years to take account of, for example, the variation in coal ash composition which has lead to different ash resistivities and therefore different collection efficiencies, [57]. The need for boilers to burn low sulphur coals for SOx emission control lead to the need for flue gas conditioning to improve the performance of the precipitator. This has been accomplished by the injection of controlled amounts of gaseous sulphur trioxide ($SO_3$), into the ESP.

More recently there has been a need to increase the collection efficiency of the ESP as regulations relating to the emission of ultra fine particulate matter, known as $PM_{10}$ and $PM_{2.5}$, may soon be in force. This situation has also coincided with the fitting of LNB's to most coal-fired power stations. A side effect of the reduction in NOx emissions has been the increase in carbon-in-ash which has an adverse effect on the collection efficiency of the ESP.

This is another instance where there is a need in the near future for further development of existing equipment involving MPF. In this case, the driver is not a direct improvement in efficiency, and the costs will be increased not reduced. This is a development that will benefit the environment and will be enforced on the power generator.

Alternative technologies using electrostatic effects have been developed for other industries. Examples of these include the wet ESP, [57], and the use of charged sprays to collect dust charged with an opposite polarity, Metzler et al. [58]. The former employs irrigation of the earthed plates of tube walls to remove the dust. In this way sticking and accumulation of dust and re-entertainment of the dust are eliminated. The latter uses a large surface area and a sink for particles distributed about the entire flow area. An extensive review, [59], has been produced of this latter type.

*Fabric Filters*

Fabric filters are essentially cloth bags through which the dusty gas flows. The fabric, which can be made from natural fibres (such as cotton or wool), plastics (such as nylon, acrylic, polypropylene or polytetrafluoroethylene (PTFE)) or glass fibres, are selected so that the gas passes through but the dust is retained. Obviously, the material selection is based on the temperature of the gas stream and the resistance to chemical and abrasion attack required. PTFE and glass fibres are most suitable for higher temperatures but are still only suitable for 200°C. All others are essentially good for <80°C. The type of weaving used can also affect the characteristics of the filter.

The filter tends to consist of a number of tubes of the woven material each supported by an open framework which are mounted in a housing. The number of units is selected by reference to the required gas velocity through the filter cloth. Values in the range 0.01 to 0.06 m/s are normal. The dust is held back on the cloth and builds up into a cake. This causes an extra pressure drop to occur. Periodic dust removal procedures are carried out to remove the dust from the cloth. There are three approaches. The first involves providing a reverse flow of air. Appropriate dampers on the inlet and outlet of subcompartments of the filter housing are actuated and a special fan is used to blow air in the reverse direction through the cloth. This can dislodge the dust which falls to a catchment hopper at the bottom to the housing. Subcompartments are treated in turn. The second approach involves giving each bag in turn a shake or rap. Ideally, the gas flow should be stopped during shaking and thus there is a requirement for subcompartments. This is more effective than reverse flow but there can be heavy wear on the fabric and the shaking mechanism can be very complex. The third types are pulse jet filters. In these dust is deposited on the outside of the filter bag. A powerful jet of compressed air is directed into a venturi tube located at the mouth of the bag. The venturi tube induces more air to flow in from the clean air plenum. The pulse of air causes the bag to expand; filtration is temporarily stopped and air flows from the clean to dirty side of the bag. These actions dislodge dust from the bag and it falls into the hopper section below. The cleansing action is normally carried per row of bags and the pulses are short, typically 0.05 to 0.15 seconds.

Fabric filters can produce very high efficiencies for moderate power costs provided that the product is in dry form. Though moderate in cost for smaller plant, they can be complex and expensive for larger units. They are obviously not suitable for cases where the dust is sticky or where the temperature falls below the dew point.

As noted above, there are limitations as to the maximum temperatures at which fabric filters can be operated. For very high temperature gases this would mean that cooling of the gas, with possible dew point problems, and their subsequent reheating to ensure their dispersion from a stack might be required. For such applications ceramic filters have been considered. Indeed they have been tested on the Grimethorpe Pressurised Fluidised Bed Combustor (PFBC), [60]. These are sometimes also called candle filters and are roughly in the shape of filter bags, [61, 62]. Pulsed jets, similar to those used in fabric filters are employed to periodically remove the cake of dust which builds up, [61,63,64]. Simmons et al., [65], and Duo, [66], have studied the gas/particle flow around the filter. Data on low-density ceramic filters for gas cleaning has also been obtained, [67].

Compared with an ESP unit handling a ‘difficult’ fly ash, the cost of the equivalent fabric bag filter would be somewhat cheaper. However, its operating power, the maintenance of compressors and cleaning mechanisms, plus the cost of a complete replacement of the bag filters, probably every three years to ensure emission compliance, must be borne in mind and added to the overall cost comparison. It should be recognised that it would need 35,000 bag filters to treat the dust-laden flue gas from a 500MW boiler.

*Cyclones*

There are many different forms and arrangements of collectors which use inertial separation to collect particles from a gas stream. They are termed cyclones or centrifugal separators. The principle is that the entraining stream is caused to rotate rapidly within a cylindrical vessel. Because of the much higher mass of the particulates compared with the gas molecules, the resultant centrifugal force causes the particles to migrate across the flow to the wall of the containing vessel where they become disentrained in the low flow region of the device. Cyclones are simple but need a pressure drop of some 100mm water gauge, for effective separation and are ineffective for particles finer than about 10 microns.

**Furnace Bottom Ash Collection**

The collection of furnace bottom ash is relatively simple in that the fused material simply falls to the bottom of the furnace. There it is cooled in a wet or dry system, collected and removed from the boiler.

This material is a valuable by-product from the combustion of pulverised coal. It is in great demand as a raw material in the manufacture of concrete blocks, [68].

**Disposal of Solid Combustion By-products**

*Saleable Products*

The disposal of coal combustion by-products (CCB’s), as revenue-earning materials has become of increasing importance in recent years. Increased competition in the open power generation market has made cost-cutting and efficiency improvements priority issues.

To assist in the promotion of ash sales in the UK, there exists an organisation known as the UK Quality Ash Association (UKQAA), [69]. It was formed in July 1997 from an organisation known as the Quality Ash Association (QAA). Whereas the original organisation existed to promote the sales of a specific product, ie classified PFA, the new organisation reflects the need to maximise revenue and develop markets for new products. It promotes all ash-related by-products from the burning of pulverised coal. The full members of the UKQAA are Powergen, Innogy, TXU Europe, Scottish Power and Blue Circle (joint members), Ash Resources Ltd and Edison Mission Energy.

Other organisations involved in similar activities include the ‘European Association for Use of the By-Products of Coal-Fired Power-Stations e.V.’, (known as ecoba), [70], and based in Germany and the American Coal Ash Association, [71], in the USA.

*Cenospheres*

Fly ash that is formed during the combustion of coal contains a small percentage, usually 1% to 2%, of fine spherical particles known as cenospheres. They are formed at an estimated temperature of 1,400$^{O}$C and their formation and size are governed by the viscosity and surface tension of the fused silicate glass, by the rate of change in particle temperature and by the rate of diffusion of gases in the silicate melt.

Cenospheres have diameters in the range 20 to 200 microns and are coherent, non-porous shells of silicate glass. The thickness of the shell is about 10% of its radius and the true particle density ranges from 0.40 to 0.60 g/ml.

Due to their unique combination of shape, size, relatively high strength in uniform compression, good thermal and acoustical insulation and dielectric properties, many high value applications can be made with these materials. A price in the order of £400 per tonne may be obtained, although it should be recognised that the yield of this product is generally very small, [68].

*Pulverised Fuel Ash*

Mineral matter in coal, which becomes ash on combustion, is predominantly converted into fly ash with the minor products being furnace bottom ash and cenospheres. The split is approximately 80% fly ash and 20% bottom ash although with the fitting of LNB’s, the percentage of fine ash has increased at some stations to 90%.

*Classified PFA*

This is PFA which has been classified to remove material of size greater than 45 microns. The finer fraction usually represents about 70% by weight of the raw PFA and this material is valued for incorporation into concrete. This material, which is subject to a test procedure in British Standard 3892 Part 1, [72], must contain no more than 12% material of size greater than 45 microns, no more than 7% loss-on-ignition (LOI) and no more than 0.5% moisture. It has a current value of £20 to £25 per tonne, [68]. Note:- The term LOI is frequently used in place of carbon-in-ash. This is not strictly correct although in many cases the values are similar. LOI measurements are usually slightly higher than carbon-in-ash values for the same sample. This is because the LOI figure includes other losses such as moisture, mineralogical changes, and any volatile sulphur, nitrogen or oxygen compounds.

*Conditioned PFA*

Freshly produced fly ash is normally transported by tanker, however, it is sometimes necessary to stockpile the ash prior to its removal from the power station. In this case, to reduce air-born dust, it is necessary to condition the ash with water. It is processed in a mixer and the moisture level is raised to around 16%. It can then be stockpiled and later reclaimed for similar use to freshly produced PFA. It is used with cement and/or lime as grout or simply as fill.

*Furnace Bottom Ash*

Furnace bottom ash is a granular slag-like material which results from agglomeration of fly ash and any slag material which may become detached from locations within the furnace envelope. It collects in a central v-shaped channel in the base of the furnace and is cooled and removed by a constant flow of water. It is a valuable by product and is used in the manufacture of blocks.

*Lagoon Ash and Lagooning*

The disposal of fine ash and dust may be accomplished by pumping an aqueous slurry to old quarries, gravel pits or depression in the ground which need filling. Areas up to five miles from the station can be filled by this means but it requires a large supply of water. Ash may subsequently be removed from the lagoon for sale in grouts and fill, and cenospheres skimmed from the surface, may also be collected for sale. The ash from a lagoon is often slightly coarser than normal PFA and may be used in landscaping.

*Landfill*

The UK Landfill Tax became effective on 1st October 1996 and is levied on waste deposited in landfills. A distinction is made between inactive waste, which is £2 per tonne and includes pulverised coal ash, and other wastes which cost the standard rate of £10 per tonne. In March 1999, the Chancellor of the Exchequer announced that the standard rate would be subject to a landfill tax escalator of £1 per tonne per year for at least another five years, reaching £15 per tonne in 2004, [73]. It is assumed that by this time the inactive waste category will also have increased by 50% to £3 per tonne.

The cost of landfill tax is much higher in other European countries, for example in Germany it is currently equivalent to about £40 per tonne. The large price differential between the UK and Germany present threats to the UK market for saleable products as it may be financially viable for German coal ash to be transported to the UK for sale. It would then be in competition with UK-produced ash.

**Fly Ash Beneficiation**

Fly ash beneficiation is a technique in which PFA from pulverised coal combustion is treated to separate the carbon from the ash. The driver for power generators to consider this technique arose with the advent of LNB's and the increased awareness of the effects of combustion on the environment.

Prior to NOx control legislation, the carbon content of fly ash was very low, typically 1% to 3% and the markets for fly ash were not well developed in the UK. The retrofitting of LNB's, by the nature of the changes to the combustion process, increases the carbon content of the fly ash. This is not only an unwelcome efficiency loss but, with the development of markets for fly ash, can, in certain extreme circumstances, render the ash unsaleable.

During boiler operation using LNB’s, there is always a trade-off between unburnt carbon and NOx emissions. The lowest possible NOx emissions will coincide with the highest carbon-in-ash and vice versa. Providing that the levels of reducing gases, such as CO, do not reach unacceptable levels in the furnace, the use of fly ash beneficiation would allow the plant operator to optimise the boiler for minimum NOx emissions in the knowledge that carbon recovery can be undertaken in a post-combustion process.

There are a number of different methods by which carbon may be separated from fly ash. The cost of the plant involved and the efficiency of the process vary considerably. A number of the more extensively studied systems are described in subsequent sections of the report. Much of the development work has taken place in the US, and the US Department of Energy (DoE), has sponsored an annual conference on carbon in fly ash since 1995, [74-79].

*Combustion Methods*

One of the first methods reported, [80], involved the use of a specially designed fluidised bed combustor and was known as the CBO (Carbon Burn-Out$^{TM}$) process. In the process the fly ash acts as the bed material. The bed is heated at start-up by an oil flame. This is then ramped down and the flame is finally shut off when the bed reaches the auto-ignition temperature of the carbon at about 460$^{O}$C. Low carbon ash is removed from the bed, and high carbon feed material added as dictated by the bed temperature.

An EPRI (Electric Power Research Institute),-sponsored 1t/h pilot plant was designed and built in 1993 and was operated successfully for two years. Over 800 tons of fly ash from 15 different sources and having carbon-in-ash values in the range 5.5% to 18% were processed. The recovered heat is returned directly to the boiler and the targeted carbon-in-ash figure can, it is claimed, be set to ±0.25%.

The first full-scale application of CBO went into commercial service at the Wateree Station of South Carolina Electric and Gas in January 1999, [81]. Wateree is a two-unit, 772MW plant located south of Columbia in South Carolina, USA. It was designed to process 180,000 t/y of ash with a carbon-in-ash of 12.5%. So far over 18,000 tons per month of premium fly ash have been sold with a targeted carbon-in-ash of 2.5%. Recovery of heat and application back to the turbine cycle in the power plant has functioned fully as designed. The Wateree CBO fly ash product is finer in particle size than the high-carbon feed ash, and is very similar to the fineness of low carbon fly ash produced by the Wateree units before the fitting of LNB’s.

Another important feature of the CBO process is its ability to remove adsorbed ammonia from fly ash. This contaminant also renders the fly ash unsaleable and arises from the use of SCR or SNCR to further reduce NOx emissions from boiler plant.

*Electrostatic Methods*

Triboelectrostatics is the study of the natural charging tendency of matter via frictional collisions induced by an imposed flow field. Tribocharging occurs as a consequence of particle-particle and particle-wall collisions, the magnitude of which depends on differences between the surface work function of the colliding components. A material having a low work function will give up electrons to a material having a higher work function. For fly ash, [82], the carbon attains a positive charge whereas the ash attains a negative charge upon interacting with a copper surface. Passage of the differentially charged particles through an electric field thereby enables their beneficiation to occur. A bench-sale continuous-feed triboelectric separator has been developed and shown to operate effectively. As with most beneficiation processes a trade-off between yield of product and product quality has to be established. For example, using a PFA with carbon-in-ash of 9%, a product with 3% carbon-in-ash was produced in 55% yield, ie 55% of the weight of original PFA. However, if a product with 4% carbon-in-ash was desired, it could have been produced in almost 80% yield. It was also noticed that not all PFA's gave the same yields of lower carbon-in-ash materials ie one PFA with 7.5% carbon-in-ash gave only 15% of 3% carbon-in-ash product when beneficiated.

The cost of scale up of the process to full size has been estimated and is said to be $3 per tonne, (equivalent to around £2 per tonne at November 2000 exchange rate).

Recent developments have been reported, [83], concerning dry triboelectrostatic beneficiation techniques. A number of different configurations were tested at laboratory scale on coal and biomass flyashes. The quality of separation was found to be dependent on the nature of the coal ash and the configuration used.

*Classification Methods*

At the 1999 US DoE conference, [84], discussions were held on the removal of carbon from fly ash using an acoustically agitated fluidised bed separator. The process is centred around an inclined fluidised bed, similar to a long, nearly horizontal table. Fly ash is added at one end of the bed and fluidising air passes upward through the distributor. As ash flows along the length of the bed, segregation into carbon-rich and carbon-lean streams occurs. Because the fineness of the fly ash makes it difficult to fluidise, loud speakers located above the bed create a high intensity acoustic field. This acoustic energy promotes ash flow along the bed and improves segregation of carbon particles from fly ash. A PFA of 33% carbon-in-ash was processed. The products were a high carbon-in-ash fraction containing ~50% carbon-in-ash and a low carbon-in-ash fraction containing ~11% carbon-in-ash. The fractionation process produced similar weights of each fraction. It seems that this process, at it present state of development, does not produce a sufficient degree of cleaning to produce a marketable low carbon fly ash.

*Froth Flotation Methods*

Froth flotation is a well understood and proven technology that has been used by the minerals processing industry for over eighty years. It is logical that this technology should be applied to the separation of carbon-rich fly ash into two more valuable by-products, namely marketable carbon and pozzolanic fly ash. A number of patents, [85], have been granted to the Institute of Materials Processing at Michigan Technological University (MTU), Houghton, Michigan.

The process consists of forming a slurry of fly ash material from which the cenospheres are first removed. The unburnt carbon is then removed from the slurry by froth flotation and the remaining PFA is filtered and dewatered.

It is claimed that the process is effective with either high or low carbon feed materials and can reduce the product to a carbon-in-ash value of 1% or less. Recovery rates of the low carbon fly ash are stated to be 90% or above and the carbon product is claimed to have a purity level of 80%. If the available quantities and economics can be justified, the process can also include the recovery of cenospheres and magnetite. The MTU process can also remove basanite ($CaSO_4$), which is present on the surface of fly ash. This is beneficial if the PFA is to be used in concrete mixtures as basanite has a retarding effect. Its removal is said to improve the early set and strength in concrete. Uses for the removed carbon, in addition to combustion, include heavy metal removal from flue gases and in the treatment of waste water streams.

## 4.6. Other Fuels

Within the UK, fuels other than coal that have been burned for power generation in conventional plant have been confined to oil and, more recently, gas. The mix of fuels has changed dramatically within the last two decades. In 1980, oil produced 12.7% of the electricity supplied and gas only 0.6%. By 1999, the oil generation had fallen to 1.4% and that of gas, mostly in new advanced technology plants, increased to 38.5%. Over the same time interval, coal generation fell from 72% to 28%, [51].

### Heavy Fuel Oils

The use of HFO for power generation in the UK declined in the wake of the oil price rises of the 1970s never to recover, apart from a brief period in 1984 during the UK coal miners strike. The opportunity to burn gas and a desire by UK government to diversify the energy market by increasing nuclear generation also accelerated the decline of the oil-fired market. In addition to the socio-economic reasons for the decline in oil usage there were technical reasons which also contributed. These included changes in the practices within oil refineries which were intended to maximise the production of distillate fuels. There was a resulting decline in the availability of heavy fuel oil and that which was produced was of lower quality, [86]. This had a negative impact on the emissions of particulate, NOx and SOx which made its continuing use unacceptable from an environmental standpoint.

*Improved Atomisation*

Although the technology of atomiser development is mature, the need to maintain acceptable emission levels, especially for particulate and NOx, is still an important issue. In the certain knowledge that global gaseous emission levels will be lowered even more in the future, it is necessary for UK equipment manufacturers to be able to supply those power generators outside the UK who still rely heavily on oil for their power generation.

*Emissions*

One of the problems faced by HFO combustion is the inevitable emission of SOx. Many of the grades of HFO contain 2% to 3% or more of sulphur, which not only produces high levels of $SO_2$, but significant quantities of $SO_3$. The presence of vanadium is also unhelpful as it promotes the oxidation of part of the $SO_2$ and also forms, with sodium compounds, corrosive deposits in the convective sections of boilers. It is possible to combat the effects of $SO_3$ and vanadium by the use of additives, [87]. These are usually based on magnesium compounds, [88], although many other substances have been used, [89]. They are either incorporated into the fuel oil before combustion or are injected into the furnace or convective sections separately. Their mode of action is to combine with $SO_3$ to form magnesium sulphate and with vanadium to produce a refractory, friable material, magnesium orthovanadate, which does not adhere to boiler tubes. Their effectiveness is variable and the cost of their use can be significant. The use of additives adds to the overall burden of particulates and their collection and effect on stack opacity may cause problems and need to be recognised.

Fuel nitrogen has also increased in recent years from a figure of around 0.2% in the 1970s to 0.5% to 0.6% at present. This is also unhelpful with regard to NOx emissions although there has been work reported, [90], in which the fuel nitrogen to NOx conversion efficiency was said to fall with increasing fuel nitrogen content. This would help to offset the recent increases.

Another consequence of the fall in HFO quality is in the potential for particulate formation. The portion of heptane-insoluble material in HFO, defined as ‘hard asphaltenes’, [91], has been found to have increased steadily over the last two decades. This material is responsible for much, if not all, of the unburnt particulate matter and although additives are claimed to be able to combat the problem, improved atomisation is felt to be a more useful approach to minimising solid emissions. The total ash content has also risen in recent years and there is little that can be done to eliminate its effects.

**Emulsions**

Emulsions are two phase liquid/liquid systems and have been developed in recent years as combustion fuels. There have been two types of emulsion which have been subjected to extensive testing, one of which is now being burned in a number of boilers around the world. Most work has been done on a fuel known as Orimulsion, [92]. It consists of a naturally occurring, bitumen-in-water emulsion produced in Venezuela. Orimulsion, composed of 30% water and 70% natural Bitumen, is used commercially by utilities in Canada, Denmark, Japan, China, Lithuania and Italy. In the USA, several utilities have considered, but not implemented, the use of this fuel in existing power plants.

More than 1.2 trillion barrels of bitumen exist in the Orinoco Belt where Orimulsion is developed - an amount which is more than 50% of the worlds estimated oil reserves. Although the existence of this bitumen field has been known for 50 years, only recently has technological development allowed cost competitive and environmentally safe extraction. Economically recoverable reserves are now estimated at about 267 billion barrels.

This fuel has been successfully fired commercially in Denmark since 1995, [93,94]. It was initially fired experimentally on Asnaes #5 unit of SK Power, but has now been fired on a regular basis ever since. Consumption for 2000 is expected to be just over 1 million tonnes.

*Handling*

The bitumen-in-water emulsion is stable but it needs careful handling. It must not be subjected to conditions which cause the emulsion to destabilise since the bitumen itself is extremely viscous. There are some benefits in combustion in heating the emulsion to moderate temperatures, around $60^{O}C$ to $80^{O}C$ but higher temperatures cause destabilisation. Although a water-based emulsion, Orimulsion cannot be rinsed away completely, as dilution causes demulsification of the material.

