Assessment of Ash Re-firing and Mineral Addition – Impact on Plant Performance and Ash Disposal

Report No.
COAL R296
DTI/Pub
URN 05/1684

December 2005

by

G S Riley & T Beeley (RWE npower), J Williamson & F Wigley (Imperial College), N V Russell & M Zandi (Sheffield University), B Ricketts (UK Coal Ltd) and P R Cooper (Precol Associates)

RWE-Innogy Plc
Windmill Hill Business Park
Whitehill Way
Swindon
Wiltshire
SN5 6PB

Tel: +44 (0) 1793 896298
Email: gerryriley@rwenpower.com

The work described in this report was carried out under contract as part of the DTI Cleaner Coal Research and Development Programme. The programme is managed by Mott MacDonald Ltd. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of the DTI or Mott MacDonald Ltd

First published 2005

Assessment of ash re-firing and mineral addition on plant performance and ash disposal

DTI Cleaner Coal Project 325

Final Report

Prepared for Mott Macdonald, DTI Cleaner Coal Programme Managers

RWE npower plc

prepared by

Precol Associates Ltd

January 2005

Contents

Summary

Pulverised coal fired generation plant will continue to play a major role in the world-wide electrical power market for the foreseeable future. Emission standards have become tighter in recent years and coal fired plant has been required to become more flexible in terms of operating regimes. The changes have led to increases in the levels of unburnt carbon in ash, deposition patterns in boilers as well as increased pressure on the performance in electrostatic precipitators.

This project, to investigate if ash refiring and mineral addition were viable methods of improving boiler efficiency and reducing emissions, was supported by the DTI as part of its Cleaner Coal Programme. The project involved the collaboration of two generators (RWE npower and TXU Europe), a major coal supplier (UK Coal) plus two university groups (Imperial College London and the University of Sheffield).

A representative group of coals and minerals were selected and the Entrained Flow Reactor (EFR) at Imperial College was used for the initial laboratory scale tests and to select the most promising coal/mineral combinations for pilot scale testing on the RWE npower Combustion Test Facility at Didcot.

Pilot scale trials of ash re-firing on the CTF were used to predict the performance that could be expected on a 500MWe boiler. These trial results were used to formulate a full-scale ash re-firing test programme that was successfully undertaken on Unit 1 at Didcot power station.

The deposits from both the EFR and CTF were characterised by Imperial College using CCSEM techniques. Techno-economic assessments of both ash re-firing and mineral additions were undertaken and a set of guidelines established for re-firing of fly ash and mineral addition was established

1. Introduction

Pulverised coal fired power generation will continue to play a major role in the provision of electrical power in the UK and overseas markets for the foreseeable future. The drive to reduce CO_2 emissions as part of the UK's commitment to the Kyoto agreement requires improvements in the efficiency of existing coal fired plant in addition to the building of new higher efficiency generating plant.

Tighter emission standards have meant fitting of low NOx burners and the use of lower sulphur content coals plus the changes in the UK electricity market have required generating plants to become more flexible. All these changes have led to higher carbon is ash, changes in the deposition patterns in boiler and increased pressure on the performance of electrostatic precipitators.

One of the major losses of efficiency of coal fired boiler plant is due to the unburnt carbon found in the pulverised fuel ash (pfa). This carbon in ash is lost energy that results in an increase in the amount of fuel burnt to maintain the plant output, all of which increase emissions from the plant. High carbon in ash also adversely affects the performance of the electrostatic precipitators (ESP's) due to the change in resistivity of the ash, so increasing dust emissions.

One of the consequences of fitting low NOx burners to utility boilers has been to reduce the amount of bottom ash formed in the boiler furnace which has led to a corresponding increase in the amount of fly ash going to the electrostatic precipitators. Low NOx combustion has also led to higher levels of carbon in fly ash which can adversely affect the performance of electrostatic precipitators.

These effects are considered to be as a consequence of the lower flame temperatures associated with low NOx burners and the initial reducing conditions within the flame. Many power stations will find it difficult in complying with ongoing reductions in the level of fine particulate emissions without extensive modification and upgrading of electrostatic precipitators or restrictions in the range of coals burnt.

The majority of ash particles are essentially aluminosilicates derived from the decomposition and interaction of the clays with other minerals present in the coal. At combustion temperatures the aluminosilicates are largely molten. The viscosity of the ash particles is determined by their chemical composition and the temperature. The lower the viscosity the more likely the ash particle will be retained within the boiler furnace as a boiler deposit.

One way of increasing the “stickiness” of ash particles is to change the ash chemistry thus enhancing the formation of furnace bottom ash through particle agglomeration, thereby reducing the proportion of fine ash particles carried over the precipitators.

Two options that may improve boiler efficiency are the re-firing of high carbon content pulverised fuel ash (pfa) and mineral additions to promote increased ash deposition in the furnace.

Initial studies have indicated the carbon in ash in pfa is still sufficiently reactive to be able to be burnt off at high temperatures and with high carbon content ashes, the amount of coal burnt at a power station being reduced by up to 1% by ash re-firing. Laboratory scale trials have also shown that small additions of some minerals have produced marked changes in ash deposits and their formation.

This DTI supported project aims to provide coal fired power stations with a relatively simple yet cost effective means of improving combustion efficiency and reducing particulate emissions by re-firing ash and/or with mineral additions to the coal.

The suite of coals and minerals has been chosen for the project by the project participants, primarily RWE npower plc, Imperial College, TXU Europe and UK Coal Ltd and includes UK, South American and South African coals. Tests have been conducted on the RWE npower Combustion Test Facility (CTF) and the Imperial College Entrained Flow Reactor (EFR).

2 Project Overview

The project was a collaboration between RWE npower plc, Imperial College London, TXU Europe, UK Coal Ltd and Sheffield University, with RWE npower acting as the main contractor. TXU Europe was bought out during the course of the project and Mr P R Cooper continued his involvement with the project as an independent consultant.

