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A Review of Current Prediction Methods for Slagging and Fouling in Malaysian Coal Fired Power Plants

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Abstract:

Coal is a very important source of Energy worldwide. Current statistics show a strong indication that coal continues to contribute be one of the main sources of energy. Since coal fired power plants supply a large portion of Malaysia's electricity, outages at these plants tend to cause serious problems within the country's National Grid. Any shortcomings from coal fired generation would have to be replaced by more expensive Natural Gas based generation, especially if a sudden dip in power generation is experienced. Thus, it is important to both national security and economic considerations that the coal power plants be run as reliably as possible. In Malaysia, the impact of deposits on coal fired plant operation is varied, with some cases known to have caused Forced Outages, Forced Deration and also secondary damage to other plant equipment, such as Boiler Tubes, Burners and Bottom Ash Handling Equipment. Deposits continue to be a leading issue related to coal firing, and such is an ongoing concern for power plant operators. It is therefore important for power plants to be able to predict the potential impact of the coal to the plants, especially relating to the deposits. There are several methods utilised by the power industry, namely predictive indices, model based predictions and scale up from laboratory tests. This study will compare the available prediction methods widely used in Malaysia against actual plant observations. Comparisons will be made based on a sample of 30 full scale coal trial burns at 6 different power plants, with each test having its deposit risk assessed by both predictive indices and model based predictions. The results show the model based predictions being more reliable especially when dealing with sub bituminous coals.

***Keywords:** Coal Ash Deposits, Fouling, Prediction Indices, Slagging.*

I. INTRODUCTION

Coal is a very important source of Energy worldwide. It is estimated as much as 40.8% of the world's power generation is derived from Coal. This is generally unchanged from the generation contribution of Coal in the year 1973, which was about 38.3%. However, the with the actual electricity generation increasing from 6,131 TWh in 1973 to 24,255 TWh [1]. This clearly indicates a sustained dependency on Coal for power generation over the years.

In Malaysia, electricity generation from coal has risen steadily from 10.2% from a total of 38,320 GWh in 1995 to 41.0% from a total of 144,565 GWh generated in 2015 [2].

The total installed capacity is at 7,200 MW in 2014, with a total of 3,000 MW of coal power plants electricity generation capacity completed in 2017, and another 2000 MW in construction. In 2014 alone, a total of 13,648 ktoe of coal was consumed for electricity generation in Malaysia.

Malaysia imports the large majority of coal consumed (99.2%). In fact, Malaysia is the world's

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8th largest importer in the world in 2016. An estimated 60% of coal is imported from Indonesia, with the remaining 40% sourced from Australia, South Africa and Russia [3]. To improve security of supply, other exporting countries are being considered.

Due to the county's power plants exposure to a variety of coal brands, with differing specifications. The difference in specifications causes a need for each power plant to anticipate the behaviour of the coal, and its impact, every time a different coal is to be used. Based on results from various prediction methods, which include calculated coal flow, impact on grinding and drying, deposits predictions and emission predictions, the power plant will adjust parameters accordingly.

II. Coal Ash Deposits

All coals have a significant content of ash forming inorganic material which cannot be economically removed before combustion. This amount can range from below 3% in low ash coals, to over 40% in some low grade high ash coals. Most commonly, the ash forming material represent between 10 and 25% of the feed coal. [4]

Uncontrolled or unexpected deposits on the heat transfer surfaces in and around the boiler can interfere with operation, and cause unplanned shut downs or reduced output and efficiency. The deposits are derived from the mineral matter in coal and its other inorganic components. These deposits can be difficult to remove and can cause major damage to the boiler. These deposits can also interfere with heat transfer within the boiler. With partial blockage between tube banks, increased gas velocities elsewhere can cause erosion. Corrosion can also occur underneath a developing deposit. All these factors affect the efficiency and availability of plant electricity generation and hence cost.

While boiler manufacturers design their equipment to minimise the effect of deposit build up, problems can arise when the behaviour of the inorganic matter in the boiler environment is insufficiently understood, when the coal feed is changed, or when emission standards and regulations require changes in operating conditions.

Relatively few plants operate for long periods of time with coal supplied from the same source, which of consistent quality and gives trouble-free operation.