*Atomisation*

The quality of atomisation has been found to be good with Orimulsion as it is possible for secondary atomisation to occur with this fuel. This is the rapid vaporisation of very small droplets of water which are embedded in the bitumen particles. The relatively poor primary atomisation quality, (resulting from the need to restrict Orimulsion preheating), is counterbalanced by the benefits of secondary atomisation.

*Combustion and Emissions*

The presence of high levels of sulphur and vanadium in Orimulsion required the manufacturers to develop an additive/stabilisation system to facilitate handling and environmentally friendly combustion. The nature of the fuel, ie an emulsion of bitumen in water, enabled the package to be introduced into Orimulsion as water-soluble substances. Initially, magnesium acetate was one of the substances used but, to reduce costs, the supplier changed this to magnesium nitrate. A more recent formulation, known as Orimulsion 400, contains very little additive and a different stabiliser, [95]. It is claimed that this has been possible because of the much lower sodium content of present Orimulsion. Increased acidic corrosion from combustion of the new formulation of Orimulsion has yet to be confirmed although it is believed work, not yet in the public domain, has been undertaken to investigate the possibility. The presence of vanadium in Orimulsion also appears to assist burnout and unburnt carbon in particulate matter is very low.

## Renewables

This category of fuel has been included in the report because the MPF aspects of power generation from renewable and fossil fuels are, in many ways, similar. Renewables do present additional problems, such as handleability, low heat content etc., which exceed those of fossil fuels. This is due, in part, to the physical properties of renewable fuels and also limited experience in their use to generate electricity.

*Definition and Availability*

Renewables are, for the purposes of this report, defined as combustible, cellulosic materials such as biomass and waste-derived combustible materials.

Biomass resources which could be used as an energy source are:

- forest residues from timber production and thinning measures,
- residues from fruit plantations, public parks, road greenery, straw,
- agricultural residues from olive oil or vegetable production,
- organic wastes from households (eg vegetable residues and sewage sludge),
- organic wastes from the food processing industry and energy crops.

The total potential biomass resources for energy in Europe, including the UK, have been calculated to be around 6,800PJ per year or about 12% of the overall consumption of fossil primary energy in Europe in 1996. Wood-based biomass accounts for about 45% of the total, straw 15% and energy crops about 40%.

The use of biomass in Europe, [96], varies widely from country to country and from region to region depending on the climate, the traditional use of the land, the available biomass, and on the political and financial support for energy from biomass. In some countries, where the use of biomass for energy is supported by national programmes (eg Austria, Denmark, Finland and Sweden), biomass usage is high. In Finland 17% of the fossil primary energy consumption is from biomass. The figure is between 12% and 14% for Sweden, Portugal and Austria but less than 5% for the UK.

*Power Generation by Renewables*

The use of renewables for power generation is expected to increase as a result of their lower impact on the environment; however, more process development is needed to bring the technology to commercial maturity. It is worth noting that the issue of the use of renewables and the true cost of electricity generation from these sources is a subject which arouses deep feelings and divisions in different parts of the world. It is clear that the powerful coal lobby in the USA does not wish to see the introduction of any significant quantities of other fuels, despite the environmental benefits that they might bring. This is the same powerful voice which resulted in the USA being unwilling to match the Kyoto commitment to $CO_2$ reduction that many of the other nations were prepared to agree to in 1997 and 2000.

In Europe in 1996 energy equivalent to around 1,800PJ per year was generated from biomass. Power generation from biomass was, however, only 370PJ per year. Within this total the UK produced a total of 39PJ per year of which 26PJ per year resulted in power generation.

In 1998 in the United Kingdom, biomass accounted for 80% of renewable energy sources with most of the remainder coming from large-scale hydro electricity production. Hydro accounted for 17% and wind power contributed 3%, [97].

Of the 2.66 million tonnes of oil equivalent (MTOE), of primary energy use accounted for by renewables, 1.73 million tonnes was used to generate electricity and 0.93 million tonnes to generate heat. Renewable energy grew by 4% in 1998 and has more than doubled since 1990. Renewable electricity accounted for 2.5% of UK electricity supplies in 1998 compared with 2% in 1997.

The use of biomass in power generation currently has major support from the EU. A total of 34 projects within the subgroup ‘Energy from biomass and waste’ have been authorised in the JOULE III programme, [98]. The use of biomass also features in the Framework Five proposals, (1998-2002). Thematic programme 4, in Framework Five, is entitled ‘Energy, Environment and Sustainable Development’, [99].

Within the Energy segment of the programme is Key Action 1, which comprises four objectives as follows:

- Energy production from coal, biomass or other fuels

  The objective is to improve the efficiency and reduce the cost, external dependence, and environmental impact of electricity and heat production; whether from renewable energy sources or fossil fuels (combustion and other thermo-chemical conversion processes, such as gasification, and pyrolysis; improving the efficiency of gas turbines; combined heat and power; etc.)

- Development and demonstration of the main and renewable energy sources

  Research will support the deployment of new and renewable energies, in particular biomass, wind and solar technologies, efficient use of biomass in the context of energy generation systems for heat and power; fuel cells for stationary and transport applications; land-based and off-shore applications of wind energy; photovoltaic and solar thermal technologies.

- Integration of new and renewable energy sources into energy systems

  The goal is to develop new applications and overcome barriers to the use of renewable energy (integration of renewable energy resources into energy grids and processes; hybrid systems; improving the acceptability of renewables, eg by decreasing visual intrusion, noise; etc.)

- Reduction of the damage caused by the environment by power production

  Research will focus on emission abatement technologies for power stations ($CO_2$, SOx, NOx, and other pollutants), hot gas cleaning, and understanding of basic phenomena.

*Renewable Energy Prospects for the UK*

A detailed report by ETSU, [100], has reviewed the position in the UK of new and renewable energy now and in the 21st century. The present comments have been confined to those categories in which combustion is involved. They include materials such as straw, poultry litter, forestry wastes, farm slurries, energy crops and municipal solid waste (MSW). The report lists opportunities and constraints for each group, see Appendix 4.

*Barriers to the Use of Biomass in the UK*

The use of biomass for power generation will be primarily constrained by the availability of fuel from within an economically viable distance. As a result it is very likely that any biomass-fired plant will be rather small in size. Power plant location needs to be adjacent to biomass sources and this is likely to be unacceptable to the general public. Similarly, excessive transport movements between biomass sources and the power plant would be unwelcome to the local community. Biomass combustion is perceived to be relatively new technology and the venture capital to realise such project might be difficult to secure.

*Co-combustion and Co-gasification of Renewables*

In recognition of the problems associated with low heat content and limited availability of biomass for large-scale power generation, the EU sponsored a large research effort into the feasibility of co-combustion and co-gasification, [101]. The programme was known as APAS Clean Coal Technology. In the co-combustion study, brown and hard coal were co-combusted with a variety of biomass types using pulverised and fluidised bed systems. The results were encouraging and lower NOx emissions were observed. Care must be taken with the biomass preparation and injection systems and corrosion and slagging potential of certain biomasses needs more study. Similar positive outcomes were found with co-gasification although, as with co-combustion, some further work remains to be carried out. The benefits of substituting a proportion of coal with a '$CO_2$ neutral' fuel appear to be technical feasible and justify further development.

*Global Prospects for Biomass*

On a global scale, biomass remains the dominant renewable fuel stock in the long-term for most of the scenarios, ie economy-driven or environment-driven, irrespective of scenario drivers, [100]. This reflects the overall trend of a switch away from traditional exploitation of renewables to modern commercial energy carriers. In addition, advanced biomass energy technologies can provide modern energy services with very low local levels pollutant emissions. It is expected that there will be a significant expansion of renewables in all scenarios. The cost of energy delivered from renewables is also likely to decline with increased market penetration, which in turn will open up new market opportunities.

Potential world markets for renewables as a whole are seen, [102], as making an increasing contribution in the medium term and playing a very substantial role in the long term by most institutions producing projections of future energy needs. There is, however, wide variation between scenarios representing historic policy circumstances with modest growth in renewables and those seeking 'sustainability' with rapid growth in renewables. The EU estimated the world market for total renewables to be £31 billion in 1990. The EC White Paper on Renewables estimated that the internal business in 2010 would be valued at 37 billion Euro, with a further 17 billion Euro from exports in the expanding world markets. The EC White Paper on Renewables proposes a target of doubling the contribution of renewables from 6% to 12% of Europe's total primary energy needs by 2010. The capital investment needed to achieve this was estimated to be 165 billion Euro. The White Paper proposes a series of subsidiary targets for individual energy sources including 40GW of wind, 105GW of hydroelectricity, 3GW of photovoltaics and 135 MTOE of biomass.

The potential contribution of renewables in the UK electricity market, [102], has also been reviewed. It suggests an available resource from renewables of up to about half of current UK electricity consumption at prices below 3p/kWh in the longer term assuming a development programme can be successfully carried out. Scenario studies suggest that obtaining 10% of electricity from renewables by 2010 appears to be feasible. The figure was 2% for 1997. Wastes, wind and energy crops could make the dominant contributions with modest contributions coming from landfill gas and hydroelectricity. These technologies also offer opportunities for export.

*Biomass Fuel Availability, Handling and Preparation*

A recent report entitled 'Co-firing Wood with Coal in Utility Boilers' provides a good insight into the options available and the potential problems arising from trying to co-fire wood with coal in a large boiler, [103].

The report found that it was difficult to arrange for the supply of more than 100,000 green tonnes per year in the UK which represents approximately 5% of the energy requirement for a single 500MWe generating set. This situation could change with the growing of significant quantities of short rotation coppice (SRC), or if certain types of wood waste were allowed into the fuel chain, but would still not exceed about 10% energy requirement. Green wood, such as SRC, can contain between 20% and 60% moisture making its calorific content and handleability uncertain.

The way in which the fuel is handled and ground depends upon its condition as supplied. Construction demolition wood (CDW), is dry and can be pulverised more effectively than SRC. The latter needs to be chopped and allowed to air dry before attempts are made to burn it. Dervin, [103], found that for between 2% and 5% wood addition to coal, the wood should be all less than 6mm. This quantity of wood addition could be co-ground with coal in the normal pulverisers. For quantities between 10% and 15% wood, the size should be all less than 1.6mm and less than 20% moisture. The latter quantity of wood needs to be ground in a separate milling system.

*Biomass Ash Quality and Effect on Boiler*

The composition of biomass ash is very different to coal ash and its effect on boiler deposition has been investigated. Wood ash contains higher levels of calcium, potassium and phosphorus and lower levels of aluminium and iron when compared with most coals, [103].

Whilst this might be expected to give cause for concern, it should be recognised that the ash content of wood is low, around 1%. Consequently, in a blend of, for example, 10% wood and 90% coal, the relative ash contributions per tonne of fuel would be 1kg wood ash and 90 kg of coal ash, (assuming 10% ash in coal). The effect on overall composition and likely impact on deposition will be small. Experiments designed to confirm the minimal effect of biomass ash constituents on deposition when fired with pulverised coal are currently in progress, [104].

Of equal importance is the requirement that the lucrative PFA market will not be jeopardised by unacceptable ash quality resulting from wood/coal co-combustion.

*Emissions from Biomass*

The main reason for burning biomass is that it is $CO_2$ neutral but there are other benefits. The sulphur and nitrogen contents of biomass, such as wood are low, which results in reductions to SOx and NOx emissions.

Particulate emissions from wood combustion might be expected to produce a different fly ash which could cause stack opacity and collection difficulties due to their extremely fine size. However, at the concentrations of biomass being considered, it is not felt likely that such a problem will occur.

## 5. SURVEY OF MPF-RELATED TECHNIQUES OF RELEVANCE TO THE FOSSIL-FIRED POWER SECTOR

### 5.1. Scope and Structure of Survey

It was decided that the best way to meet the project objectives was to survey all of the areas of MPF that have relevance, either now or in the future, for fossil-fired power generation. The survey was confined to those aspects of power generation agreed in Section 1.2. Scope of Review.

The activities were divided into two main groups. The first involves those techniques which could be regarded as developmental, ie techniques which would lead to benefits, but mainly indirectly. For example, it would include modelling of flows for the development of new burner technology. This group contains activities such as Process Modelling and Experimental Verification. The second group involves techniques which have a direct impact on the operation of fossil-fired plants and includes Plant Detection Methods and Plant Operation and Control.

### 5.2. Process Modelling

#### Computational Fluid Dynamics (CFD)

Mathematical modelling is now used routinely in many industrial applications such as, for example, the power generation business, [105].

There are two very different numerical methods commonly used to model combustion plant. The first, suggested by Lobo and Evans, [106], and developed extensively by Hottel and co-workers, [107], calculates heat balances taking into account the heat released by the combustion of the fuel, the heat transferred to the tubes and the heat lost through the flue and walls. This method allows a very accurate treatment of radiative heat transfer and special methods have been developed for including tubes, but it does not attempt to calculate the flow and hence convective heat transfer.

The other method was developed largely by Spalding and colleagues, [108], at Imperial College of Science, Technology and Medicine (ICSTM); see Spalding and Patankar, [109]. This starts with the basic equations for flow, enthalpy etc. and introduces approximations to take account of turbulence. The resulting equations are then discretised on a suitable grid usually, by finite differences or volumes, and solved numerically. All of the quantities of interest, such as the gas velocities and temperature and the concentrations of the major species, are thus calculated in detail at the nodes of the grid. The method, now referred to as CFD, is very powerful, but uncertainties arise from the approximations and the numerical methods.

With the rapid advances in computing power, mathematical models have been developed for stress analysis, thermal conductivity and aerodynamics. Even when the geometries are complex and three dimensional, the commercially available computer codes are accurate, reliable and fast. As a result, many design processes have become streamlined and very cost-effective.

Modelling of combustion plant on the other hand is not nearly so well developed because of the complexity of the underlying physical and chemical processes and the interactions between them. Some of the important factors include, type of fuel, formation of pollutants, chemical reactions between fuel and oxidant, completeness of combustion, turbulent mixing of gases and fuel/ash particles, slagging and fouling of heat transfer surfaces and others. In addition, it should be stressed that these techniques can only be used for dilute suspensions. They cannot handle flows of dense suspensions where particle-particle interactions become significant.

The method can be extended to MPF's.  There are two basic approaches.  The first, termed Eulerian/Eulerian, assumes that the phases each occupy a particular point in space for a part of the time.  The void fraction or solids 'hold-up' then becomes an additional parameter.  Interfacial relations such as drag laws are then required.  The second approach is termed Lagrangian/Eulerian. Here, the gas flow field is determined and this information is utilised to calculate particle motion.  Methods are available to allow for the effect of turbulence.  Because of the random element brought in by the turbulence, the behaviour of many particles must be calculated to obtain meaning full averages.  Where concentrations are low, the interaction between the phases can be taken as one way, gas to solids.  However, once concentrations become significant, two-way coupling, ie, transfer of momentum from gas to particles and from particles to gas must be accounted for, Crowe et al. [110].  The technique has been applied successfully to pneumatic conveying by Huber and Sommerfeld, [111].

Power generators have been forced in recent years to increase plant output and reduce efficiency losses. This may be by using lower grade cheaper fuels or waste materials, whilst at the same time reducing emissions of harmful pollutants and operating their plant in an environmentally acceptable manner. Only limited data can be obtained from test rigs and in most cases the effect of scaling up the data and the use of multi-burner furnaces reduces even further the credibility of such data. Full-scale power plant trials are very costly, difficult to arrange and are time consuming. In response to these issues it is therefore not surprising that investment in the development, validation and application of mathematical modelling is increasing world wide.

The areas where the need exists for accurate, valid and rapid modelling is in assessing changes to plant operating conditions, evaluating plant retrofit options, trouble shooting and new plant design.

For further detailed evaluation of the role that CFD currently plays in the UK power industry, reference should be made to the report by Pourkashanian et al. [105].

CFD helped to diagnose the cause and eliminate fires in two ball mill cyclonic coal classifiers at Salt River Project's Coronado Generating Station Unit No.1, St. Johns, Arizona, [112]. Modelling indicated that the fires were caused by the generation of an internal recirculating vortex on the underside face of the cone plug which provided a zone for maintaining and stabilising a flame front. Alternate designs were evaluated for the cone, plug and shaft assembly and found one which eliminated the formation of internal recirculating vortices. The new design was installed in the classifiers and the problem has been eliminated.

FLUENT, [113], have developed a template based on detailed modelling of static and dynamic classifiers which they are willing to supply to customers to facilitate quick examinations of parametric design changes. Zhou et al, [114], have modelled and simulated the C-E deep bowl pulveriser. It is believed that this work is currently still in progress.

**Discrete Element Modelling (DEM)**

The DEM method is a numerical technique pioneered by Cundall, [115], for problems in rock mechanics where continuity between the separate elements does not exist. Discrete numerical simulations with particles are currently used in several different scientific disciplines. The method is capable of handling a wide range of material behaviour, inter-body interaction force laws and arbitrary geometries. DEM models granular materials which can freely make and break contacts with their neighbours and is capable of analysing interacting deformable bodies undergoing large absolute or relative motions. DEM-related research has proved to be very meaningful for enhancing the understanding of granular materials. This tool has been used for developing and validating constitutive relationships of particulate materials such as soil, rock, grain or ceramic powder by using appropriate particle properties, sizes, shapes, and gradation. Moreover, DEM is the best tool for explaining the experimentally observed facts from a more fundamental approach. It is recognised that one of the major advantages of the discrete particle model approach is that what is being done during a simulation is obvious at all times.

Flowing granular materials, undergoing both mixing and segregation, play important roles in industries ranging from minerals and food to pharmaceuticals and ceramics. Sometimes it is desirable to enhance the mixing and inhibit segregation and in other cases it is desirable to minimise the mixing and enhance the segregation. The fundamentals of these processes are poorly understood. Computational modelling of such granular flows offers a good opportunity to study these fundamentals but it is not known how well these discrete element-based modelling techniques capture the essential features of mixing processes. Cleary et al., [116], have reported on the capabilities of their DEM package. Two different methods for measuring the rates of mixing were presented and three different configurations were studied. Qualitatively reasonable flows were obtained. A detailed study of the mixing demonstrated that the amount and nature of the mixing was quite sensitive to a range of physical parameters.

The distinct element simulation of granular flow involves a distinct element time stepping approach that tracks the position of each particle in time. Figure 9 illustrates an example of the application of DEM to hopper flow. The model gives realistic predictions of discharge rate, wall stresses and velocity profiles (results compared with actual experiments).

A group in Japan is also actively looking into the application of what is termed a 'discrete particle method'.  It has application in many systems where particles are in motion such as fluidised bed combustion, [117], milling, [118], and dense, gas-solid flows,[119].

The distinct element method has many advantages over current established continuum models, but the number of particles it can model for a reasonable computer runtime is limited. Currently, it is being used on projects on paste extrusion and cohesive particulate vibrations. It has a large number of potential applications including bulk solids storage, flow, conveying, mixing, crushing, fluidisation, [120,121].

**Artificial Neural Networks (ANN)**

Where processes are too complex or too poorly understood to model on a mechanistic or 'first principles' basis, an alternative approach to computer modelling can be made using ANNs.  Here, data observed in the real process are used to programme or 'train' the ANN to mimic process response behaviour when presented with given input conditions.  The resulting ANN provides a concise, portable representation (ie a model) of the original process data.  The approach can also be used to adaptively associate sets of measured data into classes with common characteristics.

Neural networks (NNs), are powerful computing paradigms developed within the field of Artificial Intelligence (AI). They can process information more readily than traditional computer systems, [122,123]. This is due to their highly parallel architecture inspired by the structure of the brain. Applications and research into the use of NNs have evolved from their ability to understand complex relationships and hidden patterns within large data sets. NNs have now become an accepted tool across a wide range of disciplines and including applications in the process industry, [124].

Unlike expert systems, an alternative AI approach based on sets of rules, NNs differ in that they:

- do not require rules to learn
- do not require large amounts of memory
- do not possess a database

In contrast to expert systems, they are adaptive processing models that are trained to perform a specific task and to provide a specific response. NNs are robust computational structures, tolerant of faults and have the advantage over traditional computer systems in that they can respond to incomplete and/or noisy data sets. This is in contrast to conventional software which requires careful and correct programming rules and a specified input format.

An ANN may typically contain tens to thousands of neurons, the number depending upon the complexity of the task. The human brain, however, is estimated to contain $10^{11}$ neurons which govern our senses, psyche, motion and communication.

In ANNs, the response of a neuron to an input signal is dependent upon the strength of its connection with the source of the signal. In a similar fashion within the brain, the potential (signal) of a nerve cell is modified in response to impinging signals from other surrounding nerve cells. Each nerve cell has a threshold potential value. Once an individual cell's potential increases to a state above the threshold value, the cell triggers an impulse which is then transmitted.

An ANN behaves in a manner analogous to its natural counterpart, the biological NN. ANNs are required to perform tasks and depending on the outcome of the task, they adjust their internal weighting structure (ie strength of inter-node connections) according to success or failure. This constitutes a basic form of learning (ie trial and error). Using this approach, when a situation which has previously been shown to the network is encountered again, the network will show an improved response.

NNs are extremely useful in detecting trends within data sets that are not immediately apparent even to the most experienced analysts. As a result, NNs have found much success in the areas of pattern recognition with the human voice, handwriting styles and image classification.

Learning is the process of modifying the weighted connections within the network by presenting it with training data. The strengths of the connections are modified with experience. The process can be adaptive if more training data becomes available. There are two types of learning; unsupervised and supervised.

Unsupervised learning does not train the network using a target response output. rather, it allows the network to classify and group patterns using only input data. This form of learning requires a different network architecture; the most common is the Kohenen Feature Map, [125].

To find a relationship within the data there must be a relationship in existence. The NN must be presented with the correct input signals to generate the desired output. If the input vector does not contain all of the possible input variables for the function, an imperfect approximation will result. If there are no patterns due to incorrect input terms the network will be unable to find any relationships.

