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Understanding the Business of Coal

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Laboratory Methods for Predicting Coal Performance

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Introduction

The current environmental and economic pressures on the utility industry make the ability to predict and evaluate a coal's performance using laboratory analyses a powerful tool. This is because power plant equipment like the boiler, precipitator and pulverizers limit the types of fuels that can be used. The large variety of coals available make finding the most suitable fuel for a plant a complex task. This paper will summarize several techniques which can simplify this task.

The major areas of performance affected by coal quality are:

- Handling - Dust, Pluggages and Self-Heating
- Combustion Efficiency and Stability
- Boiler Efficiency
- Boiler Slagging
- Boiler Fouling
- Electrostatic Precipitator Efficiency
- Pulverizer Capacity
- Cyclone Tapping

One or more techniques will be presented here to evaluate each area. It is important to use the most representative sample of the coal under consideration. Failing to do so may lead to an incorrect evaluation of the coal's performance. It is recommended that several samples or composite samples be used.

The coal analyses used by many predictive techniques are American Society for Testing and Materials, ASTM, procedures.[1] [2] [3] [4] [5] and [6] These are:

- Proximate
- Ultimate
- Major and Minor Elements in Coal Ash
- Ash Fusion Temperatures
- Hardgrove Grindability Index

Other techniques can be used to better quantify coal characteristics. These will be included in their applicable sections in this paper.

Handling - Dust Pluggages and Self-Heating

The type of coal and the methods used to mine and process it influence many of the handling characteristics. Coals with high grindability, excessively dried or friable in nature can all have increased dustiness. The sizing of a coal can be an indication of dust potential, but may be misleading if the coal is wet, or if it is lumpy but friable in nature. A report from Westborg and Cortsen [7] using a rotating drum to measure the dustiness of coals concluded that the critical moisture content (CMC) of a coal is that moisture where dust can no longer be held on the surface of a coal particle. The CMC is equivalent to the ASTM Equilibrium Moisture [8] or the maximum content of pore held moisture in the coal. The moisture content that is above the CMC or equilibrium moisture is surface moisture. Most dust problems can be avoided at surface moisture contents above 3.5%. Surfactants and tacifiers have been successfully used to enhance the effect of this surface moisture.

Surface moisture also impacts another handling property, the susceptibility to plugged chutes, feeders and other handling equipment. The flowability of coal is impacted by three main properties: 1) the surface moisture; 2) the size consistency (which influences the surface moisture; and 3) the extraneous minerals and clays that are associated with the surface of the coal particles. It has been the author's experience that with high surface moisture, most coals will start to plug. The third property, or the clay content, of the fine size fractions is more significant than the amount of fine material. These clays act as a binder or glue and when present can cause problems at lower surface moisture contents than anticipated. A method to estimate whether or not fine clays are present in a coal is to look at the percent ash versus size. Concentration of ash in smaller particle sizes may indicate handling problems. Obviously, the amount and type of coal washing can influence this considerably.

The self-heating potential of a coal also influences the handling. Coals with high potential for self-heating need to be compacted more, or sooner than coals with a lower potential. The U.S. Bureau of Mines has proposed an expression for calculating a coal's minimum self-heating temperature (SHT).[9] This temperature is the minimum initial temperature that produced a sustained exothermic (heat-producing) reaction. The equation is for use on bituminous coals only. Subbituminous and lignites all have a high spontaneous combustion potential.

$$\text{SHT min C}^\circ = 139.7 - 6.6 \times (\text{\% DAF Oxygen})$$

Where: SHT min C° is the minimum self-heating temperature in degrees Celsius

% DAF Oxygen is the percent dry ash-free oxygen content

The SHT min C° should be evaluated with the following ranges:

SHT min C°	Spontaneous Combustion Potential
< 70°	High
70° - 100°	Medium
> 100°	Low

In addition to spontaneous combustion, coals that fall into these categories have a similar risk of dust explosions. Considerable expense may have to be spent in order to handle coals with high spontaneous combustion or dust explosion potentials. This would include dust suppression and fire protection equipment.