The personnel involved with the project and the contact details of each collaborating organisation are listed in Section 13 of this report. Just under half of the project costs were provided by the DTI under the Cleaner Coal Programme, the remainder being provided by contributions from RWE npower, Imperial College, UK Coal and TXU Europe.

2.1 Aims and Objectives

The aim of the project was to provide boiler operators with a relatively simple means of increasing cycle efficiency and reducing particulate emissions.

The specific objectives were to:-

- Determine the optimum level of mineral addition by use of an Entrained Flow Reactor.
- Determine if there are any technical show-stoppers to either ash re-firing or mineral addition by assessing the impact of these technologies on power station operation by test firing on a pilot scale combustion facility.
- Carry out a full-scale test of ash re-firing.
- Identify any constraints due to ash utilisation on satisfactory ash refining and mineral addition.
- Develop a better understanding of the effect of coal type and combustion conditions on ash properties which will allow better utilisation/disposal of ash.
- Carry out a techno-economic assessment of ash re-firing and mineral addition.
- Generate a set of guidelines for re-firing PFA and mineral additions.

The work programme consisted of nine main activities

2.2 Activity A - Coal ash and mineral selection and characterisation

TXU Europe, UK Coal and RWE npower were responsible for the selection and acquisition of a suite of UK power station coals having a representative range of ash contents and compositions for the laboratory and pilot scale trials. In addition, TXU Europe and RWE npower identified sources of high carbon content pfa material that would be suitable for the re-firing trials and also the University of Sheffield studies described in Activity C below. Imperial College and RWE npower were responsible for identifying and sourcing the materials for the mineral addition work

2.3 Activity B – Laboratory study of the effect of mineral additions on ash behaviour

Samples of fly ash and deposits from the suite of coals and mineral doped coals were generated in trials using the Entrained Flow Reactor (EFR) at Imperial College which simulates typical time–temperature conditions experienced during low NOx combustion conditions in a large utility boiler.

The deposit samples from the EFR were characterised by Imperial College using scanning electron microscopy (SEM). The results of these studies were used to determine the type and level of mineral doping that was to be used in the pilot scale tests on the Combustion Test Facility at Didcot, described in Activity E below.

2.4 Activity C – Interaction of CaO with aluminosilicate glass and the fate of Ca, Mg and trace elements in re-fired fly ash.

These two MSc projects were included as complementary studies to the main re-firing project. The first project related to the interaction of CaO with aluminosilicate glass and the second to the fate of Ca, Mg and trace elements in a re-fired fly ash.

The first project was to provide fundamental data on the effect of ash compositions on the diffusion rates of CaO and MgO in aluminosilicate glass as there is little information in the literature on this aspect of high temperature ash chemistry. Synthetic CaO-aluminosilicate slags were to be prepared in the laboratory, pelletised and then diffusion coefficients were to be established using SEM/EDS analysis following heat treatment.

The second project was to examine the stability of Ca, Mg and trace elements in fly ash using a range of fly ash samples including samples from the pilot scale test on the CTF at Didcot described below.

2.5 Activity D – Pilot scale assessment of ash re-firing on plant performance.

Previous laboratory scale studies have indicated that the carbon in pfa is still sufficiently reactive to be re-fired at high temperature. Prior to any full-scale trial, it was necessary to undertake pilot scale trials on the CTF at Didcot to verify the laboratory scale findings and also establish the viability and impacts of re-firing ash on the whole combustion process prior to any full-scale trial.

2.6 Activity E - Pilot scale assessment of mineral addition on plant performance

Following on from the results of Activity B at Imperial College and the identification of the preferred mineral additions and dosing regimes at pilot scale, a series of trials at pilot scale were to be undertaken on the CTF. These trials would investigate the likely impacts that mineral additions would have on the performance of a full-scale utility boiler and on the disposal and utilisation of pfa.

2.7 Activity F – Characterisation of coal, ashes, mineral and deposits

The chemical composition and relevant characteristics of samples of the selected coals, minerals and coal ashes were to be established by RWE npower and Imperial College using well established and proven procedures. Basic analysis of the materials selected would be undertaken by RWE npower. Imperial College would use CCSEM techniques to characterise the pulverised coal, ash particles and deposits

2.8 Activity G – Investigation of the nature of fly-ash and its ability to be collected in electrostatic precipitators

Samples of fly ash were to be obtained from a power station to determine the factors that affect the nature of pfa and its ability to be collected by an electrostatic precipitator. Samples would be obtained both at precipitator inlet and outlet and also from the main hoppers. Data would be collected for high calcium content coals as well as normal coals to examine the likely impacts of mineral additions.

2.9 Activity H - Power station evaluation of ash re-firing.

A full scale trial of ash re-firing was to be undertaken at Didcot Power Station based on the results of the pilot scale trials described in Activity D. The trial would permit a through-plant assessment of performance to be undertaken.

2.10 Activity I – Technical and economic evaluation of ash re-firing and mineral addition at full scale

Data from both the pilot and full-scale power station tests was used as the basis for a techno-economic evaluation of ash re-firing and also mineral additions.

2. 11 Activity J – Project Management and Reporting

Progress meetings took place at regular intervals throughout the project at Imperial College London. RWE npower provided financial and administrative organisation for the project.

3 Coals and minerals selected for the project

Four coals were selected to provide a representative sample of coals utilised in UK power stations and having relevant ash compositions to the project. There were two UK coals, one Colombian and a South African coal. One of the UK coals was only used in the Imperial College EFR trials and it was considered by the project participants to be unnecessary to use this grade of coal at pilot scale.

Several tonnes of the three pilot scale trail coals were ground to pf specification by James Durrans and Sons (a subcontractor) using a Lopulco coal mill. The ground coal was delivered in 25kg sealed bags to the CTF at Didcot.

