IMPORTANCE OF COAL QUALITY FROM MINES TO POWER STATIONS

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ABSTRACT

Despite common use of coal in power generation, one overlooked aspect is that coal is a significantly heterogeneous and complex material and its fuel characteristics vary significantly in the deposits in any direction depending on the geological conditions. Therefore, a thorough geological investigation to understand these changes is not only essential in characterising fuel properties, but also minimising the economic, technical and financial risks associated with coal quality parameters. A geological model supported with comprehensive database is the appropriate starting point in managing the drastic changes that customarily occur in fuel properties. Once the coal quality variation is determined from the model, it may be possible to schedule the mine production from different parts of the pit according to the fuel specs. However, it is also important to establish a good, robust coal quality monitoring program to manage the changes occurring the field by implementing a well-controlled representative sampling and testing program managed by a dedicated coal quality department. Relying on only a few parameters to characterise the entire coal deposit, and consequently the fuel specifications could result in high risk and potentially expensive consequences. If coal quality is used effectively at any part of the coal chain from mine production to power station, it is possible to make significant cost savings, mitigate risks and provide a fuel clean enough to reduce pollutants and unwanted emissions.

Keywords: Geological-model, coal mine, sampling, coal assays, quality control, power-station

INTRODUCTION

Since the start of the industrial revolution in the 19th Century, coal has been one of the most efficient fuels and metallurgical materials available to mankind, allowing us to generate energy by burning it, and converting one substance to another through metallurgical processes. Although technology has advanced exponentially since the 19th Century and has reached a mature level in converting energy from coal, there are still fundamental challenges originating from the original material, i.e. coal, for technical professionals when dealing with thermal power stations. Power generation is an industry where engineers from a number of different disciplines are extensively involved in using whatever fuel material is available; applying complex solutions to energy generation. Although many fuel sources are relatively simple in their intrinsic properties (solar, natural gas, wind, water, nuclear etc.), one commonly forgotten aspect about coal is that it is a significantly heterogeneous material when it comes to its handling due its geological nature. As coal is the end result of original vegetative material undergoing a complex geological process called “coalification”, involving a number of different physical and chemical conditions to form a decent seam in the appropriate sedimentary environments, it is inevitable that the product quality from commercial grade coal seams will vary. In addition, one particular aspect is either forgotten or conveniently overlooked when dealing with coal in the public domain: i.e. not all coals are the same, as there is a significant difference between coking (metallurgical) and thermal coals. Coking coal is the essential component in many strategic metallurgical applications e.g. steel making and requires a number of appropriate coal quality parameters and controls to be in place prior to maximise its application, whilst thermal coal is mainly used for power generation which require certain of the coal quality characteristics to be identified. Unfortunately or conveniently depending on where loyalties lie, environmentalist lobbies do not distinguish between coking and thermal coals and brand them as the same, which is not the case and of course leads to misleading the public. These differences are also reflected in the commercial transactions/price settlements where the coal producer and the end user specify what type of coal will be delivered to the customer by the mining company with bonuses and penalties attached in the contracts (Kahraman and others, 1997). For this reason, a number of coal producers blend their products in order to meet tight contract specifications on coal quality. The coal quality also determines what type of boiler design, emission controls and power plant lay-out will be implemented in power generation. Despite clear understanding on coal quality, there are still challenges regarding coal quality in any thermal power station e.g. issues related to change in calorific value, moisture content, and mineral matter consequently ash content and ash chemistry, and its handling in the stockyards and chutes. This is likely due to forgotten facts that commercial quality fuel "coal" has heterogeneous properties that can change within a deposit, where they are extracted from in any direction depending on the geological conditions (Figure 1).

Figure 1. A very young lignite seam in Turkey associated with calcite rich fossiliferous layers and iron rich bands

For example, Central Electricity Authority (CEA) of India (2006) reported that of their 85 thermal power stations, the quality of the "range coal" actually received at power plants was vastly different from that of the design coal, resulting in a mismatch in design and actual characteristics of coal, causing significant maintenance and operational problems. It was cited by the CEA that many power plants received coal with much lower gross calorific value, which in turn was due to high ash content, resulting in lowering boiler efficiency and erosion of boiler tubes leading to high outages and high wear and tear of the crushing/milling and coal conveying systems. Due to the larger particle size of the coal (>5mm), none of their power stations could unload or were able to handle the coal. Some of these problems are not unusual in their nature and are of typical issues encountered at any power station on a daily basis, whilst the power station engineers focus on optimising the fuel ratio in generating energy and minimising the waste product ash in the operations. This paper highlights some of the geological basics which need to be reiterated to all stakeholders in that the fuel "coal" is a complex material and needs to be understood and characterised thoroughly, before its final usage for power generation in order to avoid some common technical issues originating from coal quality.