The main deposits are described as being either slagging or fouling, and various definitions are used:

Slagging – Slagging refers to deposits within the furnace, in areas which are directly exposed to flame radiation such as furnace walls and some widely spaced pendant superheaters. Slagging deposits are generally molten or partially fused. Slagging takes place in the hottest parts of the boiler.

Fouling – Fouling refers to deposits in those areas not directly exposed to flame radiation, such as the more closely spaced tubes in the convection sections of the boiler. Fouling takes place as the flue gases and suspended fly ash cool down.

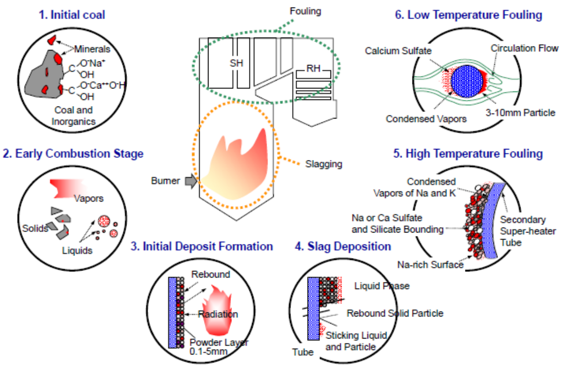

Figure 1: Slagging and Fouling Deposit Formation (modified from Couch,2006) [5]

III. Prediction of Slagging and Fouling

The prediction of slagging and fouling depositions within a coal fired boiler has been the subject of extensive studies over the past 30 years. From these studies, a number of methods have been established. However, due to the non-homogeneous nature of coal, most prediction methods have limitations. Therefore, most power plant operators will rely on several methods in conjunction with each other.

Among the common prediction methods used in the power generation industry are:

- Predictive Indices
- Model Based Predictions
- Scale Up from Lab Tests

The results from these predictions are often used by power plant operators to anticipate ash deposition

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issues and take preventive action. In some cases, prediction results are used for coal selection before utilisation.

A. Predictive Indices

Predictive indices have been used to predict various coal and ash related behaviour. These indices were developed based on experiences gathered from different boilers utilising different coals. These indices rely on the Laboratory Ash Analysis of the coal to predict the behaviour of the coal when fired. Some of the principal indices used are listed below: [6]

- Base-Acid Ratio (B/A)
- Silica Ratio
- Slagging Index
- Fouling Index

These indices have been widely used in boiler design, coal selection, operation planning and troubleshooting, even though results are not always reliable. This is due to the simplicity of use, coupled with readily available coal specifications from laboratory tests. Furthermore, when used to investigate known ranges of coal at a specific boiler, operational experience improves the confidence level of predictions, as specific correction factors can be applied.

Studies by EPRI had indicated a confidence level of 80% using predictive indices combined with the knowledge of laboratory ash chemistry and of combustion intensity. However, the confidence level quoted was achieved mainly in US utilities utilising indigenous coals, of which the plants have a large amount of operational experience. A subsequent study concluded only about 60% success rate [7], while other studies show a higher success rate (about 80%), when indices are combined with boiler heat release rate [8].

B. Model Based Predictions

Since the development of higher processing power of computers, a lot of effort has been put to the development of Computer Models to simulate the utilisation of Coal, with particular emphasis on Ash Behaviour. A large number of organisations and institutes have developed software programs aimed at evaluating the impact of coal properties on power plants. [9]

Latest models are made equipment specific, thus moving away from generic correlations to evaluate impacts. Model development have also incorporated a wealth of knowledge from laboratory tests, operational experience and in some cases from expertise of CFD analysis of coal fired boilers.

A study of slagging and fouling prediction on one 512 MW tangentially fired boiler, using a computer model and CFD combined was carried out in 2006 [10]. The predicted slagging and fouling within the boiler was consistent with visual observation during actual utilisation.

C. Scale Up from Lab Tests

Pilot scale testing had been carried out by utilities to better understand and predict the impact of coal properties on boiler operation. The reported results are somewhat mixed, as certain boiler operating conditions could not be simulated within laboratory scale furnaces. Fouling deposits could be simulated as far as physical and chemical characteristics, however growth rates could not be determined. Slagging prediction was less reliable, most likely due to the inability to simulate the complex particle dynamics and combustion conditions as in the actual boiler.