Combustion Performance

A utility boiler should be able to achieve at least 99.8% combustion efficiency. The rate of burnout or "reactivity" of a coal can influence the combustion efficiency. The reactivity of a coal is, in part, governed by the rank.[10] Bituminous coals under similar conditions burn slower than subbituminous coals. A more detailed classification of coal rank has been proposed by Hensel[11] and is used to evaluate the reactivity of a coal.

The burning profile or thermogravimetric analysis, TGA, in conjunction with differential scanning calorimetry, DSC, can be usefully in evaluating the combustion properties of coal. Publications concerning the use and evaluation of these techniques are becoming more available. Several papers describing the use and evaluation of these tests are listed in the reference section.[12] [13] [14]

Another important combustion parameter is flame stability, particularly when considering the use of low volatile coals. Rohrer [15] and Afonso [16 [17] have described several tests and their experience utilizing low volatile coals. One test cited is the higher heating value of the volatile matter. This test calculates the Btu value of the volatile and evaluates whether or not there is enough heat released to maintain stable combustion. Because the Btu value of low volatile coals is sometimes quite high, their use in utility boilers is becoming more acceptable.

Boiler Efficiency

A comparison of fuel usage can be made using boiler efficiency calculations. Higher boiler efficiencies mean less fuel use.

The moisture in the hot stack gases causes a large efficiency loss. Typically, the stack gas temperature is over 250° F., so this moisture is superheated steam. Most of this steam is generated by the combustion of hydrogen present in coal. Therefore, it is important to perform an ultimate analysis to determine the coal's hydrogen content. To a lesser extent, moisture in the coal produces efficiency losses, and a small portion of the moisture in the flue gas is present as combustion air humidity. Coals containing low moisture and hydrogen produce low moisture flue gas. This results in higher boiler efficiencies.

The actual change in boiler efficiency produced by different fuels, can be calculated using the heat loss method. This method is described in the American Society of Mechanical Engineers, ASME, Power Test Code [18] and general sources.[19] [20] Boiler efficiency starts at 100%; the losses are then subtracted. An example of the heat loss results from the coals shown in Table I is presented in Table II.

The boiler operational data was held constant for this example to show the different efficiencies resulting from the coals.

Table I. Example Coal Analyses

	Coal 1	Coal 2
Moisture	15.0	8.0
Ash	10.0	10.0
Carbon	62.0	72.0
Hydrogen	3.7	3.5
Sulfur	3.0	2.0
Nitrogen	1.0	1.5
Oxygen	5.3	3.0
BTU/lb.	11,000	12,500

Table II. Boiler Efficiency of Boiler Using Example Coals 1 and 2.

Efficiency Losses	Coal 1	Coal 2
Dry Gas	6.49	6.59
Moisture in Coal	1.59	0.74
Moisture from Combustion of Hydrogen	3.52	2.93
Moisture in Air	0.05	0.05
Other losses (Incomplete Combustion/Radiation, Unaccountable)	1.47	1.44
	——	——
Total of Losses	13.12	11.75
Boiler Efficiency (%) (100 Total Losses)	86.88	88.25

Comparisons between alternate, present and design coals are used in evaluating changes in boiler efficiencies.

Boiler Slagging

Boiler slagging is caused by molten coal ash sticking to furnace walls. Boilers are usually designed to accommodate or control some degree of slagging. Problems develop when the rate of slag formation exceeds the rate of removal. This excess slag limits the heat absorption of the furnace causing flue gas temperatures to rise. These increased temperatures may cause sticky ash which can bridge across tube banks, resulting in pluggage and other serious problems.

Little or no slag formation on the furnace walls can also be undesirable. Boilers designed to accommodate higher slagging coals, may not be able to maintain designed steam temperatures if slag is not present. Whether there is insufficient or excessive slag, the slagging behavior of a coal is important.

