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Empirical Prediction of Ash Deposition Propensities in Coal-Fired Utilities

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Januar 2, 1997

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Foreword:

This report contain an outline of some of the ash chemistry indices utilized in the EPREDEPO (Empirical **P**REdiction of **D**EPOsition) PC-program, version 1.0. (DEPO10), developed by Flemming Frandsen, The CHEC Research Programme, at the Department of Chemical Engineering, Technical University of Denmark.

DEPO10 is a 1st generation FTN77 Fortran PC-programme designed to empirically predict ash deposition propensities in coal-fired utility boilers. Expectational data (empirical basis) from an EPRI-sponsored survey of ash deposition experiences at coal-fired utility boilers, performed by Battelle, have been tested for use on Danish coal chemistry - boiler operational conditions, in this study.

The author is especially grateful to lic. techn. Ole Hede Larsen, Fælleskemikerne, Fynsværket, for providing full-scale plant and operational data, to Ms. Karin Laursen, The Geological Survey of Denmark and Greenland (GEUS), for providing the bulk ash chemical analyses and to Tom Erickson and Sean Allen, University of North Dakota Energy and Environmental Research Center for providing the EPRI Databank on slagging and fouling and for numerous beneficial discussions.

Lux et Lex.

Lyngby, January 1997,

Flemming J. Frandsen.

Empirical Prediction of Ash Deposition Propensities

By Flemming J. Frandsen

1. Introduction

The elements contained in fossil and bio fuels can be grouped in three concentration levels (Benson et al. (1993)): 1) the major elements, C, O, H, S, and N, building up the organic matrix of the fuel, 2) the ash forming elements, Al, Ca, Fe, K, Mg, Na and Si, present in the concentration range from about 1000 ppmw to a few %(w/w) on a fuel dry basis, and 3) the trace elements, e.g. As, B, Cd, Cr, Hg, Pb, Se and Zn, present typically in concentrations below 1000 ppmw on a dry fuel basis.

The ash forming elements occur in fuels as internal or external mineral grains, simple salts e.g. Na_2SO_4 or KCl or associated with the organic matrix of the fuel. During pulverized coal combustion, app. 1 %(w/w) of the inorganic metals are vaporized, while the rest stays on a condensed form as mineral grains/ash droplets (Flagan and Friedlander (1978)). Depending on the gas/particle temperature and local stoichiometry during coal particle heat-up, devolatilization and char burnout, the mineral grains will undergo phase transformations and approach each other forming fly ash. The vaporized metal species may undergo several reactions: nucleation, coagulation, heterogeneous condensation, and/or interactions with 1) mineral grains/ash droplets in the burning char or 2) residual fly ash particles. Depending on 1) the total specific surface area of the residual ash, 2) the rate of cooling of the flue gas, 3) the local stoichiometry, and 4) mixing in the gas phase, local supersaturation with respect to certain chemical species, e.g. Na_2SO_4 , CaO, MgO, and SiO_2 , may lead to formation of aerosols by homogeneous nucleation (Flagan and Friedlander (1978), Quann and Sarofim (1982)).

Vapors, aerosols, and fly ash particles may deposit on heat transfer surfaces in the boiler through a number of mechanisms (Baxter et al. (1992)): inertial impaction, thermophoresis, and condensation. Ash deposits may cause several operational problems, e.g. changes in the heat uptake of the boiler (Wall et al. (1994)), corrosion of heat transfer surfaces (Harb and Smith (1990)) and/or in extreme cases plugging of the convective pass of the boiler. This may cause unscheduled outages of the boiler and significant economical losses (Borio et al. (1992)), i.e. the ash forming elements in fuels constitute a potential operational and cost problem (Raask (1985), Benson et al. (1993), and Couch (1994)).

Thus, there is a need for development of simple and efficient computational tools for prediction of ash deposition propensities in pc-fired utility boilers: 1) for evaluating new coals for new plants, 2) when designing plants, and/or 3) when selecting coals to burn in existing plants.