The proximate and ultimate analyses of these coals is shown in the table below:-

	UKl	Colombian	South African
Inherent Moisture % (ar)	2.50	7.29	4.17
Volatile Matter % (ar)	35.04	35.88	26.87
Ash Content % (ar)	11.17	6.12	12.44
Carbon Content % (ar)	68.15	67.97	68.58
Hydrogen Content % (ar)	4.42	4.74	3.87
Nitrogen Content %(ar)	1.25	1.60	1.83
Sulphur Content %(ar)	1.67	0.62	0.59
Gross CV kJ/kg (ar)	28263	26460	27504
Volatile Matter % (db)	35.94	38.70	28.04
Ash Content % (db)	11.46	6.60	12.98
Volatile Matter % (daf)	40.59	41.44	32.22

Details of the ash chemistry of the coals were established by Imperial College.

Five mineral additives were considered as candidates for the Imperial College EFR trials namely:- albite (feldspar), blast furnace slag, calcite, dolomite and orthoclase. Of these only feldspar and calcite were considered by the project participants as candidates for the follow up mineral addition trials at pilot scale on the CTF at Didcot.

The mineral ash contents and their chemical compositions (%wt) are shown in the following table:-

	Albite	BF Slag	Calcite	Dolomite	Orthoclase
Ash Content	100.00	100.00	56.03	52.27	100.00
SiO_2	68.9	48.0	0.0	0.0	69.0
Al_2O_3	19.1	15.7	0.0	0.0	16.9
Fe_2O_3	0.1	0.8	0.0	0.0	0.1
CaO	1.7	26.1	100.0	58.2	0.4
MgO	0.1	7.3	0.0	41.3	0.0
K_2O	3.0	0.9	0.0	0.0	10.8
Na_2O	7.2	0.2	0.0	0.0	2.7
TiO_2	0.0	0.6	0.0	0.0	0.0
P_2O_5	0.0	0.1	0.0	0.0	0.1
MnO	0.0	0.3	0.0	0.0	0.0

4 Mineral addition trials on the Entrained Flow Reactor

The laboratory studies of the effects of mineral additions on ash behaviour described previously under work programme Activity B were undertaken by Imperial College using their Entrained Flow Reactor (EFR).

The key findings of this activity were:-

- The initial trials indicated that deposition efficiency and the level of deposit sintering were mainly controlled by the properties of the coal ash rather than the mineral additive.
- No consistent variation in deposit weight with nature of mineral additive was observed.

- Albite produced the greatest deposition for both UK1 and the Colombian coals.
- The addition of calcite appeared to have the greatest effect on the degree of deposit sintering.
- Albite and calcite were selected as additives to investigate further on the EFR and also at the pilot scale trials.
- UK coal 1 was selected as the preferred coal for further trial work as both of the above additives had increased the mass of this coal ash deposited.
- The further trials using UK coal 1 with additions of albite or calcite at 5 levels (0-40 wt%) indicated that mineral additions did not produce a significant increase in deposition efficiency, nor a significant change in ash particle size distribution, although the deposit microstructure did change.
- UK coal 1 with increasing calcite additions showed increased degree of deposit sintering and fusion especially at the highest level of calcite addition (40%).

5. University of Sheffield MSc Projects

As described previously in Activity C of the work programme, two MSc projects at the University of Sheffield were included as complementary studies to the main ash re-firing project. The first project was the interaction of CaO with aluminosilicate glass and the second project was the fate of Ca, Mg and trace elements in re-fired fly ash.

It should be noted that it was not possible to complete the interaction of CaO with aluminosilicate glass project within the time-scale of the re-firing project due to major technical difficulties encountered with the production of stable pellets. Until this problem can be resolved and additional funding is found to produce more glass, this project will not be able to proceed further.

The second project was completed within the ash re-firing project timescale and has provided considerable data on the mobility and leaching behaviour of power station fly ashes.

6. Pilot scale trials of ash re-firing

A series of trials, based on the outcome of the laboratory scale EFR trials at Imperial College, were undertaken using RWE npower's Combustion Test Facility (CTF) at Didcot in accordance with the requirements of Activity D of the work programme.

These trials were designed to examine the influence of coal type, the level of ash addition that is technically possible and quality of the blend required for a full-scale power station test.

Key issues to be considered at this stage were:-

- Would the ash cause the flame to become unstable?
- Would it affect the NOx generation?
- Would it result in reduced carbon in fly ash?
- Would it cause higher ash deposition?
- Would it cause higher dust emissions?
- Would ash re-firing result in problems with ash utilisation?

Following the CTF trails the overall results of these preliminary tests were encouraging:-

- Although the flame conditions were considered poor during periods of ash re-firing, the flame was found to be stable, even with relatively high levels of addition on UK coal 1.

- Test combustion conditions were found to be increasingly affected with the addition of ash as indicated by the NOx and carbon in ash data.

It was concluded from the CTF trials that :-

- Ash re-firing was technically feasible and that there was no evidence that ash addition of up to approximately 10% by weight, depending on the coal, would result in flame instability.

- Addition of ash appears to have a significant effect on NOx levels above a 10% ash addition.

7. Pilot scale trials of mineral additions

A second series of pilot scale trials were undertaken by RWE npower on the CTF at Didcot in early 2004 in accordance with Activity E of the work programme. Based on the findings of the EFR trial work at Imperial College, two minerals, albite (feldspar) and calcite were chosen for the pilot scale trials. A further series of tests using pfa would be undertaken to link with the CTF work previously undertaken and described above.

The test results of the mineral addition tests on the CTF were very encouraging and the key findings were;-

- The effect of temperature was not significant on deposition rate.
- A significant increase in deposition rate was seen with both mineral additions and pfa re-firing under oxidising and reducing conditions.
- There was considerable scatter in the data on deposition rates.
- The effect of temperature was not significant on the deposit type.
- Calcite and feldspar both caused an increase in sintering especially under reducing conditions.
- Ash deposits appeared to become more friable with ash addition.
- There was considerable scatter in the data relating to deposit type.

8. Characterisation of coals, ashes, minerals and deposits

The proximate and relevant ultimate analyses of the coals used were established by RWE npower and the ash and mineral chemistry was established by Imperial College.