Supervised learning, on the other hand, takes training patterns consisting of typical input and corresponding output vectors. The network is trained to provide the correct response for the given input data. Through the learning procedure it is expected the trained network will use the knowledge gained from the training data to adapt itself and to generalise the function to work for new data sets. To be taught to approximate an unknown function requires each pattern, within the training data set, to be presented to the network. Each input pattern is transmitted through the network to produce the corresponding output pattern. This value is compared to the target value. Any differences between the output value and the desired output is distributed backwards through the network by adjusting the weight values within the training set and the whole procedure is continually repeated until the network is producing a sufficiently small error (error back propagation).

Having a NN trained to be a function approximator or an interpolator can only provide as good a result as the data which is presented in the training set. The training data must be typical of the values to be expected in the general scenario, and must cover the complete range of values to be expected. The input, validation and recall data must be of the same precision for the functions to be compatible.

It is stated, [126], that the aim of the learning procedure 'is to find a set of weights to ensure that for each input vector the output vector produced by the network is the same, (or sufficiently close to), the desired output vector'. To find the correct set of weights involves searching many hypotheses in an iterative manner. It is not possible to search the entire range due to computer constraints and many may lead to false solutions. This is just one of the many problems associated with using NNs as universal function approximations.

The application of ANNs in power generation and associated industries has become significant. It has been used in the prediction of coal char combustion rates, [127], in the study of PF flames, [128], to optimise combustion and emissions, [129] and to predict volatile matter release in biomass/coal-fired systems, [130]. It has also been used in the development of advanced control systems such as GNOCIS (see Section 5.5).

## 5.3. Experimental Verification

### Flow Facilities

In the context of this project, the power generation industry is likely to be concerned with topics such as the determination of the flow of particulates and gases through large ducting and windboxes, around pendant tube banks, through LNB's and plumes from stacks.

In the case of ducting and windboxes, this is to ensure that the flow of combustion air to a bank of burners is even and the burners do not get deprived of their share of air. The flows are made through scaled down versions of real ducting and wind box runs from existing plant. This is carried out when the retrofitting of LNB's is being planned. The effect of introducing modifications into the wind box to remedy any maldistribution of flows can be done quite easily, although the cost and space requirements to obtain this type of test data is high.

Similar scaled down versions of LNBs and other pieces of boiler plant can also be subjected to flow measurements although more frequently this type of work is being performed using CFD as it is quicker and cheaper.

**Laser Doppler Anemometry (LDA)**

LDA is a widely accepted tool for fluid dynamic investigations in gases and liquids and has been used for more than three decades, [131]. It is a well-established technique that gives information about flow velocity. Its non-intrusive principle and directional sensitivity make it very suitable for applications with reversing flow, chemically reacting or high temperature media and rotating machinery, where physical sensors are difficult or impossible to use. It requires tracer particles in the flow. The method's particular advantages are non-intrusive measurement, high spatial and temporal resolution, no need for calibration and the ability to measure in reversing flows. As such it has application in the development of new technology burners for the power industry.

The basic configuration of an LDA consists of:

- a continuous wave laser
- transmitting optics, including a beam splitter and a focusing lens
- receiving optics, comprising a focusing lens and a photo-detector
- a signal conditioner and a signal processor

Advanced equipment may include traverse systems and angular encoders.

The laser beam is divided into two and the focusing lens forces the two beams to intersect. The photo-detector receives light scattered from tracer particles moving through the intersection volume and converts light intensity into an electric current. The scattered light contains a Doppler shift, the Doppler frequency, which is proportional to the velocity component perpendicular to the bisector of the two beams. The signal conditioner and signal processing remove noise from the signal and extract the Doppler frequency and hence the velocity information. With a known wavelength of the laser light and a known angle between the intersecting beams, a conversion factor between the Doppler frequency and the velocity can be calculated.

The tracer particles scatter light in all directions, with the highest intensity in forward scatter, ie away from the laser. Much less light is scattered in other directions, but direct back scatter is often used, because it allows integration of the transmitting and receiving optics in a single head. This is much simpler to handle than several heads, which must be carefully aligned with each other.

The addition of one or more beam pairs of different wavelengths to the transmitting optics and one or two photo-detectors and interference filters permits two or three velocity components to be measured. Each velocity component also requires an extra signal processor channel.

The basic configuration gives the same output for opposite velocities of the same magnitude. In order to distinguish between positive and negative flow directions, frequency shift is employed. An acousto-optical modulator in the transmitting optics introduces a fixed frequency difference plus the frequency shift.

Modern LDA optics employ optical fibres to guide the laser light from the often bulky laser to compact probes and to guide the scattered light to the photo-detectors. Modern signal processors use correlation or fast Fourier transform (FFT), algorithms efficiently to determine the Doppler frequency from the often noisy signals received from the photo-detectors.

The linear relationship between velocity and output, the insensitivity to temperature and pressure variations, the ability to measure in reversing flows, and in rotating machinery, (where, for example, turbine blades or engine pistons are present in the measuring volume during parts of the cycle), makes LDA the first choice in many applications where hot wire anemometry would be difficult or impossible to use. The advantage of this optical flow measurement technique over others such as PIV, is the high spatial and temporal resolution.

**Particle Image Velocimetry (PIV)**

*Principles*

PIV pioneered over the last two decades is a technique developed by fluid dynamicists to solve an age-old problem; how to instantaneously measure complex flows without interfering with the flows themselves, [132]. As with LDA it is a sophisticated way by which data on particle trajectories in complex systems such as 'rope breakers' or LNB's can be visualised. Before PIV, this was only possible by using an array of intrusive probes, or by repetition of the study while moving a single probe to an array of positions across the flow. In general, these techniques were time-consuming and inefficient. PIV is an instantaneous, non-intrusive full field flow measuring technique. The measurement is regarded as instantaneous when the time duration of the measurement is considered small, say 1/100$^{th}$ compared to the time taken for the flow to change significantly. It combines flow visualisation with quantitative measurements of instantaneous flow velocities over an extended area, providing fluid dynamics with its most powerful tool to date.

The flow to be measured is seeded with suitable particles which are illuminated by a light sheet. The particles must accurately follow the flow whilst scattering sufficient light to be detectable. As the light is scattered, the motion of the gas or liquid is revealed and captured from the side by a camera.

The light sheet is pulsed and the camera's exposure time set so that it captures two or more successive light pulses. The resulting double or multi-exposed image provides a displacement record of the particles within the measurement plane which is then analysed and scaled to velocity.

Typically, PIV images are analysed over a point-wise grid of local interrogation spots. The size of the interrogation region is selected so it is large enough to include a sufficient number of particle image pairs for an accurate measure of local displacement, but small enough so there is little variation in velocity across the spot, (<5%).

A synchroniser is used to synchronise the light pulses with the image acquisition system and to allow accurate determination of the pulse separation. The computer, running the acquisition and analysis software, controls the acquisition system and the synchroniser.

*Seeding*

*Particle Characteristics*

In a few cases it is possible to make measurements using what is naturally present as impurities in the fluid, but usually, successful seeding can require considerable effort and ingenuity.

Factors that have to be considered are:

- Flow medium, (air/water)
- Volume to be seeded
- Flow velocity
- Ability to follow the flow
- Light scattering
- Particle image size
- Safety considerations (ingestion, risk of explosion)
- Cost.

Particle size and density, and fluid density and viscosity, determine the effects of buoyancy and inertia. Exact neutral buoyancy is difficult to achieve, but particles must remain suspended throughout the experiment. In general, seeding is easier in fluids. Lower viscosities and accelerations combined with the higher density and viscosity of liquids means larger, more easily detectable particles may be used. In fluids, they may be up to tens of microns in diameter; in air, diameters range from 5 microns to submicron. For very large accelerations, such as in aero shock waves, particle lag can introduce gross errors and requires careful optimisation with other requirements.

The light scattered from the particles is only a fraction of the light introduced into the flow. Of this scattered light, only that within the solid angle defined by the lens aperture of the imaging system will be collected to form an image. Conventional PIV systems record side-scattered light which can be orders of magnitude weaker than forward-scattered light. the size and material of the seed particles can affect scattering efficiency and small particles also affect particle image intensity. The average particle image should exceed the fog level of photographic emulsions or the noise level of solid state detectors.

The size of the images formed for a given particle and recording system directly affects velocity resolution, accuracy and dynamic range. The diffraction limit of the lens used imposes a limit on image size. In general, to optimise measurement accuracy/detectability with resolution, the geometrical size of a particle image should be no larger than the diffraction spot size of the lens.

Seeding is, in general, easier in water than air. This is because the lower velocities and accelerations likely to be encountered in a liquid flow enable the use of larger more easily detectable particles to be used. The following materials may be used: -

| | |
|---|---|
| Air flows at low temperatures | - atomised oil, 1 to 1.5 microns |
| Air flows at high temperatures | - titanium or zirconium dioxide, 0.5 to 5 microns |
| Air and water flows | - latex particles, 0.25 to 5 microns |
| Water flows | - conifer pollen, 30 to 50 microns |

*Introduction of Particles into the Flow*

The concentration and homogeneity with which particles are introduced into the flow is the primary factor in determining the quality of PIV images. In water flows, seed particles can be injected in either solid or liquid form. The dry powders, which are used, consist of polydispersed, non-spherical particles of relatively high density.

When using dry powders in air flows, particles tend to agglomerate in the delivery mechanism, resulting in the injection of large particle clusters. It is usually easier to spray fluids into air flows.

*Illumination*

*Light Sources*

Sufficient light energy must be delivered to the measurement plane to allow recording of particle images in a short enough time period so that the images are recorded without significant streaking, ie the particle should not move more than a particle image diameter during this period.

Non-coherent light sources can be used but the application is then limited to slow flows, usually in fluids, as longer pulses are required to achieve sufficient exposure for particle detection. Also, it is difficult to obtain a very thin light sheet over a significant distance.

For these reasons, most systems are based on laser sources: this provides a highly directional, intense collimated beam which is well-suited for producing intense light sheets down to a thickness of tens of microns, if required.

*Light Sheets*

Light sheets can be formed from either continuous wave (CW), lasers which are then modulated, or pulsed lasers. The laser beam is delivered to the measurement area by an articulated arm (Nd:YAG lasers), or a multimode fibre optic link (Argon-Ion lasers). Usually the beams are expanded into a sheet by a cylindrical lens. Alternatively, a modulated pseudo light sheet can be created directly by a scanning polygon mirror so no beam expansion is needed. This approach is more appropriate when investigating low-speed flows over large measurement areas.

*Synchronisation*

In a PIV system, the timing of the light pulses used to record the flow is important for two reasons: determining the pulse separation for scaling measurements to velocity, and for synchronisation with the image acquisition system.

Some form of synchronisation is required to either have the rest of the system respond to the strobing of the light sheet as is the case of CW scanning, or to trigger the light pulses in the case of pulsed laser illumination systems. This is usually achieved by a programmable pulse delay generator, either as a stand-alone device or hosted by the computer controlling the image acquisition and analysis.

*Acquisition*

*Cameras*

The choice of image recording equipment is of considerable importance in PIV. The recording system is required to map the motion of illuminated particles into a faithful record of distance travelled.

The lens used to image particles should be capable of near diffraction limited performance while operating with large apertures. This ensures particle images are as small as possible, which not only improves the accuracy of measurements, but also increases the velocity dynamic range and detection.

The camera body and triggering mechanism is also important for accurate measurements when using photographic recording.

A high quality camera mechanism will allow more accurate focusing, as the focus screen is more likely to correspond to the lens image plane. Also, the delay between triggering and the shutter opening should be measurable and repeatable, so that precise synchronisation is possible. Similarly, an accurate measure of the actual shutter times, rather than the quoted times, is important if the number of particle exposures is to be predictable. These problems are avoided with the use of electronic recording media as shutter timing is precisely controlled and the image focus can be monitored at the image plane in real time.

The recording media, whether photographic film or solid state detector such as CCD (charge-coupled device) or CID (charge injection device), array, should be sensitive at the illumination wavelengths. The resolution of the recording media should be consistent with the resolution of the imaging lens.

In most cases, direct image recording onto CCD arrays has replaced the use of photographic film. This allows separate recording of exposures to permit directionally resolved measurements. The resolution and frame rate of the CCD camera will influence how much of the flow can be measured, with how much detail, and how frequently. Other less obvious factors such as the type of the CCD array will determine whether the camera can be used to acquire closely separated images for cross-correlation (directionally resolved measurements) or whether it is suitable for single image-multiple exposure acquisition. Frame rate and CCD running temperature also have a bearing on the background noise levels in the readout image signal and therefore the sensitivity and accuracy of the measurements. The average particle image should exceed the noise level of solid state detectors.

Cross correlation cameras developed by PIV equipment manufacturers provide the ability to capture image pairs separated by a small adjustable interval. Multi-megabyte high-resolution images can then be down loaded to the computer where direct, quantitative feedback can be obtained on-line within a fraction of a second.

*Frame Grabber*

Image acquisition is accomplished with a frame grabber board, which is installed in the acquisition/analysis computer. Frame grabber boards combine all the programmable functions needed in PIV, or flow-mapping techniques in general: dual channel digital video interface for standard cameras, asynchronous frame grabbing, programmable synchronisation/delay generation, high data rate transfer etc.

*Control and Processing Software*

The central task of PIV analysis software is to automatically determine particle displacement from the random particle background. The whole PIV image will typically be divided into a local value of displacement when the analysis algorithm is applied. A local ‘interrogation’ area is a region of a PIV image smaller than the smallest recorded flow scale, but larger than the largest particle displacement.

Techniques used to determine the correct pairings within an interrogation region fall into two general groups: particle tracking and correlation processing. Both have advantages and may even be combined, but generally, correlation processing is the more robust technique when nothing is known of the flow being measured.

Correlation processing produces a measure of the average local particle displacement within each interrogation area. Autocorrelation, the earliest form of correlation processing used in PIV, correlates the local area to itself. For a PIV image with two or more exposures, there is a 180-degree directional ambiguity, which can be resolved with an image shifter. In all but a few application areas, cross-correlation has become the norm: two different interrogations are correlated, thus removing the 180-degree directional ambiguity. An additional benefit of this approach is that zero velocities can be resolved and shorter pulse separations used. This improves spatial resolution and the dynamic range of the velocity.

Ultimately, the quality of the data is determined by the quality of the images acquired. However, even with high quality images which exhibit good contract and a high concentration of seed particles, there is a finite probability that the outcome of a correlation or tracking measurement will be erroneous or unrelated to the flow field being investigated. This can arise due to insufficient particle pairs, out–of-plane velocity, strong velocity gradients or other decorrelations. For this reason, it is generally necessary to perform post-processing on PIV data sets, removing the erroneous vectors with interpolation and applying smoothing techniques to reconstruct areas depleted by validation. Analysis and post-processing software is therefore essential for accurate interpretation of data. It can also be used to control every aspect of the PIV measurement

**Phase Doppler Anemometry (PDA)**

PDA extends the capabilities of laser Doppler anemometry (LDA), to simultaneous measurements of velocity and size of the scattering particles, [133]. Although this technique seems to be an ideal tool for simple dispersed flows, it is subject to limitations and remains quite difficult to master in real two-phase flows.

**Laser Light Scattering (LLS)**

LLS is a widely used technique allowing the measurement of particle size or molecular weight, [134]. The fluctuating motion of submicroscopic particles in liquid suspension reveals not only their size but also their shape and tendency to aggregate.

**Image Analysis (IA)**

IA is a very wide topic which has so far been restricted, within the objectives of this project, to coal evaluation for predicting carbon burnout, [135-138]. It has proved very useful at determining whether a coal sample is a blend and whether it will burn without problems. The technique is being further developed so that it will be able to determine not only the presence of a blend but also the blend composition, [139].

**Chemometrics**

*Introduction*

A data collection task, whether in engineering, science or business, typically involves many measurements made on many samples, [140-142]. Such multivariate data has traditionally been analysed using one or two variables at a time. However, this approach misses the point; to discover the relationship among all samples and variables efficiently, we must process all of the data simultaneously. This is where the subject of chemometrics can help. Chemometrics is the field of extracting information from multivariate data using tools of statistics and mathematics. Chemometrics is typically used for one or more of the three primary purposes:

- To explore patterns of association in data;
- To track properties of materials on a continuous basis; and
- To prepare and use multivariate classification model.

The algorithms in primary use in the field have demonstrated a significant capacity for analysing and modelling a wide assortment of data types for an even more diverse set of applications.

The benefits to the power industry could be in the use of chemometrics in experiment design. Rather than use the technique to evaluate historical data, it is felt that more use could be made by the involvement of the chemometrics expert at the experimental design process.

*Exploratory Data Analysis*

Patterns of association exist in many data sets, but the relationship between samples can be difficult to discover when the data matrix exceeds three or more features. Exploratory data analysis can reveal hidden patterns in complex data by reducing the information to a more comprehensible form. Such a chemometric analysis can expose possible outliers and indicate whether there are patterns or trends in the data. Exploratory algorithms such as the principal component analysis (PCA), and hierarchical cluster analysis (HCA), are designed to reduce large complex data sets into a series of optimised and interpretable views. These views emphasise the natural groupings in the data and show which variables most strongly influence these patterns.

*Continuous Property Regression*

In many applications, it is expensive, time consuming or difficult to measure a property of interest directly. Such cases require the analyst to predict something of interest based on related properties that are easier to measure. The goal of chemometrics regression analysis is to develop a calibration model which correlates the information in the set of known measurements to the desired property. Chemometric algorithms for performing regression include partial least squares (PLS), and principal component regression (PCR), and are designed to avoid problems associated with noise and correlations in the data. Because the regression algorithms used are based on factor analysis, the entire group of known measurements is considered simultaneously, and information about correlations among the variables is automatically built into the calibration model. Chemometric regression lends itself handily to the on-line monitoring and process control industry, where fast and inexpensive systems are needed to test, predict and make decisions about product quality.

*Classification Modelling*

Many applications require that samples be assigned to predefined categories, or ‘classes’. This may involve determining whether a sample is good or bad, or predicting an unknown sample as belonging to one of several distinct groups. A classification model is used to predict a samples class by comparing the sample to a previously analysed experience set, in which categories are already known, k-nearest neighbour (KNN), and soft independent modelling of class analogy (SIMCA), are primary chemometric workhorses. When these techniques are used to create a classification model, the answers provided are more reliable and include the ability to reveal unusual samples in the data. In this manner, a chemometric system can be built that is objective and thereby standardise the data evaluation process.

**Granular and Suspended Flows**

The understanding of flows both into and out of hoppers is of particular importance in the feeding of coal blends into day silos prior to their being ground. Modelling of the processes is also referenced in Section 5.2 on DEM.

A further currently active project involves particle tracking in hoppers using a technique known as positron emission particle tracking (PEPT). Here the objectives are to identify major regions of segregation on a bulk level in batch discharge of a model hopper using sieve analysis and identify segregation models by studying particle velocities, trajectories and residence times using PEPT, [143].

The technique of PEPT was developed at the University of Birmingham. It is a variant of the medical technique of PET, adapted for engineering use. It allows a single positron-emitting tracer particle to be accurately tracked at high speed and has proved to be a very powerful tool for studying the behaviour of granular materials and viscous fluids in systems such as mixers and fluidised beds, [144]

Other applications of PEPT include the following of the dynamics of a radioactive fuel pellet in a fluidised bed combustor, [145], for measuring granular temperatures in dense systems, [146], and powder flow in rotary kilns, [147].

## 5.4. Plant Detection Methods

### Sensors

Sensors cover a multitude of applications many of which are outside the scope of this review. The most relevant sensors, however, within the context of this project are believed to be those which detect the composition of gaseous compounds. These are for use in flue gas analysis, pollutant emission control and continuous emission monitoring. The state of development of these sensors is well advanced in terms of their accuracy, sensitivity and robustness. The challenge in the future is to be able to detect reliably those trace quantities of substances which are subject to new emission regulations, for example, specific volatile organic compounds (VOC's), dioxins, polycyclic aromatic hydrocarbons (PAH's), etc. The accurate determination of such substances in the presence of other possible interfering molecules may be a difficult instrumental problem.

There is another important role for sensors which is for them to be linked with an artificial intelligence system, such as a neural network or ANN, whereby the combined system may be used to control and optimise the plants operations. This has already been achieved with systems such as Powergen's Generic NOx Control Intelligent System (GNOCIS), [148,149] and Ultramax, [150,151], where plants have been optimised, usually for minimum NOx emissions.

### Tomographic Techniques

The word 'tomography' is derived from the Greek words 'tomos' meaning 'to slice' and 'graph' meaning 'image', [152]. The earliest use of tomography was in the field of medicine where so-called x-ray tomography was used to improve the quality of conventional x-ray photographs. Structures that are obscured by overlying organs and soft tissues that are insufficiently delineated on normal x-rays are revealed by this technique. The need to use ionising radiation or isotope sources initially made it an unsuitable method to be applied to the processing industry for safety and cost reasons. Most of the radiation-based methods used long exposure times, which meant that dynamic measure of the real time behaviour of process systems, were not feasible. However recent changes have improved the situation.

Although it might be perceived as an imaging tool for medical purposes only, this is far from the case. The concept of tomography and its non-invasive way of imaging has been developed over the last decade into a reliable tool for the imaging of numerous industrial applications. This field of application is commonly known as industrial process tomography (IPT), or simply, process tomography (PT).

Currently, there are a number of tomographic techniques available for studying complex multiphase phenomena. These include, for example, infra red, optical, X-ray and gamma ray tomographic systems, positron emission tomography (PET), magnetic resonance imaging (MRI), and sonic or ultrasonic tomographic systems. The choice of a particular technique is usually dictated by many, very often contradictory, factors. These include; physical properties of the constituents of multiphase flow, the desired spatial and temporal resolution of imaging, cost of the equipment, its physical dimensions, human resources needed to operate it, and potential hazards to the personnel involved (eg radiation).