The molten phases of ash can be the result of high combustion zone temperatures, or low fusion ash components. Usually, it is the low fusion temperature materials that are most troublesome.

Many publications describe the fusion or melting temperature behavior of coal ash in terms of acidic or basic content.[21] [22] [23] [24] [25] The elements silicon, aluminum and titanium reported as oxides are termed acids, and iron, calcium, magnesium, potassium and sodium reported as their oxides are called bases.

Acids	Bases
SiO_2	Fe_2O_3
Al_2O_3	CaO
TiO_2	MgO
	K_2O
	Na_2O

Most of these oxides alone would have high fusion temperatures.[26] However, coal ashes are usually mixtures of these oxides. A useful term in predicting the fusion behavior of these mixtures is the base to acid ratio, B/A.[21] [22] [23] Numerically, this is the sum of the weight percentage of the bases divided by the sum of the weight percentage of the acids. The term B/A is most useful between 0.1 and 1.0.[27] Coal ashes with low B/A, less than 0.2, would be composed mostly of acids. These ashes have high fusion temperatures and do not usually cause excessive slag build ups. Low B/A ashes can be associated with low steam temperature problems due to lack of slag on furnace walls.

Generally, low fusion temperature ashes have B/A in the 0.3 to 1.2 range. Figure 1 from [28] shows a quadratic equation fitted to a coal data base showing the relationship between the reducing fluid temperature and the B/A. The data used to generate Figure 1 utilized eastern coals with bituminous type ash in the range 0.1 to 0.9, and western coals with lignitic type ashes., where B/A is in the 0.8 to 1.4 range. The ash types are determined by the ratio of iron oxide to the sum of calcium and magnesium oxides.[21]