Following the production of ash deposits on the EFR and CTF for both fly ash and mineral additions, these deposits were characterised by Imperial College using SEM techniques allowing the behaviour of the CTF and EFR samples to be compared.

The key findings of the Imperial College characterisation activities were:-

- For both CTF and EFR deposits, there were significant changes in deposit microstructure as the level of mineral addition increased:-
  - the degree of deposit sintering increased and the porosity decreased,
  - the chemical homogeneity of the deposits increased,
  - a matrix with a distinct composition, richer in CaO (calcite additions) or Na_2O (albite additions), appeared and became abundant.
- These effects were strong for calcite additions, weak for albite additions, and not significant for PFA additions.
- The calcite had transformed to lime and interacted with aluminosilicate coal ash particles, some of which had deposited and formed a lime-rich aluminosilicate melt. The presence of a lime-rich melt significantly increased the degree of sintering and fusion of the deposit, and changed the nature of the crystalline phases that grew within the deposit. The abundance of pure lime regions (calcite addition) or soda-rich regions (albite addition) in the deposits was low, indicating that the coal ash and additives had fully interacted in the deposit.
- Characterisation of the CTF deposit samples showed that the increase in deposit CaO concentration with calcite addition was about the same as calculated. The increase in deposit Na_2O concentration with albite addition was about one-third less than calculated, due to vaporisation of the Na_2O.
- When the CTF deposition efficiency was corrected for temperature, using the sheath thermocouple temperatures and the temperature-viscosity relationship

for UK coal 1, no significant change in deposition efficiency with level of calcite or albite addition was identified.

- In summary, mineral additions have interacted with the coal ash in the deposit, to change the deposit microstructure and chemistry (more strongly for calcite than for albite). The addition of minerals to combusting coal has not increased the proportion of fly ash that deposits as slag or coarsened the fly ash particle size distribution.
- The mineral addition trials on the Imperial College EFR and the RWE npower CTF do not appear to have reversed the changes in coal ash behaviour introduced to pulverised coal fired boilers with the retro-fitting of low-NOx burners.

9. The nature of fly ash and its ability to be collected in electrostatic precipitators

Data was gathered from the full-scale trials at Didcot as well as from a number of tests previously undertaken on full-scale utility boiler plant by RWE npower and TXU Europe.

This information has been used to help understand the factors that affect the nature of pfa and its ability to be collected by an electrostatic precipitator. Particular attention was paid to high calcium content coals to examine the potential impact on pfa quality of mineral addition.

Ash resistivity is a key factor in the efficient collection of dust particles in a power station electrostatic precipitator. The range of ash resistivities for good precipitator performance is normally accepted as 10^9 to 5×10^{11} Ωcm. Resistivity can fall below this figure if there are high levels of unburnt carbon and alternatively can rise above this accepted range due to variations in the ash chemistry.

Traditionally the main problem in precipitator operation in UK has been the reduction of resistivity due to high carbon in ash content. The introduction of low

NOx burners has increased the probability of boilers producing higher unburnt carbon levels in the resulting pfa. This has been offset to a considerable degree by stricter management of pulverised coal milling to increase the fineness of the pf product thereby increasing the opportunities for complete combustion in the furnace.

Tests with blended coals in the past have given some very unpredictable dust emission (and precipitator collecting efficiency) results. A very small content of a low volatile component that is much harder to grind than the main body of the blend has been found to cause major increases in dust emission levels. This was found to be due to an increase in the proportion of relatively large char particles caused by the partial combustion of lower volatile coal component.

These particular tests were undertaken prior to the current dust emission monitoring regime, any re-occurrence of this problem would now lead to major de-rating on the plant concerned.

In another series of fuel and combustion tests, a similar problem of high dust emissions occurred but this was during tests with single seam coals. The occurrence of high levels of dust emissions did not follow any of the normally anticipated patterns and some of the low sulphur imported coals in the test programme were giving significantly better emission results that medium sulphur content UK coals.

An examination of the precipitator inlet dust data for each of the three parallel inlet channels showed the concentration of large char particles in just one channel. The high level of large char particles in this part of the precipitator was sufficient to result in a significant plant derate in output.

The other two channels had much lower dust emissions results and their individual performances were adequate to meet the emission standards in place at the time. The cause of the high level of large char particles was attributed to poor coal milling and air ingress in the furnace causing flame chilling on the wing burners which are closest to furnace walls.

Following the use of lower sulphur imported coals as a means of reducing SOx emissions, problems began to arise with high resistivity ash and decreased precipitator efficiencies. Tests have shown resistivities for imported coals to be as high as 10^{13} Ωcm. However, these coals have less than 20% of the sulphur of typical UK mined coals and this benefit easily outweighs the problems created by the higher resistivity.

Many imported coals, particularly from the Southern Hemisphere sources have a resistivity / flue gas temperature curve is virtually flat or has a slightly rising characteristic. In the case of Northern Hemisphere coals, the resistivity / flue gas temperature curve which rises to a peak at around 150^{o}C and then falls quite markedly as flue gas temperatures rise to around 190 ^{o}C.

A large number of power stations have adopted SO_3 gas injection into the flue gas stream. The levels of SO_3 injection required are very low. For example, with a typical Chinese coal, the ash resistivity at 140^{o} C was reduced from 10^{12} to 10^{10} Ωcm by the injection of 1ppm of SO_3 into the boiler ducting upstream of the precipitator inlet.

It has been found that the injection of SO_3 is most effective at lower flue gas temperatures. For example in the case above, where the ash resistivity was reduced from 10^{12} to 10^{10} Ωcm by the addition on 1ppm of SO_3 in a flue gas stream of 140^{o} C, the reduction in resistivity at 170^{o}C was from 10^{12} to 10^{11} Ωcm. With a flue gas temperature of 180^{o} C the resistivity was halved once again.