One of the valuable tests that has been carried out at pilot scale, with significant impact to actual boiler design and operation involves monitoring the heat transfer on test panels, and how it is affected by deposit build up. Simulated sootblowing during these tests give good indication on how hard would it be to remove the deposits in the actual boiler.

Given time, and in conjunction with the advance analytical techniques available, pilot scale lab tests can be improved up to the stage where it is possible to establish what coals can be used for what boiler, up to a reasonable level of confidence. However, results from pilot scale tests require validation from full scale boilers, as extrapolation alone is extremely difficult.

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IV. PREDICTION OF ASH DEPOSITION IN BOILERS IN MALAYSIA

The current Ash Deposition Prediction methods utilised in Malaysia are:

1. Comparisons against Rejection Limits
2. Prediction Indices
3. Model Based Prediction
4. Laboratory Tests
5. Trial Burn

A. Rejection Limits

Method (1) is the basis for the pre-qualification of coals to be used at Malaysian Power Plants. These consists of six to seven main parameters which constitute each plants' Rejection Limits, which are derived from the equipment's Design Specification. All coal to be used at a specific plant must meet exceed the requirements of all Rejection Limits.

Typical Rejection Limits are:

- Gross Calorific Value
- Total Moisture
- Ash Content
- Total Sulphur
- Volatile Matter Content (some plants)
- Ash Fusion Temperature (some plants)
- Sizing

From the list of Rejection Limits, Ash Fusion Temperature (Initial Deformation, Reducing) is the only indicator of potential ash deposition. If the Initial Deformation Temperature is below the limit, it is assumed that the coal may cause slagging in the furnace beyond what would be acceptable.

B. Predictive Indices

Predictive indices have been used to predict various coal and ash related behaviour. These indices were developed based on experiences gathered from different boilers utilising different coals. These indices rely on the Laboratory Ash Analysis of the coal to predict the behaviour of the coal when fired.

Some of the principal indices used are summarised in table 1.

Table 1: Typical Coal Ash Deposition Prediction Indices [6]

Index	Factors	Low	Med	High	Severe
Ash Descriptor					
Base-Acid Ratio (B/A)	$\frac{\%(Fe2O3 + CaO + MgO + Na2O + K2O)}{\%(SiO2 + Al2O3 + TiO2)}$	< 0.5	0.5 - 1.0	> 1.0	
Ash Viscosity					
T250 of Ash oC	Temperature when Ash Viscosity = 250 poise	> 1,302	1,399 - 1149	1,246 - 1121	< 1,204
Silica Ratio	$\frac{\%SiO2}{\%(SiO2 + Fe2O3 + CaO + MgO)}$	Viscosity Proportional to Silica Ratio			
Slagging Propensity					
Base-Acid Ratio (B/A) (for Lignitic Ash: %CaO + %MgO > % Fe2O3)	$\frac{\%(Fe2O3 + CaO + MgO + Na2O + K2O)}{\%(SiO2 + Al2O3 + TiO2)}$	< 0.5	0.5 - 1.0	1.0 - 1.75	
Slagging Factor (for Bituminous Ash: %CaO + %MgO < %Fe2O3)	(B/A) x Sdry	< 0.6	0.6 - 2.0	2.0 - 2.6	> 2.6
Iron - Calcium Ratio	$\frac{\%Fe2O3}{\%CaO}$	< 0.31 or > 3.0	0.31 - 3.0		
Silica - Alumina Ratio	$\frac{\%SiO2}{\%Al2O3}$	Low			High
Slagging Factor	$\frac{(Max\ Hemispherical\ Temperature + 4 \times Min\ Initial\ Deformation\ Temperature)}{5}$	> 1,343	1,232 - 1,343	1,149 - 1,232	< 1,149
Viscosity Slagging Factor	$\frac{(T250(Oxidisation) - T1000(Reducing))}{(975 \times Fs)}$ (Fs ranges from 1.0 - 11.0 for Temperature Range 1037 - 1593 oC)	< 0.5	0.5 - 0.99	1.0 - 1.99	> 2.0
Fouling Propensity					
Sodium Content	%Na2O3 (for Lignitic Ash: %CaO + %MgO > % Fe2O3)	< 2.0	2.0 - 6.0	6.0 - 8.0	> 8.0
	%Na2O3 (for Bituminous Ash: %CaO + %MgO < %Fe2O3)	< 0.5	0.5 - 1.0	1.0 - 2.5	> 2.5
Fouling Factor	(B/A) x (%Na2O in Ash) (for Bituminous Ash: %CaO + %MgO < %Fe2O3)	< 0.2	0.2 - 0.5	0.5 - 1.0	> 1.0
	(B/A) x (%Na2O Water Soluble / Low Temperature Ash)	< 0.1	0.1 - 0.24	0.25 - 0.7	> 0.7
Total Alkaline Metal Content in Ash (Expressed in Equivalent %Na2O3)	%Na2O + %K2O (for Bituminous Ash: %CaO + %MgO < %Fe2O3)	< 0.3	0.3 - 0.4	0.4 - 0.5	> 0.5
% Chlorine in Dry Coal		< 0.3	0.3 - 0.5		> 0.5
Strength of Sintered Fly Ash, psi		< 1,000	1,000 - 5,000	5,000 - 16,000	> 16,000