$$\frac{Fe_2O_3}{CaO+MgO} > 1.0 \quad \text{Bituminous type}$$

$$\frac{Fe_2O_3}{CaO+MgO} < 1.0 \quad \text{Lignitic type}$$

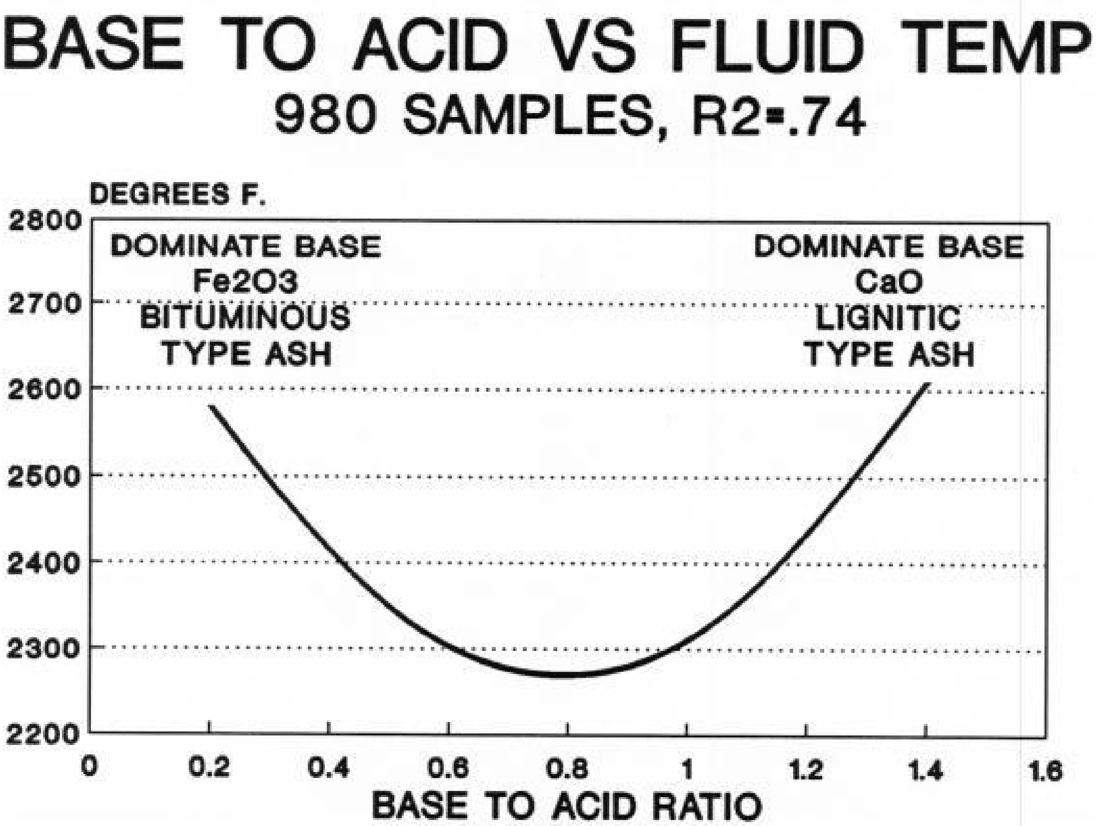

FIGURE 1. BASE TO ACID RATIO VERSUS FLUID TEMPERATURE

On eastern U.S. coals where pyrite is a predominate mineral, the slagging index, Rs, [23] is a useful term. This is found by multiplying the B/A by the dry coal sulfur, S.

$$Rs = B/A \times S$$

Four types of slagging behaviors are indicated by Rs.

Slagging Index Rs	Slagging Type
Less than 0.6	Low
0.6-2.0	Medium
2.0-2.6	High
Greater than 2.6	Severe

The net effect of multiplying the B/A by sulfur is to double-weight the iron in the pyrite. High iron is a major cause of slagging behavior in coal and is scrutinized carefully in suspicious coals.

A second method of evaluating the slagging behavior of pyrite-containing coals is given by Borio and Narcisco.[29] In this procedure the coals are gravity fractionated with the amount of iron in the heavy fraction used as an indicator of slagging behavior.

An investigation of a slagging problem by Hatt [30] also showed iron to play a major role in bonding the deposit. Samples of the deposit were examined using scanning electron microscopy, SEM, with analysis. A correlation between the degree of fusion and the amount of iron was found. Figure 2 shows a simplified schematic of the results of this investigation.

