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COMBUSTION CHARACTERISTICS OF LOW QUALITY BATTLE COALS

Mineral matter transformations

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KEYWORDS

pulverised coal combustion, blend, mineral matter, ash, slagging, fouling, index, prediction

PREFACE

The results of the work conducted within the scope of this project have been disseminated through three international conference papers, as referenced below:

Paper 1
Korbee, R., Eenkhoorn, S., Heere, P.G.Th. and Kiel, J.H.A., "Low quality coals and blending: ash formation and deposition", *Proceedings of the 10th International Conference on Coal Science*, Taiyuan, P.R. China, September 12-17, 1999.

Paper 2
Korbee, R., Eenkhoorn, S., Heere, P.G.Th., Visser, H.J.M. and Kiel, J.H.A., "Low quality coals and blending: opportunities for mitigation of fouling", to be published in the final *Proceedings of the UEF Conference Mitigation of Heat Exchanger Fouling and its Economic and Environmental Implications*, Banff, Canada, July 11-16, 1999.

Paper 3
Korbee, R., Eenkhoorn, S., Heere, P.G.Th. and Kiel, J.H.A., "Low quality coals and blending: lab-scale evaluation of ash behaviour and leaching properties", *Proceedings of the 5th International Conference on Technologies and Combustion for a Clean Environment*, Lisbon, Portugal, July 12-15, 1999, Vol. 2, pp. 1213-1220; also to be published in a special edition of the International Journal Environmental Combustion Technologies.

These three papers make up the body of this report and have been included as such in the Results section. The conference papers have been submitted in prescribed formats which usually include a limitation with respect to the length of the paper. In this report, the information given in the papers is made more explicit and is supplemented by data that had up till this point been left out.

ABSTRACT

This report describes the results of an experimental study on the ash behaviour of selected low-quality battle coals for pf-fired boilers. The study was run parallel to a test program supported within the International Energy Agency Coal Combustion Sciences Program annex 2 part 4 addressing the combustion behaviour of these coals.

A suite of coals and blends, varying in rank from medium-volatile bituminous to sub-bituminous, was selected in consultation with the Dutch electricity producers and extensively analysed, focusing on ash composition. Relatively high levels of the elements Ca, Mg, Fe, Na and K were found in these coals. The speciation of the inorganic constituents in terms of mineral composition and size distribution was determined by means of Computer Controlled Scanning Electron Microscopy (CCSEM).

Single coals as well as binary blends were fired in a 2.5 MW_{th} boiler furnace simulator, and ash and deposit samples were collected for off-line analysis and evaluation. The results have been expressed and ranked in terms of slagging and fouling propensity for each coal, and have been compared with the outcome of a considerable number of commonly used predictive ash deposition indices. Observations of significant slagging or fouling were in many cases related to the presence of alkali and alkaline earth metals, which were often ill-predicted due to the occurrence of mineral interactions.

Selected tests were performed in a laboratory-scale combustion simulator under well-defined (low-NO_x) conditions to elaborate further on the prevailing ash deposition mechanisms. The observed mechanisms were generalised into three classes in order to allow a certain extension of the conclusions towards new, similar fuels. From these mechanisms guidelines were derived for coal blending aiming to reduce ash deposition problems.

The methodology of lab-scale fuel testing to evaluate in advance their potential to induce or enhance typical ash-related problems - here slagging and fouling - is currently being extended to an integral assessment of ash behaviour and ash quality for utilisation options. This report includes the initial development of a procedure involving lab-scale fly ash production and miniaturised leaching testing for advance evaluation of fly ash quality.

ACKNOWLEDGEMENT

The authors kindly acknowledge the help of the EPZ personnel in a prompt provision of test fuels and fly ash samples, and the assistance by the IFRF personnel during deposit sampling.

CONTENTS

1. INTRODUCTION

The Netherlands is one of the largest coal importing countries in Europe. With the liberation of the European electricity market, there is a strong incentive for minimising the cost of electricity production.

One option is to import coals, so-called battle coals, which are offered at a lower price than the standard range of high volatile bituminous coals. In general, these coals are of a lower quality while only limited information is available on their combustion characteristics. Often lower quality here means lower heating value, higher sulphur content or higher ash content. However, also subbituminous coals may be considered low quality coals, since their specifications are outside the standard ranges for most coal-fired power stations.

In several coal-fired power stations in the Netherlands, but also abroad, trial runs have been conducted to get an impression of the applicability of some of these battle coals. Generally, in these trials a battle coal is co-fired with a standard coal and the battle coal fraction is gradually increased. Major questions to be answered concern ignition, flame stability, NO_x-formation, burnout, slagging and fouling, and ash quality.

Although these full-scale trials yield valuable information for the specific battle coals tested, it is a rather expensive way to determine whether a certain battle coal can be used. Therefore, a project was initiated to investigate the possibilities for characterising the combustion behaviour of battle coals by a combination of semi-industrial and laboratory-scale testing.

This was implemented by two parallel, interrelated projects conducted by IFRF and ECN respectively. The results of the ECN project are described in the current report. The IFRF project entitled "Evaluation of the combustion characteristics of low quality, low price battle coals and blends of battle coals and standard coals" was conducted in the framework of the International Energy Agency (IEA) Coal Combustion Sciences (CCS) Program annex 2 part 4, and is reported in [1]. The main activities within the IFRF project were:

- to conduct a 8-10 days experimental campaign at the scale of 2.5 MW_{th} for the determination of flame characteristics, ignition, stability and NO_x-reduction potential for a range of battle coals and blends;
- to take slag/deposit samples during this campaign for investigation of the slagging/fouling potential;
- to characterise the combustion behaviour of the battle coals and coal blends at laboratory scale in an Isothermal Plug Flow Reactor (IPFR) by determining volatile matter release, fate of fuel nitrogen, char burnout and (bulk) ash composition.

2. OBJECTIVE AND APPROACH

Brief description

The general objective is to determine combustion characteristics of a range of low quality battle coals and advance the knowledge base for the prediction of their combustion behaviour at full scale. In the project, emphasis is placed on the characterisation and prediction of ash formation and possible ash deposition problems.

Detailed description

The project addresses the issue of firing a range of coals, so-called battle coals, which are offered at a lower price than the standard range of high volatile bituminous coals fired currently in the Netherlands. In general, these battle coals are of a lower quality and their combustion characteristics are less well-known. The project is aimed at advancing the knowledge base for the prediction of the combustion behaviour of these coals in full scale installations through:

- investigation of ash formation and ash deposition in the IFRF boiler furnace simulator and (if available) in full-scale plants for a range of battle coals and battle coal / standard coal blends;
- combustion characterisation for this range of battle coals and blends using ECN's Atmospheric Entrained Flow Gasification and Combustion simulator (AEFGC-simulator), with the emphasis on ash formation and ash deposition;
- interpretation of the experimental results and translation into predictions of the slagging/fouling potential of the tested battle coals and blends in full-scale applications.

In concordance with the above objectives, the following more specific tasks were defined:

Task 1. To evaluate existing information and select test coals in consultation with electricity producers;

Task 2. To make detailed analyses of coal, ash and deposit samples from full-scale units, provided that these samples could be made available by electricity producers;

Task 3. To sample coals, ashes and deposits during the 8-10 days campaign, to be conducted by the IFRF, and to conduct detailed sample analysis using a.o. Scanning Electron Microscopy;

Task 4. To conduct lab-scale characterisation studies in the AEFGC-simulator, emphasising the characterisation of ash and deposit formation for a range of battle coals and blends; in addition to information on the slagging and fouling potential of the selected battle coals, part of this task would be dedicated to a more general characterisation of mineral matter transformations;

Task 5. To predict the slagging/fouling potential of the tested battle coals in full-scale applications: based on a detailed analysis of the data collected in tasks 1, 2, 3 and 4, considerations would be given concerning the mechanisms for the mineral matter transformations observed and the slagging/fouling potential of the selected battle coals in full-scale applications.

3. RESULTS

3.1 Task 1. Existing information and selection of coals

In this task the everyday practice of Dutch electricity producers with respect to coal supply and utilisation is summarised. Discussions were organised with the power company EPZ and with Coal Supply Dutch Utilities / Dutch Fly Ash Corporation to provide a clearer understanding of the meaning of the term battle coal, and to provide a baseline coal quality with which the selected test coals could be compared. The discussions were also intended to help direct and optimise the research programme.

The Netherlands is one of the major coal importing countries in Europe. In 1998, coal-fired pf boilers covered 42% of the national public electricity production (Energie Verslag Nederland, 1999). All coal is imported, primarily from South-Africa, Colombia, Indonesia, Australia, Poland and the United States. With the liberalisation of the European electricity market, the urge to minimise the cost of electricity production is increasingly leading to the use of low price coals. As a consequence, the number of countries and mines from which coals are obtained increased significantly in the last decade. The price is related to the quality (primarily lower heating value) of the coal, and a number of parameters which depend on the current market situation, such as availability and demand. All coal is bought, imported and sold by a central company: Coal Supply Dutch Utilities / Dutch Fly Ash Corporation. This company is responsible for fuel preparation and blending to the individual requirements of Dutch electricity producers and for the sales and (when necessary) upgrading of the fly ash produced.

The low price coals are often - but not always - of a lower quality with one or more properties like heating value, ash content, sulphur content, volatile matter content or grindability lying outside the normal operating window. Coal blending is applied to counterbalance the deviating properties of individual coals. The blending is performed at dedicated, near-sea blending stations, from which the blends are then shipped or conveyed by belts to the power stations. Extensive experience with operation on blends involving lower quality coals has also led to a relaxation of the requirements for some of the averaged properties of the blend. For example, the average heating value (LHV) of the blends dropped from around 30 MJ/kg to 24 MJ/kg (Moret, 1997). Partly, the behaviour or properties of a blend can be calculated in advance, which explains a large part of the successes up till now. The calculable part concerns the fuel data that can be considered additive: a property that allows a simple yet reliable estimation of e.g. the calorific input, the production of sulphur and nitrogen oxides, the throughput of ash, or the bulk composition of the fly ash produced. Non-additive properties, however, such as the behaviour and the properties of the ash that is produced, remain difficult to predict for a given blend. In practice, experience and rules of thumb are important factors in securing trouble-free operation. Ongoing developments are also reported to adjust and calibrate the EPRI Coal Quality Impact Model (CQIM) to the Dutch situation. A model as CQIM is considered promising for evaluating complex matters such as the impact of firing certain coal blends on the plant's maintenance cost (increased costs can be caused e.g. by more frequent outages as a result of underestimated ash deposition or tube corrosion).

In order to evaluate (the behaviour of) out-of-spec coals, it is necessary to know the current baseline coal quality. Table 1 gives the required ranges for the most important properties, A) in case of a basic evaluation including only properties such as heating value and the content of sulphur, volatile matter and ash, and B) in case of a more detailed specification which also includes the ash composition.

Table 1. *Required approximate coal (blend) specifications for pulverised fuel boilers.*

Property			**Required value** *A. basic evaluation* (data from Moret, 1997)	*B. detailed evaluation* (from Skorupska, 1993)
Cal. value	LHV	MJ/kg	≥24	
Proximate	moisture	% ar	≤15	
	ash	% db	avg. 15	
	volatile matter	% db	25-45	
Ultimate	carbon	% daf		
	hydrogen	% daf		
	nitrogen	% daf		
	sulphur	% daf	0-1.5	
	ox. (diff)	% daf		
Ash	SiO_2	% db		45-75
	Al_2O_3	% db		15-35
	Fe_2O_3	% db		1-12
	CaO	% db		0.1-2.3
	MgO	% db		0.2-1.4
	Na_2O	% db		0.1-0.9
	K_2O	% db		0.8-2.6
	TiO_2	% db		0.4-2.2
	P_2O_5	% db		0.1-1.5
	SO_3	% db		0.1-1.6

The selection of coals has been accomplished in two ways, namely through the IFRF (in the framework of their IEA-CCS 2/4 programme) and directly in consultation with EPZ. The analyses of the selected coals are presented and discussed in the next section of this report.

3.2 Task 2. Coal and sample analysis

In this task, all selected coals have been analysed using common methods for the determination of moisture, volatile matter and ash (together proximate analysis), content of C, H, N and O (together ultimate analysis), and inorganic elemental composition (Si, Al, Fe, Ca, Mg, Na, K, Ti, P, S and a number of minor constituents). The resulting data are presented in Appendix 1.

As the elemental analysis does not give any information on the nature of the ash, the coals have also been analysed for their mineral matter content using Computer Controlled Scanning Electron Microscopy (CCSEM). This analysis provides a complete overview of the weight percentage of (up to 33 defined) mineral entities in the fuel, and their distribution over 8 size groups in the range 1-250 μm. For each coal, the mineral distribution is listed in Appendix 2.

The samples provided by EPZ included two coal blends and the 6 underlying (parent) coals, as well as fly ash which is routinely sampled from the ESP ash collectors. Full-scale ash deposit sampling is not a part of day-to-day operating procedures, and was not defined as a task for this project; therefore no full-scale deposits have been investigated.

3.3 Tasks 3 + 4 + 5. Experimental deposit formation studies and full-scale predictions

The specific goals of this project were 1) to obtain experimental information on the ash behaviour of the selected battle coals, 2) to evaluate this information in terms of slagging/fouling propensity of the coals in pulverised coal boilers, and 3) to generalise the information obtained for application to other coals and blends. For this, the approach was adopted to perform experimental tests on two different scales, to collect and analyse ash particles and ash deposits from these tests and to relate the results to the fuel mineral compositions as determined under Task 2. This would then allow to develop mechanistic knowledge on the transformation of various mineral species with a more general applicability.

This chapter starts with a short introduction on the experimental work performed in the IFRF furnace and in the ECN lab-scale combustion simulator, the subsequent analysis of the ash and deposit samples and the evaluation thereof to obtain useful information on the quality of each tested coal and blend with respect to their slagging and fouling propensity. Following this introduction, the conference papers which have been introduced earlier are printed in full.

IFRF furnace deposit sampling campaign
In this campaign ash deposit samples were obtained from a semi-industrial coal-fired furnace, primarily to provide a (semi-)quantitative comparison of the test coals' ash behaviour in terms of slagging and fouling propensity.

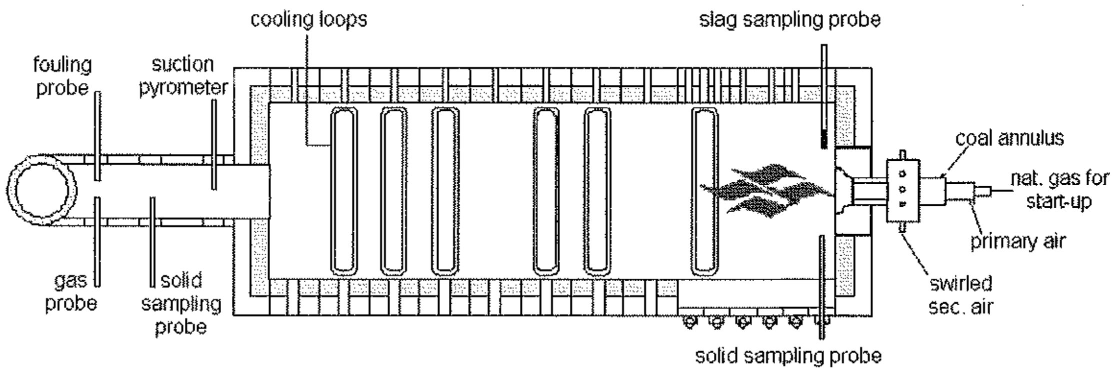

Figure 1. *Schematic of the 2.5 MW$_{th}$ furnace configured as a boiler furnace simulator (Haas et al., 1999)*

Air-cooled deposit probes were equipped with two (75 mm length, 31 mm outer diameter) tubes made of stainless steel (type 316) and alumina, respectively. The two different substrates served to simulate both well-cooled (metal) and non-cooled (ceramic) boiler surfaces. For each fuel to be tested, one probe (slag sampling probe in Figure 1) was located in the recirculation zone of the burner to simulate near-burner slagging at a gas temperature of 1300-1400 °C and another (fouling probe in Figure 1) was located in the flue gas exit channel to simulate fouling at a gas temperature of 1100-1200 °C.
The probes were brought into position once a stable combustion process had been established, and then left in position for one hour. The probes were then retracted from the furnace and allowed to cool as gradually as possible. They were subsequently sprayed for conservation, photographed, weighed and transported to ECN for further analysis.
Ash samples were collected (solid sampling probes in Figure 1) simultaneously from a location opposite to the deposit probe, inherently assuming an axi-symmetric combustion profile. Further details on the experimental setup are given by Haas *et al.* (1999).

The campaign at the IFRF was scheduled in such a way that, each day, one fuel was tested, being either a single coal or a blend of two; the blend ratio was set to achieve a fuel input equivalent to a thermal input of 2.25 MW. To compose the binary blends, coals were selected which had properties that would not allow them to be burnt as a single fuel. Such an approach resembles - in a simple but basically similar manner - the way blending is performed in practice. Following this procedure, the high ash, high sulphur Spitsbergen coal was combined with the low ash, low sulphur Envirocoal, and the high sulphur content of the Egyptian coal was also counterbalanced by the low sulphur Envirocoal. Other blends were fired as such for practical reasons.

ECN lab-scale combustion simulator experiments

ECN's lab-scale combustion simulator (Figure 2) was used to provide more mechanistic ash-related information, to be used for the further interpretation of the observations made from the semi-industrial scale tests and to deduce relevant mechanisms of mineral matter transformations. The experiments were carried out under well-known conditions (see Figure 2, right part), established to simulate the conditions prevailing in a full-scale pf boiler equipped with low-NO_x burners.