The behaviour of coal with regards to deposition propensity has long been accepted as a function of the coal bulk ash composition, ie.

$$\text{Ash Chemistry Indices} = f(x^{ASH})$$

Where x^{ASH} is the composition, in weight percent oxides of total dry bulk coal ash content.

Depending on the chemical composition of the coal ash, the ash may be classified as Bituminous or Lignitic. This definition with regards to the ash is not related to the classification of Coal, thus a Bituminous or Sub-Bituminous coal may have ash which can be classified as Lignitic. [11].

A Bituminous Ash meets the following two criteria:

$$\%Fe_2O_3 > \%CaO + \%MgO$$
$$\%SiO_2 > \%Fe_2O_3 + \%CaO + \%Na_2O$$

otherwise, the ash is categorised as Lignitic.

The Base to Acid Ratio (B/A Ratio) is one of the most used indices. This ratio indicates the melting potential of the coal ash, and has been shown to be in line with the viscosity at elevated temperatures and ash fusion temperature [11,12]. However, the prediction requires confirmation with other indices or factors, especially if the value is below 0.1 or above 1.0 [13].

The Slagging Factor is derived from the multiplication of the Base to Acid Ratio and the Sulphur Content of the coal (wt% DB). The B/A Ratio gives an indication of the melting potential and

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viscocity of the ash, while the %S indicates the potential content of Pyritic Iron in the coal, which influences the oxidation state of iron. [13]. However, the Slagging Factor is applicable for Bituminous ash only.

Another Slagging Factor has been developed utilising the Ash Fusibility Temperatures, however, again, applicable for Bituminous ash only.

The Iron - Calcium Ratio is applicable to all types of coal ash.

The Ash Viscosity (T250) and the Viscosity Slagging Factor are based on studies correlating the viscosity of coal ash temperature at a viscosity of 250 poise with the slagging propensity and the ease of deposit removal in in coal fired boilers. However, these correlations hold true for a limited range of coal ash chemical compositions. [11].

These indices have been widely used in boiler design, coal selection, operation planning and troubleshooting, even though results are not always reliable. This is due to the simplicity of use, coupled with readily available coal specifications from laboratory tests. Furthermore, when used to investigate known ranges of coal at a specific boiler, operational experience improves the confidence level of predictions, as specific correction factors can be applied.

C. *Model Based Predictions*

Since the development of higher processing power of computers, a lot of effort has been put to the development of Computer Models to simulate the utilisation of Coal, with particular emphasis on Ash Behaviour. A large number of organisations and institutes have developed software programs aimed at evaluating the impact of coal properties on power plants [9].

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A study of slagging and fouling prediction on one 512 MW tangentially fired boiler, using a computer model and CFD combined was carried out in 2006. [10]. The predicted slagging and fouling within the boiler was consistent with visual observation during actual utilisation.

In 2017, through and initiative from the Energy Commission, Malaysia and funded by the Malaysian Electricity Supply Industries Trust Account, under the Ministry of Energy, Water and Green Technology, a Model Based Coal Quality Evaluation System was commissioned for the six (6) already running Coal Fired Power Plants. The project involves constructing plant specific models based on equipment specifications and operation data. The models were validated against the plant data during utilisation of various coals. Since project completion, the system has been under continuous evaluation, with improvements carried out.