Another method is electrical tomography (resistance, capacitance and impedance). It is relatively fast, (providing up to 200 images per second), simple to operate, has a rugged construction and is sufficiently robust to cope with most industrial environments. The apparent drawback of electrical tomography is its relatively low spatial resolution – typically 3-10% of a pipe diameter. However, this is sufficient for many practical applications.

*Industrial Process Tomography*

There is a widespread need for the direct analysis of the internal characteristics of process plants in order to improve the design and operation of equipment. The measuring instruments for such applications must use robust non-invasive sensors which, if required, can operate in aggressive and fast moving fluids and multiphase mixtures. Process or Industrial Tomography, [152], involves using precise quantitative information from inaccessible locations. The need for tomography is analogous to the medical need for body scanners, which has been met by the development of computer-aided tomography.

Process Tomography will improve the operation and design of processes handling multi-component mixtures by enabling boundaries between different components in a process to be imaged in real-time using non-intrusive sensors. Information on the flow regime, velocity vector and component concentration distribution in process vessels and pipelines will be determined from the images.

The basic idea is to install a number of sensors around the pipe or vessel to be imaged. This reveals information on the nature and distribution of components within the sensing zone. The sensor output signals depend on the position of the component boundaries within their sensing zones. Most tomographic techniques are concerned with abstracting information to form a cross-sectional image. A computer is used to reconstruct a tomographic image of the cross-section being observed by the sensors. This will provide, for instance, identification of the distribution of mixing zones in stirred reactors, interface measurement in complex separation processes and measurements of two-phase flow boundaries in pipes with applications to multi-phase flow measurement. The image data can be analysed quantitatively for subsequent use to improve process control or to develop models to describe individual processes.

The basic components of any process tomographic instrument are hardware (sensors, signal/data control) and software (signal reconstruction, display and interpretation facilities, and generation of output control signals to process hardware). The sensor system is at the heart of any tomographic technique. The basis of any measurement is to exploit differences or contrast in the properties of the process being examined. A variety of sensing methods can be used based on measurements of transmission, diffraction or electrical phenomena. Whilst most devices employ a single type of sensor, there are a number of opportunities for multi-mode systems using two (or more) different sensing principles. The choice of sensing system will be determined largely by:

- the nature of the components contained in the pipeline, vessel, reactor or material being examined (principally whether they exist as a solid, liquid, gas or a multi-phase mixture, and if so in what proportions).
- the information sought from the process (steady-state, dynamic, resolution and sensitivity required) and its intended purpose (laboratory investigations, optimisation of equipment, process measurement or control).
- the process environment (ambient operation conditions, safety implications, ease of maintenance, etc).
- the size of the process equipment and the length-scale of the process phenomena being investigated.

The spatial resolution required, plus speed and robustness will need to be taken into account by the potential user when selecting a sensor system.

Whichever sensing system is used to acquire the data, the next stage of any tomographic imaging system is to process that raw data using an appropriate image reconstruction algorithm run on suitable computer hardware.

## 5.5. Plant Operation and Control

### Model Based Control

Control of industrial process systems is mainly based around use of three term (ie proportional, integral and derivative) feedback control loops. Whilst representing a well proven, reliable and surprisingly powerful technology there are limitations, mainly arising from the reliance on fixed (ie manually set) action factors. In the face of non-linear or time-varying processes there is a high manpower overhead in controller re-tuning which, if not undertaken, results in poor loop performance and stability. More advanced strategies to overcome these limitations generally involve use of a process model either implicitly or explicitly as part of the control scheme. Some examples are given in a recent set of papers dealing with gasifier control, [153-160]. Amongst the wide variety of advanced control techniques now available the Model Predictive Control (MPC) approach, which makes explicit use of a process model, has had wide acceptance in the process industry and, where prior experience and knowledge limits modelling ability, machine-learning approaches, such as reinforcement learning (RL), are also of increasing interest.

*Model Predictive Control (MPC)*

In addition to being limited by having fixed tuning parameters, conventional three term control also experiences difficulties when variables must be controlled as close as possible to an operating constraint, as is often required in operating at optimum conditions. Manual supervision by the plant operator will often be called for. However, MPC, a group of model-based approaches which grew originally from an industrial perspective and which can handle constraints directly, has been accepted rapidly into use within the process industries and provides a potential solution, [161]. Typically the core of the approach is a process model which is used to predict the response of the system to a set of manipulated variable moves over a set time horizon into the future, starting from the current known state. At each measurement sample instant, and with the aid of this predictive model, the future control moves are chosen to satisfy some optimum future performance (including the avoidance of violating any constraints). The first control move in the predicted optimum sequence is then executed and the whole procedure is repeated again at the next measurement sample period. The predictive process model can be developed from either simple on-plant experimentation or a variety of alternative methods and, as already stated; operating constraints are defined and incorporated explicitly. Control of multivariable systems (ie where multiple manipulated input variables interact with multiple plant measurements) can also be addressed. A wide range of process industry applications have been reported but of most relevance here is an example of gasifier control, [159].

*Reinforcement Learning (RL)*

Where no explicit process model already exists and historical data is inadequate as a basis for ANN training, model-based control of complex and poorly understood processes might still be approached through RL. Starting with a minimal set of process observation data this AI based approach offers the potential to progressively learn how to control a process most effectively by direct ‘trial and error’ interaction. In effect an RL system is designed to mimic the learning approach of an intelligent process operator, [162].

There are many unsolved problems that computers could solve if the appropriate software existed. Automated systems, ranging from sophisticated avionics and flight control through to manufacturing and process systems all present difficult non-linear control problems, [163]. Many of these problems are currently unsolvable not because current computers are too slow or have too little memory, but simply because it is too difficult to determine what the programme should do (ie no suitable model available). A computer that could learn to control systems through trial and error interaction would be of great practical value. Reinforcement learning (RL), is an approach to such machine intelligence that combines two disciplines to successfully solve problems that neither discipline can address individually, ie Dynamic Programming and Supervised Learning.

Dynamic programming is a field of mathematics that has traditionally been used to solve problems of optimisation and control. However, available computer power limits the size and complexity of the problems traditional dynamic programming can address.

Supervised Learning is a general method for training a parameterised function approximator, such as a neural network (NN), to represent particular functions. However, supervised learning requires sample input-output pairs from the function to be learned. In other words, supervised learning requires a set of questions along with the corresponding right answers (ie historical process data). Unfortunately, there are many situations where we do not know the correct answers that supervised learning requires. If we could obtain them initially we would in effect know how to build a suitable controller in the first place, so supervised learning alone will not help.

Thus RL is not a type of neural network, nor is it an alternative to neural networks. Rather it is an orthogonal approach that combines the fields of dynamic programming and supervised learning to yield a generalised machine-learning system. In RL the computer is simply given a goal to achieve. The computer must then learn how to achieve that goal by trial and error interactions with its environment. The generality of the approach makes it attractive as a basis for implementing machine intelligence and a range of applications, including some in the process sector, are under investigation [164].

**Advanced Plant Optimisation Systems**

*GNOCIS*

GNOCIS, [148, 149], is a software programme based on advanced mathematical models, ie neural networks, developed jointly by Powergen, Southern Company and EPRI. The programme, which is connected to a power stations existing digital control system, predicts NOx and carbon-in-ash but what is unique is that it is able to optimise the boilers performance to a desired NOx or carbon level. The models continuously adapt, responding to long and short term changes such as plant wear and variations in fuel type and quality. When introduced at Powergen's Kingsnorth plant, savings worth more than £100K per annum were achieved, due to carbon-in-ash reduction. Other applications in the USA have been undertaken and are performing according to expectations.

*Ultramax*

Developed by the Ultramax Corporation and EPRI of the USA, this system uses three steps for boiler optimisation - process formulation, sequential optimisation and engineering analysis, [150,151]. It is a Windows-based, dynamic process modelling and optimisation tool. It uses a unique combination of Bayesian statistics and weighted regression analysis algorithms to build locally accurate, goal-oriented models. This combination allows Ultramax to start with very little or a great deal of data to improve a process while still reaching an acceptable product/solution. As the data becomes richer, the regression algorithms are introduced to determine the best combination of control settings to meet the desired objectives.

It has been applied to a 235MW tangentially-fired twin furnace boiler at Hennepin Power Station in the USA. Input parameters were oxygen trim, windbox and coal/air damper settings and burner tilts. Outputs were NOx, carbon-in-ash and superheater/reheater temperatures, oxygen and CO in superheater and reheater and boiler efficiency.

Ultramax has also been installed at Scottish Power's Longannet power station. These units have been selected to demonstrate 'Best practice' in terms of improved efficiency, improved environmental performance, reduced production costs, reduced energy consumption and improved availability. The results of installing the Ultramax package for boiler operation have included improvements in carbon-in-ash values, optimal performance at all loads and conditions and assisting with consistent operation for various operators on different shifts. Details of these improvements and others are shown in the DTI Cleaner Coal Technology Programme Best Practice Brochure 001, [39].

Other applications of Ultramax include optimisation of ESP, SCR and SNCR and coal cleaning systems.

*Other Systems*

A number of other systems have been developed which perform similar functions to those described previously. These include 'NOx Advisor' developed by the Energy Research Centre of Lehigh University (USA) with support from EPRI and Potomac Electric Power Company, [165]; NOxEA System developed by Stone and Webster of the USA, [165]; and NOxSMART, developed by TransAlta Utilities of Canada, [165]. Westinghouse Process Control Inc. have developed their SmartProcess modules for optimising a range of boiler operating parameters, [166].

**Plant Advisory Computer Systems**

*Least Cost Coal/Coal Blend Models*

This is the simplest type of model which will simply assesses the cost of the coal and its associated transport costs. It is capable of calculating acceptable coal blends according to the power stations own design specification to provide the lowest cost option. The model may incorporate some maintenance and disposal cost factors.

*Component Evaluation Models*

These models are capable of predicting the performance or efficiency of subsytems within the power plant. For example, models may be produced to provide data on the coal mills or ESP's.

*Unit Models*

Models such as these that offer coal quality impact evaluation of an entire power station, and which may include the effect of fuel variations in the generating costs, are based on two methods. These are described below.

*Statistically-Derived Regression Analysis*

This type of analysis is one which leads to the development of models with an overall power station input/output. These models, however, do not contain detailed predictions of system operation or design requirements.

*Systems Engineering Analysis*

This approach is useful for defining relative impacts of fuel properties on each systems performance. These type of models have been developed by both equipment manufacturers and research companies and utilise conventional analysis data and pilot plant and other specialised information.

Although there are several categories of model in existence in this category, the best known and most widely used is the CQIM, [167]. It was jointly developed in 1985 by Black and Veatch and EPRI.

The role of CQIM is to quantify both performance and cost impacts associated with changes in coal quality. CQIM evaluates alternative coals by comparing them with a reference or current coal supply. It is also designed to consider station-specific design and operation characteristics on a component-by-component basis, as well as the unit as a whole.

*Integrated Site Models*

These models bring together information from unit models, system performance and other models and are integrated directly into the control room data system.

Further detailed information on the specific models and reference to their developers can be obtained from IEA Coal Report IEACR/52, [168].

# 6. IDENTIFICATION AND ESTIMATION OF KEY AREAS OF ENERGY, EFFICIENCY AND/OR COST SAVINGS FROM MPF IMPROVEMENTS

## 6.1. Selection Criteria for Improvements

This project has been tasked with ultimately identifying areas within the UK fossil-fuelled power sector where improvements can be realised in plant efficiency and cost reduction. Information has been gathered from the major UK power generators as to what they regard as the areas where such improvements can be realised.

What became apparent from the discussions, however, was that although the utilities are extremely cost conscious, they cannot devote their future development budgets solely to secure improvements in the cost of electricity generation. There are many technical challenges which are being forced on the generators by emissions regulations which will almost certainly lead to considerable expenditure. For example, the continuing downward trend in gaseous emission limits for gases such as NOx and $SO_2$, and the potential future costs of possible $CO_2$ sequestration, are cases in point. Of more immediate concern than $CO_2$ is the need to improve the performance of particulate collection equipment, especially regarding $PM_{10}$, $PM_{2.5}$ and air toxic emissions.

The cost of combustion by-product disposal will undoubtedly increase and there is a need to optimise the saleability of such waste streams and further develop the market for such items. These are, perhaps, activities which the generator may feel are not their major concern  but a fresh perspective has to be applied in what are changing times.

In the scenario of a competitive electricity generating market and with the relatively small numbers of coal-fired plant owned by most of the generators, the long-term future of such plants has to be questioned. It is probable that the generators have plans regarding what levels of expenditure they are prepared to provide to enable the coal-fired stations to continue operating. If legislative regulations impose punitively high retrofit costs on these stations, it must be regarded as very unlikely that they would survive. The only reason they might survive would be if the government was to insist that a broad ‘mix’ of fuel generating capacity was to be retained. In the face of increasing use of natural gas to generate cheap electricity, the future for the coal stations recently received encouragement by the commitment of some of the UK generators to fit FGD plant to some of their recently acquired plant.

The view has been taken in this report that rather than concentrate purely on those areas which would give cost reductions, all of the possible plant changes, both voluntary and enforced, should be considered. Some of the improvements have cost benefits as well as helping to meet new emission legislation. For example, the fitting of improved PF flow control will improve NOx performance but will also reduce carbon-in-ash. This is part of the rationale to include all of the identified areas for improvement in the report.

## 6.2. Pulverised Coal Flow Measurement and Control

### Background

The problems of pulverised coal flow and measurement arise from the particular way in which the burners are fed from the coal mill. The raw coal is fed into either a roller or ball mill which is fitted with an air classifier system. When sufficiently fine, the coal is drawn from the mill and is transported to the burners. A single pipe may have to supply up to eight burners and it is the splitting of flows that creates the problem. Pulverised coal flows are split by bifurcation’s and/or trifurcations within the pipe which themselves are fitted with riffles or orifice plates. The fact that pulverised coal is known to segregate in the pipe and form ‘ropes’ when it is turned through ninety degrees further causes uncertainties in the way in which flows divide.

Since the introduction of LNB’s, the optimisation and control of pulverised coal distribution and size have assumed greater significance. Balanced PF distribution and satisfactory fineness are two of the fundamental criteria for effective NOx reduction in flue gases whilst maintaining acceptable combustion efficiency, [169]. Maldistribution of coal between burners caused by roping leads to large and uncontrolled differences in the coal-to-air ratio between burners. This results in localised fuel-rich regions where there is insufficient air to burn the coal and high carbon-in-ash will result. In addition there will be fuel-lean regions where high NOx levels result from locally high oxygen concentrations.  High carbon-in-ash will adversely affect the collectability of the PFA and also render it unsaleable. It is clear that the problems of poor PF distribution and uncontrolled flow can have potentially very serious consequences to power generators.

An awareness that PF flow control is critical for successful operation of a modern boiler was not helped by the lack of any technology, until recently, for the non-intrusive, on-line measurement of PF flows.

**Recent Developments**

To address the concerns described previously, a series of demonstration trials was carried out at Powergen's Kingsnorth station, [170-172]. A series of PF flow meter demonstrations were undertaken on one of the corner fired units at the above station, sponsored by EPRI. Five PF flow measurement technologies, three electrostatic and two microwave, were installed on the PF transport system associated with one mill and demonstrated over a range of mill operating conditions. The flow meters were assessed and it was found that all of them gave agreement with the benchmark tester, the Rotoprobe. No reliability problems arose during the three month test period. The meters all were capable of being integrated into a NN system and costs ranged from £4,000 to £10,000 per meter. The choice of meter would depend on the specific site requirement, ease of use, ease of installation, preference for microwave or electrostatic system and similar considerations.

**Cost Benefits**

Development has been undertaken and the technological requirements appear to have been met to enable measure and control of PF in pipes to be achieved. However, the process has yet to be fully commercialised. A number of competing technologies are still under development and undergoing further evaluation. It has been reported, [172], that the costs per burner pipe would be, depending on the site requirement and the make of the instrument, between £4,000 and £10,000.

Recommendations have been made, [171], to the four instrument manufacturers to improve their equipment and it was also suggested that particle size distribution would be important and that the instruments should be linked to an intelligent control system to derive most benefit from the system.

Quantification of the cost benefit of fitting such a system would be complex as it would be site specific and equipment specific. In addition, although the financial benefits of reduced carbon-in-ash could be calculated, the 'value' of reduced NOx and any associated 'benefits' would be more difficult to determine. However, most of the generators felt that the savings would be 'large'. It is possible, however, based on certain assumptions, to estimate the cost savings from a reduction in carbon-in-ash. An example is shown in Table 4. For a given carbon-in-ash level, say 6%, using the assumptions shown in the table, a reduction of £157K in coal costs per 500MW unit can be realised if the carbon-in-ash can be reduced to 4%. A 1% reduction in carbon-in-ash would produce a £78K saving in cost of coal.

This is an area which the generators already accept is important for other reasons such as NOx emissions reductions and lower fireside corrosion.

## 6.3. Low NOx Burners

### Current Status

Many power plants have installed LNB's and OFA; some successfully while others have dealt with a number of difficulties. However, as legislation becomes increasingly more stringent the success rate becomes more important. Newly-built power plants have the advantage that the combustion system and furnace can be designed for minimum NOx emissions, while physical boundaries in older power plants can limit the NOx reduction achievable.

Common problems arising after the installation of LNB's and OFA include high carbon-in-ash, corrosion, burner damage and changes in the slagging and fouling patterns. In retrofit cases these issues are more profound. High carbon-in-ash and corrosion are concerns directly linked to the operation of the low NOx combustion system which perform best with low excess air levels. The challenge is to generate solutions which do not jeopardise the NOx emissions.

### Potential Costs/Benefits

This is another important area which the generators recognise will require addressing in the near future. A comparison of the relative costs of NOx removal can be gained by reference to Table 5. This summarises 1995 US$ costs per ton of NOx removed, for eight different removal options, [173]. Although rather simplistic, the table shows clearly the significant increase in costs as NOx removal efficiency increases. It also shows why LNB's represented the most economical option given the NOx targets at that time. Actual costs incurred by the generator will depend on the NOx target, the unit size, burner configuration and fuel.

In this respect there has been a cost involved and this will continue to be the case if newer burner technologies are deemed necessary. However, reducing the cost by which new statutory NOx limits can be achieved is important and the benefits of improved MPF control and measurement will undoubtedly help. It is felt overall that the inevitable tighter legislation will mean that, at best, it will be a cost minimisation exercise.

## 6.4. Coal Milling and Classification

### Current Status

There is a need for the cost-effective comminution of coal to size distributions finer than are currently acceptable for PF combustion. The benefits are several. For example, smaller particles will devolatilise quicker and release volatile nitrogen into locations where it can be reduced to elemental nitrogen, thus reducing NOx emissions. Smaller particles of char would be formed, which will contain lower nitrogen contents, and would burn out more quickly than would larger particles. Better milling should produce lower NOx emissions and carbon-in-ash. The extra cost of producing improved size distributions has, nevertheless, to be balanced against the benefits it would bring.

In addition, the current design rules are inadequate for the development of improved milling equipment. There is perceived to be a need for models to simulate the milling process and that these must take into account the effects of hardware design, operating conditions and coal properties. To validate such models, conditions at key locations within the mill will need to be established together with sampling techniques for these positions. In addition, there exist problems such as mill vibration and abrasive wear.

**Potential Costs/Benefits**

The benefits of a finer coal size distribution would need to be linked to the costs associated with the comminution process and the quantifiable benefits that it brings. It is known that milling devices already exist that are capable of producing more finely divided coal, as seen by the use of micronised coal as a reburn fuel, [174]. The grinding costs are naturally higher and the quantification of benefits to NOx and carbon-in-ash reductions would need a separate study which could cover the variables such as plant size, fuel grindability and mill costs and maintenance requirements.

## 6.5. Fine Particulates ($PM_{10}$ and $PM_{2.5}$)

**Current Status**

There is increasing concern over the need to control ultrafine particulate matter. Interest is focusing on particles known as $PM_{10}$. These describe the fraction of airborne particulate matter that is less than 10 microns in size. Fine particles are of the greatest concern since they are capable of being easily transported over long distances on currents of air. Also, fine particles may be drawn into the respiratory airways where they may adversely affect health. Recently, the attention of scientists has been drawn towards studying the $PM_{2.5}$ fraction and even smaller particles which can penetrate the very deepest parts of the lung. $PM_{10}$ and other particulate matter may vary considerably in chemical and physical composition. The principal sources of these particles are combustion processes, including traffic and industry.

Of the UK national emissions of $PM_{10}$ in 1996, 25% was derived from road transport, 38% from industrial sources, 16% from power stations and 17% from domestic sources, [175]. Overall the UK emissions of $PM_{10}$ particulates have fallen by 70% since 1970, and by 67% for the power generation industry, [176]. Nevertheless, the National Air Quality Standards office have issued limits on allowable $PM_{10}$ concentrations of 50µg $m^{-3}$ for a 24 hour running mean to be achieved by 31st December 2004.

Work is on going, particularly within the USA, to obtain a better understanding of the problem, [177]. The USA National Energy Technology Laboratory (NETL), Airborne Fine Particulate Matter Research Programme addresses the problem of $PM_{2.5}$ particulate matter. The three specific objectives of this programme are; firstly to evaluate the nature and concentration of such particles; to characterise primary and secondary particulate emissions in this size range and finally to develop and evaluate cost-effective control technologies.

**Potential Costs/Benefits**

The present state of knowledge concerning the nature, composition and origin of ultrafine particulate is incomplete. In 1997 the US EPA promulgated a new ambient air quality standard for $PM_{2.5.}$ This standard has resulted in controversy, not only with respect to the stringent limit selected, but also due to the many problems associated with complying with a standard for a pollutant which is so poorly understood. Until further data is available and until the emission limits for these materials are known, it is impossible to quantify the cost implications of meeting future compliance limits.