Issues Related To Coal Quality

Coal Characterisation In Coal Deposits By Geological Investigation

Coal characterisation in what are referred to as “coal basins” or “deposits” in relation to original depositional conditions is probably the most important aspect in fuel depiction. The aim of the whole coal characterisation exercise can be summarized as “determining the quantity and quality of fuel available from the ground”.

Coal characterisation can be undertaken by understanding the geological conditions that govern the properties of coal seams, which will subsequently determine coal quality specifications. As the coal formation is time dependent in terms of the geological history, it is important to consider that not all coal seams will have similar physical and chemical characteristics, even and despite being from the same deposit. Therefore, a thorough geological investigation through exploration campaigns, drilling and sampling programs, and laboratory assays is essential to characterise coal seams prior to their provision for consumption in coking or power generation.

Once the collected data has been entered into an electronic geological database and is evaluated for its accuracy, a geological model is run to predict seam properties and geological conditions, prior to coal winning from the ground (Figure 2).

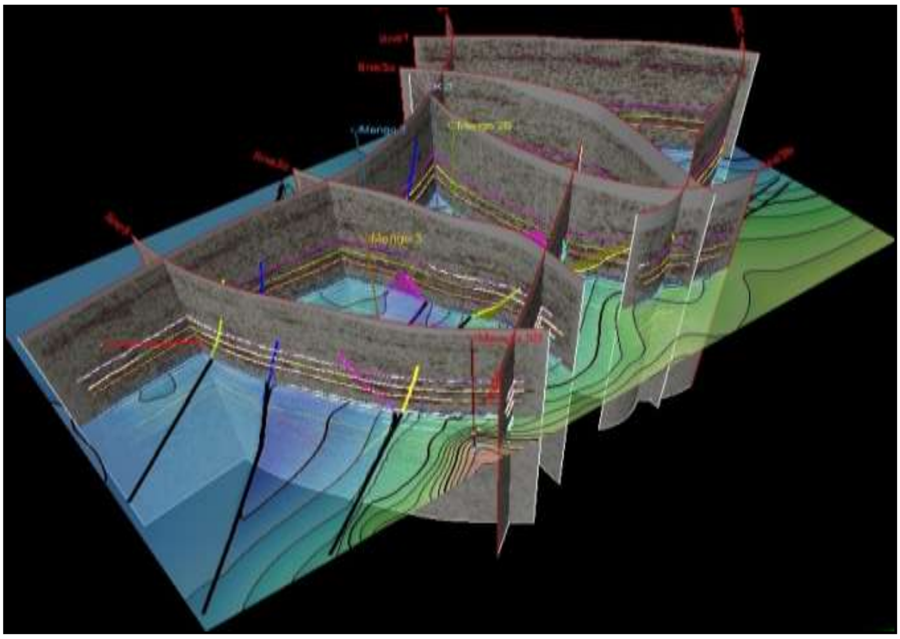

Figure 2. A geological model to predict coal seam properties and overall geological conditions

These investigations, using geological models, will also identify changes in seam geometry and morphology, trends and variation in chemical and physical properties as well as establishing the basic parameters essential to quantify the available resources/reserves from the deposit prior to its commercial use.

If insufficient investigations are conducted and the investment decisions are taken on this basis, it is inevitable that some expensive lessons will be learnt.

There are number of international standards, guidelines and safeguards (e.g. JORC (2012), PERC (2013) etc.) dictating how proper investigations can be undertaken in order to solicit investment which is beyond the aim of this paper (Arden & Lewis, 2014). However, it is highly recommended that the thorough investigations should be undertaken based on these international classifications, in order to minimise the uncertainties and financial risks.

Nevertheless, it may seem odd to point out the obvious but it is still critical to indicate the fact that the power plant must have sufficient and sustainable quality fuel throughout its economic life if the thermal plant and captive mine are part of an integrated operation. Therefore, establishing the amount of power plant fuel supply at the beginning of the power generation project, which will be reflected in coal seam resource/reserve estimation for the planned period (usually between 20-40 years), is essential for the project economics.
In the following sections, some of the important geological factors governing the coal quality aspects in relation to power stations are given.