One advantage of the model based system is that aside from the model being plant specific, the evaluation calculations and results interpretation are consistent. Therefore, the use of the system has made discussions across several parties, ie TNB Fuel, the Power Plants, regulators and Grid Operators, much easier and constructive.

From figure 2, the summary of the coal predicted behaviour in a particular power plant is shown. The summary is a simplified score result for the impact of the coal on certain systems of interest. The score is a result of comparing several predicted parameters against plant design and benchmarks. To investigate further, the detailed results of the prediction can be viewed separately, with additional comments generated to further guide the users on the prediction results.

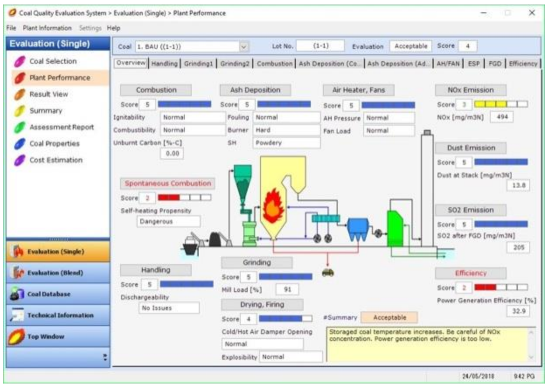

Figure 2: Snapshot of a Coal Quality Evaluation System used in Malaysia

Figure 3 shows one snapshot of the predicted operational conditions of one coal in one boiler, and

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its predicted impact in terms of deposit build up. Users can take note of the wealth of relevant information displayed to determine the impact of each coal on the boiler, for example:

- Area specific predicted temperature (from boiler model) and the predicted ash sintering and melting temperature (from coal properties) give a direct indication of potential deposit build up
- Predicted ash composition at specific area (from boiler model) and subsequent sintering index given indication of deposit condition
- Each item can be compared with other coals evaluated together
- From given predictions, the software also gives comments which could be used as guide by user

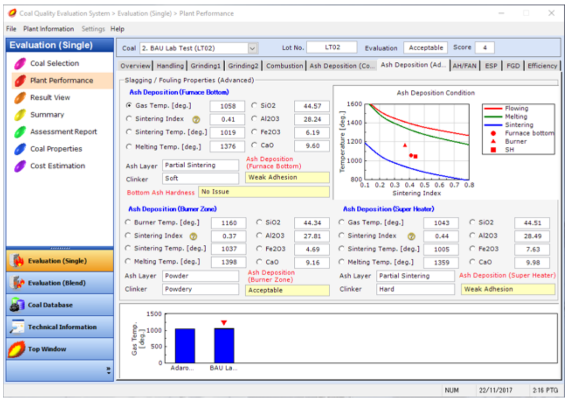

Figure 3: Snapshot of Ash Deposit Prediction Detail from CQES

D. *Scale Up from Lab Tests*

Pilot scale testing had been carried out by utilities to better understand and predict the impact of coal properties on boiler operation.

The reported results are somewhat mixed, as certain boiler operating conditions could not be simulated within laboratory scale furnaces. Fouling deposits could be simulated as far as physical and chemical characteristics, however growth rates could not be determined. Slagging prediction was less reliable, most likely due to the inability to simulate the complex particle dynamics and combustion conditions as in the actual boiler.

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Given time, and in conjunction with the advance analytical techniques available, pilot scale lab tests can be improved up to the stage where it is possible to establish what coals can be used for what boiler, up to a reasonable level of confidence. However, results from pilot scale tests require validation from full scale boilers, as extrapolation alone is extremely difficult.

In 2017, Laboratory Tests for new candidate coals in Malaysia was introduced. Coal sent to an independent laboratory were subjected to the following tests:

- General Coal Analysis
- Spontaneous combustion potential test (Spontaneous Ignition Tester)
- Handling behaviour (Dunham Cone Tester, Adhesion Force Tester and Montmorillonite Content)
- Coal Grindability (Hardgrove Test and Modified Hardgrove Test)
- Combustion Performance, Emissions, Slagging and Fouling Potential (Turbulent Flow Furnace with Ash Deposition Probes and Hot Stage Test)
- ESP performance and dust emission (Ash Resistivity Test)

From the results of the tests, a suitability study is conducted to ascertain the potential issues that may be faced during utilisation at specific plants. This information was then used to prepare the power plants before the first shipment of the new candidate coal.