2. Prediction of Ash Deposition Propensities

A model or technique for prediction of ash deposition propensities will have to rely on the available fuel, plant and operational data. Traditionally, three types of models have been used:

- 1) Models based on ash chemistry indices, i.e. indices characterizing the chemistry of the fuel ash, eventually combined with plant or operational indices/parameters, characterizing e.g. the size and/or geometry of the furnace.
- 2) Thermochemical equilibrium models, i.e. assuming that the thermal fuel conversion system of interest is in mechanical, thermal, and chemical equilibrium. The composition of such a system can be calculated by minimizing the total Gibbs energy of the system, see e.g. Frandsen (1995).
- 3) Comprehensive combustion and ash formation/deposition models, based on detailed sub models for ash formation, transport and deposition.

The level of information needed, e.g. fuel composition data, furnace size and geometry, and operational data, increases significantly from 1) to 3). Thus, as a first approach, the applicability of a number of ash chemistry indices for empirical prediction of ash deposition propensities has been investigated. The work has been performed parallel to a deposition measuring campaign conducted at a number of full-scale pc-fired utility boilers (Larsen et al. (1995), Laursen (1997)).

2.1. Ash Chemistry Indices

During several years, utility people and boiler manufacturers have been judging the deposition propensity of coals by use of empirical parameters (ash chemistry indices), being a function of the coal bulk ash composition, i.e.

$$\text{Ash. Chem. Ind.} = f(\underline{x}^{\text{ASH}}) \quad (1)$$

where $\underline{x}^{\text{ASH}}$ symbolizes the composition (typically expressed as weight percent oxides on an ash basis) of a coal bulk ash.

Ash chemistry indices have been used - alone or in connection with other indices such as parameters that characterizes the geometry and/or operation of the furnace/boiler: 1) for evaluating new coals for new plants, 2) when designing plants and/or 3) when selecting coals to burn in existing plants. Comprehensive reviews of coal ash chemistry indices are given by Winegartner (1974), Singer (1991), Skorupska (1993) and Skorupska and Couch (1993).

Below, some of the most common coal ash chemistry indices, used for prediction of ash deposition propensities, are introduced.

2.2. Lignitic/Bituminous Ashes

Depending on its chemical composition, expressed as %(w/w) on an oxide basis, a coal ash may be classified as either lignitic or bituminous.

A coal ash for which

$$\% \text{Fe}_2\text{O}_3 > \% \text{CaO} + \% \text{MgO} \quad (2)$$

$$\% \text{SiO}_2 > \% \text{Fe}_2\text{O}_3 + \% \text{CaO} + \% \text{Na}_2\text{O} \quad (3)$$

is classified as **bituminous**, otherwise the ash is **lignitic**.

Notice! The words *bituminous* and *lignitic* ash used above have no relation to the use of these words in the ASTM coal classification procedure, i.e. a bituminous coal can have a lignitic ash etc.

2.3. Ash Fusibility Temperatures

An ash fusion test, e.g. the ASTM Test Method D1857, measures the softening and melting behavior of a coal ash. The high temperature fusibility of a coal ash residue can be a critical factor in the selection of the coal for combustion applications. Ash fusion temperatures are often used to judge the relative slagging and fouling propensities of coal (Skorupska (1993)).

The ASTM Test Method D1857 is based on the gradual melting of a cone of coal ash (19.1 mm high and with an equilateral-triangular base width of 6.4 mm). The cone is heated, at a rate of 8 °C per minute, in a furnace with a controlled atmosphere (reducing/oxidizing). The cone is observed during heating and four temperatures are reported (Skorupska (1993)):

- 1) IDT - Initial Deformation Temperature
- 2) ST - Softening Temperature (height = width of cone)
- 3) HT - Hemispherical Temperature (height = ½ width of cone)
- 4) FT - Fluid Temperature (height = 1/16 width of cone)

The basic idea of the Initial Deformation Temperature (IDT) is to indicate the temperature, where the ash particles have cooled sufficiently to be still capable of a slight tendency to stick together and slowly form a deposit on heat transfer surfaces. The implications for design are that the furnace exit gas temperature, i.e. the flue gas temperature at the exit of the furnace, should be below the initial deformation temperature by about 50 °C to avoid sintering and potential fouling in the convection pass (Bott (1991)).

The Softening Temperature (ST) indicates the tendency of particles to stick to heat transfer surfaces and furnace walls (Winegartner (1974)).