Influence Of Coal Seam Formation And Mineral Matter

Coal seam formation depends on geological conditions and locations where original vegetative material was initiated to accumulate and transform into carbon rich substances known as “macerals” (similar to minerals in other rocks, namely vitrinites, liptinites and inertinites) after burial through coalification process.

Significant chemical changes occur in the original plant material through time combined with burial and thermal processes resulting in rank increases that usually follows the pattern during the coalification process below (Figure 3).

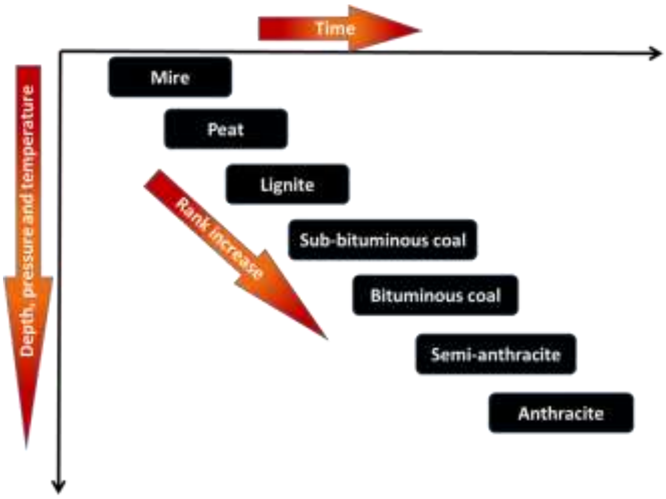

Figure 3. Stages of coalification and rank increase as a function of age, depth, pressure and temperature

Although the principles of the coalification process are similar everywhere throughout geological history, the geographical location and geological era, and different geological conditions governing coal deposits can make a significant impact on the end product. This is particularly well pronounced in seams developed during Permian in Gondwana (Southern Hemisphere) and during Carboniferous in Laurasia (Northern Hemisphere) coal deposits due to different floras and climatic conditions dominating these geographical areas at the time (Reifenstein and others, 1993; Kahraman, 1996).

Decrease in volatile matter and increase in vitrinite reflectance is the most pronounced chemical effect observed in the coalification process.

The effect of rank is clear in the physical appearance of coal by displaying a dull earthy looking mixture of vegetative material at peat stage to well-developed lustrous banded structure at bituminous stage to a dense vitreous blackish grey matter at anthracite stage.

In the majority of cases, plant assemblages contributing to the coal seam formation deposited in the original sedimentary area, need to be away from clastic influence in order to form a decent coal seam. The resultant seam after deposition, burial and subsequent coalification will compose of mostly macerals, volatiles, moisture and some mineral matter.

During the coalification process, the original plant matter from different floral assemblages is converted to macerals; and macerals along with the majority of the volatile matter will crucially provide the fuel component in coal. However, the behaviour of individual macerals are also important in combustion characteristics. For example, vitrinite rich macerals (originally woody and gelified tissues) will have a relatively shorter combustion time in the boilers compared to inertinite rich components (original charcoal like appearance with cell walls) (Falcon and others, 2012; Gentzis & Chambers, 2009). However, Holcombe and others (1997) demonstrated that that there is no general correlation between the combustion reactivities of vitrinite and inertinite macerals in Australian coals i.e. in some coals vitrinite macerals are more reactive, whereas in other coals the inertinite macerals are more reactive. Su and others (2001) later demonstrated for a group of Australian and international coals that a proposed maceral index with vitrinite reflectance and fuel ratio correlates with the burnout and has potential for correlating the ignitability and flame stability.

Moisture is a particular issue in lower rank coals as the maturation process in coalification is incomplete hence the excess amount of water present in the seams. In addition, many coals are washed with water during preparation for market specifications and then maybe subject to humidity (rain and snow) during extraction, transportation and storage. All of these sources contribute to the moisture in coal and, therefore, to the problems associated with its measurement. The total moisture in coal is the determination of moisture (in all forms except water in crystal structure of the mineral matter) that resides within the coal matrix. Once it is present in high quantities, moisture can adversely affect the calorific value and coal handling properties in the stockyard and chutes. Therefore, it may be essential to dry the product coal either in the ground (dewatering) or on the surface, prior to its usage in the boilers.

In the geological history of coal deposits, the mineral matter in coal has commonly been introduced into the seams through frequent flooding from water courses or marine incursions, from volcanic eruptions in the form of volcanic ash, from igneous intrusions in the form of dykes, veins and sills, or from diagenetic processes resulting in accumulation of newly formed minerals in the strata. For example, any encroachment into depositional area by rivers during the formation of peats would end up having some horizontally laid down dirt partings and lenses in coal seams (Figure 1). For this reason, the amount of mineral matter in the coal varies from seam to seam, even along the same seam.