E. *Coal Trial Burn*

Finally, once the first shipment of the candidate coal is delivered to the power plant, a Coal Trial Burn will be carried out by an Independent Party. The trial

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burn is a thoroughly observed utilisation of the coal at the power plant, with the objective to finalise the suitability of the coal at the power plant, and determine any specific settings or even if any blending arrangements are required.

The coal trial burn will cover, but is not limited to:

- Coal Unloading and Stacking
- Storage Consideration
- Reclaiming
- Short Term Storage (Bunkering)
- Preparation (Grinding and Drying)
- Combustion
  - Ash Deposition (Slagging and Fouling)
  - Post Combustion (Flue Gas & Ash Handling)

A trial burn will typically take 7 days at site, depending on the time taken to switch coals, and also other factors caused by plant operation. Since the trial burn is conducted at a live plant, which is running commercially, extra care has to be taken to ensure the firing of this new coal does not disrupt operation.

F. *Effectiveness of Prediction Methods*

Individually, each prediction methods cannot comfortably anticipate all potential slagging and fouling issues from all coals at all plants. This has been observed extensively by the industry over the years. Through a sample of 30 Coal Trial Burns, conducted between 2011 - 2017, the effectiveness of the prediction methods are investigated. The study covers 6 existing power plants, as listed in table 2:

Table 2: Trial Burn Samples

Plant	Description	Coal Utilised	Trial Burns
Plant A	500 MWg Sub Critical Coal Fired	100% Bituminous	9
Plant B	700 MWn Sub Critical Coal Fired	100% Sub-Bituminous	7
Plant C	700 MWn Sub Critical Coal Fired	70%:30% Bituminous:Sub-Bituminous	6
Plant D	700 MWn Sub Critical Coal Fired	70%:30% Bituminous:Sub-Bituminous	3
Plant E	1000 MWn Supercritical Coal Fired	100% Sub-Bituminous	2
Plant F	1000 MWn Supercritical Coal Fired	100% Sub-Bituminous	3

The comparison of prediction results and the actual findings are shown in figure 4. The Indices are able to predict a fair amount of cases involving Bituminous and Bituminous Blend cases. However, the Indices are unable to consistently predict deposits of Sub-Bituminous cases, often predicting much higher risks than observed. For the Model Based Prediction, most of the predictions were close to what was observed.

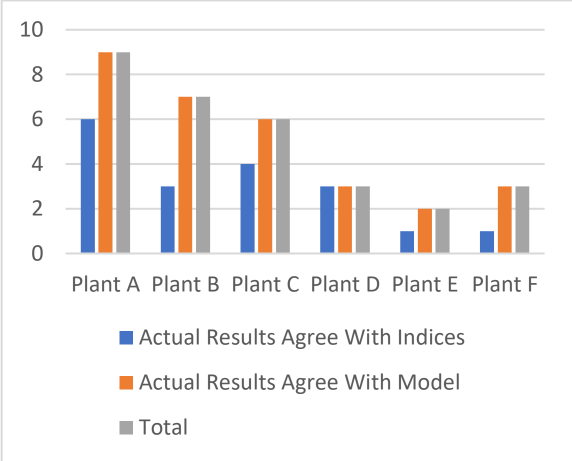

Figure 4: Comparison of Prediction Methods against Observation

V. CONCLUSION

From the study on the different prediction methods used in Malaysia, the obvious shortcoming of Prediction Indices is on predicting deposits of Sub-Bituminous Coals. This could be said to be due to the development of the indices was based predominantly on Bituminous Coals in Europe and North America. Although some adjustments to the Indices have been made to cater for Sub-Bituminous Coals and Lignite, these mere adjustments are still inadequate for consistent prediction.

The other shortcoming of the Prediction Indices, is that current Boiler Technology has allowed for Boiler Designs based on Sub-Bituminous Coals which negate the impacts of deposit forming factors. This caused the previous benchmark of deposit formation of Sub-Bituminous Coals to be misleading.

The Model Based Prediction has shown good promise during the first year of utilisation. However, the coals utilised are still within the normal expected

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range. It is yet to be seen what would be the impact if coals outside the typical supply range or the rejection range is used. It is clear that the use of several methods for prediction concurrently, as utilised in power plants in Malaysia, give the best indication of potential issues with deposits.

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