The Hemispherical Temperature (HT) is the temperature of increased tendency for particles to stick or agglomerate (Bryers (1981)).

The Fluid Temperature (FT) gives a measure of the temperature where the ash will be liquid-like, i.e. the temperature where the ash may flow on surfaces (Bott (1991)).

Bryers (1981) has provided a list of attempts to develop empirical correlations capable of calculate ash fusibility temperatures.

2.4. The Base-to-Acid Ratio

The base to acid ratio (B/A) is defined as the ratio of basic oxides to acidic oxides (Winegartner (1974)), i.e.

$$B = \% \text{Fe}_2\text{O}_3 + \% \text{CaO} + \% \text{MgO} + \% \text{Na}_2\text{O} + \% \text{K}_2\text{O} \quad (4)$$

$$A = \% \text{SiO}_2 + \% \text{Al}_2\text{O}_3 + \% \text{TiO}_2 \quad (5)$$

where % Fe_2O_3 is the weight percent Fe_2O_3 on an ash basis etc..

The base to acid ratio should not be used as a single parameter to judge the ash deposition propensities, especially not if its value is below 0.1 or above 1.0 (Winegartner (1974)). The ratio reflects the melting potential of an ash and has been related to viscosities and ash fusion temperatures (Bryers (1981)).

With most ashes, B/A - values in the range 0.4 to 0.7 indicates low ash-fusibility temperatures and thereby a higher slagging potential (Singer (1991)).

2.5. Fouling Indices

Depending on the mode of occurrence in coal, sodium may be vaporized in the flame and then condensed on heat transfer surfaces in the cooler convective pass of a boiler, causing alkali-matrix deposits on, and corrosion of these surfaces. For this reason, the content of sodium oxide in the ash and the total content of alkali on a coal dry basis have been used to judge potential fouling problems (Winegartner (1974)).

The total alkali content on a coal dry basis is calculated as:

$$\text{Total Alk.} = \frac{(\% \text{Na}_2\text{O} + 0.6589 \cdot \% \text{K}_2\text{O}) \cdot \% \text{Ash}}{100} \quad (6)$$

where:

- % Na_2O - %(w/w) of sodium oxide on ash basis.
- % K_2O - %(w/w) of potassium oxide on ash basis.
- % Ash - %(w/w) of ash in the coal (dry basis).

Recommended values for evaluation of the fouling propensity of sodium and total alkali content in coal are given in Table 1.

The ash fouling factor, R_F , is an empirical parameter developed to predict the propensity of alkali bonded deposits to form on convection tube banks, especially super- and reheaters, which is not exposed to radiant heat from the furnace. R_F is defined as

$$R_F = (B/A) \cdot \% \text{ Na}_2\text{O} \quad (7)$$

where (B/A) is the base to acid ratio and $\% \text{ Na}_2\text{O}$ is the weight percent of sodium in the ash (oxide basis). A modified version of R_F , R_F' , utilizes the percentage of water soluble sodium (based on leachability of a low temperature ASTM ash). R_F' is defined as

$$R_F' = (B/A) \cdot \% \text{ Water soluble Na}_2\text{O} \quad (8)$$

Recommended values for evaluating the fouling propensity of a coal are given in Table 2.

Lignitic Ash	Bituminous Ash		Fouling Propensity
$[\text{Na}_2\text{O}], \%^{(1)}$	$[\text{Na}_2\text{O}], \%^{(1)}$	Tot. Alk, $\%^{(2)}$	
< 2	< 0.5	< 0.3	Low
2 - 6	0.5 - 1.0	0.3 - 0.45	Medium
6 - 8	1.0 - 2.5	0.45 - 0.60	High
> 8	> 2.5	> 0.6	Severe

Table 1: Recommended values for the evaluation of the fouling propensity of sodium and the alkalies in coal. (1): ash (oxide) basis. (2): coal dry basis. Source: Winegartner (1974) and Weierman (1982).

2.6. The Slagging Factors, R_s' and R_s

Gray and Moore (1974) have reported a slagging index, R_s' , based on ash fusibility temperatures:

$$R_s' = \frac{HT + 4 \cdot IDT}{5} \quad (9)$$

where HT and IDT are the hemispherical, respectively the initial deformation temperature based on ASTM Test Method D1857.