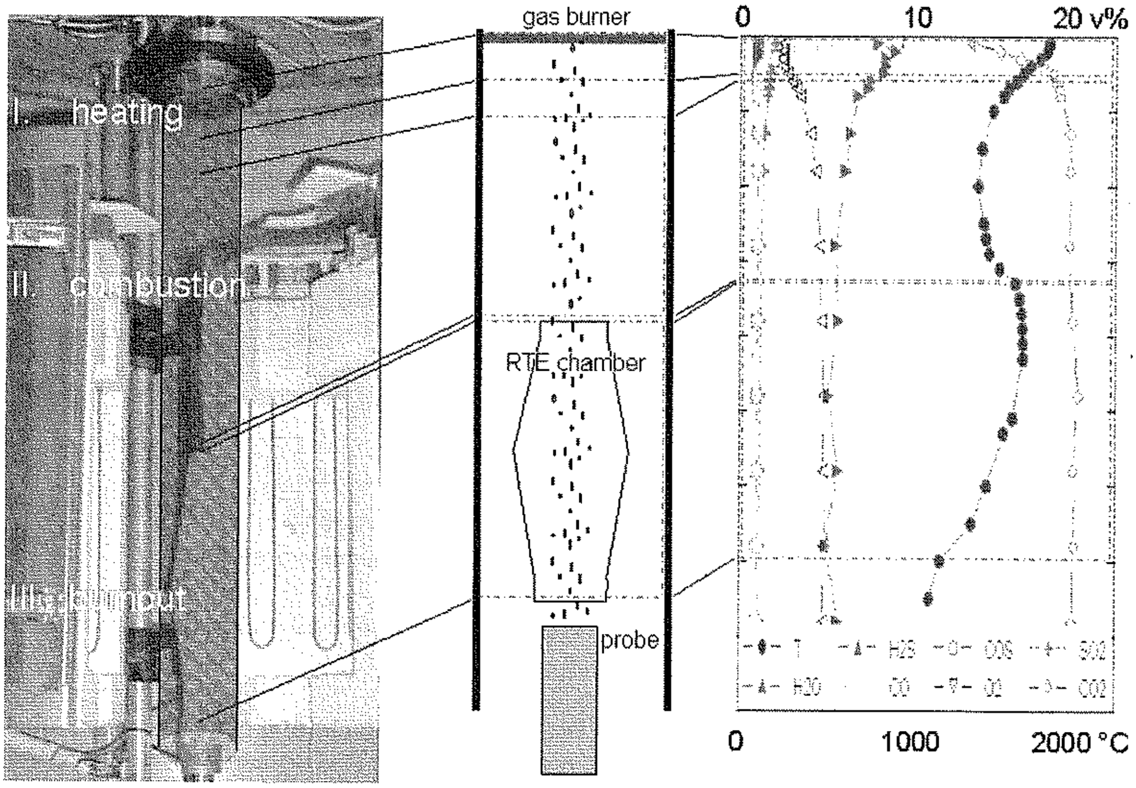

Figure 2. *Lab-scale combustion simulator; left: installation with flat-flame gas burner, reactor tube (illustrated) and residence time extension (RTE) chamber; middle: schematic of particle flow through heating, combustion and burnout zones; right: axial temperature and gas concentration profiles*

The reaction conditions in the combustion simulator are created by a multi-stage flat flame gas burner in such a way that, initially, the fuel particles which are fed through the gas flame experience an oxygen-deficient (reducing) environment and are then combusted in a zone with approximately 4% excess oxygen. The gas and particle flows are in the laminar regime and are thus well-controlled and well-known.

Probes were inserted into the simulator to collect particles and deposits at different residence times. The majority of the deposits was collected in the near-burner area to study slagging under reducing high-temperature (1500 °C) conditions. Small alumina plates were used to simulate a

non-cooled surface. Particles were collected at low residence times of approximately 25 ms (near-burner area) and high residence times up to 2000 ms (flue gas exit area). After sampling, both particle and deposit samples were stored in their entirety for further analysis.
A more detailed description of the combustion simulator equipment and operating procedures is given in one of the conference papers, "Low Quality Coals and Blending: Lab-Scale Evaluation of Ash Behaviour and Leaching Properties".

Experiments were carried out with selected coals and blends, primarily Genesee, Envirocoal, Egyptian coal, Spitsbergen, Douglas Premium, Anker Diversen and an industrial blend of four coals.

Analysis and evaluation of samples
The deposit samples from the 2.5 MW_{th} furnace were too large to be mounted in the Scanning Electron Microscope and therefore had to be embedded in an epodye fluorescent resin and subsequently cut to yield smaller cross-sections. These cross-sections were then polished and sputtered with carbon for examination by means of SEM-EDX. The deposit samples from the lab-scale simulator were much smaller in size and could be examined directly (without prior embedding) as well. From the SEM-EDX analyses, information was obtained with respect to the thickness, orientation and composition of the ash layer on the deposition surfaces. Relevant mechanistic information with respect to ash behaviour and deposit formation was derived, and is presented and discussed in the three conference papers. An overview of properties as analysed for the semi-industrial deposit samples is given in Appendix 3. The table in this appendix comprises both quantitative and qualitative (visual) information on the deposits which are considered relevant to its evaluation.

Results described in three conference papers; an introduction
The results obtained from this study have been presented in three papers. The experimental results have been translated into slagging and fouling propensities and are described in the first paper, "Low Quality Coals and Blending: Ash Formation and Deposition". The coals, including the tested blends, have thus been "ranked" in terms of their ash deposition potential. Predictive calculations were carried out using a number of commonly applied indices; Appendix 4 explains the use of these indices and Appendix 5 lists the calculated results for the coals used in this study.

The second paper is entitled "Low Quality Coals and Blending: Opportunities for Mitigation of Fouling". In the context of the conference the paper was prepared for, the term fouling here includes slagging. It deduces generalised mechanisms of mineral matter transformation and applies this information to coal blending as a tool to reduce the risk of problematic ash deposition.

The third and last paper, "Low Quality Coals and Blending: Lab-Scale Evaluation of Ash Behaviour and Leaching Properties", discusses the outlook for cheap lab-scale testing of coals for an integral assessment of their ash behaviour *and* quality in pulverised coal boilers.

PAPER 1. "Low Quality Coals and Blending: Ash Formation and Deposition"

R. Korbee, S. Eenkhoorn, P.G.Th. Heere and J.H.A. Kiel

Proceedings of the 10th International Conference on Coal Science, Taiyuan, P.R. China, September 12-17, 1999.

ABSTRACT

Several low-price, low-quality coals were evaluated with respect to their ash deposition propensity in pulverised coal-fired boilers. In general, the coals considered are lower rank coals with a relatively high content of Fe, Ca, Mg, Na and K. Deposition tests with single coals and blends were performed in a lab-scale facility and in a semi-industrial scale furnace. The results were compared to indices for predicting coal slagging and fouling propensity. The predictions were found to be inadequate especially where mineral interactions occurred. Coal mineral analysis and standard lab-scale tests are suggested for a more accurate prediction.

Keywords: Coal ash, slagging, fouling, experimental, predictive indices.

INTRODUCTION

In the Netherlands, electricity production cost minimisation stimulates the use of low-price import coals. As a consequence, the Dutch fuel envelope has been considerably extended, including many new, low-quality coals. Properties like heating value and ash, sulphur, moisture or volatile matter content often lie outside the normal operating window. Coal blending is applied as a means to counterbalance the deviating properties. With models like the EPRI Coal Quality Impact Model (CQIM) plant operating data such as heat input, production of sulphur and nitrogen oxides, ash throughput, or fly ash bulk composition can be estimated reliably using weight-averaged blend properties. In CQIM, the expected ash behaviour can be evaluated using a selection of indices. The indices are weighted by the user, according to experience with a specific boiler and specific fuels.

An experimental study was undertaken to evaluate the slagging and fouling propensity for a suite of coals and blends. In this paper, the observed ash deposition is compared with predictive indices. Two other aspects of the study, *viz.*, blending as a tool for the mitigation of deposition problems and the advance evaluation of ash behaviour and fly ash quality, are discussed elsewhere [1,2].

FUEL ANALYSIS

Table 1 compares the properties of the test coals with a specification coal "X". According to Skorupska [4], a basic specification includes only properties such as the heating value and the content of sulphur, volatile matter and ash; values listed represent the ones used by the Dutch institution for coal supply and fly ash utilisation [3]. In more detailed specifications, the ash composition is also included; here, a range of commonly quoted values is presented [4]. In general, the coals considered in this study are lower rank coals with a relatively high content of Fe, Ca, Mg, Na and K.

Table 1. *Comparative analyses of specification coal "X" and test coals*

Name (country)		**Coal "X"**	Spitsbergen (Russia)	Econ-Zaf (S.-Africa)	Polish blend (Poland)	Egyptian (Egypt)	Envirocoal (Indonesia)	Genesee (Canada)
Ash	% db	**avg. 15**	24.4	17.4	16.6	8.4	2.0	28.4
Volatile matter	% db	**25-45**	29.5	23.5	28.6	46.3	47.0	27.0
Sulphur	% daf	**0-1.5**	3.0	0.8	0.9	2.7	0.3	0.3
SiO_2	% db	**45-75**	41.0	45.8	46.6	22.2	37.8	61.4
Al_2O_3	% db	**15-35**	20.5	32.0	26.1	12.0	23.3	21.8
Fe_2O_3	% db	**1-12**	9.0	5.6	9.0	**18.4**	12.4	5.0
CaO	% db	**0.1-2.3**	**5.2**	**8.0**	**5.0**	***2.9***	**11.0**	**4.7**
MgO	% db	**0.2-1.4**	1.4	1.2	**3.5**	0.6	**4.2**	1.5
Na_2O	% db	**0.1-0.9**	0.9	0.2	0.6	0.3	**3.9**	**2.6**
K_2O	% db	**0.8-2.6**	2.1	0.7	***2.9***	0.5	1.8	2.4
TiO_2	% db	**0.4-2.2**	0.7	1.3	0.9	1.3	0.9	0.6
P_2O_5	% db	**0.1-1.5**	1.2	1.2	0.5	0.2	0.2	0.1
SO_3	% db	**0.1-1.6**	17.9	4.1	4.9	41.7	4.7	0.0

xx : 10-30 % higher than upper limit for specification coal "X"
xx : >30% higher than upper limit for specification coal "X"

More detailed analytical data (including CCSEM) can be found elsewhere [1,2,5].

PREDICTIVE INDICES

For all coals, a large number of indices which are commonly used to predict slagging or fouling propensity, were calculated. While the majority of the indices is based on the so-called base-acid ratio which includes all eight major ash elements, some are more advanced and specificly related to the (anticipated) behaviour of certain elements. For the blends the indices were calculated based on the weigth-averaged ash content. A detailed overview of the calculations can be found in [5].

DEPOSITION TESTS

An experimental programme was carried out to assess the ash behaviour of coals and blends. Tests were performed in ECN's laboratory-scale combustion simulator [6] and in the single-burner semi-industrial furnace at the IFRF in IJmuiden, the Netherlands [7]. In the semi-industrial furnace, ash and deposits were sampled near the burner and at the flue gas exit, and analysed by means of SEM-EDX. A detailed description of the programme is given in [5].

EXPERIMENTAL RESULTS

The slagging and fouling propensity of each coal/blend was qualified in the range from low to very severe. The qualification was based on the amount of deposit formed and the likeliness that the deposit would be removed by sootblowing. By the inspection (SEM) of a deposit cross-section, the degree of particle sintering was obtained, which was related to the removability of the deposit according to Raask [8]. Table 2 summarises the results.

Table 2. *Experimental evaluation of coal quality in terms of ash deposition behaviour*

Coal	Blend (mass ratio)	Slagging	Fouling
Econ-Zaf		low-medium	low
	Ec-Eg (60/40)	medium	low
Egyptian		low-medium	low
	Eg-En (61/39)	high	low
Envirocoal		low	low
	En-Sp (36/64)	severe	medium-high
Spitsbergen		very severe	severe
Polish blend		high	low
Genesee		very severe	high-severe

Quantitatively, the high-ash coals Spitsbergen and Genesee show the most severe deposition problems, both in the near-burner area (slagging) and at the flue gas exit (fouling). Moreover, deposit sintering (Genesee) and fusion (Spitsbergen) significantly reduces the potential of sootblowing to remove such deposits. With the Polish coal, near-burner deposits were formed at a lower rate, but similarly fused. The Egyptian coal showed a low-medium slagging propensity. However, due to its high pyrite content it can initiate slag formation. Although Envirocoal is an extremely low-ash coal, in combination with the Egyptian coal, it results in the formation of low-melting ash particles, which would otherwise have remained solid at the prevailing temperatures. The deposits resulting from firing a blend of Envirocoal and the Egyptian coal were highly fused and enriched (relative to Egyptian coal deposits) in calcium and sodium. A mechanistic evaluation of the deposit formation can be found elsewhere [1,5].

COMPARISON OF OBSERVATIONS AND PREDICTIONS

The present study shows that the slagging, and in some cases also the fouling propensity of the coals tested could not be predicted reliably using common indices. This was found for single coals and blends. In nearly all cases, ill-predicted deposition behaviour was a result of interaction between inorganic species. Fused or highly sintered near-burner deposit formation occurred due to either initiation by pyrite, or fluxing of clays by calcium or iron. Fouling was related to clays, enriched in potassium or sodium, and to the formation of alkali sulfates [1]. Typically, indices such as used in EPRI's CQIM do not account for the behaviour of specific mineral *species*, as they are rather based on the alleged bulk behaviour of specific *elements*.

CONCLUSION

Several low-quality coals and blends were evaluated with respect to their ash deposition behaviour. The elements Fe, Ca, Mg, Na and K play an important role in the formation of highly sintered or fused deposits which cannot be (easily) removed by sootblowing. For many of the coals/blends, the occurrence of such deposits cannot be well predicted by commonly used indices, since they rely on bulk ash analyses. The actual involvement of certain elements in ash deposition strongly depends on their speciation, the variety of which increases with the number of coals in a blend. Therefore, mineral composition (CCSEM) analysis, together with a standard lab-scale test yielding strategic data in the form of a coal ash behaviour "fingerprint" are recommended for a more accurate prediction [2,5].

ACKNOWLEDGEMENT

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PAPER 2. "Low Quality Coals and Blending: Opportunities for Mitigation of Fouling"

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ABSTRACT

Several out-of-spec coals have been studied with respect to their ash behaviour in relation to ash deposition problems in pulverised coal-fired boilers. The coals have been analysed in detail and show increased concentrations of Ca, Fe, Mg, Na or K. Experimental deposition tests with single coals and blends have been performed in a lab-scale facility and in a semi-industrial scale furnace. The results have been evaluated especially with respect to interactions between inorganic species from different coals. Observed mechanisms for the formation of sticky ash particles, responsible for the initiation of ash deposition, are used to derive blending guidelines for the coals.

Keywords: Coal blending, fouling, slagging, experimental, mechanism.

INTRODUCTION

The Netherlands is one of the major coal importing countries in Europe. With the liberation of the European electricity market, the urge to minimise the cost of electricity production is increasingly leading to the use of low price, low quality coals in pf fired power stations. For these coals, often one or more of the main characteristics like heating value, ash, sulphur, moisture, or volatile matter content lies outside the normal operating window. Coal blending is applied as a means to counterbalance the deviating properties. Blending in the Netherlands is performed at dedicated, near-sea blending stations, from which the blends are then shipped by river to the power stations. The blending procedure is largely based on the additivity of coal properties, such as heating value, sulphur, nitrogen and ash content, and ash (elemental) composition. This allows a simple yet reliable estimation of e.g. the calorific input, the production of sulphur and even nitrogen oxides, the throughput of ash, or the bulk composition of the fly ash produced. The expected *behaviour* of the ash is expressed in terms of an ash fusion window (initial deformation, softening, hemispherical and fusion temperature) and various slagging or fouling indices. An ash fusion window, however, is not an additive coal property [1], and should therefore be experimentally determined for each blend. The use of indices to predict a coal's slagging or fouling propensity has its limitations due to the fact that their predictive capability is based on bulk, laboratory-derived ash data, rather than on the recognition of the fact that coal ash is a heterogeneous matter consisting of individually reacting particles. This shortcoming was already recognised with single fuels, and is likely to be increasingly felt with blends, which show an even increased diversification of ash constituents.

In addition to the IEA Coal Combustion Sciences programme, ECN has recently undertaken a study on the slagging and fouling propensity of selected coals and their blends. Based on experimental work, this paper discusses possibilities to use blending as a mitigation tool for deposition problems; two additional papers evaluate the use of predictive indices [2], and a procedure for the assessment of fly ash quality [3], respectively.

The first part of the paper presents detailed fuel analyses and summarizes the set-up of deposition tests that have been performed in a lab-scale facility and in a semi-industrial scale furnace. The results of these tests are evaluated with the aim to provide a better understanding of specific coal mineral matter behaviour, concentrating on interactions observed between coal minerals from different coals in a blend. Based on the observations, possibilities are proposed to exploit, or prevent, such interactions with the aim to mitigate fouling and slagging problems.

FUEL ANALYSIS

Several coals of interest have been selected by the Dutch and Canadian power generating industry. The following coals were included: Spitsbergen (Russia), Econ-Zaf (South Africa), a Polish blend coal, an Egyptian coal, Envirocoal (Indonesia) and Genesee (Canada). In addition, a pulverised blend sample (as fired) was obtained from a Dutch power producer as representative for the average coal quality that is currently being fired in the Netherlands. Besides Envirocoal, this blend included Anker Diversen and Douglas Premium (both South Africa) and Kaltin Prima (Indonesia). Table 1 shows how the properties of the parent coals vary around the average blend values.

Table 1. *Fuel analyses of a Dutch coal blend and its four parent coals*

Name			Blend	Enviro coal	Anker Diversen	Douglas Premium	Kaltin Prima	Δ
Country			**Utility**	Indonesia	S.-Africa	S.-Africa	Indonesia	[%]
Cal. Val.	LHV (calc!)	MJ/kg	**24.2**	31.3	24.5	27.1	29.2	
Proximate	moisture	% ar	**11.8**	13.6	1.1	0.5	1.1	
	ash	% db	**11.4**	2.0	20.4	14.4	5.2	
	volatile matter	% db	**33.5**	47.0	23.9	23.1	39.7	
Ultimate	carbon	% daf	**80.5**	84.0	82.0	83.5	78.2	
	hydrogen	% daf	**4.6**	5.9	4.4	4.5	5.5	
	nitrogen	% daf	**1.8**	1.2	2.0	2.1	1.8	
	sulphur	% daf	**0.8**	0.3	1.2	0.6	0.8	
	oxygen (diff)	% daf	**12.3**	8.7	10.3	9.4	13.8	
Ash	SiO_2	% db	**50.1**	37.8	42.9	44.7	50.6	8
	Al_2O_3	% db	**28.7**	23.3	29.0	32.8	29.3	6
	Fe_2O_3	% db	**5.5**	12.4	5.8	5.0	8.5	34
	CaO	% db	**4.9**	11.0	10.6	8.0	2.1	48
	MgO	% db	**1.6**	4.2	2.4	1.7	2.1	43
	Na_2O	% db	**0.5**	3.9	0.2	0.2	1.5	179
	K_2O	% db	**0.9**	1.8	0.9	0.6	2.5	52
	TiO_2	% db	**1.5**	0.9	1.2	1.3	1.0	15
	P_2O_5	% db	**1.0**	0.2	2.3	2.2	1.1	49
	SO_3 (CCSEM)	% db	**3.8**	4.7	4.7	3.4	1.3	19

Note: Sampling and blending procedures may lead to slight differences between blend properties that can be calculated from parent coals properties and their respective mass fraction in the blend, and the measured blend properties as given in this table.