Mineral matter will form the basis of the ash content and consequently the composition of ash and its behaviour and impact in power station boilers and its handling in the coal stockyards and chutes. The efficiency of a combustion unit is related to the amount of ash produced due to its diluent nature. Any presence of dirt/clastic partings in the seam will also lower the calorific value of the coal seams.
Coal seams can contain a variety of minerals. These include;

- **common species**: quartz, clays (illite, montmorillonite, kaolinite, mixed layer clays) carbonates (calcite, siderite, ankerite), sulphides (pyrite, marcasite); oxides ores (hematite, goethite), phosphates (apatite), and
- **some accessories**: galena, sphalerite, chalcopyrite, crandallite group, monazite, barite, rutile, zircon, feldspars, zeolites, and micas.

In addition to the above list, a number of trace elements associated with the minerals listed above and outside the list may be present in the coal and dirt partings present in the run-of-mine (ROM) product. This is particularly important as emissions of some of these trace elements into the environment are strictly restricted by local rules and regulations. For example Dale (1995, 2002, 2006) indicated that the most significant difference between Australian and international coals was in the levels of arsenic, selenium, mercury and boron. Australian coals contained substantially lower concentrations (up to 35 percent of the levels in international coals) of these elements which are of major environmental concern internationally and is to be enforced under IFC (International Finance Corporation) Performance Guidelines, Standards and Equator Principles.

These elements are volatile and therefore may be released to the atmosphere through gaseous emissions and in stack particulates. For example, selenium and boron are of particular concern to Japanese utilities because these elements are volatile during combustion and report to the discharge streams of Flue Gas De-sulphurisation (FGD) units. Water and soil regulations imposed by Japanese Government authorities place limits on the discharge of trace elements from wet FGD units for a number of trace elements including arsenic, boron, cadmium, chromium, mercury, fluorine, copper, lead, selenium and zinc (Dale, 2006). Limits are also imposed on the leaching of trace elements from fly ash and include arsenic, cadmium, lead, chromium, mercury and selenium. These limits apply to both the leaching of landfill and water at landfill sites.

It is inevitable that fuel composed of useful organic carbon components and the waste product originating from the above minerals will ultimately determine the performance of coal in power station use. Speight (2005), however, commented that it is difficult to determine, either qualitatively or quantitatively, the mineral matter content of a coal from high-temperature ash [usually >750°C]. Of the major mineral groups, only quartz is not significantly altered during high-temperature ashing whilst clay minerals containing water is lost during high-temperature ashing.

However, Kahraman and others (2001) demonstrated from a newly developed ash fusion test that this test uncovered a prime dependence of the fusion behaviour on the mullite content of the ash, which in turn is governed by the original alumina content of the coal mineral matter. The results indicated that the greater the amount of mullite in the sample the greater the event temperatures which might be the function of both a chemical effect and a physical effect of the interlaced structure of the mullite crystals. Quartz and kaolinite were found in all low temperature coal ash samples as major components, with anatase, gypsum, siderite and illite-smectite (IS) as accessories. Minor analcite or leucite and trace jarosite or pyrite could be present in some coals tested, but no trace of phosphate minerals such as apatite could have been identified with any certainty.

Behaviour of some minerals at high temperature is given in

Table *1*.

Table 1. Behavior of some minerals on high temperature (from Speight, 2005)

Inorganic Species	Behavior on Heating
Clays	Loose structural OH groups with rearrangements of structure and release of H_2O
Carbonates	Decompose with loss of CO_2; residual oxides fix some organic and pyritic S as sulphate
Quartz	Possible reaction with iron oxides from pyrite and organically held Ca in lignites; otherwise, no reaction
Pyrite	In air, burns to Fe_2O_3 and SO_2; in volatile matter test, decomposes to FeS
Metal oxides	May react with silicates
Metal carboxylates (lignites and subbituminous	Decompose; carbon in carboxylate may be

only)	retained in residue

It is also common knowledge that presence of Na and other alkali rich minerals will contribute into the fouling whilst minerals containing high amounts of Fe, Mg, and Ca along with Na and K will result in excess amount of slagging in the boilers based on their “base/acid ratio”. In the meantime, high concentration of Si rich minerals will contribute into the formation of fly ash.