Bituminous Ash:		Fouling Propensity
R_F :	R_F' :	
< 0.2	< 0.1	Low
0.2 - 0.5	0.1 - 0.25	Medium
0.5 - 1.0	0.25 - 0.7	High
> 1.0	> 0.7	Severe

Table 2: Recommended values for evaluation of the fouling propensity of bituminous coal ashes.

Source: Winegartner (1974).

The slagging factor, R_S , is an empirical parameter developed to relate ash analysis to fused slag deposits formed on furnace walls and other surfaces exposed primarily to radiant heat (Attig and Duzy (1969)).

The definition of R_S is

$$R_S = (B/A) \cdot \% S \text{ (coal db)} \quad (10)$$

where (B/A) is the base to acid ratio and % S is the sulfur content on a coal dry basis. The B/A ratio provides an indication of the melting point and viscosity of the slag, while %S indicates the quantity of pyritic iron present, which influences the oxidation state of iron in the slag (and thus the rheology of the slag) (Winegartner (1974)). Thus, R_S is only applicable to bituminous ashes.

Recommended values for evaluation of the slagging propensity of coal ash is provided in Table 3.

Bituminous Ash:		Slagging Propensity
$R_S^{1)}$:	$R_S'^{2)}$:	
< 0.6	> 1340	Low
0.6 - 2.0	1230 - 1340	Medium
2.0 - 2.6	1150 - 1230	High
> 2.6	< 1150	Severe

Table 3: Recommended values for evaluation of the slagging propensity of bituminous coal ashes.

Source: (1): Winegartner (1974). (2): Gray and Moore (1974).

2.7. Viscosity-Based Ash Chemistry Indices

The temperature, T_{250} , where the viscosity of a coal ash is equal to 250 Poise has been related to the slagging propensity and the ease of deposit removal in coal-fired units. Below, three different methods of calculating T_{250} are outlined.

Hoy et al. (1965) have derived the following relation between the viscosity, η [Poise], and the temperature, T [K], of an ash:

$$\log_{10}(\eta) = 4.468 \cdot (\text{SILPER})^2 + \left(\frac{1.265 \cdot 10^4}{T} \right) - 7.44 \quad (11)$$

In eqn. (11), SILPER is the silica percentage defined as:

$$\text{SILPER} = \frac{\% \text{ SiO}_2}{\% \text{ SiO}_2 + \% \text{ Fe}_2\text{O}_3 + \% \text{ CaO} + \% \text{ MgO}} \quad (12)$$

where % denotes weight percent on an ash basis (expressed as oxides).

Setting the viscosity in eqn. (11) equal to 250 poise, T_{250} can be directly determined.

Watt and Fereday (1969) have introduced a procedure for the calculation of the viscosity of a coal ash completely in the liquid state. The chemical composition of the coal ash is normalized:

$$\begin{aligned} \% \text{ SiO}_2 + \% \text{ Al}_2\text{O}_3 + \% \text{ Fe}_2\text{O}_3 + \% \text{ CaO} \\ + \% \text{ MgO} = 100 \end{aligned} \quad (13)$$

The parameter M is defined as

$$M = 0.00835 \cdot \% \text{ SiO}_2 + 0.00601 \cdot \% \text{ Al}_2\text{O}_3 - 0.109 \quad (14)$$

and the parameter C is defined as

$$\begin{aligned} C = 0.0415 \cdot \% \text{ SiO}_2 + 0.0192 \cdot \% \text{ Al}_2\text{O}_3 + \\ 0.0276 \cdot \% \text{ Fe}_2\text{O}_3 + 0.0160 \cdot \% \text{ CaO} - 3.92 \end{aligned} \quad (15)$$

The slag viscosity may be estimated from the following equation:

$$\log_{10}(\eta) = \frac{10^7 \cdot M}{(T + 123.15)^2} + C \quad (16)$$

where η is the viscosity [Poise] and T is the absolute temperature [K].

The T_{250} may be calculated directly from eqn. (16) for a coal ash with viscosity equal to 250 poise.