For the ash composition, the last column (headed "Δ") lists the percent deviation for each oxide, averaged for the coals in the blend. Typically, the minor elements – Na, K, P, Ca, Mg (Fe) – show the largest concentration variation, whereas the concentrations of Si and Al are much more constant. In Table 2, the new coals are compared with coal "X" which represents target values as used by the Dutch institution responsible for coal supply and fly ash utilisation [4]; such target values were obtained only for the properties LHV, moisture, ash, volatile matter and ash content, whereas values for a "normal" ash composition were taken from Skorupska [5]. From this table, besides a variation among concentrations of standard ash oxides, it becomes apparent that the concentrations of the specific elements Fe, Ca, Mg, Na and K often considerably exceed the upper limit given for target coal "X", thus giving an impression of the changes to be expected for the coals of tomorrow. The shift in ash composition is most pronounced for the elements Ca, Mg and Na, which show 3-4 fold increased concentrations for some coals. Generally, such an increased (earth) alkali metal content is not unusual when moving towards lower rank coals.

Table 2. *Comparative analyses of Dutch target coal "X" and selected test coals*

Name & Country			Coal "X"	Spitsbergen (Russia)	Econ-Zaf (S.-Africa)	Polish Blend (Poland)	Egyptian (Egypt)	Envirocoal (Indonesia)	Genesee (Canada)
Cal. val.	LHV (calc!)	MJ/kg	**≥24**	25.1	25.8	26.6	28.2	31.3	21.0
Proximate	moisture	% ar	**≤15**	0.6	1.5	1.6	1.9	13.6	7.7
	ash	% db	**avg. 15**	24.4	17.4	16.6	8.4	2.0	28.4
	volatile matter	% db	**25-45**	29.5	23.5	28.6	46.3	47.0	27.0
Ultimate	carbon	% daf		84.2	82.9	82.9	76.8	84.0	80.7
	hydrogen	% daf		5.6	4.5	5.1	6.0	5.9	5.1
	nitrogen	% daf		1.7	2.0	1.5	1.4	1.2	1.2
	sulphur	% daf	**0-1.5**	3.0	0.8	0.9	2.7	0.3	0.3
	ox. (diff)	% daf		5.5	9.9	9.7	13.1	8.7	12.8
Ash	SiO_2	% db	**45-75**	41.0	45.8	46.6	22.2	37.8	61.4
	Al_2O_3	% db	**15-35**	20.5	32.0	26.1	12.0	23.3	21.8
	Fe_2O_3	% db	**1-12**	9.0	5.6	9.0	18.4**	12.4	5.0
	CaO	% db	**0.1-2.3**	5.2**	8.0**	5.0**	2.9*	11.0**	4.7**
	MgO	% db	**0.2-1.4**	1.4	1.2	3.5**	0.6	4.2**	1.5
	Na_2O	% db	**0.1-0.9**	0.9	0.2	0.6	0.3	3.9**	2.6**
	K_2O	% db	**0.8-2.6**	2.1	0.7	2.9*	0.5	1.8	2.4
	TiO_2	% db	**0.4-2.2**	0.7	1.3	0.9	1.3	0.9	0.6
	P_2O_5	% db	**0.1-1.5**	1.2	1.2	0.5	0.2	0.2	0.1
	SO_3 (CCSEM)	% db	**0.1-1.6**	17.9	4.1	4.9	41.7	4.7	0.0

* : 10-30 % higher than upper limit for target coal "X"

▨** : >30% higher than upper limit for target coal "X"

With respect to coal ash deposition behaviour, knowledge about the speciation of the ash elements is indispensable. Computer Controlled Scanning Electron Microscopy (CCSEM) was, therefore, used as a tool to determine the mineral composition of each coal. Depending on the coal ash content, per coal 500 to 7000 individual (included and excluded) mineral particles were analysed and classified as specific minerals. Figure 1 shows the amount of the six most abundant minerals for each coal. Combining the information given by Table 1 and 2 and Figure 1, it can be seen what is the dominant speciation for each element. For instance, in Douglas Premium, Si is mostly present as kaolinite.

For more detailed information concerning the analyses, one is referred to the final project report [6].

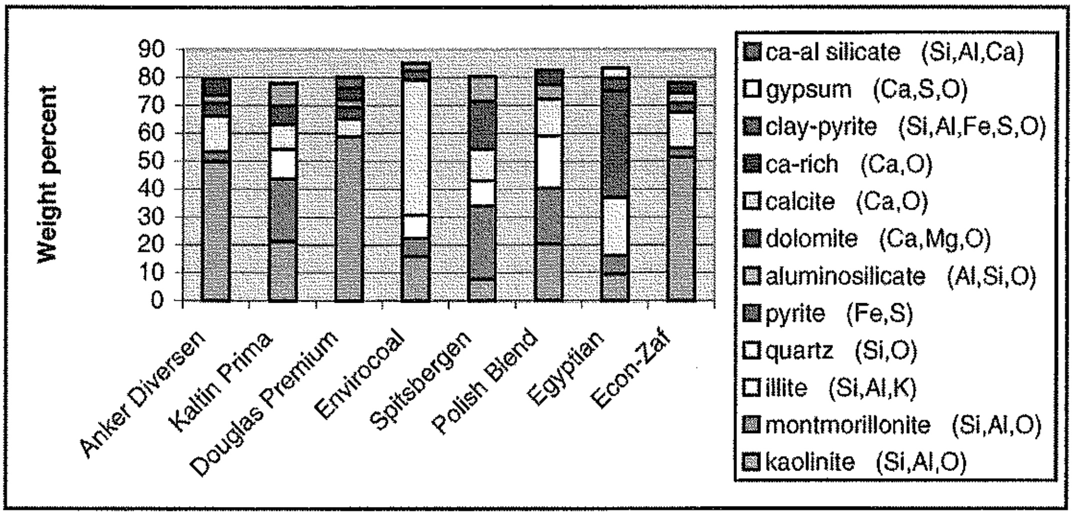


Figure 1. *Dominant coal minerals from CCSEM analysis (only the six most abundant are given)*

For all coals the majority of the minerals (80-85%) consists of the main ash elements Si, Al, Fe, Ca, S, and O. The remaining 15-20% of the minerals is covered by another ten, less abundant minerals. In the current mineral classification scheme, minor ash constituents such as Na, and to some extent also K, Mg and Ca are also often encountered as a contamination (i.e., present in very low concentrations) of various minerals; sometimes this results inorganic particles to be non-classifiable in terms of the mineral definitions used in this scheme.

DEPOSITION TESTS

An experimental programme has been carried out to assess the combustion and ash behaviour of single coals and blends. Tests have been performed on both a laboratory and a semi-industrial scale. For a more general assessment of combustion behaviour, per coal (or blend) a one-day trial was carried out in the IFRF 2.5 MW_{th} furnace. Ash particles and deposits were sampled at different locations in the furnace. In order to support and complement the semi-industrial scale tests, lab-scale experiments have been carried out under well-defined conditions. The applied lab-scale experimental facility consisted of an entrained-flow reactor with an integrated, staged flat flame gas burner, with the coal particles being fed through the burner. This concept enabled an accurate simulation of initial heating rates and temperatures, and of the particles' temperature as well as gaseous environment histories. A more detailed description of both the furnace and the lab-scale facility is given elsewhere [6].

MINERAL INTERACTIONS / IMPLICATIONS FOR BLENDING

In this paper, the experimental results will be evaluated in the light of the potential of coal blending as a tool for mitigation of fouling and slagging. A thorough knowledge of the blend partners' mineral composition is a prerequisite for this purpose, as reliable prediction tools for ash fouling and slagging propensity, especially in the case of blends, are not yet available [2,7].

Coal blending can be a promising tool for the mitigation of ash deposition problems by controlling the permanent deposition of ash onto HE-surfaces within manageable limits. This may be achieved, first of all, by means of avoiding an increased formation of sticky ash particles inside the normal temperature window of the boiler. Therefore, a blend partner must be reviewed in terms of 1) the presence of *minerals/inorganics in this specific coal* that may yield sticky ash particles, and 2) the presence of a *combination of minerals/inorganics in the blend* that may yield sticky particles. In most cases, item 1 is related to low-melting minerals, and item 2 to interactions between two or more coals, where the latter can be roughly divided into particle-particle (may be solid, liquid or in between) interactions and particle-gas interactions.

The various transformations of mineral/inorganic matter that have been observed as mechanisms in (the initiation of) fouling and/or slagging are discussed in the light of blending strategies that may be adopted for an improved control of ash deposition.

Melting of single minerals

Many mineral species in the fuel melt in the high-temperature flame in the boiler and solidify upwards to yield spherical fly ash particles. Minerals which have a relatively low melting temperature (<1200 °C) remain fluid over a wider temperature and thus spatial envelope. If this spatial envelope contains solid surfaces, deposition of fluid ash particles will start depending on boiler-specific flow patterns. Surfaces may be burner metal, near-burner refractory, or waterwall surfaces. Pyrite was shown to be such a mineral in Spitsbergen, Egyptian and Polish coal (see Figure 2).

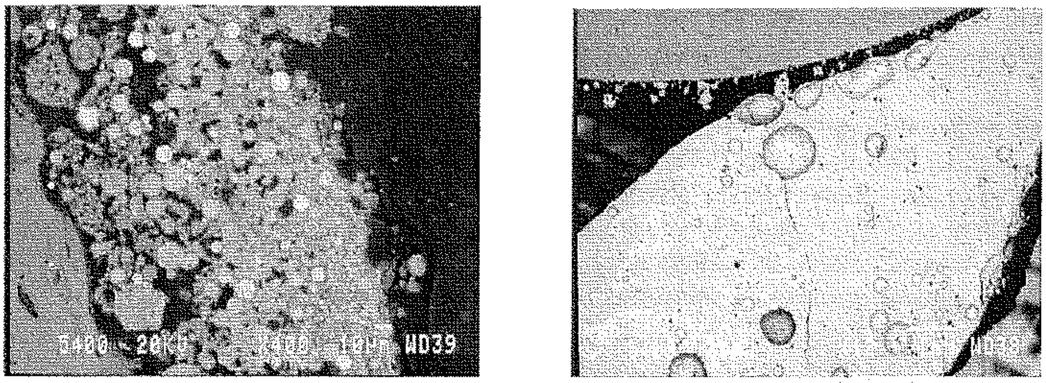


Figure 2. *SEM images showing iron-rich deposits from the near-burner zone of the semi-industrial furnace. Left: sintered particle layer in Egyptian coal deposit; right: over 28 wt% of iron in Spitsbergen coal deposit causes complete melt*

Upon heating, pyrite first decomposes into pyrrhotite which starts melting at 1083 °C. At this stage, that is before further oxidation to iron oxide (T_{melt} 1327 °C), it is a potential initiator of deposit formation. The growth rate of the initial deposit is significantly related to the fuel pyrite content while only these fluid particles will stick to the surface. While growing, the deposit surface temperature increases due to a worse heat transfer to the cooling medium. As a result, the deposit growth rate increases while the deposit surface itself becomes sticky, and starts collecting non-sticky ash particles. The Canadian coal Genesee contains large amounts of a (shale-type) clay as an external mineral, having an average composition of $Al_{0.22}Si_{0.60}Fe_{0.07}Na_{0.01}Mg_{0.04}K_{0.02}Ca_{0.01}Ti_{0.01}$ (measured as oxides). The deposits found near the burner (Figure 3) showed a striking resemblance with this clay, with significant enrichment in sodium; the low melting temperature of this clay, in combination with its abundancy resulted in rapidly growing, highly sintered deposits.

With respect to blending, the amount of low-melting minerals in the blend should be kept small. This will slow down the deposit initiation phase, but also allows a dilution effect to be created by other minerals. Dilution of the concentration of sticky particles with non-sticky particles may be a practical means to render a loose in stead of a completely solid deposit; a loose deposit is still manageable through normal soot blowing.

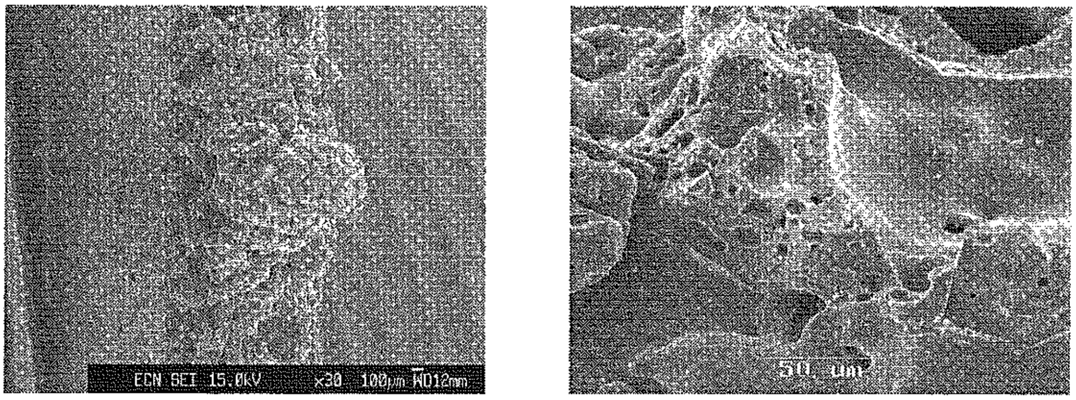
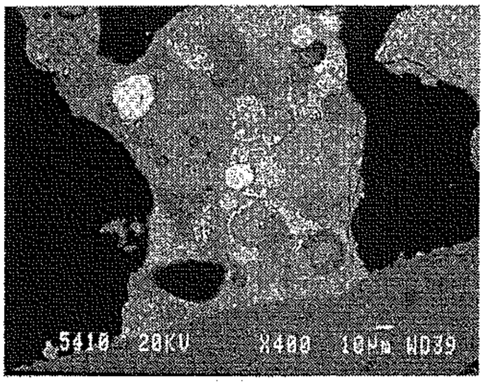


Figure 3. *Genesee coal deposit. Left: top view of highly sintered/fused ash deposit sampled in lab-scale facility; right: view of fracture in similar deposit sampled in semi-industrial scale furnace*

However, dilution can only be effective provided that the non-sticky ash particles do not interact (react) with the sticky particles in such a way that a low-melting eutectic is formed, as this will seriously worsen the character of deposit formation in terms of growth rate and of deposit removeablility.

To prevent these kind of interactions, thermodynamic considerations may be applied in the blending strategy, using phase diagrams in order to evaluate whether combined melts will be formed. The extent to which such melts will be formed – and thus would pose a problem – can be estimated from the mass ratio of the sticky to non-sticky species. As was seen in the experimental work, pyrite (Egyptian coal) and various calcium-rich species (Envirocoal) result in completely molten deposits in near-burner zones (Figure 4). In this case, a phase diagram may be used to estimate how much of a low-temperature melt can be formed as a function of the amount of calcium.



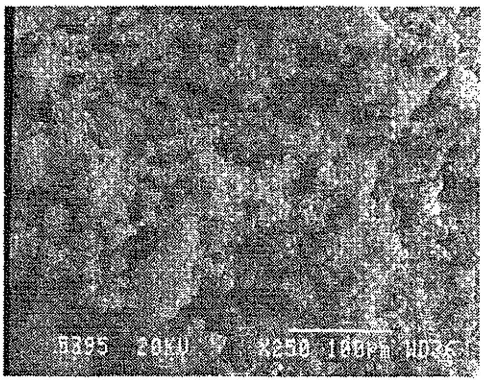


Figure 4 (left). *Deposit from semi-industrial furnace firing a blend of Envirocoal and Egyptian coal. The deposit has been completely molten and is rich in iron and calcium*
Figure 5 (right). *Deposit from the near-burner zone of the semi-industrial furnace, firing Econ-Zaf coal. The deposit consists of kaolinite clay, enriched with calcium and iron*

Fluxing species
When coals of different origin are blended, in many instances the variety of mineral/inorganic species is increased. Difficult as it is to predict the deposition propensity of a single coal, intractions between different coals are rarely taken into account. As indicated above, certain elements may act as a flux, i.e., combining or reacting with a species to form a product that has a lower melting point. If the fluxed species is a solid – e.g. a fly ash particle or a solidified deposit – the flux can cause the product to melt at the prevailing temperature; if it is already

fluid, the flux will dissolve while further decreasing the product's melting temperature and thereby delaying solidification to a lower temperature. In all cases, the effect of stickiness is enhanced and an increase of deposition problems can be expected. Important fluxing elements include Ca (used in practice for lowering slag viscosity), Fe, K, Na and Mg, which are sometimes called the basic elements of coal ash (as opposed to the acid elements Si, Al and Ti). Examples from the experimental work are the interaction of calcium and sodium originating from Envirocoal with iron-rich deposits initiated by Egyptian coal-derived pyrite (Figure 4), and the fluxing of Econ-Zaf's kaolinite clay by calcite-derived calcium and pyrite-derived iron from the same coal (Figure 5).

In blending coals which contain high concentrations of clays (kaolinite, montmorillonite and illite are the most abundant), blend partners with fluxing agents such as calcium (e.g. calcite, dolomite or gypsum) or iron (e.g. pyrite or iron oxide) should be used with care. If coals from these specific categories are combined in a blend, the fluxing agents increase the deposition propensity of the blend by decreasing the lowest melting temperature of the clays, while the quantity of the clays in the blend guarantees a high deposit growth rate. Again, a thermodynamic review of the species involved can be used to estimate in what ratio the coals can be blended.