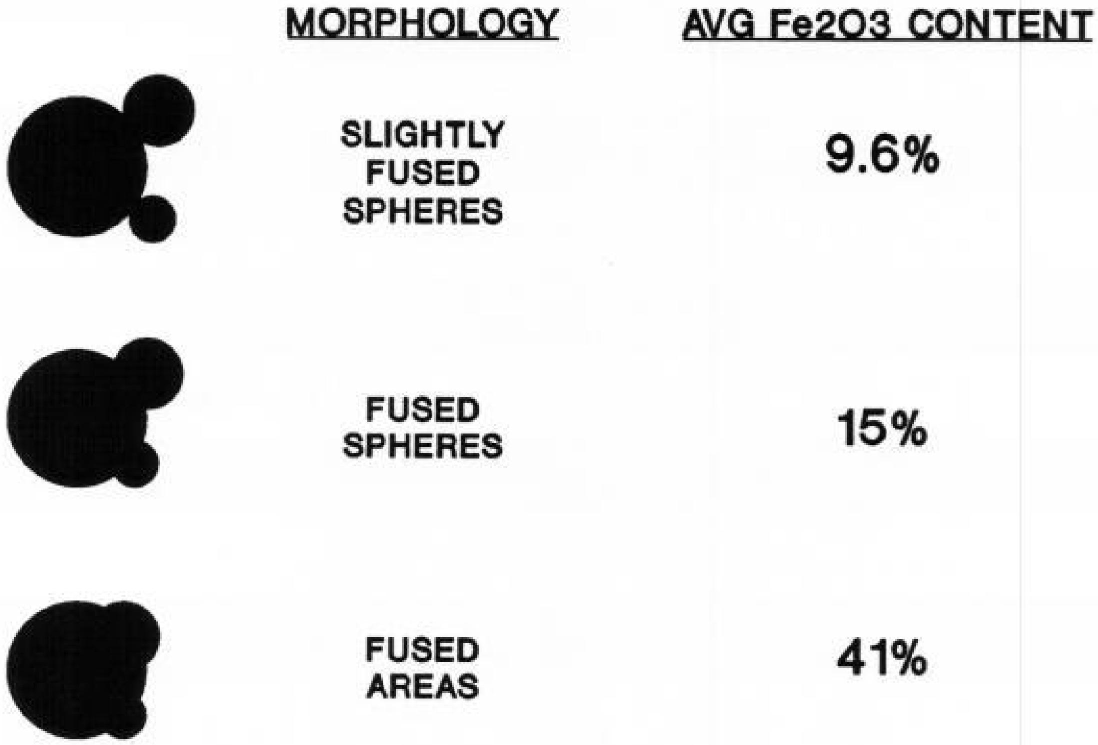

FIGURE 2. DEPOSIT MORPHOLOGY VERSUS IRON CONTENT

A third index in which the iron content of a coal plays a role is the iron to calcium ratio (FE_2O_3/CaO). It has been described in a publication [31] as being important in the range 0.3 to 3.0.

These various indexes, experiences and other publications [32] [33] [34] [35] all indicate that iron plays an important role in slagging of boilers.

For coals that are low in pyrite, or have lignitic type ash, or lack chemical analysis of the ash, a fusion temperature slagging index, Rfs has been proposed by Babcock and Wilcox.[36] However, the author knows of no work that supports or substantiates this index.

Another slagging index commonly used is more difficult to calculate. However, some believe that it is the most accurate. This index is referred to as the Viscosity Slagging Index, Rvs, and is applicable to both bituminous and lignitic type ashes. Details on how to use this index are given in References.[37]

A method that is gaining wider recognition is computer controlled scanning electron microscopy (CCSEM).[38] [39] The scanning electron microscope has the ability not only to determine the size of a mineral inclusion, but also an elemental analysis. The electron beam generates characteristic s that can be analyzed by an energy dispersive detector. By using a computer to control the microscope and store and evaluate data, information on the size and types of minerals can be determined. As this technique is used more often, the results will be better characterized as to the impact on deposit formation.

Experience has shown that coal properties are not always to blame when slagging occurs. The combustion system must be operating within design parameters because factors such as coal sizing, excess air and soot blower operation can affect slagging.

Boiler Fouling

Fouling occurs when ash deposits accumulate in the convection passes at a rate greater than soot blowing can remove them. These deposits are not normally molten, like slag, but usually consist of fly ash sintered or bonded together with a sulfate salt. These deposits can become quite hard with time and are troublesome to remove.

The most common fouling index used for bituminous type ashes is found by multiplying the B/A by the percent sodium oxide in the ash.[23]

$Rf = B/A \times Na_2O$

Where: Rf is the fouling index.

B/A is the base to acid ratio.

Na_2O is the % sodium oxide in ASTM prepared ash.

The classification for interpreting the fouling index is shown below:

Fouling Index Rf	Fouling Classification
Less than 0.2	Low
0.2 - 0.5	Medium
0.5 - 1.0	High
Greater than 1.0	Severe

The fouling index for lignitic type ashes is based on the sodium oxide content alone. The following is a guide for classification of fouling behavior for lignitic type ashes.[25] [27]

% Sodium Oxide Na_2O	Fouling Classification
Less than 3	Low to medium
3 - 6	High
Greater than 6	Severe

It appears that for coals with a high fouling index that the amount of ash is important. A recent paper [40] gave an example where coal with 5% Na_2O and 12% ash had a rate of deposition almost six times higher than for a coal with 6% ash and the same Na_2O concentration. Other authors have also observed this phenomenon.[25]