As with many of these enforced plant upgrades and modifications, additional costs will be incurred.

## 6.6. Gaseous Pollutants

**Current Status**

NOx emissions may be addressed by improvements to burners and mills, (see Sections 5.2. and 5.3.). The ability to further reduce NOx by simpler, cheaper and more flexible SNCR systems would be desirable.

$SO_2$ emissions can be addressed by mature technologies and fully developed options, (see Section 4.4.); however cheaper systems would again be of benefit. The reduced emissions of $SO_2$ from low sulphur coals can lead to ESP problems, which require $SO_3$ injection.

**Potential Costs/Benefits**

Emissions of $SO_2$, like NOx, will continue to give the generators cause for concern. The main issue is not that the emission cannot be controlled but that the control measures are usually fairly expensive. FGD plant is expensive and requires large ground areas; low sulphur coals are more expensive and ESP performance is adversely affected, requiring flue gas conditioning. What is needed is a cheaper option by which SOx can be reduced, possibly in conjunction with NOx and even particulates. The space requirements must also be reduced as space availability is usually a serious problem in a retrofit situation.

This improvement in performance would be another example of expenditure being linked to statutory requirements and not to cost savings.

## 6.7. Improvements in ESP Performance

**Current Status**

Excessive carbon-in-ash not only represents incomplete release of available energy from the fuel, and thus a loss of potential energy and thereby revenue, but also has other undesirable side effects. A high level of carbon-in-ash also impairs the efficiency of the ESP's. If the emission of dust occurs in quantities above the statutory limit, it could lead to closure of the power station and/or fines to the generator. In addition, sales of fly ash may be suspended if the quality deteriorates by an unacceptable increase in unburnt carbon. Not only would the income from this valuable by-product be lost, but it may be necessary for the generator to have the unacceptable fly ash disposed of at their own cost.

**Potential Costs/Benefits**

Collection of particulate emissions to the new legislative limits may require new or modified precipitators. Work is in progress, [178], at methods by which the performance of current technology precipitators may be improved to take account of the finer particles and carbon from LNB's.

Cost savings will not be made by improving the performance of ESP's. This is another example of the power generator having to respond to a further tightening of emission regulations, in this case, with respect to particulate emissions. Situations in which inevitable costs are incurred in order to meet new regulations could be the subject of future studies. In this case the objectives would be to determine the minimum cost necessary to achieve compliance. As with most of these exercises, they would require significant effort as variables such as plant size, location, fuel type and desired performance would need to be considered.

Consideration must be given to the space available to improve collection efficiency. A recent example has been the opportunity to add additional ESP capacity at TXU's Drakelow plant to meet the new particulate emission limits, [179]. This has been possible because of the demolition some years ago of an old boiler which provided the necessary space. Most power station sites do not have such space available to them.

## 6.8. <u>Controls and Instrumentation</u>

**Current Status**

Development of intelligent control systems should be applied to PF plants. However, because of the complexity and interaction of the large number of physical and chemical processes, much development of the systems would be needed for the production of a successful commercial system.

As well as systems which advise on or control the operation of boilers, there is also a need to consider computer software packages and additional on-line monitoring equipment. The software packages enable choices to be made on fuel selection and blend compositions for minimising NOx. They are sophisticated enough at present, (although further work is still needed), to incorporate ancillary and maintenance costs into their coal selection criteria. The in-situ monitors include instruments which can monitor carbon-in-ash, [180,181]. In addition, recent work has been reported on improvements in on-line particulate emission monitoring, [182].

**Potential Costs/Benefits**

The benefits of artificial intelligence systems such as GNOCIS have already been shown to produce significant savings in plant operational costs. The pace of computer system development and the benefits such technology can bring to plant operation means that this is a field in which continuing development will surely accelerate.

The benefits, in terms of cost reduction, by the use of these systems require a depth of knowledge of plant costs which are simply not available. Each generator, not surprisingly, does not disclose details of coals used, fuel costs or operating costs, which make the evaluation of any benefits from using these systems difficult if not impossible.

## 6.9. <u>Air Toxics</u>

### Current Status

Current environmental legislation in the UK requires operators of prescribed processes to minimise or render harmless emissions of trace metals and other trace pollutants. These materials are termed ‘air toxics’. As legislation becomes more rigorous the range of materials categorised as pollutants is likely to widen considerably. Efforts to limit pollution of the environment will initially require improved methods for the measurement of trace pollutants.

Air toxics vary in nature and type but most interest and concern has been focused on the volatile elements such as mercury, arsenic, cadmium, lead, selenium and zinc.

In the USA there are regulatory standards for 189 air toxics from sources which emit 25 tons annually of any combination of pollutants or 10 tons of any single pollutant. Several of the hazardous air pollutants (HAP’s) are trace elements such as chromium, arsenic and lead, which are associated with the primary particulates emitted from coal-fired utility boilers. To address the need for information to combat future legislation, the Environmental Protection Agency (EPA), has proposed an air toxics programme. This seeks to measure air toxic emissions from individual pollution sources and at ambient concentrations throughout the USA to determine the need for further control measures.

Work in the UK is also on-going with work having been recently completed by Powergen on their 1MW combustion test facility (CTF), in which they studied the fate of mercury, [183], and the partitioning of trace elements from three power station grade coals, [184]. The latter work showed that ash removal had little effect on trace element emission levels, indicating that removed mineral matter was primarily ‘trace element-free’.

### Potential Costs/Benefits

Air toxics cover a wide range of substances of great complexity from elemental metals such as mercury, to metallic compounds and a wide range of organic molecules. Until there is a clearer understanding of what specifically is to be controlled and to what levels, the costs involved in such an exercise are cannot be determined.

Work is continuing to understand the nature of the problem, [185], and with these data becoming more readily available, the assessment of costs of flue gas clean-up to remove air toxics may become a little easier.

## 6.10. Fly Ash Beneficiation

### Current Status

Improvements to the overall efficiency of the boiler plant and to NOx emissions can be made if the carbon-in-ash can be reduced. The savings in this case are not confined to efficiency alone. There is an additional benefit which may be realised if the lower carbon-containing PFA can be sold. In this instance, the potential cost of lagooning or using as landfill is converted into an income stream.

### Potential Costs/Benefits

*Process Selection*

Many fly ash beneficiation process concepts have been explored or are in development. Most focus on reducing the effects of carbon-in-ash. Many different beneficiation methods have been identified, either as commercial processes, advanced development technologies, or emerging concepts. One, or some combination of these methods, might be customised and implemented in a cost-effective manner to meet the needs of PFA producers.

Selecting the best process technology is complex. There are a number of factors to consider and on which judgements must be made. Some of the factors are economic and some are physical. The following steps are recommended for identifying promising benefication processes:

- Definition of the market drivers - This is a complex issue and involves a consideration of the cost of the coal, the quantities of fly ash produced, landfill costs and revenue opportunities. The market for the PFA will be determined by the type of ash produced, the quantities available and its proximity to the point of use. If the fuel costs are high, any loss of efficiency through unburnt carbon will be correspondingly high. If the quantities of PFA produced are only moderate, say less than 100,000 tonnes per year, the cost of the beneficiation plant and the likely income stream from the sale of the ash may not be justified. The availability of landfill or lagooning both on site and off needs to be assessed for future requirements. There are several grades of fly ash which may be produced to particular specifications, [72]. The highest quality, in terms of carbon-in-ash and particle size, command the best price. It will be necessary to determine the potential quantities which will be available from the combustion of the station coals.

- Characterisation of the fly ash - This includes the normal range of carbon-in-ash, size, elemental composition, resistivity, density and reactivity of unburnt carbon. The range of carbon-in-ash will determine what type of beneficiation process is most appropriate to obtain the desired products, since some processes are less efficient than others at removing carbon. If a wide range of different types of coal are burned this will produce fly ashes which contain different ash compositions and carbon which will have different reactivities. This would be undesirable to the cement producers who are looking for consistency in their raw materials. It is also important to recognise that low ash coals generally produce higher levels of carbon-in-ash. Pozzolanic behaviour is also important if the ash is to be used in cement admixture and this is generally enhanced by fine particle size. The relative size distribution of carbon and ash is important since if they are similar, separation techniques such as sieving are unlikely to be successful.

· Identification of potential beneficiation processes - Once all of the criteria have been considered, it will be possible to select the optimum process for the particular application in question.

*Process Economics*

The implications of fly ash benefication are shown in Table 6. If the carbon-in-ash could be reduced from, for example, 8% to 4%, which is not technically unreasonable, then a saving of approximately 30 tonnes per day of 'coal' are possible. If coal is assumed to cost approximately £40 per tonne, the daily savings would be £1,200 per day. With a capacity factor of 65% this is equivalent to a saving of £285K per 500MW unit per year.

If the ash cannot be sold then disposal costs are incurred. At the present rate of £2 per tonne, this would amount to a cost of £340K per 500MW unit per year, which is likely to increase in the future.

The cost implications of fly ash beneficiation are clear and it is felt that further study by the generators to maximise added value to fly ash should be seriously considered if not already in hand.

## 6.11. Reduced Ash Deposition and Corrosion

### Current Status

Poor distribution of coal to the burners can exacerbate the depositional characteristics of the mineral matter in coal and can result in slag formation in the furnace or around the individual burner nozzles. A better understanding of the mechanisms of deposit formation and the mineralogy of the coals used by power generators will result in lower instances of unacceptable deposit build-up.

The formation of excessive CO within the furnace can also result from a maldistribution of coal to the individual burners. This will accelerate high temperature corrosion leading to a thinning of the furnace tubes.

### Potential Costs/Benefits

The benefits of reduced ash deposition and corrosion are realised in higher plant efficiency (due to the removal of insulating layers of deposited ash), extended tube life and lower operational and maintenance costs. There are a number of ways by which reduced ash deposition and corrosion can be achieved such as the use of lower ash coals, the use of lower slagging and fouling coals, the installation of more sootblowers or improvement in existing sootblowers.

This is an area where cost savings are possible. However, it is a topic which needs an in-depth analysis in order to quantify the overall cost benefits. For example, details of the current plant efficiency, depositional behaviour with regard to its current fuel, costs of current fuel, availability of replacement lower ash or lower slagging coals, costs of installation/operation of new sootblowers. These factors would be different for different plants and the size, capacity factor and other considerations would need to be evaluated. It is felt to be outside the scope of the present study.

### 6.12. Difficulties in Assessing Cost of Changes

What has become very clear from this report is that although it has been possible to identify areas of concern to power generators in the UK, it has proved to be difficult, within the constraints and objectives of the project, to quantify the extent of such improvements. There are a number of reasons why this is the case, the main one being that each aspect of cost reduction is potentially large and to provide meaningful data would have required an in-depth study which was outside the time-scale of this project. Another reason was that, except for the cost benefits of fly ash beneficiation, the benefits were unquantifiable in cost terms, but were necessary for legislative compliance.

## 7. OBSERVATIONS AND CONCLUSIONS

The data obtained from the questionnaires returned from power generators has formed the basis of the recommendations for further development work which is listed below.

It was interesting that all of the generators who responded saw the distribution of PF to burners as being either their most or equal most important issue. Upon close examination the implications of being able to improve the present status of PF flow measurement is far reaching. Within the context of this project, in which improvements in efficiency and cost are of major concern, the closer control of PF flow will result in a direct efficiency improvement. However, it is not simply the cost of better control that will lead to cost savings. Other financial benefits will accrue from the sale of low carbon PFA. If carbon-in-ash levels were excessive, not only would the ash be unsaleable, but expenditure would be incurred as disposal would require outlay for transportation and landfill taxes.

One other major result from improved PF flow control is lower NOx emissions. Whilst there appears to be no obvious cost benefit from this, it could allow the generator to operate with a lower quality,  (and hence cheaper), coal due to the ability to exercise tighter control over the combustion process. Furthermore, any maldistribution of coal flow to burners will lead to the production of unacceptably high local regions of reducing gases, such as CO and hydrogen sulphide. Prolonged operation under these conditions would result in accelerated corrosion of furnace tubes. The benefit of better PF control should be a longer life expectancy for boiler furnace tubes with the attendant cost reductions.

If further improvements in efficiency are judged to be necessary in terms of lowering unburnt carbon-in-ash, one option to be considered is fly ash benefication. This technique, where a number of successful methods have been demonstrated, not only improved the quality of the PFA, thus allowing it to realise its full market value, but allowed the recovered carbon to be either refired in the boiler or sold on for a higher value use. This ability to recover efficiency lost by high carbon-in-ash allows the boiler to be operated at low excess air for minimum NOx emissions. This operation needs to be carefully monitored to ensure excessive tube corrosion, due to reducing gases, is not allowed to occur.

The introduction of LNB's into boilers has resulted in the production of higher than previous levels of carbon-in-ash. This has produced a reduction in the collection efficiency of ESP's, which in turn has caused the generators to identify high stack opacity as one of their major concerns. These concerns do not arise from a desire to improve the efficiency of the boiler but are driven by prospective legislation which will reduce the current level of solids which can be emitted from the stacks of power stations. In addition there is mounting anxiety in the industry over the measurement and control of the $PM_{10}$ and $PM_{2.5}$ particulate matter, over which there will soon be legislated limits.

There has been an increasing use of imported coals in the UK in recent years, prompted by lower prices and certain properties. The combustion of such coals, either singly or as blends, can be beneficial to the generator for several reasons. However, there are a number of problems which result from the preparation and combustion of blended fuels which cannot be predicted form a knowledge of the individual coals. These may originate in the preparation of the blends and in their pulverisation. Similarly, the interaction of the mineral matter in constituent coals during combustion and their incipient fusibility cannot be predicted.

Research into relevant aspects of MPF is current in several UK Universities. Areas such as instrument development, pneumatic conveying and CFD are well represented at international conferences by these groups. This fact is witnessed by the organisation of recent international conferences by the groups. Examples are the 1st International Conference on On-line Measurement of Particulate Solids organised at the University of Greenwich in July 1998, the Second International Conference on Computational Fluid Dynamics in the Minerals and Process Industries held in Melbourne, Australia in December 1999 and the 9th International Conference on Flow Visualisation held at Heriot-Watt University, Edinburgh in August 2000.

In instrumentation developments the Universities of Nottingham (Dr A. Aroussi), Greenwich (Dr Y.Yan), Heriot-Watt (Professor Grant), Teesside (Professor J. Coulthard), Edinburgh (Professor C. Greated and Dr D.Glass) and Leeds (Professor R.Williams) as well as Imperial College (Professor A.M.Taylor) are strong. In pneumatic conveying the Wolfson Centre for Bulk Solids Handling at the University of Greenwich as well as the group at Glasgow Caledonian University are very well known. There is increasing work at the University of Nottingham. In CFD and other modelling techniques applied to gas/solids MPF there is activity at Imperial College and at Newcastle, Heriot Watt and Plymouth. There is work on Discrete Element Simulation at Surrey, Nottingham and Aston Universities.

It is believed that the potential for UK universities to provide innovative solutions to the problems faced by the UK generators exists and compares favourably with similar organisations in other parts of the world. However, two problems need to be overcome.

Firstly, there is a need for clarity in terms of the future for current UK fossil-fired power stations as effort will not be best utilised on power systems with a short future life. Secondly, UK universities need to be made more aware of the scope for the application of new and more advanced techniques into what are perceived as ‘yesterdays’ technology.

## 8. RECOMMENDATIONS FOR FURTHER MPF-RELATED R&D

Future R&D activities for fossil-fired power generation in the UK can be summarised as follows:

- to further develop and demonstrate pulverised coal flow measuring and control devices and techniques for improving coal and airflow distribution to individual burners with a view to achieving improved plant performance. In particular there is a need for better understanding of the formation and decay of ‘ropes’ and the occurrence of settling of solids. Additionally, robust methods for measurement of gases and solids flowrates are required.

- to demonstrate cost-effective and efficient NOx control technologies based on combustion modifications such as advanced LNB’s using integrated reburn and gas co-firing, and gas or coal reburn;

- to better understand the impact of coal mill design and operation models on particle size distribution. This should include mill benchmarking to explain differences seen in the performance of similar mills. An investigation into methods by which higher quality PF, ie finer size distribution may be obtained at a lower cost than at present would be useful;

- to seek ways in which lower cost emission control systems, such as FGD, can be developed and introduced;

- to improve the performance of ESP’s in the light of higher levels of carbon-in-ash, a need for lower overall dust emissions and the need to collect ultrafine materials. In addition, there is the need to evaluate alternative technologies for particulate removal.

- to further develop and demonstrate intelligent control systems for optimising combustion performance while minimising emissions;

- to improve knowledge on the distribution and analysis of air toxics in preparation for the introduction of new emission limits from power plants;

- to find improved methods for the collection, utilisation and disposal of solid waste streams from the combustion of pulverised coal;

- to continue the work in progress which will allow a better understanding of the impact on overall plant performance activities. This will include the effect of blending for added fuel flexibility and reduced gaseous emissions. This should include the MPF activities involving coal preparation, pulverisation, combustion performance and mineral interactions;

- to apply existing advanced, non-intrusive diagnostic techniques to monitor temperature, gas flow, coal particle size, velocity and mixing, gas species concentrations with a view to improving combustion performance and reducing emissions;

- to develop and validate modelling techniques such as CFD for the analysis of pneumatic conveying problems. Though the techniques have been well worked through in combustion, there are still outstanding areas. However, in the denser flows of pneumatic conveying, there are still needs.

- to provide improved data for performance prediction with regard to NOx generation and carbon burnout at full sized scale by the development of innovative laboratory-scale coal characterisation techniques,

- to improve atomiser design capability by the development of better prediction methods for droplet sizes in oils and emulsion fuels using modelling techniques. Although of low priority for UK application this is felt to be relevant for the overseas interests of UK power generators, especially with the possible further exploitation of emulsions fuels such as Orimulsion..

- to investigate costs, feasibility and technical requirements for innovative $CO_2$ mitigation strategies.

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## 10. REFERENCES

1. Tombs, R., 'Privatisation of the UK Electricity Supply Industry- Current and Future Impacts on Coal-Fired Generation', paper presented at NEDO Clean Coal Day '99; International Symposium, Tokyo, Japan, September 3rd 1999.

2. Conclusions of the Review of Energy Sources for Power Generation and Government response to fourth and fifth Reports of the Trade and Industry Committee; White Paper Cm 4071 October 1998.

3. Brown D.W., and Atkin, B.P., 'The Industrial Evaluation of a Coal Handleability Monitor', Contractors Report for DTI Cleaner Coal Technologies Programme; Contract No. C/03/00247/00/00; University of Nottingham.

4. Thompson, A.W., and Cloke, M., 'An Approach to the Correlation of Boiler Performance with Coal Blend Composition', paper presented at the 2000 Conference on Unburned Carbon on Utility Fly Ash, sponsored by the US DoE, National Energy Technology Laboratory, May 16th 2000, Pittsburgh, Pa, USA.

5. Welling, J.C., 'Impact of dynamic classification on low NOx performance and unburnt carbon in flyash', from Proc. 1995 Int. J. of Power Gen. Conf. part 1, pg. 271-284.

6. Salewski, G., and Mors, F., 'Retrofits and its Effects on Burner, ie Boiler Performance', The Proc. of the 25th Int. Tech. Conf. on Coal Utilisation and Fuel Systems, March 18-21 1996, Clearwater, Fla., USA.

7. Loesche GmbH, Dusseldorf, Germany; product information. www.loesche.com/products/classifiers.htm

8. Babcock Borsig Power; product brochure. www.dbriley.com/sls/htm

9, Babcock & Wilcox, product brochure www.babcock.com/pgg/ps/dsvs.htm

10. Foster Wheeler, product brochure www.fwc.com/pow_services/parts/mb/heprot.cfm

11. Kunimoto, T., et al. 'MRS Pulverisers', presented at Int. Mech. Eng. Congress and Exhibition - MECH 91 (1991), pg. 101-105, Sydney, Australia.

12. Azzopardi, B.J. (1999), 'Phase split at T-junctions', Multiphase Science and Technology, vol. 11, pp223-329.

13. Lempp, M. (1966), 'Die Strömungsverhältnisse von Gas-Festoff-Gemischen in Verzweigungen Pneumatische Förderanlagen', Aufbereitungs._Techn., Vol 7, pp81-91.

14. Maeda, M. and Ikai, S. (1976), 'Distributions of solid particles transported by air in branched lines', Chem. Engng. Ronbunshu, Vol. 2, pp25-30.

15. Morikawa, Y., Kondo, T. and Hiramoto, T. (1978) 'Pressure Drop and Solids Distribution of Air-Solids Mixture in a Horizontal Unsymmetric Branches', Int. J. Multiphase Flow, Vol. 4, pp397-404.

16. Huber, N. and Sommerfeld, M. (1994), 'Characterisation of the cross-sectional particle concentration distribution in pneumatic conveying systems', Powder Technology, Vol. 79, pp191-210

17. Yilmaz, A. and Levy, E.K. (2001), 'Formation and dispersion of ropes in pneumatic conveying', Powder Technology, Vol. 114, pp168-185.

18. Cook, D. and Hurworth, N.R. (1980), 'Recent research on pulverised fuel settlement in power station pipelines, and the significance of roping', Proc. Pneumatransport 5: Fifth Int. Conf Pneumatic Transport of Solids in Pipes, London, U.K., B.H.R.A. Fluid Engineering

19 Park, Y. and Zenz, F. (1980), 'Pressure loss in horizontal-to-vertical upflows elbows', Proc. Pneumatransport 5: Fifth Int. Conf Pneumatic Transport of Solids in Pipes, London, U.K., B.H.R.A. Fluid Engineering

20. Easson, W.J., and Xu, B., 'Inhomogeneous Particle Loading in Pulverised-Fuel and Low-NOx Burners. EPSRC Project:- University of Edinburgh, Department of Mechanical Engineering, International Combustion Ltd.