Also, if a high concentration of sulphur is present in coal either in organic (intrinsic sulphur embedded in the original plant matter) or inorganic (e.g. pyrite, marcasite, barite, gypsum, anhydrite etc.) form, this will eventually contribute into the SO_x emissions though reactions involving oxidation of pyrite and marcasite to ferric sulphate [$Fe_2(SO_4)_3$] and Sulphur dioxide (SO_2). Some of the sulphur dioxide may remain in the ash in combination with calcium, but much is lost.

Sulphur in combination with sufficient moisture level and grain size distribution, combined with other complex intrinsic (rank and petrographic constituents of coal, friability, particle size and surface area of coal, presence of iron pyrites and other minerals, presence of bacteria etc.) and external conditions (temperature, wind, atmospheric pressure etc.) can also propagate spontaneous combustion in the pits and stockyards which ends up in losses of the fuel and dangerous working conditions (Figure 4).

Figure 4. Spontaneous combustion a) in a lignite stockpile in Turkey; b) and in a coal seam in Kazakhstan

Presence of chlorine in the form of organic compounds and inorganic forms such as halide minerals and other chlorine containing minerals such as hydrophilite and chloromagnesite can cause severe corrosion in boilers.

Excess amounts of clay associated with the coal seams in ROM product will cause handling problems at the pit level, and the primary/secondary crushers, conveyor belts, train wagons (O’Brien and others, 2002; Planner, 2014), stockyards, and chutes due to the stickiness of the coal particles mainly associated with the clay film enveloping the particles ending in an agglomeration process between the coal lumps. This can have severe consequences at the power station supply chain such as fuel shortage or delays due to coal not being fed into the boilers through malfunctioning primary and secondary crushers, conveyor belts and blocked chutes.

Therefore, as the above examples indicate, it is essential to know how the coal seams are formed and developed throughout the deposit, so that advance planning can be undertaken in the mine production schedule in order to meet power plant quality and quantity requirements.

Minimising Risks On Coal Quality For Power Station Usage

In order to minimise the adverse effects of coal quality, it is important to implement some fundamental measures at the coal pit and power plant stockyard if both the coal mine production and power plant generation are particularly part of an integrated power generation system. However, these measures also applicable to any mine that sells its products in the open market to any power generation utility, or any power station that buys thermal coal from any coal producer.

Mitigation measures on the adverse effects of coal quality include a number of crucial steps:

- Establishing a good geological and exploration/coal quality database containing all necessary information to characterise the target seam/s feeding into the power station. This is also a fundamental part of the power stations' design criteria to determine the operational inputs for the duration of power station's lifespan;
- Implementing a good robust sampling and sample monitoring program reflecting accurate representative results obtained at pit level and power plant stockyard;
- Performing the appropriate tests and assays which represent the real performance of coal and its waste product prior to plant design and during plant operations; and
- Providing fuel by blending the ROM product from the pit based on the coal quality and boiler design parameters.

Database Establishment

The creation of a comprehensive database not only helps to exhibit the spatial relationships of outcrop, borehole and sampling locations allowing the creation of contour plans for coal quality parameters in the deposit, but also assists in the preparation production schedules, sampling and blending activity for coal specifications.

Once the coal is characterised in the field from a captive mine, the design criteria for the power station's operational inputs can be determined for the duration of a power station's lifespan accordingly. This will also give the opportunity for boiler engineers to operate the boiler efficiently by adopting either an online analyser and monitoring program or implementing a manual quality control protocol managed by a dedicated quality control team. Either way, a manual or automated system, should ensure that the data collected from the field is suitable for the thermal coal to be burnt in the boilers. For example, Tillman & Duong (2007) reported that a database and online analyser monitoring program was successful in managing slagging and fouling and was extended to provide guidance for the operators managing opacity through controlling SO_3 injection to influence ash resistivity using models driven by data from the online analyser.

Mahr (2010) reported that poor lignite product quality significantly improved at mine mouth Red Hills Thermal Power Plant located in northern Mississippi, USA when an online system had been introduced into operations.

However, it is also important to choose an appropriate online system to control coal quality. Kavouridis and Pavloudakis (2007) considered that the poor performance of the chosen online analyser was due to the multi-seam structure of the lignite deposit that consisted of many lignite layers of varying thickness separated by waste layers which led to significant fluctuations of the produced lignite quality. The most important causes for the errors were attributed to the intense variation in ash content and the fluctuation in mineral matter composition, especially the changes in FeO_3 and CaO content and also the rapid changes in lignite weight per conveyor belt unit area.