Other tests used to evaluate the fouling potential of a coal can be used if the coal is suspected to cause fouling problems. Several methods use water or the weak acid soluble alkali (sodium, potassium) content of the ash or coal in place of the sodium oxide percentage.[23] [27] This is done because the soluble alkalais are more available to form sulfates than the non-soluble alkalis associated with clays or other minerals. Another test uses gravity fractionation to separate the organic alkalis from inorganic, and postulates that the alkali in the fraction lighter than 1.7 specific gravity is more likely to volatilize and react to the form sulfates.[29]

The chlorine content of the coal may be indicative of fouling behavior, but a direct relationship to the sodium or potassium content has not been established.[23] [41] [42] It is now becoming apparent that calcium plays a major role in fouling. Utilities [43] and others [44] have shown that calcium sulfate is a primary binding agent in fouling deposits from coals with low sodium and high calcium contents.

Electrostatic Precipitator Efficiency

Most utility boilers are equipped with electrostatic precipitators, ESP, to control fly ash emissions. There are two major coal-related factors that affect the performance or efficiency of a precipitator: the amount of fly ash and the electrical resistivity of the ash.

The allowable mass emission rate for a plant is usually expressed in pounds of ash per million Btu, lbs./MBtu. It is convenient to express the coal ash content in lbs./MBtu using the following expression:

$$\text{lbs. Ash MBtu} = \frac{\text{\% Ash}}{\text{BTU Content}} \times 10{,}000$$

When the coal's ash content is expressed in this manner, a comparison with other coals is more meaningful, i.e., a coal with 5.0 lbs. Ash/MBtu will have half the fly-ash to collect than a coal 10.0 lbs. Ash/MBtu.

An estimate of the required ESP efficiency can be made by using the equation shown below:

$$\text{ESP Eff.} = \frac{(\text{Ash} \times \text{FAF}) - \text{EL}}{\text{Ash} \times \text{FAF}} \times 100\%$$

Where:	ESP Eff.	=	the estimated precipitator efficiency
	Ash	=	the coal's ash content expressed in lbs/Mbtu
	FAF	=	the fly ash fraction, usually about 0.8 for pulverized units and 0.4 for cyclone units
	EL	=	the emission limit expressed in lbs./MBtu

If the boiler has had previous mass emission testing, actual ESP efficiency can be found using similar methodology. If this information is available, comparisons can be made between the estimated ESP efficiency and the actual ESP efficiency. For example, if the present actual ESP efficiency is 95.0%, a coal requiring 99.9% ESP efficiency to meet emission limits would probably not be suitable. Coals with estimated ESP efficiency requirements at or below the actual ESP efficiency would be more suitable.

Fly ash electrical resistivity is the second major coal-related factor affecting precipitator performance. Fly ash resistivity normally is in the 1 x 10E8 to 1 x 10E12 ohm-cm range. For a particular coal, it could vary within an order of magnitude and should be used as a rough guide. It is possible to estimate the fly ash's resistivity using major and minor elemental analyses and flue gas characteristics. The calculations are too long to easily describe in this paper, but are well documented in readily available sources.[45][46]

Experience has shown that for cold-side precipitators, resistivities in the 5 x 10E8 to 9 x 10E9 ohm-cm range are preferable to resistivities higher or lower. Resistivity in ESP operations below about 400 $^\circ$ F is controlled by flue gas sulfur trioxide concentrations. It is important to have estimates of the SO_3 concentration. If SO_3 flue gas conditioning is used, experience has shown it to be more effective on ashes with >5% CaO than highly silicious ashes.

Hot-side precipitators can tolerate somewhat higher resistivities if there is enough sodium. At temperatures above 400° F, sodium and lithium act as charge carriers as opposed to sulfuric acid in cold-side ESP's. The best performing coal ashes in hot-side ESP's have high silica, glassy fly ash with about 1-2% Na_2O in them. High CaO ashes with low Na_2O (<0.8%) don't perform well.