The η - T -relations in eqn. (11) and (16) were derived for the coal-ash chemistry compositional range shown in Table 4.

Parameter:	Compositional range:	
	Eqn. (11)	Eqn. (16)
SiO ₂	31 - 59 %	29 - 56 %
Al ₂ O ₃	19 - 37 %	15 - 31 %
Fe ₂ O ₃	0 - 38 %	2 - 28 %
CaO	1 - 37 %	2 - 27 %
MgO	1 - 12 %	1 - 8 %
Na ₂ O + K ₂ O	1 - 6 %	1.5 - 5 %
SILPER	0.45 - 0.75	0.40 - 0.81
SiO ₂ /Al ₂ O ₃	1.2 - 2.3	1.4 - 2.4

Table 4: Coal-ash chemistry compositional range basis of the Hoy et al. (eqn. (11)) and the Watt and Fereday (eqn. (16)) η -T-relationships.

Urbain et al. (1981) have derived the following η -T-relationship:

$$\log_e(\eta) = \log_e(A) + \log_e(T) + \frac{1000 \cdot B}{T} \quad (17)$$

Molar fractions of all components, as oxides, are determined. Iron must be expressed as FeO.

Then the parameters M and α are calculated:

$$M = \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{FeO} + 2 \cdot \text{TiO}_2 \quad (18)$$

$$\alpha = \frac{M}{M + \text{Al}_2\text{O}_3} \quad (19)$$

Finally, B is defined as:

$$B = \sum_{i=0}^3 B_i \cdot (\text{SiO}_2)^i \quad (20)$$

where SiO₂ denotes the molar fraction of SiO₂ in the ash and the constants B_i, $i \in \{0, \dots, 3\}$ are defined as:

$$B_0 = 13.8 + 39.9355 \cdot \alpha - 44.049 \cdot \alpha^2 \quad (21)$$

$$B_1 = 30.481 - 117.1505 \cdot \alpha + 129.9978 \cdot \alpha^2 \quad (22)$$

$$B_2 = -40.9429 + 234.0486 \cdot \alpha - 300.04 \cdot \alpha^2 \quad (23)$$

$$B_3 = 60.7619 - 153.9276 \cdot \alpha + 211.1616 \cdot \alpha^2 \quad (24)$$

In the original work of Urbain et al. (1981) the constant A - in eqn. (17) - was calculated as

$$\log_e(A) = - (0.2693 \cdot B + 11.6725) \quad (25)$$

Kalmanovitch and Frank (1990) have modified the original Urbain equation by introducing a new A-B-relationship:

$$\log_e(A) = - (0.2812 \cdot B + 11.8279) \quad (26)$$

Using eqn. (17) with $\eta = 250$ Poise, the T_{250} can be found by use of a simple Newton iteration scheme.

Gray and Moore (1974) have developed a slagging index based on T_{250} and T_{10000} , i.e. the temperatures where the viscosity of the slag is equal to 250, respectively 10000 Poise. A slag with a viscosity of 250 Poise has Bingham (non-Newtonian) flow characteristics and is highly fluid, while at 10000 Poise, a severe plastic slag, resisting flow, is observed.

Thus, the slagging index, R_{vs} , is based on the idea that the severity of deposit formation depends on a large difference in $T_{250} - T_{10000}$, and an increase in severity as the range of plasticity decreases. R_{vs} is defined as:

$$R_{vs} = \frac{T_{250} - T_{10000}}{97.5 \cdot f_s} \quad (27)$$

The factor, f_s , is defined as:

$$f_s(X) = 133.3 - 0.2446 \cdot X + 1.694 \cdot 10^{-4} \cdot X^2 - 5.268 \cdot 10^{-8} \cdot X^3 + 6.323 \cdot 10^{-12} \cdot X^4 \quad (28)$$

where

$$X = 1.8 \cdot T_{2000} + 32 \quad (29)$$

T_{2000} [$^{\circ}\text{C}$] is the temperature where the slag viscosity is equal to 2000 Poise. T_{250} , T_{2000} and T_{10000} may be calculated using any of the η -T-relations outlined above, although care must be taken when using a η -T-correlation (Nowok et al. (1993)). Recommended values for R_{vs} are given in Table 5.