21. Schallert, R. and Levy, E. (2000), 'Effect of a combination of two elbows on particle roping in pneumatic conveying' Powder Technology, Vol. 107, pp226-233.

22. Levy, E., and Yilmaz, A., 'Characteristics of particle ropes in coal pipes', paper presented at 1998 International Joint Power Generation Conference, (FACT Vol. 22), Volume 1, pg 79-84; Baltimore, MD, USA, 23-26 Aug 1998.

23. Ropemaster- Improved Distribution Leading to Lower NOx and LOI, company brochure, International Combustion Ltd, 1996.

24. Zipse, G. (1966), 'The mass flow density distribution in pneumatic conveying and the influence on it of inserts in the conveyer duct', Fortschr. Ber. VDI Z, Ser 13 (3).

26. Dyakowski, T. and Williams, R.A., (1993), 'Measurement of particle velocity distribution in a vertical channel', Powder Technology, Vol. 77, pp135-142.

27. Sen, S., Das, P.K., Dutta, P.K., Maity, B., Chaudhuri, S. Mandal, C. and Roy, S.K. (2000), 'PC-based gas-solids two-phase mass flowmeter for pneumatically conveying systems', Flow Measurement and Instrumentation, Vol. 11, pp205-212.

28. Xu, L., Weber, A.P. and Kaspar, G. (2000), 'Capacitance-based concentration measurement for gas-particle system with low particle loading', Flow Measurement and Instrumentation, Vol. 11, pp185-194.

29. Xia, J., Liu, R. and Wang, S. (1998), 'Mathematical models of gas/solids two phase flowrate measurement using differential pressure-concentration method', Proc. 1st Int. Conf. on On Line Measurement of Particulate Solids, University of Greenwich, U.K., pp133-137.

30. Yang, W.Q. and Liu, S. (2000), 'Role of tomography in gas/solids flow measurement', Flow Measurement and Instrumentation, Vol. 11, pp237-244.

31. Ma, J. and Yan, Y. (2000), ‘Design and evaluation of electrostatic sensors for the measurement of velocity of pneumatically conveyed solids’, Flow Measurement and Instrumentation, Vol. 11, pp195-204.

32. Millen, M.J., Sowerby, B.D., Coghill, P.J., Tickner, J.R., Kingsley, R. and Grima, C. (2000), ‘Plant tests of an on-line multiple-pipe pulverised coal mass flow measuring system’, Flow Measurement and Instrumentation, Vol. 11, pp153-158.

33. Azzopardi, B.J., Teixeira, S.F.C.F. and Pulford, C.I. (1999), ‘A quasi-one-dimensional model for gas/solids flow in venturis’, Powder Technology, Vol. 102, pp281-288.

34. Barratt, I.R., Yan, Y., Byrne, B. and Bradley, M.S.A. (2000), ‘Mass flow measurement of pneumatically conveyed solids using radiometric sensors’, Flow Measurement and Instrumentation, Vol. 11, pp223-235.

35. Mennell, J. Byrne, B. and Yan, Y. (2000), ‘Appraisal of radiometric techniques to determine absolute solids fraction in pneumatic suspensions of particulate solids’, Flow Measurement and Instrumentation, Vol. 11, pp213-221.

36. Fenimore, C.P., ‘Reactions of Fuel-Nitrogen in Rich Flame Gases’, Combust. Flame, 26, 249, (1976).

37. IEA Clean Coal Technologies Database, ‘Burner optimisation for NOx control (excess air control, burner fine tuning)’. http://www.iea-coal.org.uk/CCTdatabase/burnopt.htm.

38. ‘Coal and Gas Reburn Technologies for NOx Reduction’; Workshop held at DTI Conference Centre, 1 Victoria Street, London, 30 January 2001.

39. ‘Longannet Power Station’, DTI Cleaner Coal Technology Programme, Best Practice Brochure 001, February 2000.

40. ‘Gas Reburn Demonstration Project’, Scottish Power plc; Document No LGR/DTG/023; Contract SF 394/94 UK/IR/IT; THERMIE.

41. Canning, P., Performance, Operating Experience and Costs of Coal Reburn on a 320MWe unit at Vado Ligure Power Station, Italy; presented at DTI Workshop on ‘Coal and Gas Reburn Technologies for NOx Reduction’; held at DTI Conference Centre, 1 Victoria Street, London, 30 January 2001.

42. Osborn, J., ‘Operating Experience of Gas Reburn on a 600MWe unit at Longannet Power Station in Scotland’, presented at DTI Workshop on ‘Coal and Gas Reburn Technologies for NOx Reduction’; held at DTI Conference Centre, 1 Victoria Street, London, 30 January 2001.

43. NOx-OUT Process; Wheelabrator Air Pollution Control Inc., 442 Smithfield Place, Pittsburgh, PA, USA. http://www.wapc.com/nox.htm.

44. Energy Information Administration/Electric Utility Phase 1 Acid Rain Compliance Strategies for the Clean Air Act Amendments of 1990. Section 3. 'Compliance Strategies for Control of Sulfur Dioxide Emissions'.

45. Doig, A., and Morrison, G.F., 'The use of natural gas in coal-fired boilers', IEA Report IEAPER/35, September 1997.

46. Soud, H., and Takeshita, M., 'FGD performance and experience on coal-fired plant', IEA Report IEACR/58, July 1993.

47. Soud, H., 'FGD Installations on coal-fired plant ($2^{nd}$ Edition)', IEA Report IEACR/71, June 1994.

48. Fukasawa, K., 'Low cost, retrofit FGD options', IEA Report IEAPER/34, September 1994.

49. DTI Technology Status Report TSR 012, Flue Gas Desulphurisation (FGD) Technologies, March 2000.

50. Smith, I.M., and Thambimuthu, K.V., 'Greenhouse gases, abatement and control – the role of coal', IEA Report IEACR/39, June 1991.

51. UK Energy Sector Indicators 1999, DTI publication.

52. 'Carbon Dioxide Disposal from Power Stations', IEA Greenhouse Gas R&D Programme, $3^{rd}$ Report; http:/www/ieagreen.org.uk/displ.htm.

53. 'Carbon Dioxide Capture and Storage' DTI/Pub URN 00/1081.

54. Couch, G., 'Understanding slagging and fouling during pf combustion', IEA Report IEACR/72, August 1994.

55. Raask, E., 'Mineral Impurities in Coal Combustion, Behaviour, Problems, and Remedial Measures', published by Hemisphere Publishing Corporation, 1985; ISBN 0-89116-362-X

56. EPSRC Project, 'Development of a Model to Predict the Life of Pneumatic Conveyor Bends Subject to Erosive Wear', Grant Ref. GR/10410 and M05980, October 1998 –September 2001, Universities of Greenwich and Cambridge.

57. Parker, K.R., (ed.) 'Applied Electrostatic Precipitation', published by Blackie Academic and Professional, 1997; ISBN 0 7514 0266 4.

58. Metzler, P., Wiess, P., Büttner, H. and Ebert, F. 'Electrostatic enhancement of dust separation in a nozzle scrubber', J. Electrostatics, Vol. 42, pp123-141, (1997).

59. Allen, R.W.K. (1982), 'Electrostatically augmented wet dedusters', Filtration and Separation, 19, pp333-340.

60. EPRI (1992), Grimethorpe high pressure/high temperature gas filter experimental programme, vol. 1: Design, commissioning and modification of a large hot-gas filter on the Grimethorpe PFBC', EPRI Report TR-100-499 vol. 1, September.

61. Berbner, S. and Löffler, F. (1993), 'Pulse jet cleaning of rigid filter elements at high temperatures', in Gas Cleaning at High Temperatures, Ed R. Clift and J.P.K. Seville, Blackie Academic and Professional, London, pp225-243.

62. Jones, M. and Rogers, P. (1993), 'The evaluation of low-density ceramic filters in a boiler flue gas clean-up system', in Gas Cleaning at High Temperatures, Ed R. Clift and J.P.K. Seville, Blackie Academic and Professional, London, pp190-202.

63. Laux, S., Giernoth, B., Bulak, H. and Renz, U. (1993), 'Aspects of pulse-jet cleaning of ceramic filter elements', in Gas Cleaning at High Temperatures, Ed R. Clift and J.P.K. Seville, Blackie Academic and Professional, London, pp2203-224.

64. Koch, D., Schulz, K., Seville, J.P.K. and Clift, R. (1993), 'Regeneration of rigid ceramic filters', in Gas Cleaning at High Temperatures, Ed R. Clift and J.P.K. Seville, Blackie Academic and Professional, London, pp244-265.

65. Simmons, K., Aroussi, A. and Pickering, S.J. (1996), 'Filtration of dirty gases by ceramic candle filters', Proc. $8^{th}$ Int. Symp. On Applications of Laser Techniques to Fluid Mechanics, Lisbon , 8-11 July, pp37.3.1-7.

66. Duo, W., Seville, J.P.K., Kirkby, N.F., Buchele, H., and Cheung, C.K., 'Patchy cleaning of rigid gas filters - II Experiments and model validation', Chemical Engineering Science, Vol. 52, No. 1 pp153-164, 1997.

67. Smolders, K., and Baeyens, J., 'Cleaning of hot calciner exhaust by low-density ceramic filters', Powder Technology 111 (2000) 240-244.

68. Private communication, Powergen.

69. http:/www.ukqaa.org.uk

70. http:/www.ecoba.com

71. http:/www.acaa-usa.org

72. BS 3892-2:1996 Pulverised fuel ash. Specification for pulverised fuel ash to be used as a Type 1 addition.

73. 'The Landfill Tax', Voelcker Science, http:/www.voelckerscience.co.uk/envsc/info6.html

74. 'Unburned Carbonaceous Material on Utility Fly Ash Conference', sponsored by US DoE, Feb.28-Mar.1 1995, Pittsburgh, Pa, USA.

75. 'Second Conference on Unburned Carbonaceous Material on Utility Fly Ash', sponsored by US DoE, March 5-6 1996, Pittsburgh, Pa, USA.

76. 'Third Annual Conference on Unburned Carbonaceous Material on Utility Fly Ash', sponsored by US DoE, May 13-14 1997, Pittsburgh, Pa, USA.

77. '1998 Conference on Unburned Carbonaceous Material on Utility Fly Ash', sponsored by US DoE, May 19-20 1998, Pittsburgh, Pa, USA.

78. '1999 Conference on Unburned Carbonaceous Material on Utility Fly Ash', sponsored by US DoE, May 18 1999, Pittsburgh, Pa, USA.

79. '2000 Conference on Unburned Carbonaceous Material on Utility Fly Ash', sponsored by US DoE, May 16 2000, Pittsburgh, Pa, USA.

80. Cochran, J.W., 'Fly Ash Beneficiation By Carbon Burn-Out', paper presented at 'Unburned Carbonaceous Material on Utility Fly Ash Conference', Feb.28-Mar.1 1995, Pittsburgh, Pa, USA.

81. Keppeler, J.G., 'Full Scale Carbon Burn-Out Ammonia Removal Experience', paper presented at '2000 Conference on Unburned Carbonaceous Material on Utility Fly Ash', May 16 2000, Pittsburgh, Pa, USA.

82. Neathery, J.K., Gurupira, T., Jones, C.L., and Stencel, J.M., 'Pneumatic Transport, Triboelectric Processing of Combustion Fly Ash', paper presented at '2000 Conference on Unburned Carbonaceous Material on Utility Fly Ash', May 16 2000, Pittsburgh, Pa, USA.

83. Soong, Y., Baltrus, J., Champagne, K.J., Fauth, D.T., Gray, M.L., Knoer, J.P., Link, T.A., Newby, T.L., Sands, W.D., and Schoffstall, M.R., 'Separation of High LOI Fly Ash', paper presented at '1999 Conference on Unburned Carbonaceous Material on Utility Fly Ash', sponsored by US DoE, May 18 1999, Pittsburgh, Pa, USA.

84. Levy, E.K., and Herrera, C., 'Removing Carbon from Fly Ash with an Acoustically Agitated Fluidized Bed Separator', paper presented at '1999 Conference on Unburned Carbonaceous Material on Utility Fly Ash', sponsored by US DoE, May 18 1999, Pittsburgh, Pa, USA.

85. U.S. Patents 5,047,145; 5,227,047 and 6,027,551.

86. 'The Heavy End of the Barrel', Institute of Energy symposium held November 26th 1981, Portsmouth Polytechnic, UK.

87. 'Electric Utility Use of Fireside Additives', EPRI Report CS-1318 Research Project 1035-1, Final Report, January 1980.

88. Blauenstein, E., ‘Technical Evaluation of Magnesia’s Influence on Fireside Deposits, Combustion, and Emissions on Oil-fired Boilers’, paper presented at the International Conference on Ash deposits and Corrosion from Impurities in Combustion Gases’, ASME Conference, June 26 to July 1 1977, Henniker, NH., USA.

89. Boyce, T.R., ‘The Merit of Fuel Oil Additives’, publication by The Rolfite Company, November 1976.

90. Turner, D.W., Andrews, R.L., and Siegmund, C.W., ‘Influence of combustion modifications and fuel nitrogen content on NOx emissions from fuel oil combustion’, Combustion, August 1972, pg.21.

91. Institute of Petroleum Method IP/143-96 ‘Asphaltenes (Heptane Insolubles) (ST-B-5).

92. Petroleos de Venezuela S.A. website, http:/www.pdv.com/Orimulsion

93. Bitor America Corporation website, http:/www.orimulsionfuel.com

94. http:/www.skpower.com/braendsler/tekst-orimulsion.htm

95. DB Riley website, http:/www.dbriley.com/orimul.htm

96. Biomass Gasification in Europe, EU study AIR30CT-94-2284, October 1998.

97. UK Energy in Brief December 1999 DTI publication.

98. Specific programme for research and technological development, including demonstration, in the field of non-nuclear energy, (1994-98). JOULE III Project synopses 1997-98.

99. The Fifth Framework Programme. The Research Programmes of the European Union 1998-2002

100. New and Renewable Energy: Prospects in the UK for the 21st Century. Supporting Analysis. Produced by ETSU March 1999.

101. Co-Utilisation of Coal, Biomass and Waste; Vol. 1 Summary of Final Conference 28-29 November 1994, Lisbon, Portugal.

102. New and Renewable Energy: Prospects for the 21st Century. Produced by ETSU March 1999.

103. Dervin, C., ‘Co-firing Wood with Coal in Utility Boilers’, ETSU Report B/U1/0047/REP, 1996.

104. ‘Prediction of Ash and Deposit Formation for Biomass Co-combustion’, JOULE Project JOR3-CT98-0198, July 1998 to June 2001.

105. Pourkashanian, M., Williams, A., Jones, J.M., and Sykes, J., 'A Review of Modelling of Combustion Processes in Stationary Plant/Appliances', ETSU Report No. COAL R146, March 1998.

106. Lobo, W.E., and Evans, J.E., 'Heat Transfer in the Radiant Section of Petroleum Heaters', Trans AIChE, 35, pg. 743-778, 1939.

107. Hottel, H.C., and Sarofim, A.F., 'Radiative Transfer', published by McGraw Hill Book Co., New York, 1967.

108. Spalding, D.B., 'Concentration fluctuations in a round turbulent free jet', J. Chem. Engg. Sci. 26, pg 95-107, 1971.

109. Spalding, D.B., and Patakhar, S.V., 'Heat and mass transfer in boundary layers', published by Morgan, Grampian, London, 1967.

110. Crowe, C., Sommerfeld, M. and Tsuji, Y. (1997), 'Multiphase flows with droplets and particles', CRC Press, Boca Raton.

111. Huber, N., and Sommerfeld, M., 'Modelling and numerical calculation of dilute phase pneumatic conveying in pipe system', Powder Technol. 99: (1), 90-101, Sept 1998.

112. Frazier, K.J., 'Computational Fluid Dynamics Eliminates Fires In Coal Classifiers', www.fluent.co.jp/applicat/powerg/articles/coal.htm

113. FLUENT Consulting; Coal Mill and Coal Classifier; Custom Templating for Virtual Prototyping; www.fluent.de/consulting/problems/mill.htm

114. Zhou, G., Si, J., and Taft, C.W., 'Modeling and simulation of C-E deep bowl pulverizer', IEEE Transactions on Energy Conversion, Vol. 15, No.3, (Sep 2000), pp312-322.

115. Cundall, P.A., 'Formulation of a 3-Dimensional Distinct Element Model. 1. A Scheme to Detect and Represent Contacts in a System Composed of many Polyhedral Blocks', International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 25 (3) 107-116, June 1988.

116. Cleary, P.W., Metcalfe, G., and Liffman, K., 'How well do discrete element granular flow models capture the essentials of mixing processes?' Applied Mathematical Modelling 22: (12) 995-1008, December 1998.

117. Tsuji Laboratory, Complex Particulate Systems, Department of Mechanophysics Engineering, Osaka University, Japan. http://www-mupf.eng.osaka-u.ac.jp/english/tsuji_home.html

118. Inoue, Y., Yokoyama, Tanaka, T., and Tsuji, Y., 'Analysis of Grinding Rate in a Tumbling Ball Mill by Three-Dimensional DEM', Transaction of the Japan Society of Mechanical Engineers, Vol. 66, No. 641C, 2000, pp1-8, (in Japanese).

119. Tanaka, T., 'Models for Numerical Simulation of Moderate or Dense Gas-Solid Flows', Journal of the Society of Powder Technology, Japan, Vol. 35, No. 10, (1998), pp726-734, (in Japanese).

120. Langston P. A., Tüzün U., Heyes D. M., 1996. Distinct Element Simulation of Interstitial Air Effects in Axially Symmetric Granular Flows in Hoppers. Chem. Eng. Sci., 51, 873-891

121. Seville JPK, Tüzün U, Clift R, 'A Processing of Particulate Solids', Blackie Academic and Professional. ISBN 0 7514 0376 8 .1997

122. Accurate Automation Corporation, 7001 Shallowford Road, Chattanooga, TN 37421, USA. http://www.accurate-automation.com/products/nnets.htm

123. Environmental Molecular Science Laboratory, Pacific Northwest National Laboratory,Richland,Washington,USA.http://www.emsl/pnl.gov:2080/proj/neuron/neural/what.html.

124. Himmelblau, D., M., 'Applications of artificial neural networks in chemical engineering', (2000), Korean J. Chem. Eng., vol 17, no 4, pp373-392.

125. 'Self Organisation and Associative Memory', Kohenen, T., Springer-Verlag, New York, 1988.

126. 'Learning Representations using Back Propagating Errors', Rumelhart, D.E., Hinton, G.E., and Williams, R.J., Nature, Vol.323, October 1986.

127. Zhu,Q., Jones, J.M., Williams, A., and Thomas, K.M., 'The predictions of coal/char combustion rate using an artificial neural network approach', Fuel, Vol. 78, No. 14, pp1755-1762, 1999.

128. Awais, M.M., Lockwood, F.C., and Abbas, T., 'Application of Neural Networks to PF Flames', paper presented at the 18th Topic Oriented Technical Meeting, (ToTEM), of the International Flame Research Foundation, September 27th Paris.

129. Awais, M.M., Lockwood, F.C., and Abbas, T., 'Application of Neural Networks to Coal Combustors Performance and Control', presented at the Fifth International Conference on Technologies and Combustion for a Clean Environment, 12-15 July 1999, Centro Cultural de Belem, Lisbon. Vol 11, pp110.

130. EU Contract JOR3-CT97-0170, ‘Modelling for higher efficiency and lower NOx emission from biomass fuel systems’, March 1998 to March 2001. Project co-ordinator Alstom Combustion Services, Sinfin Lane, Derby DE24 9GH, England.

131. Dantec Corporation, http:/www.dantecmt.com/lda/Princip/Index.html

132. ‘Introduction to PIV’ document, Optical Flow Systems, The Bush Research Park, Technopole Centre, Bush Loan, Penicuik, Scotland, EH26 0PJ.

133. LadHyX Hydrodynamics Laboratory, Ecole Polytechnique, 91128 Palaiseau cedex, France. http:/buck.polytechnique.fr/euromech/Cartellier/node5.html

134. National Aeronautics and Space Agency, Glenn Research Center. http://technology.nasa.gov/scripts/nls_ax.dll/twDispTOPSItem(111;TOPS3-43;0;1)

135. Cloke, M., and Lester, E., ‘Characterization of coals for combustion using petrographic analysis: a review’, Fuel 1994 Volume 73 Number 3 315.

136. Cloke, M., Lester, E., Allen, M., and Miles, N.J., ‘Repeatability of maceral analysis using image analysis systems’, Fuel 1995 Volume 74 Number 5 654

137. Cloke, M., Lester, E., and Gibb, W.H., ‘Characterization of coal with respect to carbon burnout in p.f.-fired boilers, Fuel, 1997 Volume 76 Number 13 1257.

138. Gibb, W.H., Cloke, M., Lester, E., Mehta, A., and Stallings, J., ‘The application of image analysis techniques for the prediction of carbon burnout in PF-fired boilers’, paper presented at EPRI conference ‘Effects of Coal Quality on Power Plants’, Kansas City, Missouri, USA, May 20-22 1997.

139. Lester, E., ‘Coal Characterisation using Enhanced Image Analysis Techniques’, paper presented at 3rd UK Meeting on Coal Research and its Applications, 12-14 September 2000, University of Aston, Birmingham, UK.

140. Applied Chemometrics Inc. P.O. Box 100, 77 Beach Street, Sharon MA 02067 USA.

141. Frank, IE, and Friedman, J.H., ‘A statistical view of some chemometrics regression tools’, Technometrics, Vol.35, 109-148.

142. Beebe, K.R., Pelland, R.J., and Seasholtz, M.B., ‘Chemometrics, a practical guide’. New York, John Wiley & Son 1998.