The most extreme effects were found with high silica content fly ashes from certain Australian coals where SO_3 injection had no effect on resistivity whatsoever, even at 10ppm injection rates, once the flue gas temperature rose to 170^{o}C

NaO has also been found to have a significant impact on the resistivity of fly ash. A decrease in NaO content of fly ash from 0.3% to 0.10% can typically give an increase in resistivity from 10^{12} to 10^{13} Ωcm

A considerable amount of new work in relation to high calcium content coals was undertaken by Imperial College and its project partners as part of DTI Cleaner Coal Project 120, Coal mineral transformations – Effects on power station ash behaviour and properties.

It was found that the relationship between total CaO and free CaO was non-linear and for a population of 23 coals with total CaO contents ranging from 0 to 23%, CCSEM analysis showed that only three coals gave Ca rich particles with more than 2.5%wt CaO. These three coals were grades that are likely to be encountered in commercial power station operation in UK.

This conclusion has been borne out by previous commercial operational experience on a number of power stations burning high CaO content coals. These coals included South African imports with CaO contents of up to 16%, where the resultant pfa was sufficiently low in free CaO content to permit the pfa to be used in the cement replacement market. This application requires the most stringent quality control regime in terms of calcium content of any of the pfa utilisation markets.

10 Power station evaluation of ash re-firing

Full scale trials of ash re-firing at both 5 and 10% levels were undertaken on Unit 1 at Didcot Power Station by RWE npower in 2003.

The key findings and conclusions from the trials were;-

- The plant performance at 5% ash addition level was comparable to that with coal only.

- The plant performance at 10% ash addition level was constrained and it was necessary to reduce output by up to 10% in order to achieve reasonable emission levels.
- The maximum plant output that could be achieved at 10% ash addition level was 98% of the coal only test.
- Based on sample analysis, the belt blending method previously described as Option B proved satisfactory.
- Neither the 5 or 10% levels of addition caused any operational problems.
- SOx, NOx and CO emissions were similar for the coal only base line test and the 5% ash addition tests. Dust emission levels were found to be slightly higher for the 5% test.
- Compared with coal only operation, it was necessary to run an extra coal mill for the 5% test in order to achieve full load.
- SOx, NOx and CO emissions were all higher than base line for the 10% ash addition tests.
- Dust emission levels were similar at all blend levels.

11. Techno-economic assessment

11.1 Ash re-firing

This study is based on the findings of the pilot and full-scale trials for re-firing of fly ash and also the pilot scale trials for the addition of minerals to the coal feed stock as well as generic data on power station plant and handling processes.

11.1.1 Ash handling and supply issues

Storage of the fly ash presents a number of technical issues that need to be addressed at power station level. Open storage of material on either a hard standing area or in a corner of the coal stocking area is not considered as viable due to both dust blow problems in dry conditions and also water-logging of stock in the autumn and winter.

Fly ash is already in a dry powdered form and most power stations already have a silo storage system that, although somewhat remote from the coal plant ground hopper, could be used to provide a supply of suitable fly ash for blending as required.

Thus adequate supplies of fly ash exist on all power stations and there is no need to consider the impacts of additional supply logistics to the power station site

11.1.2 Ash quality issues

Based on operational experience at a number of power stations, it has been shown that it is possible to create an ash grading system by adjusting the operating regime of the various zones of the electrostatic precipitators. In effect it is possible to concentrate the high carbon in ash proportion of the total fly ash stream in the first zone of the precipitators. Samples with as high as 75% carbon in ash from the front zone of a precipitator have been achieved on a boiler having an overall carbon in ash of approximately 10%.

This technique would provide a carbon rich ash stream comprising less than 25% of the total fly ash production which could then be re-fired without the risks of derate or increases in emission levels that were encountered with the higher levels of “ordinary” ash re-firing during the full scale trials.

Some power stations already have ash beneficiation facilities installed in order to improve the sales of pfa into the cement replacement market by reducing the carbon in ash content of the product. Currently the reject stream from this process which contains up to 30% unburnt carbon is of little value and is normally mixed into landfill or the low value ash market. This stream is effectively a ready made source of high carbon in ash material that could be used for the re-firing at little or no additional capital cost.

Samples of material from both the ash beneficiation process and selective precipitator zone operation have shown both material streams contain a high proportion of particles over 100μm in size and the larger size particles have the greatest unburnt carbon content of any size fraction.

11.1.3 Key findings from pilot and full scale test programme

- It was demonstrated with UK coal 1 that even at high ash addition rates, the flame was still stable. This indicates that there is no need to use a high quality blending regime and the type of scheme described in Option B later in this section is adequate for fly ash addition.

- Ash addition rates over 10% had a significant effect on NOx levels.

- Full scale testing with the South African coal showed that the 5% fly ash test performance was comparable to baseline coal only test, but 7 mills required to make full load compared with the normal 6 mill full load operating regime on coal only.

- The 10% full-scale fly ash addition test showed that emissions were higher and that it was necessary to derate the overall output of the plant.

11.1.4 Main blending options for ash re-firing

A number of alternative methods can be used for blending of fly ash with the coal feedstock of which four have been considered as representative of the range of options, namely:-

- Option A - Front end loader blending at the ground hopper.
- Option B - On belt blending using a separate conveyor to feed the fly ash onto the main conveyor stream of coal.
- Option C - Metered feed to individual mills by screw conveyor or similar to individual coal mill feeders.
- Option D - Stockpile blending.

.

Of the four options, Option A involves virtually no capital investment but offers the least control over the blend homogeneity. This option has the greatest risk of “slugs” of unblended fly ash or mineral additive reaching the boiler burners, which could lead to unacceptable operating conditions of flame instability and possible flame loss in the boiler. Also the blending regime is completely reliant on the operating procedures of the power station coal plant which in most cases is based on rapid transfer of bulk materials with no provision for accurate measurements of any type.

Thus Option A must be considered the least favoured way of blending fly ash or mineral addition on technical and boiler safe operation grounds and was not considered as an acceptable option for the full scale trials at Didcot power station.