Bituminous Ash	Slagging
R_{vs}	Propensity
< 0.5	Low
0.5 - 0.99	Medium
1.0 - 1.99	High
> 2.0	Severe

Table 5: Recommended values for evaluation of the the slagging propensity of coal bituminous ashes. Source: Moore and Gray (1974).

3. Utilization of Ash Chemistry Indices

Utilizing air- and water-air-cooled deposition probes (Laursen et al. (1995)), ash deposition propensities were investigated in pc-fired boilers at: 1) the Ensted Power Station, Unit No. 3 (EV3), 2) the Funen Power Station, Unit No. 7 (FV7), and 3) the Vendsyssel Power Station, Unit No. 2 (NV2) (Larsen et al. (1995)). For a detailed outline of the probe design, handling, and the operational conditions in each of these combustion trails, see Laursen (1997). Ash chemistry indices based on the bulk ash analyses shown in Table 6, were calculated, and their prediction of the ash deposition propensity was compared with the observed extent of ash deposit formation at probes in the furnace and convective pass of the respective boilers, see Table 7.

According to Barrett et al. (1984), low slagging frequency means formation of troublesome slag deposits a few times a year, while severe slagging frequency means formation of troublesome slag deposits several times a day.

Referring to Table 7, there is no reason to expect coal A to cause any troublesome deposit formation in the EV3 boiler, while coal E is expected to cause problems in the NV2 boiler. Actually, coal E was observed to cause significantly more slag formation in the NV2 boiler, than e.g. coal D in the FV7 boiler (Laursen (1997)). Thus, in this case, the bulk ash chemistry indices seems to give a correct prediction.

Barrett et al. (1984) have conducted a study with the aim of improving the understanding of slagging and fouling as affected by coal characteristics, boiler design, and operating conditions. The U.S. boiler manufacturer Battelle has designed a 24 page questionnaire to use in soliciting data from utilities, see section 4 in this report. In a statistical analysis of the utility data, Battelle has examined correlations between commonly used slagging and fouling parameters as predictors of slagging and fouling problems. A 65 % correct prediction of ash deposition propensities were reported when using bulk ash chemistry indices alone. Use of bulk ash chemistry indices and plant parameters together, i.e. in a 2-dimensional prediction of ash deposition propensities, has increased the correct prediction to app. 80 %.

Coal	A	B	C	D	D/E	E
Boiler	EV3	FV7			NV2	
%S ¹	0.81	0.77	0.47	0.80	1.35	2.45
%Ash ¹	6.5	11.4	14.3	11.8	11.1	8.8
SiO ₂	48.5	61.0	47.1	48.4	48.0	46.1
Al ₂ O ₃	25.4	20.4	30.8	26.6	22.8	20.9
Fe ₂ O ₃	11.1	7.6	3.15	9.11	11.1	16.6
CaO	2.13	3.07	6.73	4.32	4.97	4.87
MgO	2.24	1.61	1.65	2.85	2.50	1.11
Na ₂ O	0.41	0.63	0.14	1.17	2.19	1.82
K ₂ O	2.13	1.96	0.66	2.39	0.79	0.88
TiO ₂	1.12	1.03	1.78	1.15	1.01	1.00
P ₂ O ₅	0.52	0.30	1.44	0.61	0.56	0.37
SO ₃	2.40	2.69	3.76	3.18	3.91	3.88

Table 6: Major bulk ash compositional data used in this study to test the applicability of ash chemistry indices. 1: As received. The ash composition is given in %(w/w) (oxide basis).

Source: Laursen (1997).

Coal	A	B	C	D	D/E	E
Boiler	EV3	FV7			NV2	
Ash	Bit	Bit	Lig	Bit	Bit	Bit
B/A	0.24	0.18	0.16	0.26	0.30	0.37
Predicted Ash Deposition Propensities:						
%Na ₂ O	Low	Medium	Low	High	High	High
R _F	Low	Low	ND	Low	High	High
R _S	Low	Low	ND	Low	Low	Medium
R _{vs}	Medium	Medium	ND	High	Medium	Medium

Table 7: Ash deposition propensities based on bulk ash chemistry indices. The significance of the symbols is outlined in the text. Lig: Lignitic ash. Bit: Bituminous ash. ND: Not Defined.