143. Shepparson, J., and Seville, J., ‘Investigation of Segregation Mechanisms during the Discharge of Hoppers using Positron Emission Particle Tracking’, paper presented at 3rd UK Meeting on Coal Research and its Applications, 12-14 September 2000, University of Aston, Birmingham, UK.

144. web page of Positron Imaging Centre, University of Birmingham, http://np.ph.bham.ac.uk/pic/

145. Snieders, F.F., Hoffmann, A.C., Cheesman, D., Yates, J.G., Stein, M., and Seville, J.P.K., ‘The Dynamics of Large Particles in a Four-Compartment Interconnected Fluidized Bed’, article posted on http://www.fwn.rug.nl/chemeng/research/Displ/abshoff/ifbabs.html

146. Department of Mechanical Engineering, Loughborough University, web page http://www-staff.lboro.ac.uk/~mcrdw/research.html

147. Paste Flow Mechanics and Powder Mixing, Department of Chemical Engineering, University of Cambridge, web page http://www.cheng.cam.ac.uk/groups/paste/powder.html

148. GNOCIS - Generic NOx Control Intelligent System ETSU Case Study 003 March 1997.

149. Facchiano, T., ‘GNOCIS - A tool for optimization of NOx and performance in utility boilers’, paper presented at ‘Unburned Carbonaceous Material on Utility Fly Ash Conference’, sponsored by US DoE, Feb.28-Mar.1 1995, Pittsburgh, Pa, USA.

150. Ultramax Corporation; http:/www.ultramaxcorp.com

151. Patterson, P.D., and Yunker, S.B., ‘Simultaneous reduction of LOI and NOx while maintaining boiler performance using constrained sequential optimization’, paper presented at ‘Unburned Carbonaceous Material on Utility Fly Ash Conference’, sponsored by US DoE, Feb.28-Mar.1 1995, Pittsburgh, Pa, USA.

152. UMIST, Manchester, UK, http://www.ce.umist.ac.uk/ptcentre/whattom/htm.

153. Asmar, B.N., Jones, W.E., Wilson, J.A., ‘A process engineering approach to the ALSTOM gasifier problem’, J. Syst. & Cont. Eng., vol. 214, no. 6, pp.441-452, (2000).

154. Dixon, R., Pike, A.W., Donne, M.S., ‘The ALSTOM benchmark challenge on gasifier control’, J. Syst. & Cont. Eng., vol. 214, no. 6, pp.389-394, (2000).

155. Griffin, I.A., Schroder, P., Chipperfield, A.J., Fleming, P.J., ‘Multi-objective optimization approach to the ALSTOM gasifier problem’, J. Syst. & Cont. Eng., vol. 214, no. 6, pp.453-468, (2000).

156. Liu, G.P., Dixon, R., Daley, S., ‘Multi-objective optimal-tuning proportional-integral controller design for the ALSTOM gasifier problem’, J. Syst. & Cont. Eng., vol. 214, no. 6, pp.395-404, (2000).

157. Munro, N., Edmunds, J., M., Kontogiannis, E., Impram, S.,T., 'A sequential loop closing approach to the ALSTOM gasifier problem', J. Syst. & Cont. Eng., vol. 214, no. 6, pp.427-439, (2000).

158. Prempain, E., Postlethwaite, I., Sun, X.,D., 'Robust control of the gasifier using a mixed-sensitivity H∞ approach', J. Syst. & Cont. Eng., vol. 214, no. 6, pp.415-426, (2000).

159. Rice, M., J., Rossiter, J., A., Schuurmans, J., 'An advanced predictive control approach to the ALSTOM gasifier problem', J. Syst. & Cont. Eng., vol. 214, no. 6, pp.405-413, (2000).

160. Taylor, C., J., McCabe, A., P., Young, P.,C., Chotai, A., 'Proportional-integral-plus (PIP) control of the ALSTOM gasifier problem', J. Syst. & Cont. Eng., vol. 214, no. 6, pp.469-480, (2000).

161. Morari, M., Lee, J., H., 'Model predictive control: past, present and future', Comput. Chem. Eng., Vol. 23, 4-5, pp667-682, (1999).

162. Sutton, R.S., Barto, A.,G., 'An introduction to reinforcement learning', MIT Press, Boston, Ma., (1997).

163. Adaptive Networks Laboratory, Department of Computer Science, University of Massachusetts, Amherst, MA, USA. http://www-anw.cs.umass.edu/~mharmon/rltutorial/tut.html

164. Martinez, E.,C., Wilson, J., A., 'A hybrid neural network first principles approach to batch unit optimisation', Comput. & Chem. Eng., vol 22, Suppl, pp893-896, (1998).

165. 'NOx Control for Pulverised Coal-fired Power Plant', DTI Coal R&D Technology Status Report TSR 002, March 1997.

166. SmartProcess Modules, Westinghouse Process Control Inc., http:www.westinghousepc.com/smartprocess/modules.cfm

167. Evans, R.J., 'A computer expert system to reduce power plant emissions', PETC Review; (4); 24-28, (1991).

168. Skorupska, N., 'Coal specifications - impact on power station performance', IEA Coal Report IEACR/52, January 1993.

169. Storm, R.F., 'Optimising Combustion in Boilers with Low NOx Burners', Power, October 1993, pg 53.

170. Bindemann, K.C.G., and Colechin, M.J.F., 'On-line Measurement of PF Flow and Carbon-in-Ash: Its Present Technology Status and Future Developments', PowerGen Report PT/97/RA304/R.

171. Bindemann, K.C.G., Hayward, P., and Brown, R., 'PF Flow Meter Demonstration Trials on a 500MWe Boiler', paper presented at EPRI-DOE-EPA Combined Utility Air Pollution Control Symposium: The MEGA Symposium, August 1620 1999, Atlanta, Ga., USA.

172. Bindemann, K.C.G. Miller, D., and Hayward, P., 'Demonstration of On-Line PF Flow Measurement Technology', DTI Report No. R167 April 1999.

173. Pratapas, J.M., 'Gas Re-burning GRI Programme Overview'. International Workshop on Gas Re-burn Technology, Malmo, Sweden, February, 1995.

174. Damiani,P.J., Teachout, R.J., and Finn, D.P. 'Micronized coal firing boiler facility and potential utility applications', paper presented at the 12th Annual Pittsburgh Coal Conference, 11-15 September 1995, 44-51.

175. 'Source Apportionment of Airborne Particulate Matter in the United Kingdom', Third Interim Report of the Airborne Particles Expert Group.

176. UK Energy Sector Indicators 2000.

177. Airborne Fine Particulate Matter (PM) Research Programme, US NETL, October 1998.

178. 'The Effects of High Carbon-in-Ash on Particulate Emissions and Electrostatic Precipitator Performance', ETSU DTI Project Profile 261, March 2000.

179. Private Communication, TXU Europe Ltd.

180. Bonnano, A., Smith, W., Serio, M.A, and Solomon, P.R., 'An Instrument for In-situ Analysis of Carbon in Fly Ash','Second Conference on Unburned Carbonaceous Material on Utility Fly Ash', sponsored by US DoE, March 5-6 1996, Pittsburgh, Pa, USA.

181. Larrimore, L., Sorge, J., and Bunch, K., 'Demonstrations of On-line Carbon-in-Ash Measurement Technologies''Second Conference on Unburned Carbonaceous Material on Utility Fly Ash', sponsored by US DoE, March 5-6 1996, Pittsburgh, Pa, USA.

182. Averdieck, W., 'Improvements to equipment for on-line monitoring of particulate emissions from coal utilisation processes', DTI Report No. COAL R174, DTI/Pub URN 00/508, January 2000.

183. Gibb, W.H., Clarke, F., and Mehta, A. 'The fate of mercury during combustion', paper presented at Conference on air quality, mercury, trace elements and particulate matter; McLean, Va, USA, 1-4 December 1999.

184. Quick, W.J., and Irons, R.M.I., 'Trace element partitioning during the firing of washed and untreated power station coals at 1MW scale', 3rd UK Meeting on Coal Research and its Applications, 12-14 September 2000, University of Aston, Birmingham, UK.

185. Irons, R.M.A., Quick, W., Whitehouse, M., Wardle, D., and Miles, N., ‘The Fate of Trace Elements in PF Combustion Systems’, ETSU DTI Report No. COAL R193. DTI/Pub URN 00/947.

**TABLE 1: Responses from Power Generators on Potential Problem Areas**

| POTENTIAL PROBLEM AREA | PG 1 | PG 2 | PG 3 | PG 4 | PG 5 | PG 6 | PG 7 | PG 8 | PG9 | PG10 | Total | RANK (Top 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Coal Handling** | | | | | | | | | | | | |
| Transport -Dust | 1 | 1 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 5 | |
| Unloading-Holdup | 1.5 | 0 | 0 | 1 | 3 | 0 | 0 | 2 | 0 | 0 | 7.5 | |
| Unloading-Moisture | 1.5 | 0 | 1 | 1 | 4 | 0 | 0 | 0 | 0 | 0 | 7.5 | |
| Unloading-Freezing | 1.5 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 2.5 | |
| Unloading-Dust | 1.5 | 0 | 1 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 5.5 | |
| Stockpiling-Fires | 1.5 | 0 | 0 | 1 | 0 | 2 | 0 | 3 | 0 | 0 | 7.5 | |
| Stockpiling-Fires | 1.5 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 3.5 | |
| Recovery-Dust | 1 | 0 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 4 | |
| Conveying-Dust | 1 | 1 | 0 | 1 | 0 | 2 | 0 | 0 | 0 | 0 | 5 | |
| Blending-Adequate Mixing | 4 | 2 | 1 | 3 | 0 | 0 | 0 | 4 | 0 | 0 | 14 | 8 |
| Milling-Mill Wear | 3 | 0 | 0 | 1 | 0 | 1 | 2 | 0 | 3 | 0 | 10 | |
| Milling-Fires | 3 | 0 | 1 | 1 | 0 | 2 | 2 | 0 | 0 | 0 | 9 | |
| Milling-Segregation | 0 | 0 | 2 | 1 | 0 | 3 | 3 | 0 | 3 | 0 | 12 | |
| Milling-Blends of Coals | 4 | 0 | 2 | 1 | 0 | 3 | 0 | 0 | 2 | 0 | 12 | |
| Milling-Explosions | 1 | 0 | 1 | 1 | 0 | 4 | 4 | 0 | 0 | 0 | 11 | |
| **Coal Combustion** | | | | | | | | | | | | |
| PF-Distribution to Burners | 5 | 5 | 3 | 1 | 0 | 4 | 4 | 5 | 5 | 5 | 37 | 1 |
| PF-Elimination of Ropes | 4.5 | 5 | 2 | 1 | 0 | 3 | 4 | 0 | 3 | 0 | 22.5 | 5 |
| PF-Correct Air / Fuel Mixing | 5 | 5 | 3 | 1 | 0 | 2 | 5 | 5 | 5 | 5 | 36 | 2 |
| PFA-Collection | 4 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 6 | |
| PFA-Handling | 2 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 5 | |
| PFA-Deposition | 3 | 0 | 0 | 1 | 0 | 0 | 1 | 3 | 0 | 5 | 13 | 9 |
| PFA-Corrosion | 3.5 | 0 | 0 | 1 | 0 | 0 | 2 | 3 | 3 | 0 | 12.5 | 10= |
| PFA-Erosion | 1 | 0 | 1 | 1 | 0 | 0 | 2 | 3 | 3 | 0 | 11 | |
| PFA-Fly Ash Beneficiation | 2.5 | 0 | 1 | 1 | 0 | 2 | 3 | 1 | 2 | 0 | 12.5 | 10= |

Note: PG 1 to 10 denotes power generators

**TABLE 1: …………Continued**

| POTENTIAL PROBLEM AREA | PG 1 | PG 2 | PG 3 | PG 4 | PG 5 | PG 6 | PG 7 | PG 8 | PG9 | PG10 | Total | RANK (Top 10 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Emissions** | | | | | | | | | | | | |
| NOx | 5 | 1 | 1 | 3 | 0 | 1 | 5 | 0 | 4 | 5 | 25 | 4 |
| Fine Particulate | 4.5 | 0 | 2 | 1 | 4 | 2 | 0 | 0 | 0 | 5 | 18.5 | 6 |
| SO2 | 3 | 0 | 0 | 1 | 2 | 2 | 4 | 0 | 2 | 2 | 16 | 7 |
| Air Toxics | 3 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 2 | 8 | |
| CO2 | 3 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 2 | 0 | 8 | |
| Stack Opacity | 4 | 0 | 1 | 4 | 2 | 2 | 5 | 4 | 2 | 5 | 29 | 3 |
| **Other Issues** | | | | | | | | | | | | |
| Liquid fuel-Improved Atomisation | 1 | 0 | 0 | 4 | 0 | 0 | 0 | 0 | 0 | 2 | 7 | |
| Orimulsion-Recovery of Vanadium | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Biomass Fuels-Handling | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 2 | 8 | |
| Biomass Fuels-Availability | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 6 | |
| Wastes-Combustibility | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 2 | 9 | |
| Wastes-Acceptability | 4.5 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 3 | 2 | 11.5 | |
| **Others, (Specify)** | | | | | | | | | | | | |
| Dust Collection-Efficiency Optimisation | | 2 | | | | | | | | | 2 | |
| Dust Collection-Hopper Hang-up | | 3 | | | | | | | | | 3 | |

Note: PG 1 to 10 denotes power generators

**TABLE 2: Status of Conventional UK Power Stations**

| STATION | GENERATOR | YEAR BUILT | FUEL | CAPACITY (MWe) | TYPE & MANUFACTURER | No. OF UNITS |
|---|---|---|---|---|---|---|
| Aberthaw 'b' | Innogy | 1977 | coal | 1500 | Downshot - FWEC | 3 x 500 |
| Cottam | London Electricity | 1969/70 | coal/gas | 2018 | Wall-Fired - John Thompson | 4 x 500 |
| Didcot 'a' | Innogy | 1973 | coal/gas | 1025 | Wall-Fired - MBEL | 4 x 500 |
| Drakelow 'c' | TXU Europe | 1962/66 | coal | 3960 | U9 & U10 Wallfired - FWEC<br>U12 T-Fired - ICL | U9,U10 2 x 350<br>U12 1 x 325 |
| Drax | AES Electric | 1974 | coal | 2000 | Opposed-Fired - MBEL | 6 x 660 |
| Eggborough | British Energy | 1968 | coal | 1995 | Wall-Fired - FWEC | U1,2 & 4, 3 x 505<br>U2, 1 x 480 |
| Fawley | Innogy | 1969 | oil | 517 | Oil-Fired - FWEC | 483 |
| Ferrybridge | Edison Mission Energy | 1968 | coal | 2000 | Wall-Fired - FWEC | 4 x 500 |
| Fiddler's ferry | Edison Mission Energy | 1971 | coal | 2000 | T-Fired - ICL | 4 x 500 |
| Grain | Powergen | 1979 | oil | 1980 | Venturi Oil-Fired - MBEL | 3 x 660 |
| High marnham | TXU Europe | 1959/62 | coal | 1000 | T-Fired - ICL | 5 x 200 |
| Ironbridge | TXU Europe | 1970 | coal | 1000 | Wall-Fired - FWEC | 2 x 500 |
| Kingsnorth | Powergen | 1970 | coal/oil | 2000 | T-Fired - ICL | 4 x 500 |
| Littlebrook | Innogy | 1982 | oil | 790 | Wall-Fired - NEI C.CHAPMAN | 685 |
| Ratcliffe | Powergen | 1968 | coal | 2008 | Wall-Fired - MBEL | 4 x 502 |
| Rugeley 'b' | TXU Europe | 1970 | coal | 1000 | Wall-Fired - FWEC | 2 x 500 |
| Tilbury | Innogy | 1968 | coal | 1400 | Wall-Fired - FWEC | 4 x 350 |
| West burton | TXU Europe | 1967/69 | coal | 2000 | T-Fired - ICL | 4 x 500 |

**TABLE 3: Overseas Fossil-fired Plant with UK Interests**

| OPERATING COMPANY | POWER STATION | FUEL | OUTPUT (MW) | PRESENT STAKE (%) |
|---|---|---|---|---|
| International Power | EOP, Czech Republic | Coal? | 539 | ? |
| International Power | Pego, Portugal | Coal | 300? | ? |
| International Power | Hub River, Pakistan | Coal | 1,292 | ? |
| International Power | Hazelwood, Victoria, Australia | Coal | 1,600 | 91.8 |
| Powergen International | LG & E Energy | Coal | ~8,000 | 100 |
| Powergen International | Schkopau, Germany | Lignite | 900 | 23? |
| Powergen International | Yallourn, Australia | Coal | 1,450 | ? |
| Powergen International | Paiton, Java, Indonesia | Coal | 1,220 | 35? |
| Powergen International | Bina, India | Coal | 578 | 49.9? |
| Powergen International | Map Ta Phut, Thailand | Lignite | 1,400 | 35? |

**TABLE 4: Cost Savings by Carbon-in-ash Reduction**

| | | | |
|---|---|---|---|
| Ash in coal, (%, as fired) | 15 | 15 | 15 |
| Carbon-in-ash, (%) | 6 | 4 | 3 |
| GCV of carbon, (J/g) | 33,700 | 33,700 | 33,700 |
| GCV of coal, (J/g) | 28,750 | 28,750 | 28,750 |
| Combustible loss, (%) | 1.0550 | 0.7033 | 0.5275 |
| | | | |
| Change in carbon-in-ash, (%) | | 2 | 1 |
| | | | |
| Change in loss, (%) | | 0.3517 | 0.1758 |
| Coal fired, (t/y) | | 1,716,960 | 1,716,960 |
| Capacity factor, (%) | | 65 | 65 |
| Coal used, (t/y actual) | | 1,116,024 | 1,116,024 |
| Saving on coal, (t/y) | | 3925 | 1962 |
| Cost of coal, (£/tonne) | | 40 | 40 |
| Saving per year / 500MW unit, (£K) | | 157 | 78 |

**TABLE 5: Effectiveness of $NO_X$ Reduction Techniques**

| TECHNIQUE | POTENTIAL $NO_X$ REDUCTION (%) | COST PER TON OF $NO_X$ REMOVED (US $) |
|---|---|---|
| Gas Co-firing | 10-20 | 50-250 |
| Low $NO_X$ Burners | 40-55 | 300-400 |
| Low $NO_X$ Burners + Overfire Air | 50-60 | 350-550 |
| Reburn | 45-60 | 550-2,000 |
| Reburn + Low $NO_X$ burners | 55-70 | 550-2,000 |
| Advanced Reburn | 95+ | 600-2,300 |
| SNCR | 70 | 700-1,500 |
| SCR | 90 | 1,500-4,000 |

**TABLE 6: Cost Savings by Fly Ash Beneficiation**

The cost benefits of reducing the carbon-in-ash content from 8%, which would be unacceptable, to 4% which would, can be calculated, as follows:-

## VARIATION IN ASH DISPOSAL COSTS / INCOME

| | |
|---|---|
| *Coal consumption of one 500MW PF-fired boiler, (tonnes/day) | 4,800 |
| *Ash content of coal 'as-fired', (%) | 15 |
| Ash production rate, (tonnes / day) | 720 |
| Disposal **costs** , (£ / day) (*£2/tonne) | **1,440** |
| Production rate of classified PFA, (tonnes/day) (*70% -45um) | 504 |
| **Income** from sale of classified ash, (£ / day) (*~£20 / tonne) | **10,080** |

* assumed values

## RECOVERY OF CARBON

Assuming the carbon could be recovered and refired, the amounts for the above example would be:-

| | |
|---|---|
| Carbon in 720 tonnes fly ash @ 8% carbon in ash, (tonnes) | 57.6 |
| Weight of 'C-free' fly ash, (tonnes) | 662.4 |
| Weight of fly ash containing 4% C, (tonnes) | ~690 |
| Weight of carbon in 4% carbon fly ash, (tonnes) | 27.6 |
| Weight of carbon recovered for reuse, (tonnes) | 30 |

The figures for this report are not available electronically. If you wish to receive a hard copy with the figures please contact:

Cleaner Coal Technology Programme Helpline
Building 329, Harwell International Business Centre
Didcot, Oxfordshire OX11 0QJ
Tel: +44 (0) 1235 43 3422
Fax: +44 (0) 1235 43 3961
E-mail: helpline@cleanercoal.org.uk

## QUESTIONNAIRE PARTICIPANTS APPENDIX 1

### A1.1 Generators

PowerGen UK plc
Scottish Power Generation Business
TXU Europe Power Ltd.
Alcan Smelting and Power UK
British Sugar plc.
Edison Mission Energy-
Edison First Power Ltd.
British Energy
RWE Power AG
ENEL Produzione SpA

### A1.2 Universities

UMIST - Chemical Engineering
Aston University
University of Sheffield - Chemical and Process Engineering Dept.
Cardiff University - Cardiff School of Engineering
University of Leeds - Department of Fuel and Energy
Imperial College of Science, Technology and Medicine - Department of Materials
University of Teeside - School of Science and Technology
University of Nottingham - School of Chemical, Environmental and Mining Engineering
University of Greenwich - School of Engineering
University of Leeds - Mining and Mineral Engineering
Chemnitz University of Technology, Germany
University of Magdeburg - Chemical Instrumentation - Technical Chemistry
Graz University of Technology - Department of Chemical Engineering and Combustion
University of Stuttgart - Institute of Process Engineering and Power Plant Technology
University of Erlangen-N_rnburg - Institute of Mechanical Process Engineering
Vienna University of Technology - Department of Chemical Engineering
University of Braunschweig - Institut f_r Verfahrens- und Kerntechnik
Martin-Luther-Universität, Halle-Wittenberg
University of Hull

