

Names for boiler ash deposits include slag, clinkers, bloody muck, boiler snot, fouling and pluggages. These all describe coal ash sticking to the boiler rather than properly flowing out of it. How to successfully manage boiler deposits is not well understood or documented, due to the world of fuel being full of change and compromise.

The main cause of ash deposits depends on where you work. In steam plant operations, the main cause is poor quality coal. For coal buyers, the main cause is poor quality steam plant equipment. In engineering, the main cause is poor quality steam plant operation. All three of these causes are accurate, but scientific analyses reveal that it is usually a combination of all three.

Slag is primarily caused by elevated concentrations of iron, calcium and sodium, the main fluxing elements. The iron-based slags are very sensitive to the amount of carbon (C) and or carbon monoxide (CO) levels, and become wetter and stickier when found in a reducing, fuel-rich, environment. Almost all iron-based slags can be made more controllable if there is a combustion tune-up that minimises the C and CO levels. Large particles of the iron-based mineral pyrite (FeS₂) also cause an increase in slag, as they are harder to oxidise.

Slag is also caused by fluxing with calcium and/or sodium. However, unlike iron, these

elements are not as influenced by the combustion conditions. The total amount of these elements appears to be the most significant when encountering slag at generating units. Table 1 presents the major causes of ash deposits.

Analytical procedures for slag

Coal ash slag is a sophisticated material. It covers a wide range of mineralogical transformations, including glass formation, devitrification (crystals that form on the cooling of glass), changes in oxidation state, and reactions between individual minerals at high temperature. Coal ash does not have a distinct melting point, unlike ice or other pure compounds, so when melting is mentioned it is used to represent a decrease in viscosity, rather than a melting point. Viscosity is a measurement of how a material flows. Water flows well and is giving a value of 1 centipoises. Honey is more viscous and has values of 2000 centipoises. When coal ash melts it occurs on both a large and microscopic scale. On the large or bulk scale most ash behaves like glass. As the temperature of the material increases, its viscosity decreases. At temperatures less than 2000 °F the ash may appear solid, or at least stiff, such as a stick of gum. On a microscopic scale, several minerals may have already melted, but their concentrations are low when compared to

other minerals with higher melting temperatures. As the temperature is increased, the ash becomes less viscous or more fluid. Many reactions are now occurring between the minerals as they melt, increasing the fluidity. As the molten components mix they become more like molten glass. This molten material starts to dissolve the non molten materials such as quartz. In this way the melting temperature of minerals such as sandstone and shale are lowered by other minerals such as pyrite and limestone.

Ash fusion temperatures

The ash fusion temperature test is a documented observation of this coal melting process. The ash is shaped like a small cone, and is placed in a furnace with increasing temperatures. The initial deformation temperature is usually over 100 °F above where the first low melting temperature minerals start to melt. The remaining fusion temperatures represent an ever increasing amount of molten material, and a lowering of the viscosity of the glass-like material. It should be noted that even at the fluid fusion temperature there may be solid or non-melted minerals such as quartz. The atmosphere of the furnace is controlled to either an oxidising condition such as air with good combustion, or a reducing condition such as CO and C present with poor combustion. This is important due to

Sloppy when hot

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provides an understanding of how
to deal with coal ash deposits.***

Table 1. Major causes of ash deposits

Fuel related	Large pyrite particles that impact the furnace wall before they completely combust
	Clay minerals that contain significant amounts of iron, calcium, sodium or potassium, causing them to have low melting temperatures
	Interaction of pyrite, clays and alkalis with aluminosilicates to form low viscosity melts
	Extremely fine or organically bound alkalis
	Firing low reactivity fuels that introduce unburned carbon into slags with elevated iron (Fe ₂ O ₃) concentrations
	An increase in concentration of any of the materials listed above
Equipment related	Soot blowers and other deposit removal equipment not in operation or used improperly
	Poor pulverisation of fuel
	Improper air to fuel ratio
	Burners damaged or improperly adjusted
	Changes in operation of boiler or other equipment
Design related	Furnace size too small for fuel
	Tube material and/or spacing inadequate
	Soot blowing and ash removal coverage inadequate
	No means provided to observe slag buildup

the oxidation behaviour of iron (Fe) atoms. Reduced iron lowers melting and fusion temperatures of ash much better than the oxidised form. In coals that have significant iron levels, usually those with elevated sulphur content, the oxidation state of the iron is critical. The difference between the oxidising and reducing fusion temperatures can be hundreds of degrees. This phenomenon is one of the variables that make consistent fusion temperature data hard to obtain. It is also why some fuels are sensitive to low NOx firing conditions that create an excessively reducing environment that is good for NOx and bad for slag. The firing of low reactivity fuels such as petcoke can also add significant amounts of carbon to the slag material, making it wetter and stickier than when in an oxidising environment.

The fusion temperature test is a lower cost technique with reasonable turnaround time. Fusion temperatures have been used for years, and are contained in most coal contracts. Unfortunately, ash fusion temperatures provide no mineralogical information, are notoriously imprecise, and are influenced by all sorts of factors that cause variability.

Table 2. Acids or glass formers (add bulk to the deposit)

Silicon dioxide	SiO ₂
Aluminum oxide	Al ₂ O ₃
Titanium dioxide	TiO ₂

Table 3. Base or fluxing agents (act as bonding agents)

Iron oxide	Fe ₂ O ₃
Calcium oxide	CaO
Magnesium oxide	MgO
Potassium oxide	K ₂ O
Sodium oxide	Na ₂ O

It is the author's experience that different laboratories can produce fusion temperatures that vary well outside the governing guidelines, whilst both laboratories are performing satisfactorily.