Larson (2016) also commented on the Longview Power Plant operation built in West Virginia, USA in 2011 that the initial design problems were partly due to wrong fuel specs, inaccurate and unreliable process measurements, and online glitches were eventually rectified after an extensive rehabilitation program including replacement of the entire distributed control system which turned it into one of the cleanest and most efficient thermal power stations in the US.

Coal Quality Protocols And Monitoring

Data collected from operations will be able to be used to identify and avoid problem areas and help to predict poor performance and prepare remedies for the design coal specifications. However, this requires a dedicated technical team to handle such aspects in corporation with the power plant engineers.

For this, it is essential to establish a robust coal quality program on site which consists of various protocols on

- personnel training for coal quality;
- procedures for representative sampling from various locations including boreholes, working coal faces, stockpiles, conveyor belts, train wagons, trucks etc;
- sample registry;
- sub-sample preparation;
- sample dispatch and storage;
- sampling interval (shift-based, daily, weekly, monthly, etc.);
- chain of custody related to sampling;
- identification of necessary tests and assays;
- selection of laboratories;
- round robin exercises to check the consistency and accuracy of the results from the laboratories;
- data registry and record management; and
  technical team arrangements and management.

Once the coal quality team and protocols are in place, it is also essential to monitor the coal quality over time.

Representative Sampling

Sampling of coal is always a complicated area due to the heterogeneous and complex nature of the material and thus presents a number of challenges to the practitioners in the field. Therefore, obtaining a representative sample (usually a few hundred grams in quantity) from any particular seam, coal deposit, stockpile, conveyor belt, train wagon, or cargo is always a complicated issue since the sample selected should be able to ensure the true representative of the bulk material, and should not undergo any chemical or physical changes after completion of the sampling procedure and during storage prior to analysis.

Unfortunately, the importance of this activity is often neglected or overlooked in the operations, resulting in some unwanted consequences. For the interpretations and comparisons of elemental compositions and other coal quality characteristics to be valid, the samples collected should be representative of the coal bed or the bulk of the material where the sample was collected in as reproducible and repeatable a manner as possible. If not, the data derived from the most carefully conducted analyses are meaningless or redundant due to the substantial variation in coal quality and composition from the roof to the bottom both horizontally and vertically in a strata (Speight, 2005). This variability in coal composition and hence in coal quality is often significantly, and unintentionally, increased by mining, preparation, handling and transportation (by belt, rail, or truck).

Therefore, it is crucial to prepare, monitor and supervise the representative samples according to the well-established procedures and standards (ISO, ASTM, AS etc.) to ensure the resultant coal sample's representativeness of the composition of the whole coal (i.e., coal in a bed or pile or coal in a railcar or truck or cargo) for the properties or quality of the sample.

Speight (2005), for example, commented that blended coal samples from multi-seam operations ranging from 10% by weight mineral matter to as much as 30% by weight mineral matter could result in a corresponding difference as large as 4 to 5% with corresponding differences in the amount of ash that remains after combustion.

A carefully designed sampling program can ensure such concerns are addressed. This will take into consideration the potential for differences in the analytical data and involving acquiring samples from several planned and designated points within the coal stockpile so that provisions are made for changes in the character of the coal as well as for the segregation of the mineral matter during and up to that point in coal's history.

Unfortunately, many issues encountered at thermal power plants are partly due to samples being collected in an unrepresentative manner. This even includes the samples to characterise the fuel representing the deposits at the beginning of the project at the feasibility study stage which consequently ends up having an inappropriate boiler design for the fuel used.

Conducting Appropriate Assays And Tests

Prior to any analysis or test, it is important to store representative samples in the correct manner to avoid physical and chemical changes hence artificially induced results. For example, for all measurements of calorific value, caution is necessary during sample preparation since oxidation of coal after sampling can result in a reduction of calorific value, particularly in lignite and sub-bituminous rank coal samples. Therefore, unnecessary exposure of samples to the air from the time of sampling or delay in analysis must be avoided.

As the analyses or tests are the fundamental bases of fuel characterisation, it is important to apply all the relevant tests in line with the coal properties. The tests highlighted in

Table *1* are a suit of analyses commonly used in characterisation of the fuel properties in coal.