Pulverizer Capacity

It is important not to limit boiler load due to insufficient pulverizer capacity. An estimate of the pulverizer capacity can be found using the Hardgrove Grindability Index, HGI, the moisture, and the heating value of the coal.[47] [48] Some pulverizer manufacturers have charts available that relate a pulverizer capacity factor, Cf, to the coal's moisture and HGI; others use only the HGI.[19] [20] Pulverizer capacity is normally expressed in pounds or tons per hour. The boiler, however, requires a certain heat or Btu input per hour. It is more realistic to express pulverizer capacity in Btu or MBtu per hour. An example of how pulverizer capacity can be found is shown below:

Design Coal and Pulverizer Specifications

Moisture	10%
HGI	55
BTU/lb	11,500
Cf (from pulverizer manufacturer)	1.0
% passing 200 mesh	70
Capacity	40,000 lbs/hr

$$\text{Pulverizer BTU Capacity} = \frac{\text{Capacity lbs/hr} \times \text{Btu/lbs} \times \text{Cf}}{1{,}000{,}000}$$

BTU Capacity = 460 MBtu/hr.

The Btu adjusted pulverizer capacity of an alternate coal can be calculated and compared:

<u>Alternate Coal Properties</u>

Moisture	10%
Btu	12,500
HGI	45
Cf (from pulverizer manufacturer)	0.88

$$\text{Pulverizer} = \frac{40{,}000\ \text{lb/hr} \times 12{,}500\ \text{Btu/lb} \times 0.88}{1{,}000{,}000\ \text{Btu/MBtu}}$$

$$\text{BTU Capacity} = 440\ \text{MBtu/hr}$$

When this is compared to the design coal pulverizer rate of 460 MBtu/hr, it results in about 4% less capacity. If only the weight capacity were used for comparison, the higher heating value of the alternate coal would not be considered and a decrease in capacity of 12% would have resulted.

The number of pulverizers needed to achieve full load can be determined by dividing the total heat input to the boiler by the Btu adjusted pulverizer capacity. The calculated number of pulverizers needed should always be less than the number that exists or is required for normal maintenance schedules.

Although qualitative, several utilities have used high grindability (< 90 HGI coals) to blend with unsuitably low HGI coal to produce a blended HGI. This blend HGI coal performs well and recovers the mill performance that the low HGI coal lost. Coal petrography explains this using the maceral concept of of coal. Macerals are the organic "minerals" that make up coal, similar in nature to the concept of separate minerals making up rocks such as granite. The rank of a coal can be determined by microscopic examination of these macerals. The grindability of a coal is determined by the amounts of each maceral.[40] Since the mill pulverizers the coal smaller than most of the macerals, the mill sees only a change in maceral levels, not two separate coals.

Cyclone Tapping

Cyclone and other wet-bottom boilers must be able to drain or tap the slag from the boiler. The slag produced must have a low viscosity - temperature relationship. It has been established that a slag with a viscosity of 250 poise will tap properly. The temperature at which a coal ash has a viscosity of 250 poise is termed the T-250 temperature. There are several methods available to calculate T-250: The Nicholls and Reid method, which is based on the silica percentage; the Sage and McIlroy method, which utilizes the base to acid ratio; the method of Watt and Fereday, which is considered by many to be the most accurate; and the method of Duzy, which is used for high base/low iron slags.[50] [22] [51] [24]

The Nicholls and Reid, Sage and McIlroy and Watt and Fereday methods require major and minor elements of the coal ash to be used. These three methods work best on U.S. type coal ashes with a B/A of less than 1.0.

The Duzy method was developed to accommodate the lignitic type ashes commonly found in western United States. Specific information on how to use these methods to calculate T-250 will be found in the references.

Once the T-250 is calculated, it can be used to predict whether or not the slag will tap. Babcock and Wilcox, B&W, the sole builder of cyclone furnaces in North America, originally recommended that the T-250 be less that 2600 ° F.[21] B&W now recommends that the T-250 be less than 2450° F. This is due, in part, to the increased use of lower quality/lower Btu coals. One utility, based on their experience with cyclone type units, has developed a cyclone performance relationship using T-250 and the heating value of the coal.[52] This relationship is shown in Figure 3 and is useful for predicting performance of coals on radial type cyclones with greater than 500° F combustion air.