Alkali sulfation

A third mechanism for the formation of sticky material is presented by the reaction of (earth) alkalis with sulphur dioxide from the gas phase. In low temperature combustion systems such as fluidised bed combustors $CaCO_3$ (limestone) is added for binding SO_2 into $CaSO_4$ (gypsum). As these sulfates are stable at lower temperatures (fluidised bed combustors operate at 800-900 °C), in a pulverised coal boiler they are preferentially formed in the convective zones where the gas temperature has dropped below 1200 °C. Although $CaSO_4$ melts only at 1450 °C and $MgSO_4$ is not thermodynamically stable above 1124 °C, K_2SO_4 melts at 1072 °C, and Na_2SO_4 even at 888 °C. If the local gas temperature exceeds the melting temperature of the specific sulfate formed, sticky fly ash particles will be the result. The (earth) alkali metals in coal which are most effectively sulfated are those which have been evaporated from the coal upon heating – mainly Na and K – and those available as small mineral particles – calcite and dolomite. Typical examples have been found in the experimental work from combining Envirocoal with Egyptian coal, as well as within the industrial blend (Figure 6). In both cases, sodium which is available in high concentrations in one coal (Envirocoal and Kaltin Prima coal) reacts with gaseous sulphur dioxide to form Na_2SO_4.

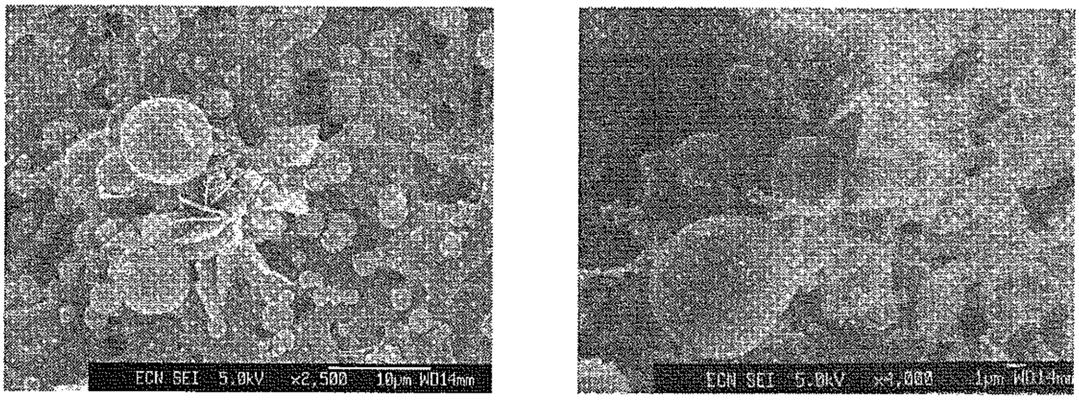


Figure 6. *SEM images showing Na_2SO_4 formation from the combination of two coals. Left: fly ash particles from a Envirocoal-Egyptian coal blend covered with leaf-like Na_2SO_4 Crystals. Right: fly ash from lab-scale firing of the industrial blend (see Table 1), showing octahedral Na_2SO_4 crystals*

Obviously, when firing coal in a pulverised fuel boiler, sulphur dioxide will be available in the gas phase. The one route to mitigate sulfate fouling of HE-surfaces in the boiler convective zone is to limit the amount of reactive alkalis – notably sodium – left over in that part of the convective zone where their respective sulfates would be (partly) molten. Blend partners with a high sodium or potassium content should be used in limited amounts. However, it is not merely the alkali content which is important, but rather its speciation which determines whether the alkalis will become available for sulfation. In this respect, the current mineral classification scheme used for the CCSEM procedure does not always pronounce upon the speciation of, especially, sodium, and may be further accentuated for this purpose.

CONCLUSION

Several coals that have been selected by the industry as economically attractive, have been studied with respect to their ash behaviour in relation to ash deposition problems. Many of the coals show out-of-normal concentrations of Ca, Fe, Mg, Na or K. In blends of these coals, interactions between inorganic species derived from different blend partners do occur. With a view to predicting the deposition propensity of a blend this poses a problem. Existing predictive tools such as slagging and fouling indices have been shown to give an ill prediction of the ash behaviour of the single coals studied here, let alone blends of these coals.

Experimental deposition tests have been carried out on a lab-scale facility and in a semi-industrial scale furnace, firing both single coals and blends thereof. Three mechanisms for the formation of sticky fly ash particles have been encountered: 1) melting of single minerals such as pyrite/pyrrhotite or alkali-rich clays, 2) fluxing of clays by one or more of the elements Ca, Fe, Mg, Na or K, and 3) sulfation of alkalis, notably Na and K.

Based on these mechanisms, and a detailed knowledge of coal mineral speciation – determined by CCSEM – recommendations for blending of the coals could be given. Thermodynamics (phase diagrams) may be used to predict minimum melting points, as well as for a prudent choice of blend ratios.

Although useful guidelines for blending coals with the aim to mitigate ash deposition problems have been given, it must be remembered that these were obtained from the observed behaviour of specific coals. When a new coal is introduced, a once-only experiment may be performed cheaply on a lab-scale to confirm the anticipated ash behaviour, for instance with respect to the formation of sticky ash particles according to the observed mechanisms (an "ash behaviour fingerprint").

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PAPER 3. "Low Quality Coals and Blending: Lab-Scale Evaluation of Ash Behaviour and Leaching Properties"

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ABSTRACT

This paper discusses several experimental aspects of a methodology to obtain an integral ash behaviour "fingerprint". The methodology involves lab-scale experiments under closely simulated pf combustion conditions to study ash formation and deposition on simulated boiler wall (slagging) and heat exchanger surfaces (fouling). In addition, it is attempted to produce fly ash with a sufficiently high burnout, and subject this fly ash to leaching tests.
In close connection with a study on the slagging/fouling propensity of a suite of low quality coals, experiments in ECN's lab-scale combustion simulator were conducted focusing on optimisation of the ash production, both in terms of quantity and burnout. To investigate the leaching properties of the resulting ash, batch pH-static leaching tests were used. But, despite the maximisation of the ash quantities produced in the simulator, the ash quantities produced in the simulator were still too small for the standard set-up of these tests. Therefore, a miniaturised version was developed. First results are discussed and considerations for further improvement of the experimental procedures are given.

Key Words: coal combustion, ash behaviour, ash quality, leaching

INTRODUCTION

The Netherlands is one of the major coal importing countries in Europe. Coal-fired pf boilers cover 40% of the national public electricity production [1]. All coal is imported, primarily from South-Africa, Colombia, Indonesia, Australia, United States and Poland. With the liberalisation of the European electricity market, the urge to minimise the cost of electricity production is increasingly leading to the use of low price coals. As a consequence, the number of countries and mines from which coals are obtained, has increased further over the past ten years. Often, these low price coals are of a lower quality with one or more properties like heating value, ash content, sulphur content, volatile matter content or grindability lying outside the normal operating window. Generally, coal blending is applied to counterbalance these deviating properties of individual coals. The blending is performed at dedicated, near-sea blending stations, from which the blends are then shipped to the power stations. The blending procedure is largely based on the additivity of certain coal properties, allowing a simple yet reliable estimation of e.g. the calorific input, the production of sulphur and nitrogen oxides, the throughput of ash, or the bulk composition of the fly ash produced. As a result of this blending practice, extensive experience with operation on blends involving lower quality coals has also led to a relaxation of the requirements for some of the averaged properties of the blend. For example, the average heating value (LHV) of the blends dropped from around 30 MJ/kg to 24 MJ/kg [2].
All fly ash produced in the Netherlands is utilised. The quality of the fly ash is an important condition in contracts with, e.g., the cement industry, and must be safeguarded to ensure economic plant operation. Although the bulk composition of the fly ash may be predicted reliably from the standard bulk ash analysis, in many cases this does not give the information required for a reliable prediction of ash behaviour or quality. An important reason is that, in general, ash behaviour and fly ash quality cannot be considered additive. Inherently, this makes advance evaluation of a given coal or blend complex. In practice, experience is gained

predominantly through full-scale tests and operation. However, these full-scale tests are costly, especially if severe fouling or slagging occurs or if the fly ash quality does not fulfil the requirements.

Therefore, ECN is working on improved predictive methods for both ash behaviour (slagging/fouling) and fly ash quality. Amongst others, attention is focused on the development of a methodology to obtain an integral ash behaviour "fingerprint" based on relatively low-cost lab-scale experimentation. The methodology involves lab-scale experiments under closely simulated pf combustion conditions to study ash formation and deposition on simulated boiler wall (slagging) and heat exchanger surfaces (fouling). In addition, it is attempted to produce fly ash with a sufficiently high burnout, and subject this fly ash to leaching tests in order to include the assessment of fly ash quality into the "fingerprint".

This paper discusses several experimental aspects of the methodology, in particular in relation to the fly ash production and the leaching tests. The work has been conducted in close connection with a study on the slagging/fouling propensity of a suite of low quality coals, relevant to the power plants in the Netherlands [3]. This study was carried out in co-operation with the IFRF in IJmuiden, the Netherlands, where the coals were subjected to furnace trials on a semi-industrial scale. Other results of this study, viz. an evaluation of the accuracy of predictive slagging/fouling indices and fuel blending as a means to mitigate slagging and fouling, are reported elsewhere [4,5].

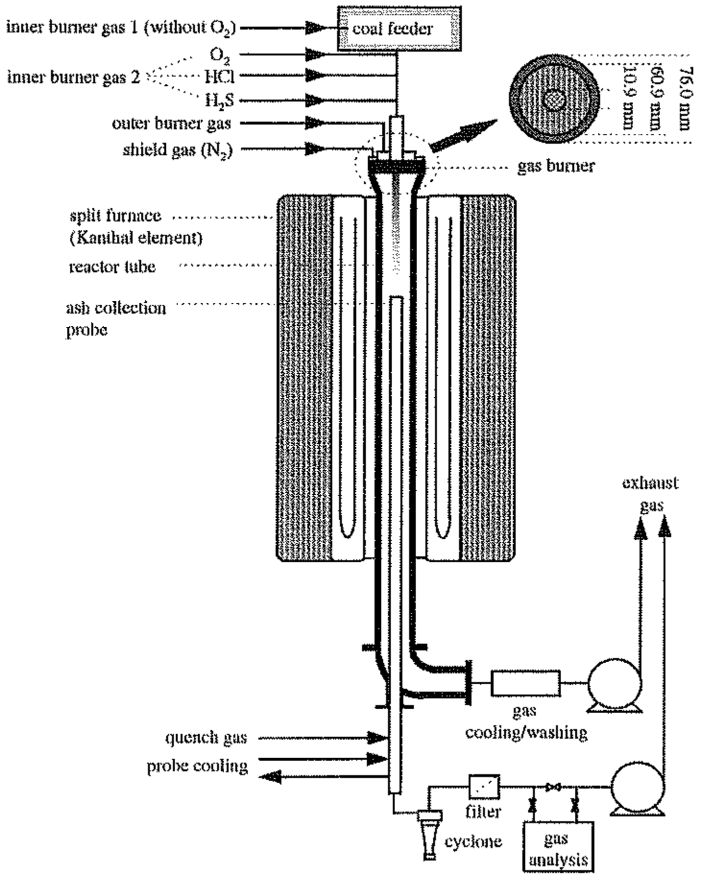
EXPERIMENTAL PROGRAMME AND SETUP

The experiments with the different low quality coals were conducted in ECN's lab-scale combustion simulator, which was applied earlier already [6,7]. Attention was focused on optimisation of the ash production, both in terms of quantity and burnout. To investigate the leaching properties of the ash, batch pH-static leaching tests were used. But, despite the maximisation of the ash quantities produced in the simulator, the ash quantities produced in the simulator were still too small for the standard set-up of these tests. Therefore, a miniaturised version was developed.

Lab-scale Combustion Simulator

For lab-scale studies of fuel behaviour, a careful simulation of the various phases - i.e., rapid heating, devolatilisation/ pyrolysis, volatile and char combustion – is essential. At ECN, an atmospheric experimental facility is available to simulate the appropriate particle reaction conditions with respect to temperature history, gas composition history and residence time. With this Atmospheric Entrained-Flow Gasification and Combustion simulator (AEFGC-simulator), both entrained-flow gasification and pulverised fuel combustion can be simulated. A schematic of the facility and its main features is shown in Figure 1.

The AEFGC-simulator can be characterised as an entrained-flow reactor with an integrated, premixed and multi-stage flat flame gas burner. By feeding different gas mixtures to the different stages, the gas burner is used to simulate the high initial heating rates, temperatures and the gaseous environment history that fuel particles experience in either pulverised coal combustors or entrained-flow gasifiers. From Figure 1 it can be observed that the burner consists of two sub-burners viz. an inner burner (ID 10.9 mm) and an outer burner (ID 60.7 mm).



Typical particle feed rate (g/h)	1
Particle residence time (ms)	10 – 2000
Particle heating rate (°C/s)	$> 10^5$
Gas supply inner burner	CH_4, CO, CO_2, H_2, N_2, O_2, H_2S
Gas supply outer burner	CH_4, CO, H_2, O_2, H_2S
Operating pressure (MPa)	0.1
Reactor tube inner diameter (m)	0.076
Reactor tube length (m)	1.0
Max. electrical heating temperature (°C)	1600
Probes for:	gas temperature/ composition measurement; ash/deposit collection

Figure 1. *Schematic overview of the Atmospheric Entrained-Flow Gasification and Combustion simulator, and its main features*

A tertiary gas stream (nitrogen) is applied to create suitable mixing profiles and to protect the tube from the hot secondary gas stream. Fuel particles are fed through the inner burner and undergo rapid heating ($>10^5$ °C/s), up to the high temperature level of the near-burner zone in an actual pf boiler. The particles are fed at a rate of typically 1 g/h by means of a commercial rotating brush feeder. This low flow rate ensures that in the reactor the conditions for each coal particle are determined by the staged gas burner, the influence of the other coal particles being insignificant. In the coal feeder, the coal is contained in a cylinder and a piston presses the particles against a rapidly rotating brush. The particles are dispersed by the brush and then transported into the reactor pneumatically. The gas/particle flow is confined in a 1 m long, 76 mm ID, alumina reactor tube. The tube is surrounded by a controllable heating section equipped with Kanthal Super 33 elements to create the adequate temperature history for the particles.
Particle sampling is carried out using a fast quenching probe in combination with a cyclone ($d_{50} = 3\ \mu m$) and a filter. The probe is hot-oil cooled and helium is used for sample quenching. In the

original set-up, average particle residence times were limited to approximately 500 ms (residence time for ≤100 micron particles) due to the limited reactor length of 1 m. Clearly, these residence times were much too short to reach high fuel conversions. To overcome this limitation without having to install extra, expensive furnace sections, a new concept was devised comprising a ceramic residence time extension (RTE) chamber. This chamber with conical inlet and outlet sections can be mounted on the tip of the particle sampling probe as shown schematically in Figure 2. The top angle of the conical sections was kept smaller than 8° to prevent separation of the boundary layer. The principle of the RTE chamber is based on the notion that for the small coal particles, the particle terminal velocity is small and therefore, the particle residence time is controlled predominantly by the gas velocity. In the current version, the inlet of the chamber is bevelled, and the geometry of the chamber and the helium quenching were designed to achieve total average particle residence times up to 2000 ms at a high particle collection efficiency.

Alternatively, a deposition probe may be used for slagging and fouling tests. To this probe various substrates can be attached for simulating different deposition surfaces. For both particle and deposit sampling, an axial probe transport mechanism enables sampling at different axial positions, i.e. at different particle residence times.

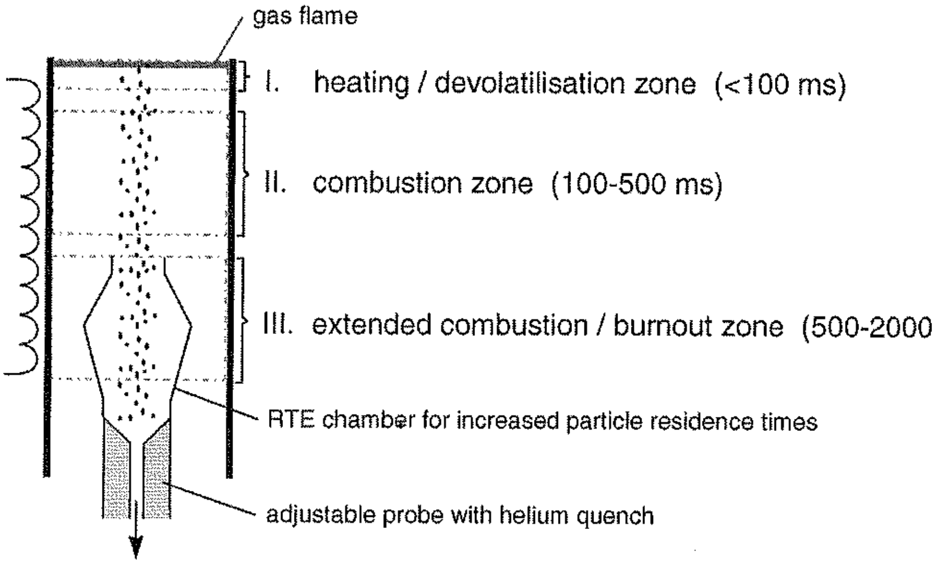


Figure 2. *Fly ash generation / sampling in the lab-scale combustion simulator*

Due to the low particle flow rates, the combustion simulator produces very small ash quantities, typically 0.1-0.2 g/h. Standard fly ash leaching tests require typically 100 g of solid material, which is leached at a liquid/solid (L/S) ratio of 10 l/kg. Applying a leaching test to fly ash produced with the combustion simulator thus required a miniaturisation of the leaching test. This is further described below. However, based on the requirements given by the detection limits of the multi-element analysis technique ICP-AES (inductively coupled plasma-atomic emission spectrometry), it was reasoned that even for a miniaturised leaching test at five pH-values, still 2 g solid material would be needed. Given the standard ash production rate of the combustion simulator, the production time for 2 g of fly ash would be 10-20 hours. To decrease this production time, it was decided to try to increase the ash production rate. The coal feed rate was increased stepwise and the conversion of the combusted particles was determined as a quantifiable means to verify that no significant increase of particle-particle interaction would result from the increased particle density inside the combustion simulator.

PH-static Test

The batch pH-static leaching test was used here to investigate the leaching properties of the ashes. In this test, ash leaching is measured as a function of leachate pH, typically in the range of pH = 4-12. In comparison to other standard leaching tests, the pH-static test is particularly useful because it provides information about leaching mechanisms and the speciation of major and trace elements in the ash matrix [8,9]. However, a typical pH-stat test requires tens of grams of solid material for each pH value at which leaching is tested. Hence, at least 100 g of ash are needed for a typical test of 5-8 pH values.