Major and minor elements

When trying to determine the behaviour of coal ash in a boiler, both the type and size of minerals present is important information. This can be performed using computer controlled scanning electron microscopy (CCSEM), X-ray diffraction, and other advanced techniques. Unfortunately, it is both difficult and expensive to determine the actual minerals in coal. The ash chemistry, or major and minor elements in coal ash test, is the next best test. This is because melting properties can be estimated and minerals can be inferred. Although the cost of ash chemistry is higher than fusion tests, the information obtained is well worth the expense. Tables 2 and 3 show the elements that are normally reported as oxides in the major and minor elements test.

There are several well recognised slagging calculations that can be performed using the results of this ash chemistry test. The simplest is the base to acid ratio (B/A) that compares the amount of basic (or fluxing/bonding) elements to the acidic (or glass formers/bulk) elements and is shown as follows:

$$B/A = \frac{\text{sum of bases}}{\text{sum of acids}} \\ = \frac{(\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O})}{(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2)}$$

The ash is dry and has high fusion temperatures when the B/A is low. As the concentration of the fluxing elements increases, the ash becomes stickier and the

ash fusion temperatures begin to decrease. There is a point above B/A = 0.5 where the fusion temperatures reach a minimum, and further increases of the B/A above 0.75 only serve to increase the amounts of fluxing or bonding material rather than meaningfully influencing the fusion temperatures. The fusion temperatures can then start to increase as the B/A increases. These are typically low rank coals with elevated calcium levels. The aluminosilicate material becomes saturated with calcium and the excess calcium remains solid. This mix of liquid and solid creates a slushy material that makes the fusion temperatures appear higher. There are several utility experiences that indicate that wall slag with these coals increases with lower B/A and the lower fusion material.

There is a well documented slagging index that uses the B/A multiplied by the dry sulphur percentage. This works for coals with pyrite as a major form of sulphur, and is expressed in the following way:

$$\text{Slagging index} = \text{dry sulphur} \times B/A$$

As the slagging index increases, the slagging potential of the coal is deemed to increase. This calculation is in effect an iron squared (Fe₂O₃)² term. This is because the B/A has Fe₂O₃ on top and the dry sulphur content has a pyritic component that increases proportionally to the total sulphur. The use of this index is generally limited to bituminous coals with B/A less than 0.5, but could be used on any coal that has significant (>~0.5%) iron pyrite levels.

The concern regarding these tests is that they do not incorporate the amount of ash present in the system. Any experienced plant operator will soon realise that with the same fusion, B/A, etc. and double the amount of ash, there could be a real situation on hand controlling deposit build ups.

There have been several good methods developed by the boiler and utility industry that use a chart to correlate ash loading, fusion temperature, and B/A to a slagging potential or cleanability index. The approach chosen by Coal Combustion, Inc., is to rate the slagging potential to the ash and the main bonding elements iron, calcium, sodium on a mass/calorific value basis. This methodology can easily be applied to any heat units whether imperial, metric, or other. So whether Btu/lb, calories/gram, Kcal/kg or joules/kg are used, the same theory applies. The coal quality data needs to be put in the form that the boiler sees it. Boilers do not need percentages, they need energy. The

laboratory procedures (ASTM, ISO) require labs to put levels into percentages. The company converts levels to an energy basis, which is easily achieved.

Ash loading and elemental loading

Ash levels

Ash levels in coal are generally reported from the lab as a percentage. This is convenient for the lab but not completely representative of what the boiler sees. Boilers demand Btus, not t of fuel. A more representative way for the boiler to express ash levels is to use ash lb/million Btu. These units are easy to calculate using the following expression:

$$\text{lb ash/million Btu} = \% \text{Ash} / (\text{Btu/lb} / 10,000)$$

The author has on numerous occasions found that the ash deposits formed in utility sized boilers correlate best with ash and elemental loading data, rather than fusion temperatures or traditional slagging and fouling indices.

Basic or bonding elemental loading

Basic or bonding elemental loading is iron (or other elements) lb/million Btu. The coals are then compared on a total ash and elemental loading level basis. This procedure works well if the combustion system is tuned up and there are not excessive carbon and combustion issues.

Slagging with bituminous type ash

By understanding how different coals behave in the boiler, utilities are able to lower the ash fusion specification. Typically utilities have specifications for total ash (%) and a fixed fusion temperature spec. Published accounts of utilities experience in this area have led many slag specialists to consider the amount of ash loading to be important. When ash levels are expressed in lb/million Btu, they more closely reflect the levels seen by the boiler. The author has also proposed that the iron loading (lb Fe₂O₃/million Btu) level is an important consideration. In several eastern/midwest US coal

slagging events worked on by the author, the problematic coal had elevated iron loading levels. Using this information, several utilities have conducted test burns of coals with lower fusion characteristics. Their strategy was to limit the iron loading by considering lower ash, higher iron coals. These coals had lower than design fusion temperatures, but it was suggested that the lower ash levels would offset this. The results of the test confirmed that the iron loading levels more accurately predicted the slagging behaviour of the coal than the fusion temperature of the coal.

Conclusion

The science and technology of slag formation is complicated and not completely understood. It is influenced by many factors, including where you work. It should be encouraged that companies share their slagging experiences. The more information that becomes available, the more accurately an understanding of slagging will evolve. This will help improve every business that uses coal as a fuel. _____ ■