Table *1*. Laboratory assays to assess the suitability of coals for power station usage

Test	Preferred Standard
Proximate analysis (moisture, ash, volatile matter, fixed carbon)	ISO
Ultimate analysis (C, H, N and O by difference)	ISO
Calorific value (gross and net)	ISO
Sulphur determination (pyritic, sulphate and organic)	ISO
Ash chemistry (oxides of Al, Ca, Fe, Mg, Mn, P, K, Si, Na, and Ti)	ISO
Crucible Swelling Number/Free Swelling Index	ISO
Apparent Relative Density	ISO
Petrographic analyses (maceral and reflectance [Rvmax])	ISO/AS
Size distribution	ISO
Washability tests	ISO/AS
Hardgrove Grindability Index	ISO
Spontaneous Combustion Test	ISO/AS/GOST
Ash fusion characteristics in reducing atmosphere	ISO/AS
Trace element analysis, (Sb, TI, Te, Ti, V, Zn, Mn, Ni, Cd, Cr, Co, Cu, Pb)	ASTM
Mineralogical studies (XRD, Thin Sections, SEM)	Various
Gas tests (desorbed and residual)	ISO

Test	Preferred Standard
Combustion tests and ash deposition characteristics	Various

The most commonly used tests include proximate and ultimate analyses. Trace elements such as Cl and Hg are also commonly included in ultimate analysis, but more specific elements are included in the more comprehensive trace element analysis to ensure that local or international restrictions on emissions will not be breached.

Coal's mechanical properties such as hardness, grindability and friability (the consequences of combination of coal macerals and its mineral content) which can affect coal pulverisation and its handleability, are also routinely determined by laboratory tests.

Coal washing is usually not a common practice in thermal coals, but it gains acceptance due to improvements in coal quality and sizing for handling, processing, and combustion requirements by removing the inorganic impurities. Therefore, it is possible to make significant improvements to the fuel specifications as well as the environmental concerns (for example SO_x, NO_x and CO_2 emissions) if the project economics have been calculated to allow coal to be washed prior to its use in thermal power stations.

For combustion characteristics, the calorific value or heating value, the ash composition, and its behaviour at high temperature in ash fusion tests are commonly used.

Although the correlation of the laboratory tests with the actual utilisation of coal is only an approximation of the real situation due to the relative homogeneity of the test sample compared to the heterogeneous mixture of ash, conditions during coal combustion are so complex that they are impossible to duplicate in a small-scale laboratory test completely.

For this reason, a number of formulas based on ash analysis and ash fusion temperatures alone cannot be precise to predict the performance of ash i.e. its slagging and fouling characteristics in the boilers. In some circumstances it is necessary to know the heat capacity and thermal conductivity of a coal as well as combustion performance in a test furnace.

Kahraman and others (1998a) demonstrated that using standard ash fusion temperatures cannot on their own explain the performance of the coals in thermal power stations due to the difficulties associated with the existing test's subjectivity and with coals being identified as having a wide range of initial deformation temperatures (Figure 5).

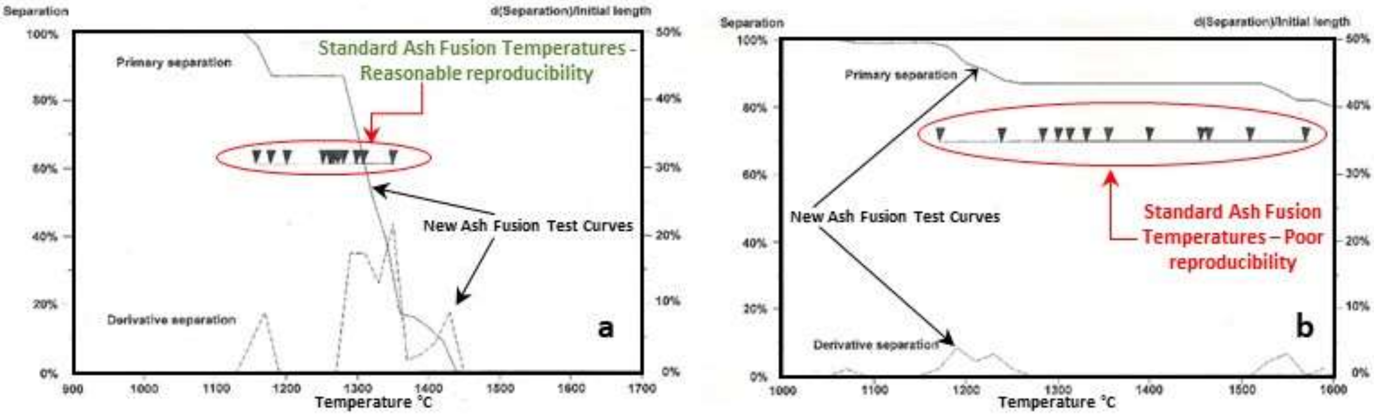

Figure 5. Comparison of standard ash fusion temperatures with a newly developed ash fusion test in an interlaboratory exercise in Australia a) reasonable reproducibility where the operators had an

acceptable agreement; b) poor reproducibility where the operators had difficulty to identify initial deformation temperatures from the same ash (Kahraman et al., 1998)