For the purpose of obtaining an ash behaviour fingerprint, a miniaturised pH-static test was developed, which allows the use of sample sizes in the order of a few tenths of grams for each pH-value, which requires only 1-2 g for a test of 5 pH values. Firstly, leaching results obtained from the miniaturised pH-stat system were compared with a normal size system, and secondly, the miniaturised pH-stat system was used to compare the leaching results obtained for lab-scale fly ash with those obtained for full-scale fly ash.

EXPERIMENTAL RESULTS

Optimisation of Ash Production

As described above, with the RTE chamber, the average particle residence time in the combustion simulator could be increased from 500 to 2000 ms. Tests were carried out under simulated low-NOx combustion conditions to verify that increased conversions would be obtained. The matching axial gas temperature and concentration profiles in the reactor, determined without installation of the RTE chamber, are shown in Figure 3.

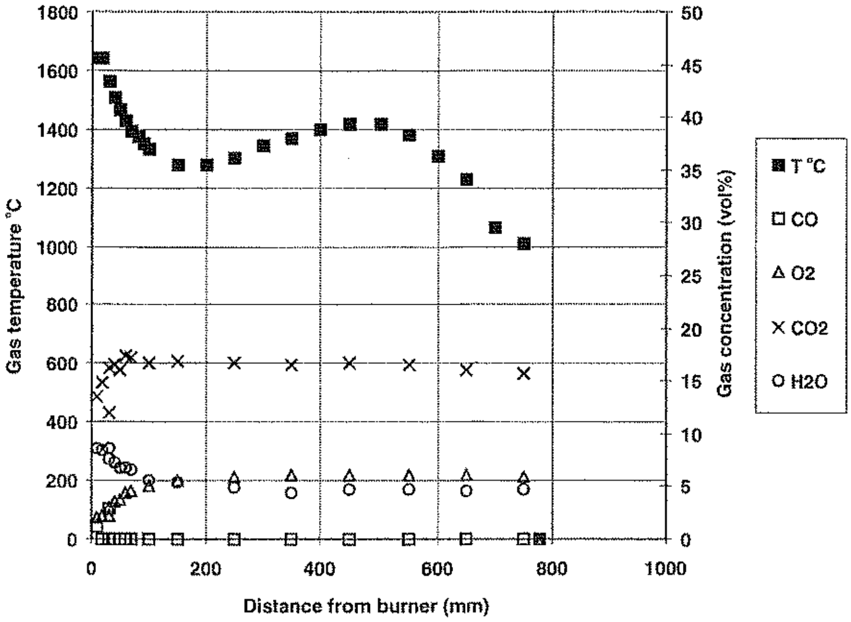


Figure 3. *Axial gas temperature and concentration profiles under simulated low-NOx combustion conditions (without the residence time extension chamber)*

The verification was done by determining the ash content of the sampled char particles and calculating the fuel conversion using the ash tracer method according to:

$$\xi = \frac{1 - {x_{fuel}}/{x_{sample}}}{1 - x_{fuel}} \qquad (1)$$

where ξ is the fractional conversion and x is the ash weight fraction (dry basis). For a coal sample with a typical size distribution (95% <150 μm), the first chars showed conversions of 80%, which is a considerable increase compared to the conversions of 50-60% that were achieved previously. Further improvements with respect to the gas flow rate through the RTE chamber and its positioning relative to the electrical furnace resulted in a further increase of the conversion to values above 90%. It is expected that, with a final optimisation, a conversion level of 95% can be exceeded.

For the evaluation of the possibility to increase the fly ash production in the combustion simulator by increasing the coal feed rate, the South-African coal Douglas Premium was used. This coal contains 14 wt% ash on a dry basis, which may be considered representative for commonly fired coals. Feed rates of 0.6, 0.9 and 1.5 g/h were applied. The results are given in Table 1.

Table 1. *Influence of coal feed rate on fuel conversion*

Coal feed rate [g/h]	X ash, sample [-]	ξ [-]
0.6	0.56	0.87
0.9	0.51	0.84
1.5	0.51	0.84

Based on these results it is concluded that, for the range of coal feed rates tested, no significant effect of feed rate on fuel conversion, or carbon-in-ash exists. For the purpose of increasing the ash production for leaching tests, it is assumed that fuel feed rates up to a maximum of 2 g/h can be used in the combustion simulator without significant particle-particle interaction. This means that the time needed to produce the ash for the miniaturised batch pH-static leaching tests can be reduced by a factor of 2.

Comparison Lab-scale with Full-scale Fly Ash

An industrial pulverised coal blend (as fired), comprising four individual coals, together with the resulting full-scale fly ash were obtained from the EPZ Amer-9 pulverised coal power plant in Geertruidenberg, the Netherlands. The full-scale fly ash was analysed at ECN by means of SEM-EDX.

The same coal blend with (with 95% of the coal particles ≤150 μm) was also fired in the combustion simulator under simulated low-NO_x combustion conditions. These conditions were established by firing the inner gas burner of the simulator substoichiometrically and the outer burner super-stoichiometrically, resulting in axial temperature and gas concentration profiles as given in Figure 3. The ash collected from both the cyclone and the filter was analysed by means of SEM-EDX as well.

With the RTE chamber in place, a fractional conversion up to 92%, determined for the cyclone ash using equation 1, was reached. Although this was still considerably lower than the conversion in the full-scale fly ash, it was decided to subject this ash to leaching tests. Already from a comparison of SEM micrographs (Figure 4) of full-scale fly ash and a combustion simulator sample with an even lower fuel conversion of 78% it was observed that the smaller, mostly molten fly ash particles had a similar size distribution, morphology and composition. It appeared that the limited conversion of the combustion simulator sample was to be attributed mainly to large char particles.

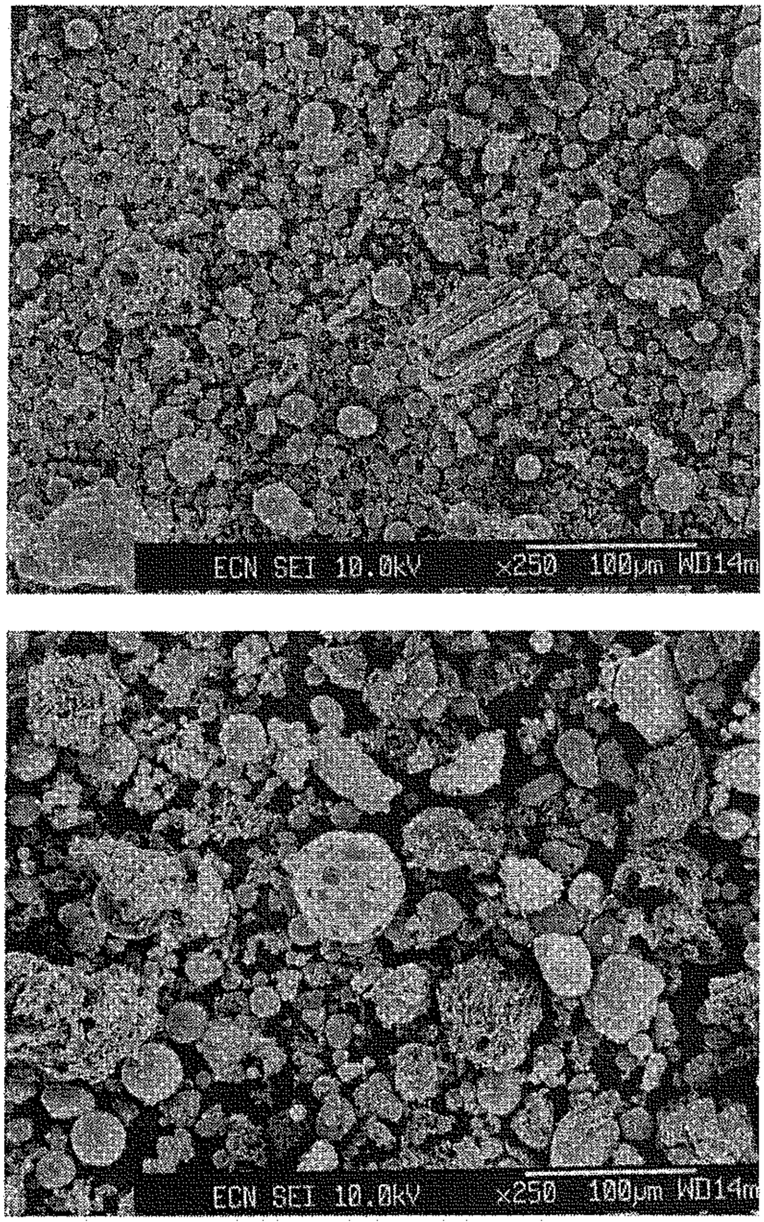


Figure 4. *SEM micrographs of full-scale fly ash (top) and lab-scale ash with 78% conversion (bottom)*

PH-stat Miniaturisation

For the purpose of obtaining an ash behaviour fingerprint based on lab-scale experimentation, a miniaturised pH-static test was developed. 10-ml Teflon (PFA) reactors were made, which contained fittings for a pH-microelectrode, and for 1/16″ Teflon tubing for the introduction of acid and base. A fourth 1/16″ fitting was kept open to allow equilibration with the atmosphere.

The pH was monitored and automatically adjusted to setpoint, by a computerised pH-stat system, in 5 reactors simultaneously at (generally 4) pre-set pH values between 4 and 12. Fly ash suspensions were prepared in nanopure deionised water at a liquid/solid (L/S) ratio of 10 l/kg by adding 0.2-0.5 g of fly ash to 2-5 ml water. The batch reactors were kept open to the atmosphere at 20±1 °C and were stirred continuously during a 24-hour equilibration period, using a Teflon coated magnetic stirring bar. The pH was adjusted with 1 M analytical grade HNO_3 or NaOH. The suspensions were filtered through 0.2 µm membrane filters and the solutions analysed for a range of major and trace elements by ICP-AES and a carbon analyser (for dissolved inorganic and organic carbon). It was generally necessary to dilute the leachates by a factor of 2 in order to obtain sufficient leachate volumes for the various analyses.

Three samples have been investigated using the miniaturised pH-stat system: (1) fly ash obtained after combustion of the pulverised coal blend in the full-scale (Amer-9) facility; (2) fly ash obtained by firing the same blend in the combustion simulator (only tested at pH = 7); (3) fly ash obtained by firing one of the blend parent coals, Douglas Premium, in the combustion simulator. In order to compare leaching results obtained from the miniaturised pH-stat system with a normal size system, sample (1) was also tested using a normal size pH-stat system [8], in which samples of 12.5 g of ash were suspended in 125 ml of deionised water. Setpoint pH-values for the comparison were pH = 4, 7 and 12.

Leaching Tests

General trends in leaching. The results of the different pH-static leaching tests are shown in Figure 5. Leaching is expressed in mg of leached elements per litre of leachate solution, as a function of leachate pH. As examples, major cations (Ca and Mg), a major anion (SO_4), cationic trace metal (Zn), and (oxy)anion-forming metals (Mo and Cr) are shown. As Figure 5 illustrates, these categories of elements show very characteristic pH-dependent leaching patterns. Cationic metals generally show increased leaching towards low pH (Ca, Mg), while typical V-shaped leaching patterns are found for hydrolising (heavy) metals such as Zn, as a result of the formation of soluble hydroxo-complexes. Relatively soluble anions such as sulphate may be fairly pH-insensitive, while the leaching of more reactive oxyanions, such as those of Mo and Cr, tends to increase towards high pH. The data shown in Figure 5 will be used to briefly discuss three issues: (1) comparison of ash leaching between the miniaturised and normal size pH-stat systems; (2) differences in leaching behaviour (speciation) of elements in ash obtained from full-scale and laboratory-scale (simulator) combustion; (3) comparison of the leaching properties of the single Douglas Premium coal and the blend containing (25 wt%) this coal.

Miniaturised vs. normal-scale pH-stat leaching. The agreement between leaching data obtained from the miniaturised and normal size pH-stat system was found to be generally very good. The only element which showed a substantial difference, was potassium (not shown), which was approximately one order of magnitude higher in the miniaturised system. However, this difference was found to be due to KCl leackage from the pH-microelectrode that was used in that system. In the normal set-up, a gel-type electrode is used, which does virtually not show any leakage of KCl.

Full-scale vs. simulator combustion. Although the fly ash obtained from combustion of the coal blend in the lab-scale simulator was only leached at a single pH of 7 (due to the limited amount available; 0.2 g in total), the leaching of most elements (at that pH) was found to be of the same order as found for fly ash from the same blend fired in the full-scale facility. However, significant differences may be observed, as Mo in Figure 5 illustrates. The small quantity of fly ash used in the miniaturised system could potentially lead to such differences if elements are not sufficiently homogeneously distributed in the ash. Also, the extent of burnout can play a role. Depending on the binding properties for specific elements, the presence of unburnt char will influence the leaching of these elements. The specific lab-scale ash sample had a conversion of 92%, whereas for full-scale fly ash significantly higher values are common.

The redox-sensitive metal chromium shows some very interesting features in Figure 5. Chromium leaching from the full-scale ash shows features typical for the chromate (Cr(VI)) anion: fairly high concentrations, increasing towards high pH. The leaching of Cr from both ashes obtained from the laboratory simulator (from the blend as well as from the single Douglas Premium coal), however, is very different and shows the concentration level and V-shaped leaching pattern typical for the Cr^{3+} cation. This difference in the oxidation state of chromium seems to indicate that the incomplete combustion in the combustion simulator has resulted in a more reduced fly ash, compared to the ash obtained from the full-scale facility. This supports the suggestion that the leaching results can be affected by the fact that combustion was incomplete. In the further development of this method, therefore, effort has to be made to increase the fuel conversion up to significantly higher values.

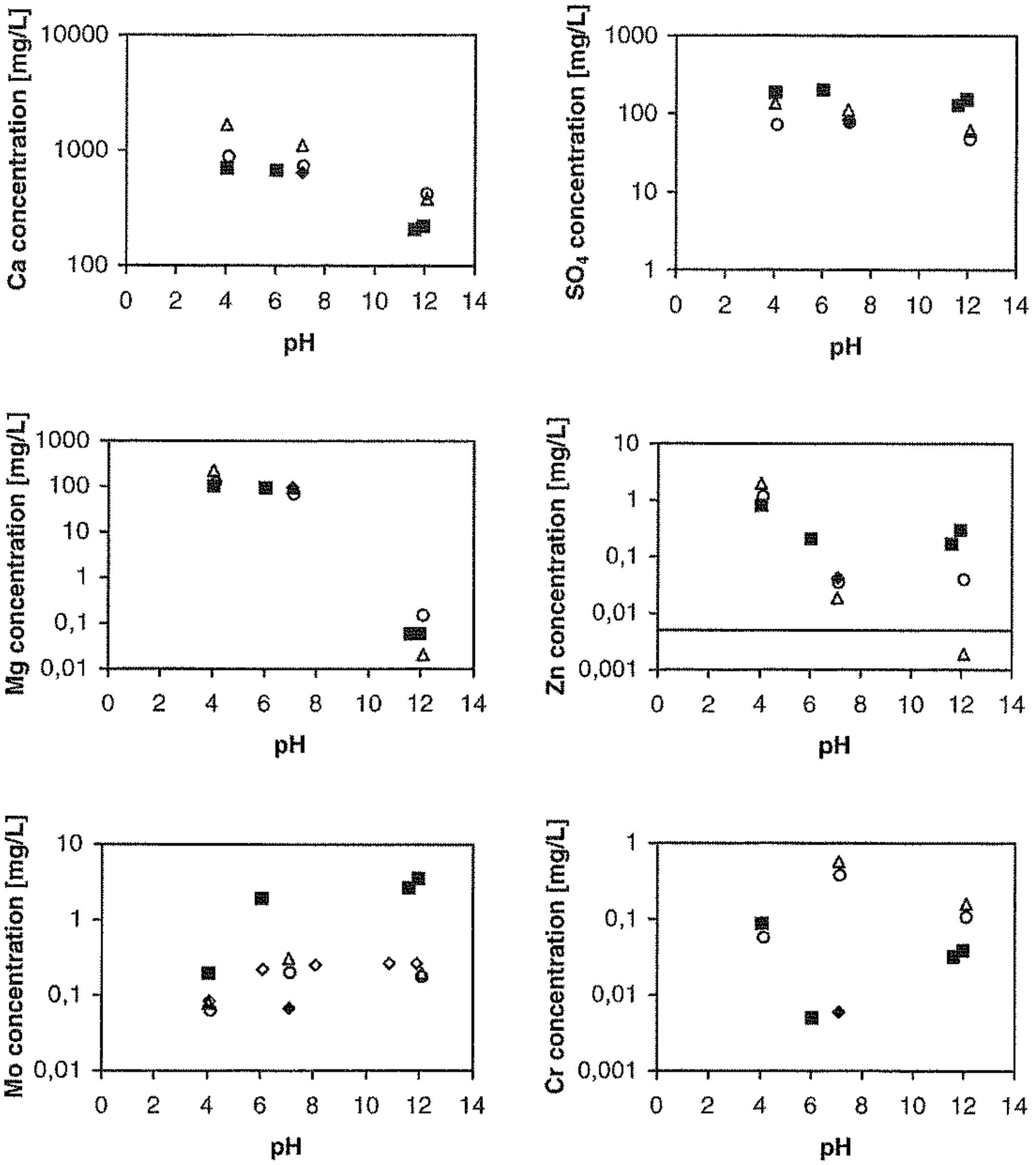


Figure 5. *Results of pH-static leaching tests: Δ full-scale fly ash from coal blend, normal-scale pH-stat; O full-scale fly ash from coal blend, miniaturised pH-stat; ◆ lab-scale fly ash from coal blend, miniaturised pH-stat; ■ lab-scale fly ash from Douglas Premium coal, miniaturised pH-stat; with Zn, the detection limit is visualised by a solid line, while for all other elements, measured concentrations were above the detection limit.*

Single coal vs. blend. The single Douglas Premium coal shows generally very similar leaching patterns and concentrations for the major elements, when compared to the coal blend. This is exemplified in Figure 5 by Ca and Mg, but was also found for typical matrix elements such as Al, Si and Fe (not shown). Some trace elements, such as Zn, show also very similar leaching characteristics. While some potential contaminants in fly ash, such as As, Se and Sb (not shown) were found to be released in lower concentrations from the single coal, than from the blend, Figure 5 illustrates that Mo shows the opposite; this oxyanion shows the same leaching pattern for both the single coal and the blend, but is leached at much higher concentrations from the Douglas Premium coal. Figure 5 shows that the blend, which contains 25 wt% Douglas

Premium coal, leaches Mo in lower concentrations than would be expected from the "dilution" of this coal alone. This difference illustrates that the other coals in the blend (which are likely to also contain at least some Mo), contribute to the binding of this potential contaminant to the fly ash matrix and, therefore, that the (miniaturised) pH-stat system may provide an upper limit of the leaching of potential contaminants from single coal samples in a blend.