### A1.3 Equipment Manufacturers

CINAR Ltd.
Talentum Developments
PCME Ltd

## A1.4 Areas of MPF and Related Expertise in Universities

| University | Area of Expertise or Current Project Activity |
|---|---|
| Aston, Chemical Engineering and Applied Chemistry | · CFD modelling of fluidised bed reactors. |
| Braunschweig - Institut für Verfahrens- und Kerntechnik | · Hot gas cleaning with aerocyclones<br>· Fluctuation of loadings in pneumatic conveying systems |
| Cardiff - Cardiff School of Engineering | · Evaluation of 3 cyclone gasifiers for powering small gas turbines using sawdust as gas precursor. |
| Chemnitz University of Technology, Germany | · Parallel numerical simulation of PF flow in pipework flow control system of coal-fired power plant. |
| Erlangen-Nürnburg - Institute of Mechanical Process Engineering | · Fluid dynamics and heat transfer in fluidised riser reactors.<br>· Tomographic study of solids distribution in downer reactors.<br>· Pressurised circulating fluidised bed reactors |
| Graz University of Technology - Department of Chemical Engineering and Combustion | · Development of cyclone apex by LDA, CFD calculation and separation measurements for limestone, quartz and magnetite. |
| Greenwich - School of Engineering | · Development of novel electrostatic instruments for flow measurement of particulate solids in pipelines. |
| Hull - Department of Engineering | · Acoustic monitoring of particulate flows. |
| Imperial College of Science, Technology and Medicine - Department of Materials | · Mineral transformations and their effects on ash properties. |
| Leeds - Fuel and Energy<br><br>Leeds - Mining and Mineral Engineering | · Particulate flow in combustion and gasification systems, modelling, CFD.<br>· Hydraulic conveying of coal using tomography |
| Magdeburg - Chemical Instrumentation – Technical Chemistry | · Gasification of solids, kinetics and burnout behaviour.<br>· Combustion diagnostics, fast response oxygen probe. |
| Martin-Luther-Universität, Halle-Wittenberg | · Modelling of turbulent atomisation of liquid jets<br>· Influence of turbulence on charged particle flow in ESPs<br>· Mechanics of bulk solids<br>· Pneumatic conveying of gas/particle flows |
| Nottingham - School of Chemical, Environmental and Mining Engineering<br>Nottingham - School of Mechanical, Materials and manufacturing Engineering and Management | · Particulate processing, heat exchangers, gas cleaning, hydrodynamics, heat and mass transfer<br>· Measurement and control of PF flows in power station pipework. CFD modelling of coal combustion |
| Sheffield - Chemical and Process Engineering Dept. | · Waste/coal co-combustion. All aspects of modelling 2-phase flow through reacting beds. |
| Stuttgart - Institute of Process Engineering and Power Plant Technology | · Combustion and pyrolysis of coal and biomass, conventional and fluidised bed combustion. In-flame techniques such as LDA. Modelling of combustion. |
| Teeside -School of Science and Technology | · PF flow meter development. |
| UMIST - Chemical Engineering | · Froth flotation models.<br>· Enhanced heat transfer surface for boiling and condenser/thermosyphon reboiler, (vacuum). |
| Vienna University of Technology - Department of Chemical Engineering | · Fast internal circulating fluidised bed gasification<br>· Solid fuel combustion under fluidised bed conditions<br>· NOx reduction in fixed and fluidised bed combustion<br>· $SO_2$ reduction in circulating fluidised bed combustion |

## <u>BLANK QUESTIONNAIRE FORMS</u> <u>APPENDIX 2</u>

### A2.1 <u>Power Generators</u>

**SURVEY OF MULTIPHASE FLOW (MPF) ACTIVITIES**

| Name of Company |
|---|
| |
| Contact person within company |
| |

Method of Communication

| Telephone number |
|---|
| Fax number |
| E-mail address |
| Postal address |
| In what area(s) involving multiphase flow do you feel there is a lack of information which is preventing a preventing a more efficient operation of your plant? |
| Would any improvement in these areas result in cost savings to your operation?<br><br>Please quantify the improvement as small, medium or large |

| |
|---|
| Which of the following areas of MPF would improvements give you better plant efficiency?<br><br>- Instrumentation<br><br>- Modelling of processes<br><br>- Knowledge<br><br>- Technology<br><br>Please identify and give brief details. |
| If you were considering building a new fossil-fuelled plant, (not gas fired), what technology would you choose? |
| Do the answers you have given reflect your needs for your overseas businesses? If not please indicate how these differ from those of your UK business and explain what you feel are the specific needs of the non-UK power generation facilities over which you have control. |

Please complete the attached form regarding potential MPF problem areas and return all of the forms to:-

Dr A.W.Thompson
School of Chemical Environmental and Mining Engineering
University of Nottingham
University Park
Nottingham
NG7 2RD

e-mail alan.thompson@nottingham.ac.uk
phone +44 (0)115 951 4198
fax +44 (0) 115 951 4115

Thank you very much for your co-operation.

**A2.2 University**

## SURVEY OF MULTIPHASE FLOW RESEARCH (MPF) ACTIVITIES

| Name of University and Department |
|---|
| |
| Researcher's name and professional title/degree(s) |
| |

Method of Communication

| Telephone number |
|---|
| Fax number |
| E-mail address |
| Postal address |
| Please indicate the major area in which you work. Enter more than one number if you work in more than one area. Arrange the areas in decreasing order of importance.<br><br>1- Modelling:- Research that is focussed on the mathematical modelling of multiphase flow systems.<br>2- Instrumentation:- Development of innovative instrumentation to improve the understanding and control of multiphase flow phenomena.<br>3- Experimental Studies:- Research that is focussed on specific multiphase flow systems either to improve input to mathematical models, or to devise semi-empirical relationships for practical applications.<br>4- Development:- Development, design and testing of equipment or devices for handling flowing multiphase systems, ( eg pumps, hydrocyclones, reactors). |
| Enter your choice(s) of number(s) in decreasing order of importance in following boxes: |

| | | | | |
|---|---|---|---|---|
| | | | | |

| |
|---|
| Please indicate the major area of multiphase flow in which you work. Select more than one area if appropriate.<br><br>1- Gas/Liquid 2- Gas/Solid 3- Liquid/Solid<br>4- Liquid/Liquid 5- Gas/Liquid/Solid 6- Gas/Liquid/Liquid<br><br>Enter your choice(s) of number(s) in decreasing order of importance in following boxes: |

| | | | | |
|---|---|---|---|---|
| | | | | |

I would be grateful if you would also attempt to complete the attached form concerning the potential MPF problem areas facing power generators. Your perception of the scope and severity of the problems would be helpful.

Please also complete the individual MPF activity sheet attached, (one per project), and return all of the forms to:-

Dr A.W.Thompson
School of Chemical Environmental and Mining Engineering
University of Nottingham
University Park
Nottingham
NG7 2RD

e-mail alan.thompson@nottingham.ac.uk
phone +44 (0)115 951 4198
fax +44 (0) 115 951 4115

Thank you very much for your co-operation

**SUMMARY OF INDIVIDUAL MULTIPHASE FLOW RESEARCH ACTIVITIES**

| | |
|---|---|
| Name | |
| Organisation/University | |
| Project title | |
| MPF system being studied | |
| Project area | |
| Types of fossil fuel being studied | |
| Time scale and duration of project | |
| Budget, (if not confidential) | |
| Total effort, (man years) | |
| Other partners/collaborators | |
| Specialised equipment | |
| Project summary | |

Please indicate the level of technological maturity of your project(s)

| | |
|---|---|
| 1- Basic research | 2- Between basic and applied research |
| 3- Applied research | 4- Between applied research and development |
| 5- Development | 6- Between development and ready to use |
| 7- Ready to use | 7- All stages of technological maturity |

Enter your choice(s) of number(s) in decreasing order of importance in following boxes:

| | | | | |
|---|---|---|---|---|
| | | | | |

**A2.3 Equipment Manufacturers**

**SURVEY OF MULTIPHASE FLOW (MPF)
R&D ACTIVITIES**

| Name of Company and Department |
|---|
| |
| Researcher's name and professional title/degree(s) |
| |

Method of Communication

| Telephone number |
|---|
| Fax number |
| E-mail address |
| Postal address |

| Which, if any, of your current power generation products involving multiphase flow, (MPF), do you feel would benefit from further development? |
|---|
| |

| Where does better knowledge of MPF processes need to be focussed in the development of new products for the power generation industry? |
|---|
| |

| |
|---|
| How would your company normally develop new products for the power generation industry? Is it likely to be in collaboration with the power industry or as a stand alone activity? |

I would be grateful if you would also attempt to complete the attached form concerning the potential MPF problem areas facing power generators. Your perception of the scope and severity of the problems would be helpful.

Please return all of the forms to:-

Dr A.W.Thompson
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e-mail alan.thompson@nottingham.ac.uk
phone +44 (0)115 951 4198
fax +44 (0) 115 951 4115

Thank you very much for your co-operation.

<u>APPENDIX 3</u>

## LIST OF POTENTIAL PROBLEMS IN MPF FOR POWER GENERATORS

| ACTIVITY | POTENTIAL PROBLEM | YES/NO | SEVERITY<br>0 TO 5, 0=LOW |
|---|---|---|---|
| **COAL HANDLING** | | | |
| TRANSPORT | DUST | | |
| UNLOADING | HOLDUP | | |
| | MOISTURE | | |
| | FREEZING | | |
| | DUST | | |
| STOCK PILING | FIRES | | |
| | WEATHERING | | |
| RECOVERY | DUST | | |
| CONVEYING | DUST | | |
| BLENDING | ADEQUATE MIXING | | |
| MILLING | MILL WEAR | | |
| | FIRES | | |
| | SEGREGATION | | |
| | MILLING OF BLENDS | | |
| | EXPLOSIONS | | |
| **COAL COMBUSTION** | | | |
| PF | DISTRIBUTION TO BURNERS | | |
| | ELIMINATION OF ROPES | | |
| | CORRECT FUEL/AIR MIXING | | |
| PF ASH | COLLECTION | | |
| | HANDLING | | |
| | DEPOSITION | | |
| | CORROSION | | |
| | EROSION | | |
| | FLY ASH BENEFICIATION | | |
| **EMISSIONS** | | | |
| | NOx | | |
| | FINE PARTICULATE | | |
| | SO2 | | |
| | AIR TOXICS | | |
| | CO2 | | |
| | STACK OPACITY | | |
| **OTHER ISSUES** | | | |
| LIQUID FUELS | IMPROVED ATOMISATION | | |
| ORIMULSION | RECOVERY OF VANADIUM | | |
| BIOMASS FUELS | HANDLING | | |
| | AVAILABILITY | | |
| WASTES | COMBUSTIBILITY | | |
| | ACCEPTABILITY | | |
| **OTHER TOPICS, (Specify)** | | | |
| | | | |
| | | | |
| | | | |

**RENEWABLES** **APPENDIX 4**

## A4.1 Summary of Prospects for Renewables in the UK

This data has been extracted from an ETSU publication, [100], summarising prospects for the use of renewables in the UK into the 21st century. The comments, regarding opportunities and threats, have been confined to those involving power generation from the combustion of renewables.

**For agricultural, forest wastes and energy crops, their findings were as follows:**

*Opportunities*

- Biomass power plant provide permanent local jobs in rural areas, and they offer farmers, foresters and their contractors stable prices and employment to supply and deliver fuel.
- They offer opportunities for UK companies to develop technology and expertise in an industry which is growing in the world market.
- Plant fired on forest residues offer a market for low-grade wood products which would otherwise have no market. This allows arboricultural residues to be recycled as fuel; it also allows derelict woodland to be brought into management with consequent environmental benefits and puts a base price into the volatile small round-wood market.
- They open up the opportunity to commercialise energy crops, offering the confidence of a long-term market with fixed prices and quality standards.
- They will allow the development of new machines and techniques for fuel collection and processing which will bring down the price of fuel.
- They offer the potential to put base-load renewable power in rural areas where the electricity grid tends to be weak. There are opportunities here to offset the cost of grid strengthening or the effects of intermittent sources such as wind power generation.
- Biomass power plants lend themselves to CHP applications, being small enough to match the heat demand of many rural businesses.
- The new conversion technologies are in their infancy and there is the potential for rapid improvements in efficiency and for cost reduction.
- Legislation may have a positive effect on the development of some biomass power technologies. For example, the landfill tax and recycling targets might make it more attractive to use arboricultural residues in power stations. Increasing environmental legislation on the control of animal slurries might make it more attractive to process them via anaerobic digestion.

*Constraints*

- Plant size will always be limited by the availability of the resource within economic transport distance, though this can be partly mitigated by the development of energy crops in some circumstances.
- Land use planning often places a restriction on the siting of power plant. The fuel normally comes from a rural area and projects need to be developed close to the fuel source. The transport movements needed to deliver the fuel are often a planning issue. There are a limited number of sites at which the public would find

development acceptable and planning restrictions may place financial burdens on the projects.

- Legislation will have a significant part to play. The cost of meeting ever tightening gas or liquid emissions legislation is likely to have a negative impact on capital and running costs.
- Using new technologies will mean that the projects are innovative in nature, which makes them expensive and difficult to finance.

**For MSW the opportunities and constraints were perceived to be as follows:**

*Opportunities*

- Exploitation of, and access to, the available resource as an energy source could be improved by better integration of the NFFO with waste management practices, eg through allowing the awarding of power sales contracts as part of the overall, (competitive), tendering of waste disposal in the local authority sector.
- Increase in the level of landfill tax will increase the economic case in favour of the incineration option.
- The introduction of the EU Landfill Directive in its then current form (May 1997) will also increase the attractiveness of incineration.
- Greater provision of guidance to local authorities on waste tendering under the Environmental Protection Act will raise awareness of the benefits incineration can bring.
- Moves to encourage local authorities to review their waste local plans could prompt them to develop waste management strategies, including operational plans for the system(s) that could be implemented.
- Any general encouragement and development of regional approaches to waste management planning will tend to result in increased opportunities for MSW combustion.
- A general raising of waste management profiles with the public by providing further information on waste management practice in the UK and overseas could address some of the public acceptance-type barriers currently affecting the deployment rate for the technology.

*Constraints*

- Landfill disposal costs are still very competitive and in the majority of cases lower than for combustion.
- Local authority decision making is in a state of confusion given uncertainties in future costs of treatment, impending legislation, and the development process under procurement rules.
- Securing both waste contracts and power sales contracts is a major stumbling block as witnessed by the large failure rate of NFFO contracts in this sector.
- Whilst the UK has a national policy on waste which sets targets for recovery, there is no mechanism for translating these into local action plans - the detail needs to be developed on a regional basis.
- The two-tier local authority system tends to cause conflict between District and County Councils and this in turn can make waste planning activities difficult.
- Public perception of the waste sector and combustion systems in particular, (eg concerning emissions, noise, smell, transport), continues to hold back development.

- Securing planning permission is made more difficult where local authorities do not develop comprehensive waste local plans - these provide the planning framework which underpins the planning application process.

## A4.2 Barriers to the Use of Biomass

Another section of the same report, [100], identifies specific barriers for renewable energy technologies. These are:-

*Agricultural and Forestry Residues*

- The current disparity between the market price of electricity and the cost of generating electricity from agricultural and forestry residues.
- The lack of awareness of the potential of these fuels.
- The failure of the industry to invest in appropriate mechanisation to supply an energy market.
- Potential environmental barriers to the exploitation of these fuels, in particular those associated with the harvesting and transport of the fuel.

*Energy Crops*

- The major barrier to be tackled is the lack of a market for energy crops that is creating a 'no market, no crop - no crop, no market' spiral. This situation is preventing other organisations and other Government Departments from becoming involved in this area.
- Electricity generation from energy crops is not currently economic.
- There is no Non-Fossil Fuel Obligation, (NFFO), type subsidy for non-fossil fuel heat markets.
- The perceived lack of a long-term biological stability associated with energy crops.
- Non-technical barriers to the adoption of energy crops associated with potential environmental impacts of crop production and use.
- The lack of a trade organisation to effectively market energy crops by forming operational links with the energy market.
- The lack of information available to farmers on how to produce energy crops.
- The lack of public awareness regarding the potential offered by energy crops.

*Combustion*

- Limited UK technical knowledge to support development activities.
- Insufficient information to optimise the match between technologies, feedstocks and scales of operation.
- Capital costs seen to be high for demonstration plant in comparison with 'off-the-shelf' conventional plant.
- Financial institutions unwilling to invest in novel technology.

*Waste Incineration*

- Little recent UK experience of modern large-scale MSW energy from waste schemes.
- Large MSW energy from waste schemes will only be economic in regions where landfill costs are highest and where sufficient quantities of waste are concentrated to sustain such plant.
- Energy-from-waste schemes require a long-term contract and guaranteed price for their power, usually above that of the free market.
- There is currently no UK experience of large-scale process and burn technologies linked to resource recovery, advanced conversion options or anaerobic digestion schemes, other than of sewage sludge.
- Unfamiliarity of some technologies in a UK setting can make some projects difficult to finance.
- Public perception can be hostile.
- Uncertainty about future emission standards and how they might be achieved.
- The decision making and contractual procedure is complex and in a state of flux.
- The costs of project preparation are considerable.
- Limited UK experience of heat distribution for community heating schemes.
- Energy recovery from small-scale incineration of specialised industrial wastes faces additional barriers:-
- Appropriate gas cleaning systems are not yet available for commercial operation.
- Advanced conversion technologies are not yet available for commercial operation.
- Considerable uncertainty over resource size and distribution.
- Market access to the grid can be difficult for small generators.

**ABBREVIATIONS** **APPENDIX 5**

| | |
|---|---|
| AI | Artificial Intelligence |
| ANN | Artificial Neural Network |
| BOOS | Burner-out-of-service |
| CBO$^{TM}$ | 'Carbon Burn-Out' proprietary process name |
| CCB | Coal Combustion By-product |
| CCD | Charge Coupled Device |
| CCGT | Combined Cycle Gas Turbine |
| CDW | Construction & Demolition Wood Waste |
| CEGB | Central Electricity Generating Board |
| CFD | Computational Fluid Dynamics |
| CHP | Combined Heat & Power |
| CID | Charge Injection Device |
| CO | Carbon Monoxide |
| CQIM | Coal Quality Impact Model |
| CTF | Combustion Test Facility |
| CW | Continuous Wave |
| DTI | Department of Trade and Industry (now known as Department for Enterprise) |
| EDP | Electricidade de Portugal S.A. |
| EPA | Environmental Protection Agency, (USA) |
| EPRI | Electric Power Research Institute. (USA) |
| ESP | Electrostatic Precipitator |
| ETSU | Energy Technology Support Unit |
| EU | European Union |
| FB | Fluidised Bed |
| FFT | Fast Fourier Transform |
| FGD | Flue Gas Desulphurisation |
| FGR | Flue Gas Recirculation |
| gC/MJ | Grammes of Carbon per Megajoule |
| GWe | Gigawatt (electrical) |
| GNOCIS | Generic NOx Control Intelligent System |
| HAP | Hazardous Air Pollutant |
| HCA | Hierarchical Cluster Analysis |
| HFO | Heavy Fuel Oil |
| HMSO | Her Majesties Stationary Office |
| IA | Image Analysis |
| IPT | Industrial Process Tomography |
| KNN | k-Nearest Neighbour |
| kWh | Kilowatt hour |
| LCPD | Large Combustion Plant Directive |
| LDA | Laser Doppler Anemometry |
| LLS | Laser Light Scattering |
| LNB | Low NOx Burner |
| LOI | Loss-on-ignition |
| MGT | Merry-go-round Trains |
| MIT | Massachusetts Institute of Technology |
| MJ | Megajoule |
| MPC | Model Predictive Control |

| | |
|---|---|
| MPF | Multiphase Flow |
| MRI | Magnetic Resonance Imaging |
| MSW | Municipal Solid Waste |
| MTOE | Million Tonnes of Oil Equivalent |
| MTU | Michigan Technological Institute |
| MWe | Megawatt (electrical) |
| $N_2O$ | Dinitrogen Monoxide, (nitrous oxide) |
| Nd:YAG | Neodymium-doped yttrium aluminium garnet |
| NETL | National Energy Technology Laboratory (USA) |
| NFFO | Non Fossil Fuel Obligation |
| NN | Neural Network |
| NO | Nitrogen monoxide, (nitric oxide) |
| $NO_2$ | Nitrogen Dioxide |
| NOx | Oxides of Nitrogen, (usually NO + $NO_2$) |
| OFA | Overfire Air |
| PAH | Polycyclic Aromatic Hydrocarbon |
| PCA | Principal Component Analysis |
| PCR | Principal Component Regression |
| PDA | Phase Doppler Anemometry |
| PEPT | Positron Emission Particle Tracking |
| PET | Positron Emission Tomography |
| PF | Pulverised Fuel |
| PFA | Pulverised Fuel Ash |
| PFBC | Pressurised Fluidised Bed Combustion |
| PIV | Particle Image Velocimetry |
| PJ | Petajoule |
| plc | Public Limited Company |
| PLS | Partial Least Squares |
| PT | Process Tomography |
| PTFE | Polytetrafluoroethylene |
| QAA | Quality Ash Association |
| R&D | Research and Development |
| REC | Regional Electricity Company |
| RL | Reinforcement Learning |
| RTD | Research and Technology Development |
| SCR | Selective Catalytic Reduction |
| SIMCA | Soft Independent Modelling of Class Analogy |
| SNCR | Selective Non-Catalytic Reduction |
| $SO_2$ | Sulphur Dioxide |
| $SO_3$ | Sulphur Trioxide |
| SOx | Sulphur Oxides, (sulphur dioxide & trioxide) |
| SRC | Short Rotation Coppice |
| t/h | Tons / Hour |
| t/y | Tons / Year |
| UKQAA | United Kingdom Quality Ash Association |
| VOC | Volatile Organic Compound |