Option B is based on the well proven practice of feeding a second stream of material on top of the material flow on a main reclaim or bunker supply conveyor. The practice has been used for a considerable time at a number of UK coal mines to feed a small stream of fine material such as washery fines onto a main load out conveyor carrying larger washed or untreated coal. The practice has also been used on a number of power stations as a way of feeding low cost fines or slurry onto the main conveyor belts as part of a fuel cost reduction exercise. More recently a number of power stations have used similar arrangements for combustion trials of a range of biomass materials.

The basic requirement for a 2000 MWe coal power station would be to install a small conveyor of up to 100 tonnes/hr capacity (typically a portable machine with self contained ground hopper) at right angles to the main conveyor. Existing coal plant front end loading equipment could then be used alongside normal coal handling operations to keep this hopper topped up. By control of the feed rate of this second conveyor it is possible to provide basic control over the blend proportions and avoid the risks of ash and additive “slugs” which were considered to be one of the major risks of Option A.

Option C is undoubtedly the most expensive option in terms of capital investment as it requires permanent fitting of new equipment to each of the coal mills on the power station and interfacing the new feeders with the existing boiler and mill control systems. This option would also require the provision of a central ash or mineral additive storage silo plus a pneumatic distribution system throughout the boiler house to the individual coal mill feeders. Whilst this option would provide the most accurate control over ash or additive flow and could be interlocked with mill feeders etc to eliminate the possibility of either “slugs” or accidental high addition rates, the cost is considered prohibitive and least favoured on economic grounds.

Option D involves the blending of fly ash with the coal on the stockpile prior to feeding the coal to the ground reclaim hopper. This option offers far better control of mixing than either Options A or B and is probably comparable with the results that would be achieved with the high capital cost Option C. Whilst this option has virtually no capital investment requirements, it has very high operating costs as it would involve double handling of all of the coal being supplied to the boilers and this would effectively increase fuel costs by approximately 50p/tonne. In addition it would not be possible to blend ash with any coal that was unloaded directly from trains to the bunkers.

Thus Option B or an equivalent system appears to be the best way to feed either fly ash or mineral additive to the main coal stream prior to combustion. In many cases, power stations already have either an existing side stream conveyor arrangement for biomass trials or from previous coal fine blending operations. For purposes of these studies, Option B has been used as the base case as it closely replicates the plant used at Didcot Power Station for the full-scale trials of ash re-firing

11.1.5 Financial data and assumptions for the economic assessment of ash re-firing

11.1.5.1 Capital Costs

Typical capital costs for Option B, a simple “belt blending” arrangement, have been assessed as follows:-

Building	£120k
Equipment	£180k
Installation	£80k
Total	£380k

If it were found necessary to install dust suppression equipment to the hopper, an additional capital investment in the order of £30k would be required

11.1.5.2 Operating Costs

For the base case, a coal cost of $70/tonne i.e. £38.04 /tonne at an exchange rate of $1.84 = £1 has been used with a typical annual coal consumption of 3,000,000 tonnes for a 2000MWe power station.

A 5% ash re-firing rate has been assumed for modelling the base case which is equivalent to an annual ash addition of 150,000 tonnes which equates to approximately 480 tonnes per day or 240 tonnes per shift.

Assuming a 5 year payback on a £380,000 capital investment and an annual plant maintenance cost of £5,000, the total costs of the new plant can be assessed as equivalent to an additional cost of £0.51/tonne of ash mixed.

Additional revenue costs of £400/day have been assumed for the provision of manpower and a front-end loader to handle the ash. This equates to an additional cost of £0.81/tonne of ash handled.

Ash sales values of £15 to £20/tonne for high quality ash into the cement replacement market can be anticipated and a return of between £2 and £10/tonne for sales into lower quality bulk markets is not unreasonable. For the base case, an average value of £5/tonne has been assumed

Ash disposal costs are approximately £2/tonne plus Landfill Tax which currently stands at £6.50/tonne but can be expected to rise in coming years to up to

£13/tonne. A total cost of £8.50/tonne has been used for ash disposal costs in the base case.

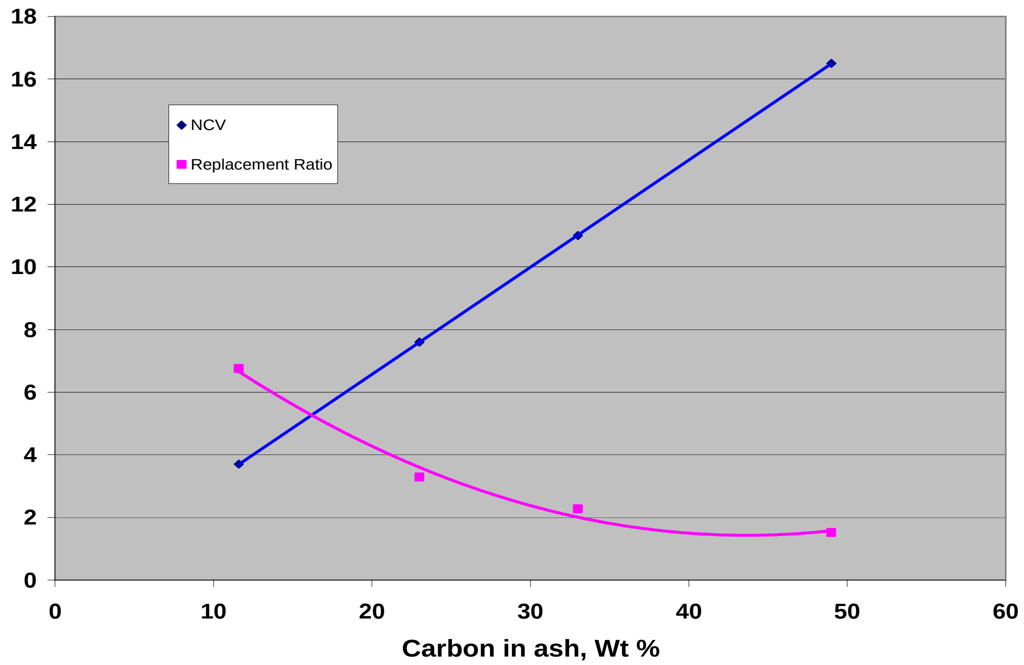
Additional works power consumption will be incurred due to higher milling power demands etc. These have been assessed for the base case as equivalent to a cost of 0.08p/tonne of coal or annual cost of £240,000.