DISCUSSION

With the extension of the particle residence time by means of the RTE chamber a large increase in fuel conversion was obtained without having to change the size of the combustion simulator. Conversions exceeding 95% are anticipated after implementation of several minor modifications. However, fuel particles with an ash content (dry basis) of 10%, still contain approximately 30% of carbon when they have been converted for 95%. With respect to the much lower carbon-in-ash values of full-scale fly ash, it is important to determine whether and if yes, how this conversion should be increased.

It must be noticed that the ash samples obtained from the combustion simulator contain all ash, including what would be bottom ash in a full-scale boiler. The SEM images in Figure 4 have shown that the lab-scale ash contains mainly large char particles, which obviously dominate the carbon-in-ash level of the sample. Therefore, it is important to know what carbon-in-ash levels are common for bottom ash from full-scale boilers, and what is the average size of the char particles therein. Based on this information, it can be judged whether it is necessary to increase the lab-scale conversion level even further. If the large char particles can be characterised as bottom ash, they can be either removed from the ash sample afterwards, or be excluded from the combustion experiment by removing the largest size fraction from the fuel. Based on the observed influence of combustion conditions on the ash leaching behaviour, the latter would probably be preferable. If the large char particles do not end up as bottom ash in a full-scale boiler, in fact, their conversion should be increased. In the current configuration of the combustion simulator, it will be difficult to accomplish this specifically for the large particles. In fact, using the residence time extension chamber leads to a larger residence time distribution, since at lower gas velocities the particle gravity forces are more dominant. If a realistic ash behaviour fingerprint requires a high burnout – and thus a high residence time - for large char particles, then it may be the an option to transfer the lab-scale simulator into an upfired system, as was used previously [10]. In an upfired mode with low gas velocities, the residence time for the larger particles can be significantly longer than for the smaller particles.

CONCLUSIONS

In this paper, several experimental aspects of a methodology to obtain an integral ash behaviour "fingerprint" based on relatively low-cost lab-scale experimentation have been discussed. Attention was focused in particular on producing ash in a lab-scale combustion simulator at a sufficient quantity and with a sufficiently high burnout, and on subjecting this ash to a miniaturised pH-static leaching test. The combustion simulator was designed to mimic pf (low-NO_x) combustion conditions, especially the corresponding particle heating rates and the gas temperature and composition histories encountered by the particles.

To obtain higher burnout, the combustion simulator was equipped with a newly designed residence time extension chamber to extend the average particle residence time from 500 up to 2000 ms within the existing, limited reactor dimensions. This led to a considerable increase in fuel conversion from 50-60% up to 92%. A first comparison of fly ash samples from the combustion simulator with fly ash from a full-scale power plant already showed some promising similarities with respect to fly ash size, morphology, composition and leaching behaviour. However, it seems that the fuel conversion in the lab-scale simulator has to be increased further to 95+% to obtain a better resemblance with full-scale fly ash. On the other hand, it is clear that the issue of ash partitioning into bottom ash and fly ash in a full-scale plant and a proper interpretation of the results of the lab-scale experimentation in this respect needs to be elaborated upon further.

A miniaturised pH-static leaching test has been successfully developed and tested on full-scale fly ash samples of 0.2-0.5 g per pH-value. The agreement of leaching results with a normal-size leaching test was very good. The miniaturised test has also been applied to compare the leaching properties of lab-scale fly ash with those of full-scale fly ash. Generally, a good comparison was obtained, although for a few elements significant differences were found. Deviating leachate concentrations of e.g. molybdenum and chromium may be attributable to insufficient burnout of the lab-scale fly ash, which should be verified in subsequent work. Finally, it was shown that a miniaturised leaching test can be used to determine the maximum extent to which a single coal (in this context: blend partner) can contribute to the leaching of potential contaminants from a blend.

In summary, some significant steps were set towards the inclusion of fly ash quality assessment by means of batch pH-static leaching tests in a methodology to obtain a low-cost integral ash behaviour fingerprint. This fingerprint of ash behaviour (slagging/fouling) and fly ash quality is considered to have a large potential as an advanced predictive tool. However, further development of the methodology and further validation with full-scale data are still required.

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4. CONCLUSIONS

Several low-quality coals and blends have been evaluated with respect to their ash deposition behaviour. Quantitatively as well as in terms of removability from boiler surfaces the high-ash coals Spitsbergen and Genesee showed the most severe deposition propensity, both in the near-burner area (slagging) and in the flue gas exit (fouling). With the Polish coal, near-burner deposits were formed at a lower rate, but similarly fused. The Egyptian coal showed a low-medium slagging propensity, related to its relatively high pyrite content. Envirocoal is an extremely low-ash coal and does not, by itself, give rise to significant ash deposition problems. In combination with e.g. the Egyptian coal, however, it results in the formation of low-melting sticky ash particles, thereby increasing the deposition propensity of this binary blend.
The elements Ca, Fe, Mg, Na and K play an important role in the formation of low-melting, highly sintered or fused deposits which may be difficult to remove during boiler operation. In general, the low-quality fuels that are currently fired are coals of a lower rank with higher levels of especially these elements.

Commonly used indices were applied to evaluate their potential for predicting the slagging and fouling propensity of the test coals. The indices greatly rely on the composition of bulk laboratory ash, and do not take account of the behaviour of specific inorganic species which are actually present. The predictions were found to be inadequate especially where mineral interactions occurred. Mineral interactions sometimes occur in single coals but the chance and therefore the risk of interactions not accounted for increases with the complexity of (or number of coals in) a blend. Interactions occur through solid-solid or gas-solid contact, of which gas-solid contact is the more effective in blends. For the test coals, this effective gas-solid interaction comprises the vaporisation of volatile alkali and alkaline earth species, which react both with entrained ash particles and with already deposited ash.

From the mineral behaviour and interactions that have been observed in this study, several generalisations (or guidelines, see Paper 2) have been derived that may be of use to those who compose fuel blends. The generalisations have been based on three experimentally observed mechanisms for sticky fly ash formation. The observations included: 1) melting of single minerals such as pyrite/pyrrhotite or alkali-rich clays, 2) fluxing of clays by one or more of the elements Ca, Fe, Mg, Na or K, and 3) sulphation of alkalis, notably Na and K.
The precondition for using such generalisations is that the mineral composition of a coal or blend is known. This requires an analysis of the pulverised (preferentially but not necessarily as-fired) coal by means of an automated CCSEM procedure in addition to the standard coal proximate, ultimate and ASTM ash analyses. The costs related to such an analysis are now around €475 per coal, which is a small amount considering the fact that this analysis does not have to be carried out as frequently as control-purpose measurements.

In case of definite plans to fire or test a new coal for which no operating experience has been gained yet, the current study has shown in principle that specific laboratory tests offer the opportunity for evaluating certain critical parameters of coal ash and its behaviour. Performed under proper (boiler-similar) conditions, such tests together result in a coal ash fingerprint which may include quantitative expressions of its near-burner or waterwall slagging propensity, its superheater fouling propensity, its carbon in ash level and its fly ash leaching properties, all relative to a known baseline coal. In this report, promising developments have been presented which will be used as a basis for further improvement of the methods involved.

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APPENDICES

Appendix 1. Datasheet test coals

Name			Spitsbergen		Econ-ZAf		Polish-56		Egyptian		Fettnuss		Genesee	
Origin			Russia		South-Africa		Poland		Egypt		Germany		Canada	
Batch			IFRF		IFRF		IFRF		IFRF		IFRF		IFRF	
Cal. val.	HHV [MJ/kg]		26.49		26.35		26.82		28.67		34.98		20.73	
Proximate														
	Moisture	[% a.r.]	0.64		1.45		1.63		1.93		0.32		7.67	
	Ash	[% d.b.]	24.42		17.35		16.55		8.40		3.26		28.40	
	Volatile matter	[% d.a.f.]	39.01		28.47		34.23		50.55		28.60		37.68	
	Fixed carbon	[% d.a.f.]	60.99		71.53		65.77		49.45		71.40		62.32	
Ultimate														
	Carbon	[% d.a.f.]	84.23		82.90		82.85		76.83		89.06		80.70	
	Hydrogen	[% d.a.f.]	5.56		4.45		5.07		6.01		5.14		5.06	
	Nitrogen	[% d.a.f.]	1.72		1.98		1.47		1.40		1.71		1.18	
	Sulphur	[% d.a.f.]	2.98		0.79		0.88		2.68		0.73		0.28	
	Oxygen	[meas., % d.a.f.]	9.34		12.28		12.62		15.69		4.70		24.60	
	Chlorine	[% d.b.]	0.05		0.01		0.10		0.07		0.09		0.00	
Ash														
			element 3) mg/kg a.r.	oxide % ash d.b.	element 3) mg/kg a.r.	oxide % ash d.b.	element 3) mg/kg a.r.	oxide % ash d.b.	element 3) mg/kg a.r.	oxide % ash d.b.	element 3) mg/kg a.r.	oxide % ash d.b.	element 3) mg/kg a.r.	oxide % ash d.b.
Si	/	SiO_2	43275	41.03	30115	45.84	29863	46.56	9863	22.22	6238	46.14	65148	61.39
Al	/	Al_2O_3	24519	20.53	23774	31.96	18975	26.13	6006	11.95	5095	33.28	26150	21.76
Fe	/	Fe_2O_3	14240	9.03	5455	5.55	8629	8.99	12230	18.42	1898	9.39	7937	5.00
Ca	/	CaO	8340	5.17	7985	7.95	4882	4.98	1985	2.93	807	3.90	7642	4.71
Mg	/	MgO	1959	1.44	1005	1.19	2923	3.53	316	0.55	126	0.72	2009	1.47
Na	/	Na_2O	1550	0.93	155	0.15	598	0.59	207	0.29	377	1.76	4407	2.62
K	/	K_2O	3910	2.09	819	0.70	3346	2.94	424	0.54	260	1.08	4437	2.35
Ti	/	TiO_2	930	0.69	1125	1.34	733	0.89	721	1.27	164	0.95	851	0.63
P	/	P_2O_5	1196	1.21	728	1.19	284	0.47	67	0.16	351	2.78	66	0.07
S	/	SO_3	16160	17.88 2)	2330	4.14 2)	2705	4.92 2)	15858	41.68 2)	n.d.	n.d.	n.d.	n.d.
Total			116079	100.00	73491	100.00	72938	100.00	47677	100.00	15317	100.00	118647	100.00

1) obtained from ash analysis
2) obtained from CCSEM fuel analysis
3) ICP-AES

Appendix 1. Datasheet test coals

Name			Envirocoal	ICF Brair Atol	Kaltin Prima Coal	Envirocoal	Douglas Premium	Anker Diversen	Enerco Fines
Origin			Indonesie	Australia	Indonesia	Indonesia	South-Africa	South-Africa	
Batch			IFRF	BIN713	BIN725	BIN710	BIN721	BIN715	
Cal. val.	HHV [MJ/kg]		28.95	28.42	28.54	28.25	27.81	25.03	29.08
Proximate									
	Moisture	[% a.r.]	13.63	1.37	1.14	6.74	0.45	1.06	1.93
	Ash	[% d.b.]	1.99	8.69	5.15	2.17	14.40	20.42	9.00
	Volatile matter	[% d.a.f.]	47.98	28.97	41.83	45.72	26.98	30.02	36.81
	Fixed carbon	[% d.a.f.]	52.02	71.03	58.17	54.28	73.02	69.98	63.19
Ultimate									
	Carbon	[% d.a.f.]	83.95	81.96	78.16	78.91	83.51	82.03	81.01
	Hydrogen	[% d.a.f.]	5.92	4.44	5.49	5.47	4.46	4.44	5.38
	Nitrogen	[% d.a.f.]	1.17	1.89	1.81	1.09	2.05	2.03	1.61
	Sulphur	[% d.a.f.]	0.29	0.49	0.77	0.17	0.63	1.16	0.77
	Oxygen [meas.,	% d.a.f.]	24.85	12.18	14.01	22.03	10.73	12.53	13.31
	Chlorine	[% d.b.]	0.01	0.02	0.01	0.01	0.01	0.01	0.01

Ash																
			element 3) mg/kg a.r.	oxide % ash d.b.	element 3) mg/kg a.r.	oxide % ash d.b.	element 3) mg/kg a.r.	oxide % ash d.b.	element 3) mg/kg a.r.	oxide % ash d.b.	element 3) mg/kg a.r.	oxide % ash d.b.	element 3) mg/kg a.r.	oxide % ash d.b.	element 3) mg/kg a.r.	oxide % ash d.b.
Si	/	SiO_2	1345	22.21	16451	52.51	10316	50.59	2756	34.79	25316	44.68	32610	42.87	18384	48.30
Al	/	Al_2O_3	1357	19.79	14063	39.64	6756	29.26	1922	21.43	21052	32.81	24981	29.01	9385	21.78
Fe	/	Fe_2O_3	2180	24.07	2311	4.93	2605	8.54	1353	11.42	4273	5.04	6632	5.83	4832	8.49
Ca	/	CaO	1124	12.15	180	0.37	666	2.14	1225	10.12	6961	8.04	12316	10.59	1134	1.95
Mg	/	MgO	338	4.33	115	0.28	542	2.06	394	3.85	1246	1.71	2349	2.39	679	1.38
Na	/	Na_2O	323	3.36	83	0.17	491	1.52	454	3.61	172	0.19	264	0.22	364	0.60
K	/	K_2O	71	0.66	187	0.34	913	2.52	231	1.64	639	0.63	1154	0.85	1727	2.56
Ti	/	TiO_2	74	0.96	500	1.25	252	0.96	80	0.79	963	1.33	1163	1.19	311	0.64
P	/	P_2O_5	18	0.31	118	0.40	207	1.09	14	0.19	1161	2.19	1631	2.30	68	0.19
S	/	SO_3	631	12.15 1)	30	0.11 1)	229	1.31 1)	825	12.15 1)	1640	3.38 1)	3090	4.74 1)	4605	14.12 2)
Total			7462	100.00	34037	100.00	22978	100.00	9253	100.00	63424	100.00	86191	100.00	41488	100.00

1) obtained from ash analysis
2) obtained from CCSEM fuel analysis
3) ICP-AES

Appendix 2. Mineral composition test coals

Anker Diversen CCSEM mineral size distribution in weight percent

Mineral category	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	32-64 µm	64-125 µm	125-250 µm	Total
oxi. pyrrhotite						0.01			0.01
alumina	0.04	0.03							0.07
aluminosilicate	0.06	0.37	0.75	1.01	0.55	0.11	0.24		3.09
ankerite			0.01						0.01
apatite			0.86	0.29	0.15	0.12			1.42
ca silicate			0.17	0.08	0.22	0.03			0.49
ca-al silicate			0.62	0.88	0.44	0.22	0.10	0.17	2.48
ca-al-p			0.02		0.05	0.01			0.08
ca-rich			0.18	0.21	0.09	0.14	0.09		0.71
ca-si-rich			0.05		0.18				0.23
calcite			0.40	0.36	0.55	0.35	0.41	0.21	2.29
clay-pyrite			0.10	0.07					0.17
dolomite			1.69	2.13	1.44	0.27	0.34		5.86
fe silicate			0.01						0.01
fe-al silicate		0.06	0.07	0.01		0.03			0.18
fe-cr oxid			0.03	0.05					0.08
gypsum			0.10	0.21	0.30	0.06		0.15	0.82
gypsum/al silicate	0.01		0.10	0.10	0.19				0.39
illite	0.02	0.12	0.53	0.34	0.19	0.05	0.04		1.29
iron oxide			0.02			0.02	0.09		0.14
kaolinite	0.09	2.84	15.83	15.69	11.55	1.97	1.19	0.71	49.86
kCl			0.01						0.01
mixed silicate		0.03	0.04						0.07
montmorillonite	0.01	0.09	0.90	0.99	0.95	0.30	0.18	0.12	3.53
na-al silicate	0.01	0.28	0.16	0.33	0.17	0.02			0.97
pyrite		0.21	1.37	1.21	0.16	0.32	0.62	0.55	4.44
pyrrhotite				0.03					0.03
quartz	0.14	1.66	4.99	3.91	1.29	0.31	0.28	0.19	12.77
quartz-pyrite		0.07	0.03						0.09
rutile			0.10						0.10
si-rich		0.14	0.58	0.75	0.66	0.09	0.09	0.16	2.47
unclassified		0.10	1.39	1.40	2.29	0.51	0.21		5.90
Total	0.39	6.01	31.09	30.05	21.41	4.95	3.88	2.26	100.06

Appendix 2. Mineral composition test coals

Blend 11310 CCSEM mineral size distribution in weight percent

Mineral category	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	32-64 µm	64-125 µm	Total
oxi. pyrrhotite			0.03	0.06				0.09
alumina	0.03		0.01					0.04
aluminosilicate	0.12	0.63	0.84	0.75	1.06	0.29		3.69
apatite	0.13	1.60	0.40	0.38	0.24			2.75
ca silicate			0.08	0.16				0.24
ca-al silicate	0.07	0.15	0.57	0.63	0.59	0.12		2.13
ca-al-p			0.04	0.03				0.07
ca-rich		0.58	0.12	0.16	0.50	0.19	0.15	1.70
ca-si-rich			0.01					0.01
calcite		0.22	0.10	0.30		0.35	0.15	1.12
clay-pyrite			0.09	0.03				0.11
dolomite	0.05	1.17	0.88	1.00	1.36	0.07		4.53
fe silicate			0.01			0.03		0.04
fe-al silicate		0.04	0.12	0.11	0.17			0.44
fe-cr oxid		0.07	0.04		0.16	0.02		0.28
gypsum			0.16	0.15		0.24		0.55
gypsum/al silicate	0.07	0.10	0.16	0.24				0.56
illite	0.57	1.66	1.36	1.08	0.85	0.17		5.70
kaolinite	2.26	9.73	11.08	10.71	6.01	2.00	0.31	42.10
mixed silicate	0.08	0.08	0.13	0.07		0.03		0.38
montmorillonite	0.25	1.13	1.54	2.11	1.27	0.79	0.19	7.28
na-al silicate	0.06	0.27	0.04	0.14	0.23	0.02		0.77
pyrite	0.05	0.36	0.75	0.65	0.58	0.28		2.66
quartz	1.53	3.80	3.34	2.44	0.94	0.45	1.12	13.61
quartz-pyrite		0.07	0.03	0.13				0.23
rutile		0.24	0.06	0.05				0.35
si-rich	0.08	0.43	0.54	0.54	0.47	0.09	0.18	2.34
unclassified	0.37	1.95	1.53	1.61	0.57	0.21		6.24
Total	5.72	24.27	24.04	23.50	15.01	5.36	2.10	100.00