An alternative test proposed Coin and others (1994) and Kahraman and others (1995, 1998a,b; 1999, 2000, 2001) showed that indications of mineralogical changes, occurring in high temperature environments, are more pronounced in the new test than the standard ash fusion test's ability to identify the fundamental changes occurring in the boilers since quartz, mullite, cristobalite, hematite, magnetite, gypsum, anatase and glass were found in both slagging panel deposits and new ash fusion test products. The new ash fusion test also successfully predicted the troublesome coals in the combustion testing.

The tests mentioned in

Table *1* above are essential to characterise the fuel properties from mine to the power station stockyard, but whatever the tests used in characterising the fuel component, it is also important to remember that the availability of the results from these analyses in a timely manner is crucial in the decision-making process. Therefore, a dedicated coal quality monitoring program must be able to predict promptly what is fed into the thermal power plant from the mine pit prior to burning and act upon if and when necessary to optimize/adjust the coal quality.

Meeting The Fuel Specs And Coal Blending

As market conditions change rapidly, and emphasis on the use of indigenous coals is becoming more important locally (Selvitop, 2016), and as environmental restrictions are increasingly tightened, coal blending is gaining more acceptance in the power generation industry.

Coal blending can be an expensive and a time consuming exercise, however, on-site blending allows blends to be created and altered to suit the plant with far more precision than a blend bought on the open market.

Since geological conditions can significantly vary in the field and the coal seams extracted from coal faces can differ considerably in composition and quality, the geological model is initially essential in order to establish these changes, particularly coal quality. Once the coal quality is known from the geological model, it is possible to determine the appropriate blend to meet the fuel specifications for the thermal power plant used at the mining operation. This can be conducted at the pit level mostly by scheduling the seam winning from the mine operations based on the inputs coming from the geological model.

Many methods of coal blending are used to meet the fuel specs at various levels. Coal blending can be undertaken almost anywhere in the coal chain: at the coal mine, at the preparation plant, trans-shipment point, or at the power station. The method selected depends upon the site conditions, the level of blending required, the quantity to be stored and blended, the accuracy required, and the end use of the blended coal.

Once the coal is transferred to the stockyard, it is still important to know the stockpiles' coal quality status to blend the fuel further so that the required specs are met for the boiler use (Han and others, 1999; Mahr, 2010; Sloss, 2014).

The desirable product either through homogenised and blended ROM material and/or washed coal should be able to ameliorate the following categories: improvement in coal handleability; reduction in ash and ash handling; reduction in emissions; reduction in maintenance and power usage cost;

Increase in boiler efficiency; decrease in slagging and fouling; and increase in power output generated from the power plant.

Since coal quality is ultimately the driving force in optimising operations and efforts to provide desirable, clean coal to power stations in line with the technical and environmental concerns, a dedicated coal quality control team in close association with the geology, mining and power plant departments should be responsible for managing coal quality issues and preparing the blends accordingly.

CONCLUSIONS

Despite coal's existence in power generation since the industrial revolution, the aspect that is commonly overlooked is that coal is a significantly heterogeneous and complex material and its fuel characteristics vary significantly in the deposits in any direction depending on the geological conditions. Therefore, a thorough geological investigation to understand these changes is crucial in characterising fuel properties.

In order to minimise the economic, technical and financial risks associated with coal quality parameters, it is important to establish a comprehensive database in regards to coal quality. A geological model is the appropriate starting point in managing the drastic changes that habitually occur in fuel properties.

Once the coal quality is determined, it is possible to schedule the mine production from different parts of the pit according to the fuel specs. However, it is also important to establish a good, robust coal quality monitoring program to manage the changes occurring the field by implementing a well-controlled representative sampling and testing program managed by a dedicated coal quality department. The analyses should be comprehensive enough to reflect the changes in fuel properties. Relying on only a few parameters to characterise the entire coal deposit, and consequently the fuel specifications could result in high risk and potentially expensive consequences.

If coal quality is used effectively at any part of the coal chain from mine production to power station, it is possible to make significant cost savings, mitigate risks and provide a fuel clean enough to reduce pollutants and unwanted emissions.

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