The following estimates for the additional costs of maintenance and breakdown have been assumed for the base case

	p/tonne of coal	Annual cost (£)
Boiler	0.02	60,000
Precipitators	0.02	60,000
ID Fans	0.01	30,000
Ash handling plant	0.19	570,000
Bottom ash handling	0.10	300,000
Breakdown	0.21	630,000
Total	0.55	£1,650,000

11.1.5.3 Derivation of coal replacement effect data

Combustion of the carbon is ash during the re-firing process will result in a decrease in the rate of coal feed to the boiler for a given output. The following figure shows the replacement levels as a function of carbon in ash contained in the fly ash. Thus for a typical station ash with 10% carbon in ash the replacement level will be about 7 but for 50% carbon in ash level, this is reduced to just 1.5.



Replacement Ratio	NCV	CinA
6.76	3.7	11.6
3.29	7.6	23
2.27	11	33
1.52	16.5	49

11.1.6 Economic evaluation of ash re-firing

Based on the data and assumptions listed above in this section of the report, the economic evaluation for ash re-firing using Option B as the base case is:-

	Additional Costs	Benefits
Preparation of ash blend	£201,800	
Additional Maintenance	£1,650,000	
Additional work power	£240000	
Coal replacement		£1,141,300
Ash Sales		£ 750,000
Landfill avoidance		£1,275,000
Totals	£2,091,800	£3,166,304

Thus the overall annual net benefit for a 5% ash re-firing scheme for a 2000 MWe power station similar to that used in the full scale trial at Didcot is £1,074,504

Some indication of the sensitivity to changes in individual costs to the base case is shown below

- Ash value reduced to £3/tonne reduces the annual net benefit to £ 774,504.
- Ash value reduced to £3/tonne and Landfill Tax increased to £13/tonne increases the annual net benefit to £2,049,504
- An exchange rate move from £1=$1.84 to £1=$1.70 increases the net benefit to £1,168,494 per annum.
- Doubling the investment cost and its associated maintenance charges reduces the net overall benefit to £997,504per annum.
- Reducing the coal replacement effect by half reduces the overall net benefit to £504,852.
- Doubling the additional works power requirement reduces the annual net benefit to £854,504.

The economics of Option D, the stockpile blending method, were tested using the Option B base above as the basic model The costs of blend preparation rose from £201,800 to £1.575,000 per annum which would result in an overall annual loss of £298,695 in the base case

Applying the same sensitivities as applied to the base case for Option B, there seems to be no scenario in which stockpile blending, as described in Option D, would be economically viable.

Whilst Option C has not been subject of any detailed engineering or costing studies, it is believed that the additional capital investment and associated maintenance costs would be of such a magnitude as to cancel out any of the net financial benefits that were identified in the base case for Option B, (the belt blending method)

11.2 Techno economic evaluation of mineral additions

Unlike the fly ash re-firing scheme options discussed above, it will be necessary to consider both the technical and financial implications of setting up a completely new supply chain from source to the dosing point at the power station site for any of the mineral additive options.

Assuming a 40% overall load factor for a typical 2000 MWe coal fired power plant, the daily requirement for mineral additive would be in the order of 400 tonnes/day for a 5% dosing regime and 800 tonnes/day for a 10% dosing regime. If this were to be delivered by road to the power station site this would require between 30 and 60 additional vehicle movements per day.

In many cases this would exceed the available number of permitted vehicle movements to and from site in the existing station operating licence. Given the distance between the source of minerals such as calcite from most power stations it is probable that the only accepted form of delivery for mineral additives would be by rail. A precedent has already been set for rail delivery at many of the power stations that have been retrofitted with wet limestone gypsum flue gas desulphutisation equipment.

As stated above, the power industry already has experience in the supply of significant quantities of calcite, in the form of crushed limestone, to power stations equipped for flue gas desulphurisation (FGD). The limestone is supplied to site by rail in dedicated wagons in the form of 600 to 1000 tonne loads. The total on site capital costs of a typical handling facility for reception and storage of calcite is likely to be in the order of £5million, depending on factors such as existing rail track configurations, land availability and current plant layouts.

In addition any scheme would have to include a provision to cover the costs of the dedicated railway wagon fleet either by outright purchase by the power plant, lease charge or a charge element in the inclusive delivery cost which was been assumed as the base case in this study.

Unlike pfa, the minerals being considered for addition can be supplied in a wide range of sized material. It has been assumed for purposes of this study that the mineral is supplied in crushed form of typically 30mm and under sizing. It is believed that such material could be added to the coal feed stream in the same manner as pfa in Options A,B and D considered previously.

However if using a replication of Option C of the ash re-firing schemes for mineral additions, it would be necessary to either supply the mineral in a ground form or else to install milling facilities and powder silo storage on site to supply the individual mill feeders.

For the purposes of this study, it was been assumed that the material in Option C would be supplied to the power station site in powder form. Thus, it would be milled off site and then delivered in dry powder rail borne tankers to the power station, where a pneumatic handing system would be installed to unload the trains and also distribute the mineral to the mills.

Whilst no detailed engineering or costing studies have been undertaken for a full scale mineral addition scheme, an initial assessment of costs has been based on the data generated for the ash re-firing scheme as considered previously.