Appendix 2. Mineral composition test coals

Blend 11317 CCSEM mineral size distribution in weight percent

Mineral category	1-2 μm	2-4 μm	4-8 μm	8-16 μm	16-32 μm	32-64 μm	64-125 μm	Total
oxi. pyrrhotite						0.11		0.11
alumina			0.02					0.02
aluminosilicate	0.04		0.98	0.77	0.65	1.25	0.61	4.31
ankerite			0.02					0.02
apatite				0.07				0.07
ca silicate				0.15				0.15
ca-al silicate			0.21	0.72		0.58	0.52	2.02
ca-rich			0.03			0.07		0.10
ca-si-rich			0.04					0.04
calcite			0.08	0.14				0.22
clay-pyrite			0.11	0.11				0.23
dolomite		0.34	0.12	0.15	0.47	0.67	0.30	2.06
fe-al silicate			0.06	0.13				0.19
fe-cr oxid			0.02	0.17				0.19
gypsum			0.02		0.35	0.08		0.45
gypsum/al silicate			0.13	0.06				0.19
illite			1.43	2.02	1.03	0.34	0.28	5.09
kaolinite	0.39	8.40	8.39	7.78	4.40	4.29	1.01	34.66
mixed silicate			0.06	0.10				0.17
montmorillonite			1.03	2.29	2.56	2.05	2.26	10.19
na-al silicate			0.04					0.04
pyrite		0.82	0.16	0.75	2.11	1.70	1.68	7.21
quartz	0.47	5.79	4.39	4.63	5.16	2.15	2.57	25.16
quartz-pyrite				0.11		0.44		0.55
si-rich	0.13		0.47	0.68	0.77	0.32		2.37
unclassified		0.11	0.51	0.59	0.63	1.70	0.68	4.21
Total	1.03	15.46	18.32	21.42	18.13	15.75	9.91	100.02

Appendix 2. Mineral composition test coals

Douglas Premium CCSEM mineral size distribution in weight percent

Mineral category	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	32-64 µm	64-125 µm	125-250 µm	Total
oxi. pyrrhotite			0.03						0.03
alumina			0.02						0.02
aluminosilicate	0.08	0.26	0.43	0.43	0.56	0.45	0.10	0.36	2.67
ankerite		0.04	0.02						0.06
apatite	0.05	0.88	0.66	0.20	0.08	0.11			1.99
ca silicate			0.03	0.02		0.02			0.07
ca-al silicate	0.13	0.27	1.08	0.75	0.99	0.59	0.31		4.11
ca-al-p			0.01		0.12	0.11			0.25
ca-rich			0.07	0.07		0.23	0.08		0.46
ca-si-rich		0.07	0.02				0.23		0.33
calcite	0.01	0.11	0.06	0.17	0.10	0.18		1.37	2.00
clay-pyrite			0.05			0.04			0.08
dolomite	0.19	1.20	1.11	0.83	0.40	0.41			4.14
fe-al silicate	0.05	0.02	0.04	0.04	0.09				0.24
fe-cr oxid		0.07	0.08	0.09		0.05			0.29
gypsum			0.03	0.09					0.12
gypsum/al silicate	0.11	0.04	0.06			0.05			0.25
illite	0.41	0.39	0.49	0.05	0.06				1.40
iron oxide			0.07			0.05			0.13
kaolinite	3.77	10.90	13.90	12.93	7.83	4.20	3.49	1.81	58.85
mixed silicate	0.09	0.03	0.03	0.02					0.17
montmorillonite	0.22	0.27	0.42	0.60	0.13	0.19	0.54		2.35
na-al silicate	0.10	0.03	0.03						0.16
pyrite	0.04	0.18	0.55	0.59	1.33	0.71	0.75		4.15
quartz	0.37	0.95	1.76	1.79	0.63	0.47	0.33		6.29
quartz-pyrite	0.02								0.02
rutile	0.03		0.06						0.09
si-rich	0.05	0.06	0.30	0.46	0.35	0.11			1.33
unclassified	0.87	1.65	1.40	1.07	1.13	1.01	0.59	0.24	7.96
Total	6.59	17.43	22.82	20.19	13.80	8.97	6.42	3.78	100.00

Appendix 2. Mineral composition test coals

Econ-ZAf CCSEM mineral size distribution in weight percent

Mineral category	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	32-64 µm	64-125 µm	125-250 µm	Total
oxi. pyrrhotite			0.01						0.01
alumina	0.01	0.04	0.02						0.07
aluminosilicate	0.19	0.26	0.54	0.42	0.06	0.61	0.62	0.47	3.16
ankerite			0.00	0.02	0.10				0.12
apatite	0.20	1.00	0.56	0.31		0.12			2.18
ca silicate		0.03	0.09	0.02		0.01			0.15
ca-al silicate	0.21	0.34	0.49	0.63	0.53	0.13			2.32
ca-rich	0.12	0.63	0.19	0.20	0.43	0.44	0.33	1.39	3.74
ca-si-rich		0.09	0.04		0.12				0.25
calcite	0.04	0.50	0.23	0.33	0.30	0.40	0.57	1.06	3.42
clay-pyrite			0.02	0.08					0.10
dolomite	0.06	0.41	0.77	0.63	0.68	0.32	0.06		2.94
fe silicate			0.01						0.01
fe-al silicate	0.04	0.03	0.09	0.07	0.10	0.07			0.40
fe-cr oxid		0.13	0.08	0.02		0.03			0.25
gypsum			0.09	0.20	0.23	0.31	0.05		0.88
gypsum/al silicate	0.05		0.07	0.13		0.02			0.27
illite	0.34	0.37	0.59	0.66	0.08	0.07	0.65		2.76
iron oxide	0.03		0.02	0.09					0.14
kaolinite	5.31	10.40	12.86	9.74	6.59	3.55	2.47	0.40	51.32
mixed silicate	0.01	0.05	0.02						0.08
montmorillonite	0.37	0.29	0.54	0.88	0.06	0.92	0.31		3.36
na-al silicate	0.05		0.01	0.02					0.08
pyrite	0.07	0.94	0.74	0.53	0.66	0.50			3.44
pyrrhotite			0.03						0.03
quartz	0.80	2.71	2.94	2.28	1.17	0.74	1.01	1.14	12.79
rutile	0.02	0.05	0.07						0.13
si-rich	0.12	0.11	0.33	0.48	0.24	0.25	0.11		1.64
unclassified	0.50	0.87	0.87	0.92	0.30	0.33	0.16		3.95
Total	8.53	19.26	22.29	18.65	11.65	8.81	6.34	4.47	100.00

Appendix 2. Mineral composition test coals

Egyptian CCSEM mineral size distribution in weight percent

Mineral category	1-2 μm	2-4 μm	4-8 μm	8-16 μm	16-32 μm	32-64 μm	64-125 μm	125-250 μm	Total
oxi. pyrrhotite			0.04						0.04
alumina	0.09		0.01						0.10
aluminosilicate	0.03	0.07	0.10	0.17		0.06	0.30		0.74
ankerite					0.18				0.18
apatite		0.04							0.04
ca-al silicate	0.02		0.03			0.06			0.11
ca-rich	0.08		0.05	0.13	0.29	0.04			0.58
ca-si-rich			0.02						0.02
calcite	0.03	0.20	0.09	0.13	0.26	0.08			0.79
clay-pyrite	0.74	1.12	1.01	0.78	0.49	0.20	0.17		4.51
dolomite	0.02								0.02
fe-al silicate	0.01		0.02	0.03	0.23	0.02	0.13		0.45
fe-cr oxid	0.07	0.29	0.03						0.39
gypsum	0.01	0.55	0.23	0.60	0.96	0.05	0.58	0.62	3.60
gypsum/al silicate	0.05	0.08	0.07	0.18	0.10				0.48
illite	0.07	0.10	0.05	0.22		0.06			0.50
kaolinite	0.79	1.31	1.26	1.97	1.34	0.96	1.55	0.37	9.54
montmorillonite	0.19	0.35	0.46	0.70	1.12	1.12	2.19	0.48	6.62
na-al silicate			0.01					0.59	0.61
pyrite	1.87	3.14	3.71	3.30	5.48	4.10	9.43	7.23	38.26
pyrrhotite	0.38	0.42	0.07						0.87
quartz	0.82	2.80	2.41	1.75	4.03	1.02	3.80	4.21	20.84
quartz-pyrite	0.04	0.08	0.08	0.09		0.12			0.40
rutile		0.06	0.05						0.12
si-rich	0.07	0.05	0.06	0.27	0.16				0.62
unclassified	1.40	1.76	1.70	1.40	0.86	0.84	0.17	1.45	9.57
Total	6.79	12.44	11.56	11.74	15.49	8.70	18.32	14.97	100.00

Appendix 2. Mineral composition test coals

Enerco Fines CCSEM mineral size distribution in weight percent

Mineral category	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	32-64 µm	64-125 µm	125-250 µm	Total
oxi. pyrrhotite				0.05					0.05
aluminosilicate	0.09	0.42	0.53	0.60	1.52	0.48	0.19	1.44	5.27
ankerite								0.72	0.72
apatite			0.01	0.24					0.25
ca silicate		0.13	0.03						0.16
ca-al silicate	0.03	0.15	0.04	0.04		0.08			0.34
ca-al-p			0.02						0.02
ca-rich			0.05	0.05	0.19	0.07			0.36
calcite			0.02			0.04			0.06
clay-pyrite	0.04	0.70	0.26	0.19		0.35			1.55
fe silicate		0.07							0.07
fe-al silicate	0.10	0.17	0.48	0.29	0.19	0.03	0.18		1.44
fe-cr oxid			0.04	0.09		0.06		1.32	1.51
gypsum		0.05	0.25	1.04	1.88	0.51			3.73
gypsum/al silicate		0.24	0.27	0.47	0.50				1.48
illite	1.41	3.11	3.13	1.98	0.38	0.70	0.18	0.53	11.42
kaolinite	1.33	4.61	3.57	1.77	0.78	0.46	1.17		13.71
mixed silicate	0.05	0.40	0.05				0.18		0.67
montmorillonite	0.41	0.27	1.35	1.36	1.52	2.00	2.71	1.94	11.56
na-al silicate		0.17	0.26			0.22			0.64
pyrite	0.27	1.98	1.84	1.95	1.92	0.29	1.92		10.18
quartz	1.34	7.15	6.89	4.27	1.50	0.93	2.41	0.72	25.20
quartz-pyrite		0.11	0.08	0.05					0.24
rutile		0.29	0.06						0.35
si-rich	0.21	0.55	0.79	0.43	0.15	0.11			2.25
unclassified	0.79	1.10	1.21	0.46	1.27	0.94	0.44	0.54	6.75
Total	6.08	21.69	21.23	15.33	11.80	7.28	9.38	7.22	100.00

Appendix 2. Mineral composition test coals

Envirocoal (BIN710) CCSEM mineral size distribution in weight percent

Mineral category	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	32-64 µm	64-125 µm	125-250 µm	Total
oxi. pyrrhotite			0.08						0.08
alumina	0.31		0.18						0.49
aluminosilicate	0.27	1.15	0.32	0.68		0.35			2.77
apatite			0.12						0.12
ca silicate			0.08						0.08
ca-al silicate	0.18		0.15						0.33
ca-rich			0.20						0.20
ca-si-rich			0.11						0.11
calcite		0.61	0.26						0.87
dolomite	0.18		0.21						0.38
fe-al silicate	0.20		0.18						0.38
fe-cr oxid		0.78	0.05						0.82
gypsum			0.08	0.42					0.50
gypsum/al silicate	0.12		0.10						0.22
illite	1.23	0.81	1.96	0.17	3.65	0.57			8.38
iron oxide				0.51					0.51
kaolinite	4.10	3.33	4.06	2.09	0.63	1.63			15.85
mixed silicate			0.05						0.05
montmorillonite	1.06	0.73	0.60	0.78	2.30	1.04			6.51
na-al silicate	0.40		0.23						0.63
periclase			0.09						0.09
pyrite	0.89	1.25	0.73	0.41					3.28
quartz	7.40	11.75	7.26	2.79	3.69	2.28	3.71	9.57	48.45
rutile		0.85							0.85
si-rich			0.45						0.45
unclassified	1.94	2.16	1.74	1.06	0.66				7.56
Total	18.28	23.43	19.28	8.93	10.94	5.87	3.71	9.57	100.00

Appendix 2. Mineral composition test coals

ICF Brair Atol CCSEM mineral size distribution in weight percent

Mineral category	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	32-64 µm	64-125 µm	125-250 µm	Total
oxi. pyrrhotite						0.09			0.09
aluminosilicate		0.39	0.54	0.93	1.09	0.87			3.82
ca silicate			0.08						0.08
ca-al silicate			0.03	0.19		0.14			0.36
ca-rich			0.03						0.03
ca-si-rich			0.04						0.04
calcite			0.07	0.07					0.14
clay-pyrite			0.03	0.37		0.19			0.59
dolomite			0.03						0.03
fe silicate				0.12					0.12
fe-cr oxid			0.02						0.02
gypsum			0.03						0.03
gypsum/al silicate			0.04						0.04
illite			0.28	0.21	0.48	0.08	0.22		1.27
kaolinite		0.55	11.88	16.64	11.77	9.68	6.58	5.74	61.86
mixed silicate			0.02						0.02
montmorillonite			0.15	0.41			0.45		1.02
na-al silicate			0.02						0.02
pyrite			0.59	0.70	4.31	1.53	2.30	4.55	13.96
pyrrhotite				0.18					0.18
quartz	0.03	0.60	4.30	3.47	3.23	1.64	1.02		14.29
quartz-pyrite			0.07						0.07
rutile			0.12						0.12
si-rich			0.05	0.22		0.28			0.55
unclassified			0.32	0.32	0.53	0.10			1.26
Total	0.03	1.54	18.76	23.84	21.41	14.59	10.57	10.29	100.02

Appendix 2. Mineral composition test coals

Kaltin Prima Coal CCSEM mineral size distribution in weight percent

Mineral category	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	32-64 µm	64-125 µm	125-250 µm	Total
alumina	0.12	0.30							0.42
aluminosilicate	0.13	0.65	0.57	1.15	3.71	0.37	0.28	1.12	7.98
ankerite		0.11	0.09	0.14					0.34
ca silicate			0.08						0.08
ca-al silicate	0.31	0.22	0.20	0.20		0.08	0.31		1.31
ca-al-p		0.13	0.28		0.36	0.06			0.83
ca-rich							0.31		0.31
calcite	0.04						0.34		0.38
clay-pyrite	0.07					0.16			0.23
dolomite	0.06	0.19	0.10			0.03			0.38
fe-al silicate	0.18	0.19		0.16					0.53
fe-cr oxid		0.15		0.23		0.05	0.60		1.04
gypsum		0.06	0.07						0.14
gypsum/al silicate	0.30	0.10	0.22	0.30		0.10			1.03
illite	1.96	2.16	1.58	0.70	0.47	1.11	2.01	0.77	10.75
iron oxide							0.69		0.69
kaolinite	2.35	4.02	3.13	4.20	4.24	1.44	1.88		21.26
kCl				0.25					0.25
mixed silicate	0.54	0.28	0.06						0.89
montmorillonite	1.25	1.52	1.52	3.16	4.29	2.77	4.50	3.38	22.39
na-al silicate	0.15	0.04							0.19
pyrite	0.41	0.46	0.45	0.65	1.15	0.62		3.05	6.80
quartz	1.63	1.79	2.62	1.06		0.59	0.32	0.77	8.78
quartz-pyrite	0.02								0.02
rutile		0.08							0.08
si-rich	0.18	0.29	0.33	0.12					0.91
unclassified	3.28	3.93	1.87	1.38	0.34	0.44		0.76	12.00
Total	12.97	16.67	13.17	13.69	14.55	7.84	11.24	9.87	100.00

Appendix 2. Mineral composition test coals

Polish-56 CCSEM mineral size distribution in weight percent

Mineral category	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	32-64 µm	64-125 µm	125-250 µm	Total
oxi. pyrrhotite			0.01	0.05					0.06
alumina			0.01	0.04					0.05
aluminosilicate	0.21	0.26	0.28	0.43	0.28	0.44	0.82	2.55	5.27
ankerite		0.04	0.03	0.03		0.07			0.16
apatite	0.05		0.07	0.04	0.14				0.30
ca silicate	0.01	0.07	0.03	0.01					0.12
ca-al silicate	0.03	0.03	0.11	0.02		0.03			0.21
ca-al-p			0.01						0.01
ca-rich			0.02						0.02
ca-si-rich			0.00						0.00
calcite		0.07	0.03			0.04			0.14
clay-pyrite	0.01	0.14	0.02	0.05	0.11	0.14			0.47
dolomite	0.13	0.56	1.08	1.02	0.81	0.80	0.79		5.20
fe-al silicate	0.16	0.37	0.48	0.34	0.24	0.02	0.22		1.82
fe-cr oxid	0.04	0.03	0.13	0.11	0.06	0.03	0.09		0.48
gypsum	0.01		0.01	0.03	0.08	0.13			0.25
gypsum/al silicate	0.08	0.14	0.06	0.09					0.38
illite	1.80	2.49	2.42	1.88	1.92	2.68	2.65	2.95	18.77
iron oxide			0.03				0.34		0.37
kaolinite	2.16	3.55	3.56	3.66	2.92	2.33	1.74	0.52	20.44
mixed silicate	0.16	0.13	0.08	0.02		0.03	0.11		0.51
montmorillonite	0.55	1.15	0.95	1.39	2.43	3.16	4.99	5.32	19.94
na-al silicate	0.09	0.08	0.14	0.15	0.07	0.05			0.59
pyrite	0.19	0.28	0.53	0.78	0.26	1.72	0.60		4.36
pyrrhotite	0.02		0.01						0.03
quartz	1.23	3.45	2.74	1.39	0.13	0.93	1.27	1.92	13.06
quartz-pyrite		0.04	0.03						0.06
rutile	0.03		0.02						0.06
si-rich	0.20	0.52	0.29	0.42	0.09	0.22	0.19	0.21	2.14
unclassified	0.81	0.93	0.83	0.97	0.50	0.33	0.35		4.72
Total	7.97	14.32	14.03	12.89	10.03	13.15	14.16	13.47	100.00