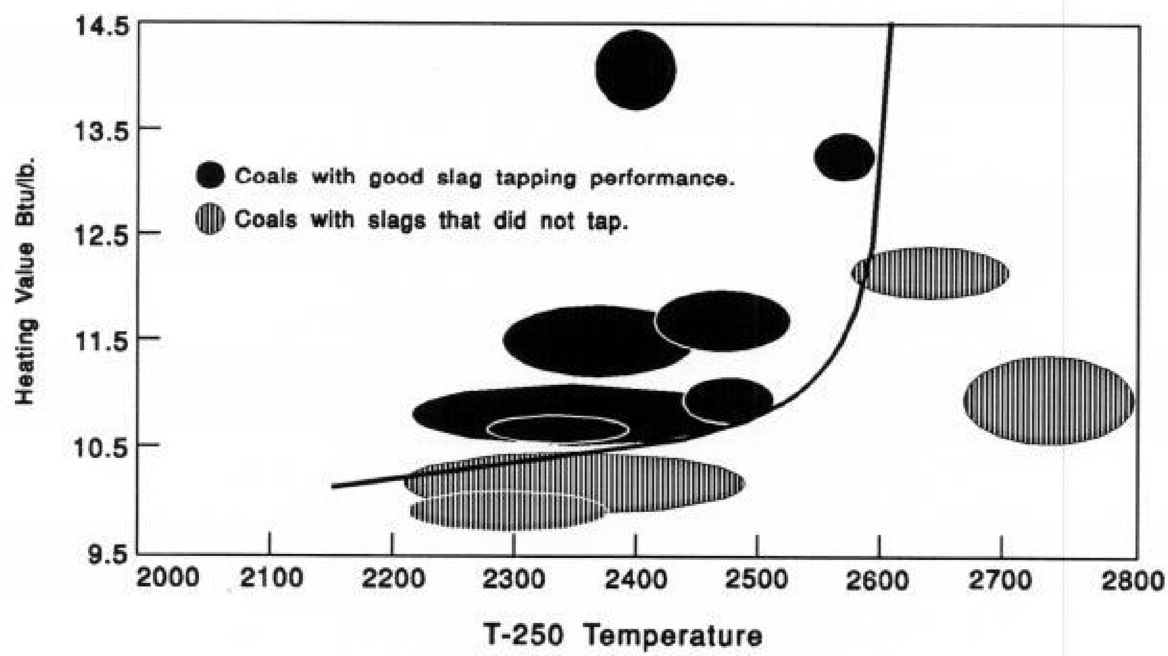

FIGURE 3. RELATIONSHIP BETWEEN T250 AND HEATING VALUE OF COAL FOR GOOD CYCLONE SLAG TAPPING

As a coal slag cools from a molten Newtonian fluid state, it starts to crystallize. When these crystals start to form, the viscosity of the slag tends to increase rapidly. This point of change in the viscosity - temperature relationship is termed, "The temperature of critical viscosity," Tvc. There are two basic methods to calculate Tcv.[22] [27] [53] The Tcv provides a guide for the use of the T-250. T-250 temperatures should not be used below the Tcv because of the influence of the crystals in the molten slag on the viscosity.

Summary

By utilizing the methods presented in this paper, it should be possible to evaluate which coals would be suitable for a test burn. Unfortunately, these methods do not replace the information gained from an actual test burn of a coal.

These methods are all readily adapted to computer or programmable calculator use. This can reduce the time needed to perform these calculations from hours to minutes. Several papers and publications are available that provide program lists to calculate several of these parameters.[46] [54] [55]

Several other programs have incorporated many of these impact areas. The most sophisticated is the Electric Power Research Institute's (EPRI) Coal Quality Impact Model (CQIM) which has been described in numerous articles.[56] [57] Simpler models exist and are available at much lower cost.[57] In either case, time not spent calculating is better used in evaluating results.

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