Whilst there was no purchase cost involved in the ash re-firing scheme, it is estimated that the typical delivered cost of calcite in the form of crushed limestone would be in the order of £50/tonne. This results in an annual cost of around £6 million for a 2000MWe power station such as Didcot. As a check on cost estimates, bulk powdered lime as used in the dry FGD process is currently being costed at £85/tonne delivered to a typical UK power station site

The annual costs of storing and preparation of a mineral addition blend are likely to be of the order of £1.5 million greater than for ash refiring. Additional maintenance costs will probably be of the same order as for ash re-firing, i.e. £1.65 million per annum and works power costs are expected to double to approximately £0.5 million per year. Thus the total annual costs of a 5% calcite mineral addition scheme would be £9.65 million for a 2000 MWe power station for an Option B type using belt blending.

In terms of savings, it would not be unreasonable to anticipate the same level of improved revenue from ash sales accrued from increased sales of furnace bottom ash and a corresponding decrease in ash disposal to landfill. There would of course be no savings in terms of coal replacement. Thus, the easily definable net savings would amount to approximately £2 million per annum. However an additional benefit would be available in terms of the ability to avoid the need to de-rate the plant output at times of high particulate emission.

The financial benefit from this exercise varies widely from power station to power station. Also there may be significant differences depending on whether the plant is operating as a single entity as far as supply to the Grid is concerned or it is operating as part of a portfolio of plant in terms of the impacts of plant derates. However the indication is that if by mineral addition it were possible to avoid annual de-rate losses etc by more than £2 million for a 500 MWe unit then it may well prove economically viable.

The breakeven figure would be much lower if mineral addition were only undertaken during periods when high dust emissions were anticipated. Under this sort of regime (say for 25% of the operating time), the overall costs for a 2000Mwe power station could be reduced to approximately £3.5 million with savings reduced proportionally to £0.5 million. Under this selective operating scenario, it would need less than £0.9 million savings per 500MWe in avoided de-rates to make the scheme economically viable.

As in the case of the ash re-firing schemes discussed earlier in this section, the economic case for both Options C and D for a mineral addition project would be far less attractive than for the more simple Option B. Thus Options C and D are both are considered not to be financially viable. A ground hopper blending scheme for mineral additives, such as the ash scheme Option A would be technically unacceptable.

In the case of the feldspar mineral additive option, there are no existing supply and handling systems at power stations for the bulk supply of feldspar. Therefore it can only be reasonable to assume that equipment for supply and handling feldspar will be equal to or more expensive than for calcite. Based on the above, the break even point for feldspar mineral addition would therefore be greater than the £2 million per annum on a 500 MWe unit as considered above for addition of calcite.

12 Conclusions

This section contains the key conclusions and findings of the project and a summary of plant operational aspects which could act as set of guidelines for the re-firing of fly ash and mineral additions for others who may be considering adopting these concepts.

- This project has demonstrated that there are no technical showstoppers to either ash re-firing or mineral additions at levels of up to 10% by weight on a 500 MWe generating unit.
- A 5% ash re-firing scheme on a 500MWe unit appears to be both technically and financially viable. The economics appear to be reasonably robust to changes in ash sales values and taxation, increases in capital costs, as well as reduced value of coal replacement and adverse effects of the £/$US exchange rate.
- There is no need to use a high quality blending regime for an ash re-firing scheme and a simple belt blending process is adequate for a 5% re-firing rate.
- Whilst the use of higher quality ash blending systems such as stockpile blending or a metered supply to individual coal mills is technically feasible, these options do not appear financially viable.
- Whilst mineral additions in the form of calcite and albite(feldspar) appear technically viable, the financial case was not proven. However, there may be circumstances for specific units where the additional costs for mineral addition may be offset by the reduced financial impact of derating the plant output due to high dust emission levels.

- Ash addition rates over 10% had a significant effect on NOx levels and it was necessary to consider plant derate due to limitations in installed coal milling capacity
- Plant performance at 5% ash re-firing rate was comparable to coal only operations. SOx, NOx and CO emission levels were similar to the coal only base line operation, whilst dust emission levels were found to be slightly higher.
- SOx, NOx and CO emission were all found to be higher than the coal base line for ash re-firing rates of 10%
- At the pilot scale trials on the CTF, poor flame conditions were encountered at relatively high levels of ash addition but the flame itself was still found to be stable.
- No operational problems were encountered at either 5 or 10% ash re-firing levels during the full-scale trials at Didcot power station.
- Albite (feldspar) produced the highest level of increased deposition at the laboratory scale trials and calcite had the greatest effect on the degree of sintering.
- Significant increases in deposition rate were seen for both calcite and feldspar under both oxidising and reducing conditions on the CTF during the mineral addition trials
- The pilot-scale mineral addition trials undertaken on the CTF showed that temperature did not have a significant effect on either the deposition rate or the deposit type.

13. List of Participants

Organisation	Personnel involved	Contact details
RWE Npower plc	Dr G.S. Riley Dr T Beeley	RWE npower plc Windmill Hill Business Park Whitehill Way Swindon SN5 6PB Tel 01 793 896298 Fax 01 793 896251 E-mail gerry.riley @ rwenpower.com
Imperial College London	Prof J Williamson Mr F Wigley	Department of Materials Imperial College London South Kensington London SW7 2AZ Tel 020 7594 6747 Fax 020 7594 6748 E-mail: jim.williamson @ imperial.ac.uk
The University of Sheffield	Dr N V Russell Mr M Zandi	The University of Sheffield Dept of Chemical and Process Engineering Mappin Street Sheffield S1 3JD Tel 0114 222 7521 Fax 0114 222 7501 E-mail n.russell @ sheffield.ac.uk
UK Coal Ltd (formerly RJB Mining (UK) Ltd	Mr B Ricketts	UK Coal Ltd Harworth Park Blyth Road Harworth Doncaster DN11 8DB Tel 01 302 755198 Fax 01 302 746552 E-mail bricketts @ ukcoal.co.uk
TXU Europe Ltd	Mr P R Cooper	Precol Associates Ltd 52 Kelvedon Drive Rushmere St Andrew Ipswich IP4 5LQ Tel 01 473 727997 Fax 01 473 727997 E-mail precol @ hotmail.com