Appendix 2. Mineral composition test coals

Spitsbergen CCSEM mineral size distribution in weight percent

Mineral category	1-2 µm	2-4 µm	4-8 µm	8-16 µm	16-32 µm	32-64 µm	64-125 µm	125-250 µm	Total
oxi. pyrrhotite			0.02	0.02					0.04
alumina	0.02	0.06	0.01						0.09
aluminosilicate	0.25	0.55	0.59	1.03	0.73	1.61	2.76	1.41	8.93
ankerite			0.01						0.01
apatite	0.07	0.29	0.04	0.02					0.41
ca silicate			0.04	0.02		0.01			0.07
ca-al silicate	0.11	0.33	0.14	0.09	0.11	0.07	0.07		0.91
ca-al-p	0.01		0.00						0.01
ca-rich	0.09	0.20	0.20	0.14		0.11	0.14		0.87
ca-si-rich	0.01		0.01						0.02
calcite		0.07	0.16	0.37	0.71	0.43	0.38		2.14
clay-pyrite	0.06	0.05	0.13	0.15	0.14	0.20	0.43	0.83	1.99
dolomite	0.09	0.09	0.16	0.13	0.15	0.03			0.65
fe silicate			0.01						0.01
fe-al silicate	0.07	0.02	0.10	0.05	0.11	0.05	0.06		0.45
fe-cr oxid	0.02	0.05	0.05	0.08					0.19
gypsum	0.02	0.10	0.03	0.17		0.31	0.70	0.33	1.65
gypsum/al silicate	0.08	0.19	0.05			0.01			0.33
illite	0.77	1.14	1.31	1.41	1.36	1.30	1.21	0.44	8.95
iron oxide			0.02						0.02
kaolinite	1.52	2.21	1.41	0.87	1.00	0.38	0.39		7.78
kCl			0.01						0.01
mixed silicate	0.05	0.05	0.02	0.03	0.10				0.25
montmorillonite	0.73	1.34	1.33	2.03	4.04	4.04	6.02	6.78	26.30
na-al silicate	0.06	0.12	0.19	0.20	0.10	0.02			0.69
pyrite	0.60	1.61	1.55	2.82	3.48	2.04	3.22	1.90	17.22
pyrrhotite	0.01		0.00	0.11					0.13
quartz	1.24	4.10	2.52	1.69	0.44	0.50	0.29	0.48	11.26
quartz-pyrite		0.06	0.04	0.02	0.06	0.02			0.20
rutile	0.01		0.03						0.04
si-rich	0.28	0.57	0.53	0.70	0.92	0.39	1.07		4.45
unclassified	0.65	0.74	0.61	0.38	0.32	0.35	0.47	0.41	3.94
Total	6.83	13.95	11.32	12.52	13.75	11.86	17.20	12.57	100.00

Appendix 3. Datasheet ash / deposit sampling campaign 2.5 MW$_{th}$ furnace

General

Fuel		Econ-Zaf	Egyptian	Egyptian |Econ-ZAf	Egyptian | Enviro	Enviro	Spitsbergen	Polish-56	Spitsbergen | Enviro	Fettnuss | Polish-56	Fettnuss | Spitsbergen	Genesee
Feed rate	(kg/hr)	320	290	180 | 120	190 |120	350		305	217 | 120	150 | 120	170 | 120	450
Air primary	(kg/hr)	112	112	115	134	120	111	120	107	107	110	110
Air secondary	(kg/hr)	2573	2555	2640	2674	2530	2553	2418	2525	2540	2606	2380
Air transport	(kg/hr)	397	398	400	398	400	400	398	391	397	396	400
Probe flame area												
Duration	(min)	73	75	78	101	87	70	77	69	68	63	72
Mass deposit	(g)	7.6	n.d.	n.d.	n.d.	n.d.	25	n.d.	n.d.	n.d.	n.d.	n.d.
Visual windside		large slag on top of probe (detached during cooling) plus small, brittle lumps	thin smooth layer (brown)	brownish layer with particulate lumps	brownish layer; small particles; some droplets, detached during cooling	alumina: brownish layer; SS316: dark brown-black layer; detached during cooling; few particles	lots of slag; droplets on top of probe (inner side black, surface grey); adhering to alumina, no to SS316	thin brownish layer; not much fly-ash; slag on top of probe; lots of slag on quarl	black, fully molten slag droplets on loose underlayer of coarse particles	top side probe: few particles (detached from SS316 by cooling); few slag droplets on SS316	loose particles (sand) on top of probe; some slag droplets	brittle deposit (grey-brown) of dendrite shaped material; rest of probe covered with white particles
Visual leeside		more, fluffy	brown layer with particles	little material	-	-	-	-	-	-	-	-
Gas temperature	(°C)	1334	1233	1330	1302	1270	1345	1270	1325	1340	1353	1040 ??
O_2	(vol%)	7.3	7.2	n.d.	5	4.6	3.4	10.2	8.2	5.2	7.9	15
CO	(ppm)	102	46	n.d.	210	340	1000	196	91	8	131	240
CO_2	(vol%)	12.9	12.5	n.d.	10.1	16.3	15.2	9.8	11.9	13.6	11.2	6.6
NO	(ppm)	537	486	n.d.	430	395	440	360	415	480	355	180
SO_2	(ppm)	475	1480	n.d.	1342	97	2050	400	882	500	640	100
SEM: x/r (*)	(-)	0.1->0.3	0.001-0.01	0.1-0.3	>0.3	<0.001	>0.3	>0.3	>0.3	0.1-0.3	0.1-0.3	0.1
Probe flue gas exit area												
Duration	(min)	105	65	70	65	84	80	76	67	69	63	70
Mass deposit	(g)	0.9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Visual windside		little brittle lumps	smooth thin layer (brown); no particles	brownish layer	brownish layer, no particles	yellow-brown layer; few particles	yellow-brown layer; few particles	yellow-brown layer; few particles; during run lots of material on probe, detached by removing the probe	grey/yellow/brown underlayer with individual particles on windside	layer of brownish particles	lots of brittle material, detached by cooling	sand-colored deposit on windside; wear pattern on top of the probe
Visual leeside		smooth 0.5 mm layer (powdery)	darker	darker	-	yellow-brown layer; no particles	-	-	only the layer	-	-	-
Gas temperature	(°C)	1080	1024	1072	1160	1100	1159	1195	1204	1126	1240	1040 (1175)
O_2	(vol%)	3.5	3.5	n.d.	3.5	n.d.	4	3.5	3.6	n.d.	n.d.	5.5
CO	(ppm)	30	3	n.d.	2	n.d.	4	4	6	n.d.	n.d.	6
CO_2	(vol%)	16	16.1	n.d.	16.6	n.d.	14.9	15.6	15.8	n.d.	n.d.	13.6
NO	(ppm)	670	473	n.d.	586	n.d.	400	480	516	n.d.	n.d.	310
SO_2	(ppm)	600	1921	n.d.	1455	n.d.	2075	700	1426	n.d.	n.d.	170
SEM: x/r (*)	(-)	<0.001	<0.001	0.001-0.01	<0.001	<0.001	>0.3	0.001-0.01	0.01-0.1	n.d.	n.d.	0.1
Probe particles												
Duration	(min)	5	5	5	5	5	5	5	5	5	5	5
Position		as deposit probe	as deposit probe	as deposit probe	as deposit probe	as deposit probe	as deposit probe	as deposit probe	as deposit probe	as deposit probe	as deposit probe	as deposit probe
Observations during sampling												
					very short flame, intensive burning, recirculation visible	furnace temperature increasing	quarl slagging; cleaned mechanically	large deposits on flue probe, detached by removing the probe			too short flame, problems tuning the flame	quarl slagging, cleaned

(*) Degree of sintering (quantified according to a definition of Raask [5]) from deposit inspection by means of SEM :

If x/r	Then
<= 0.001	deposit has no significant cohesive strenght, probably detached by gravity or boiler vibration
0.001-0.01	deposit probably removed by soot blowing
0.01-0.1	difficult to remove by soot blowing
0.1-0.3	ash particles lose their original identity, deposit cannot be removed by soot blowing

Appendix 4. Ash-related predictive indices for evaluation of slagging and fouling propensity

Ash Descriptors	Definition	Description / purpose	Comments
Base-acid ratio, B/A	%(Fe_2O_3+CaO+MgO+K_2O+Na_2O) / %(SiO_2+Al_2O_3+TiO_2)		
Lignitic ("Western") or	%(CaO+MgO) > %Fe_2O_3		
bituminous ("Eastern")	%(CaO+MgO) < %Fe_2O_3		

Ash Viscosity	Definition	Description / purpose	Comments
Ash fusion temperatures:	measured value		give indication of range where ash is sticky / viscous
T_{init} (°C)	cone is rounded	cooled particles still have slight sticking tendency	
$T_{fusion / softening}$ (°C)	cone is rounded, height=width	between initial deformation and fluidity	
$T_{hemisphere}$ (°C)	height=1/2*width	accelerated tendency to mass together or stick severely	most reported (reducing conditions)
T_{fluid} (°C)	height=1/16*width	coal ash flows down / drips	
T_x (°C)	graphically derived on basis of B / A and Si / Al ratio	temperature which gives viscosity x (Poise)	relevant for systems with fluid ash discharge; dry-bottom: T_{250} must be high (>1275 °C) wet-bottom: T_{250} should not exceed 1425 °C
Silica ratio	%SiO_2 / %(SiO_2+Fe_2O_3+CaO+MgO)	relates chemical composition to viscosity coal ash slag when $T>T_{cv}$ (transition slag from Newtonian fluid to Bingham plastic)	used to estimate slag build-up on water walls; silica ratio increases <-> slag viscosity increases

Slagging Propensity	Definition	Description / purpose	Comments
Base-acid ratio, B/A (for lignitic ash)	%(Fe_2O_3+CaO+MgO+K_2O+Na_2O) / %(SiO_2+Al_2O_3+TiO_2)	ratio of total base and total acid content of ash, correlated to ash melting and viscosity properties/problems	used in range 0-1; B/A < 0.7: T_{melt} and ash viscosity decrease with increasing B/A; low and high total base values result in high fusion temperatures; high acid slags have high T_{melt} and viscosity
Slagging factor, R_s (for bituminous ash)	(B / A) * (%Sulphur, d.b.)	relates ASTM coal ash analysis to fused slag deposits in radiant sections. expressing influence of Fe state of oxidation in slag	correlations made for eastern US coals
Iron-calcium ratio	%Fe_2O_3 / %CaO	indicator of (dry bottom) furnace slagging	seldom used
Silica-alumina ratio	%SiO_2 / %Al_2O_3	--	used to estimate T_{250} (Sage's method)
Fusion slagging factor, R_{fs} (for lignitic ash)	($T_{h.max}$ + 4*$T_{init.min}$) / 5		

Fouling Propensity	Definition	Description / purpose	Comments
Sodium content	%Na_2O_3 or %Na_2O	provide indication of how bad convection bank deposits might be if all of the coal-sodium were vaporised and condensed	additional information on form in which sodium is present is necessary for prop interpretation
Fouling factor, R_f (for bituminous ash)	(B / A) * (%Na_2O)	relate lab-ash analysis to tendency of alkali bonded deposits to form on convection tube banks	based on low-temperature ash is preferable due to Na-vaporisation; attempts made to relate R_f to strength of sintered fly ash, to relate to severity of foulir not to be applied to lignitic type ash
Total alkali content (for bituminous ash)	%(Na_2O + K_2O) expressed in %Na_2O_3, (coal- or ash-based)	used as a factor in predicting fouling tendency	esp. in Europe K is reported to be equally important as Na in fouling and corrosion; we point is lack of info on vaporisation
Total alkali content, water soluble	%(Na_2O + K_2O)	used as a factor in predicting fouling tendency, assuming that non-soluble alkalies are large complex molecules such as clays and that these will not decompose on heating	
Chlorine content	%Cl (coal, d.b.)	provide indication of volatile Na	relation between total Na and Cl not well confirmed
Strength sintered fly ash	p.s.i. (range 1000 to >16000)	indication of strength fouling deposits	based on lab-ash sintered at (normally) 925 °C; fly ash should be made with dedicat equipment
Sodium-potassium ratio	%Na_2O / (0.6589 * %K_2O)	appreciates observation that alkali iron trisulfate deposits have minimum melting point (and are most corrosive) when ratio = 1	cannot be used stand-alone

Other	Definition	Description / purpose	Comments
Organically-bound or ratio organic.-bound / mineral;	%organically-bound inorganic material;	appreciates reactive, fine inorganic species;	
Quartz, kaolinite ≤ 4.6µm;	%quartz, %kaolinite ≤ 4.6 µm;	appreciates that fine quartz may be carried to back end of boiler to react with Na or Ca to form sticky material	
Qtz≤4.6µm / Org (Ca+Na)	%(quartz ≤ 4.6 µm) / %(org-bound Ca+Na)		
CCSEM index	$\sum_{\min}[x_i \cdot (CaO + Fe_2O_3 \cdot (1 - 0.5 \cdot \frac{Fe_2O_3}{Fe_2O_3 + Al_2O_3 + SiO_2}))]$	appreciates specific "fluxing" effectiveness of Ca and Fe for aluminosilicate glass assuming that Ca assimilates completely (eff. 1) and Fe assimilation depends on form of Fe (eff. 0.5-1)	applies only to the fluidity and expected degree of consolidation of a resulting deposit

Appendix 5. Application of predictive indices to test coals

Tendency / value: low | medium | high | severe

Index		ECON mvb	<-blend-> 60/40	EGYPT (hvCb)	<-blend-> 61/39	ENVI/ifrl (subA)	ENVI/epz (subA)	<-blend-> 64/36	SPIT (hvA/Cb)	<blend> 1) 42/58	FETT 1) mvb	<blend> 1) 57/43	POLISH (hvAb)	KPC (hvA/Bb)	ENERCO (hvAb)	ICBA mvb	DGP2 mvb	AKMW mvb	B11310 blend	B11317 blend	GENS (hvBb)
Ash descriptor																					
Base-acid ratio (B/A)		0.20	0.26	0.64	0.70	1.04	0.54	0.32	0.30	0.28	0.21	0.27	0.29	0.21	0.21	0.07	0.20	0.27	0.24	0.17	0.19
Lignitic / bituminous		lignitic	bitumin	bitumin	bitumin	bitumin	lignitic	bitumin	bitumin	bitumin	bitumin	bitumin	bitumin	bitumin	bitumin	bitumin	lignitic	lignitic	lignitic	bitumin	lignitic
Ash viscosity																					
T_{250} of ash	[°C]	1482	1411	1221	1209	1179	1266	1364	1385	1392	1460	1399	1327	1488	1493	1649	1477	1399	1346	1477	1541
Silica ratio		0.76	0.70	0.50	0.48	0.35	0.58	0.71	0.72	0.73	0.77	0.74	0.73	0.80	0.80	0.90	0.75	0.69	0.72	0.80	0.85
Slagging propensity																					
B/A ratio, R_{BA} (lignitic ash, %CaO + %MgO > %Fe2O3)	2)	0.20	xx	xx	xx	xx	0.54	xx	xx	xx	xx	xx	xx	xx	xx	xx	0.20	0.27	0.24	xx	0.19
Slagging factor R_s (bituminous ash, %CaO + %MgO < %Fe2O3)		xx	0.36	1.57	1.14	0.29	xx	0.50	0.67	0.38	0.15	0.19	0.21	0.15	0.15	0.03	xx	xx	xx	0.10	xx
Iron-calcium ratio	3)	0.70	1.39	6.30	4.79	1.98	1.13	1.77	1.75	1.83	2.40	1.93	1.81	4.00	4.36	13.15	0.63	0.55	0.73	1.49	1.06
Silica-alumina ratio	4)	1.43	1.49	1.86	1.73	1.12	1.62	1.96	2.00	1.85	1.39	1.67	1.78	1.73	2.22	1.32	1.36	1.48	1.48	1.46	2.82
Fusion slagging factor R_{fs}	[°C]	n.d.	xx	xx	xx	xx	1184	xx	xx	xx	xx	xx	xx	xx	xx	xx	1396	1441	1375	xx	n.d.
Fouling propensity																					
Sodium content (lignitic)		0.11	xx	xx	xx	xx	2.86	xx	xx	xx	xx	xx	xx	xx	xx	xx	0.15	0.17	0.41	xx	2.02
(bituminous)		xx	0.14	0.21	0.48	2.80	xx	0.77	0.70	0.81	1.38	0.68	0.46	1.18	0.45	0.13	xx	xx	xx	0.57	xx
Fouling factor R_f		xx	0.05	0.19	0.45	3.49	xx	0.33	0.28	0.30	0.37	0.23	0.17	0.32	0.13	0.01	xx	xx	xx	0.13	xx
Total alkali in ash (coal-based)	6)	0.08	0.06	0.04	0.05	0.06	0.08	0.29	0.42	0.22	0.06	0.16	0.33	0.13	0.15	0.03	0.07	0.12	0.10	0.09	0.91
(expressed in equiv. %Na2O3) (ash-based)		0.47	0.47	0.47	0.74	3.17	3.72	1.79	1.73	1.77	1.94	1.97	1.98	2.48	1.72	0.30	0.47	0.61	0.95	1.19	3.22
Total alkali content, water soluble		n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Chlorine (% d.b.)	5)	0.010	0.033	0.068	0.046	0.009	0.008	0.039	0.055	0.078	0.095	0.097	0.099	0.007	0.007	0.016	0.006	0.010	0.008	0.009	0.003
Strength of sintered fly ash, psi		xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx	xx
Sodium-potassium ratio		n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Other																					
CCSEM index (Gibb, 1995)	7)	11.9		6.8			3.1		6.4				5.5	4.0	5.1	1.7	9.0	9.7	9.0	3.7	

Notes

1) SO3 n.d. 2) 1.0-0.75: high-severe 3) 0.31-3.0: medium-severe 4) low-high 5) 0.3-0.5: medium-high (relative judgement of values only) 6) not applicable to western (=lignitic) coals
7) no criteria available