4. 2-Dimensional Prediction of Ash Deposition

Ash chemistry indices have been used to predict ash deposition propensities through decades. However, in order to implement operational and plant configurational information in the prediction, an ash chemistry index can be combined with a plant parameter, transforming the prediction to a 2-dimensional empirical problem.

As subcontractor to EPRI, the Columbus division of the U.S. boiler manufacturer Battelle in the early 80ties has conducted a survey among utilities to collect data on boiler features, coals fired, operational parameters, and the frequency and nature of slagging and fouling problems. A questionnaire (EPRI (1987a)) was send out to utilities all over the U.S.A. and in the U.K.. The survey form contained information divided into four sections, as shown in Table 8.

Boiler design parameters:

Unit age, design and present maximum continuous load, steam conditions, furnace dimensions, boiler configuration, burner, pulverizer, wall and soot blower information.

Coal analyses:

Source, proximate/ultimate analysis, ash compositional and fusion temperature data.

Boiler operating conditions:

Peak, short-term and continuous load capacities, excess air, pulverizer fineness and operating frequency of wall and soot blowers.

Slagging and fouling experience:

Frequency of occurence of problem deposits, location of deposit problems, nature of deposits, operating limits imposed by deposits and occurence of specific problems.

Table 8: Information contained in survey form supplied by Batelle to U.S. utilities and boiler manufacturers.

Source: EPRI (1987a)

Data were supplied by 48 U.S. utilities on 120 units, by 4 U.S. boiler manufacturers, and by the Central Electricity Generating Board (CEGB) on 10 units in the UK. Batelle/EPRI have systemized and performed an intensive statistical treatment of the data. The results are reported in EPRI (1987a,b) and Barrett et al. (1984).

In Table 9, compositional parameters (mean values and standard deviations) for the U.S. coals with bituminous respectively lignitic ash, included in the EPRI database (EPRI (1987a,b)) and coals fired in Denmark, are compared. The ash content and calorific values are comparable, while the S-content in coals fired in Denmark is significant lower than the S-content in U.S. coals with bituminous ash. The moisture content in the coals fired in Denmark is about twice as high as in the U.S. coals with bituminous ash.

Coal Parameter:	U.S. Coals BITUMINOUS ash	U.S. Coals LIGNITIC Ash	Coals fired in Denmark
Moisture, % [ar]	$6.96 \pm 4.22(66)$	$21.62 \pm 8.97(23)$	$11.53 \pm 2.47(8)$
Ash, % [ar]	$11.87 \pm 2.58(65)$	$7.12 \pm 2.70(23)$	$10.65 \pm 2.69(8)$
Cl, % [db]	$0.12 \pm 0.06(46)$	$0.017 \pm 0.01(19)$	Not Avail.
S, % [ar]	$2.19 \pm 1.11(67)$	$0.70 \pm 0.41(23)$	$1.11 \pm 0.72(8)$
CV, MJ/kg [ar]	$27.69 \pm 2.17(66)$	$21.77 \pm 2.97(23)$	$26.15 \pm 1.08(8)$

Table 9: Comparison between mean compositional data for the U.S. coals included in the EPRI database and typical coals fired in Denmark. [db]: dry basis, [ar]: as received. Numbers in parantheses are the number of observations, i.e. coals included.

In Table 10, bulk ash composition (mean values and standard deviations) for the U.S. coals with bituminous respectively lignitic ash, included in the EPRI database (EPRI (1987a,b)) and coals fired in Denmark, are compared.

Ash Component:	U.S. Coals BITUMINOUS Ash ¹⁾	U.S. Coals LIGNITIC Ash ²⁾	Coals fired in Denmark ³⁾
SiO ₂ , % [ash]	50.00 ± 4.62	36.97 ± 8.79	49.85 ± 5.54
Al ₂ O ₃ , % [ash]	24.64 ± 4.86	16.79 ± 2.66	24.43 ± 3.99
Fe ₂ O ₃ , % [ash]	15.11 ± 8.00	6.20 ± 1.57	9.78 ± 4.45
CaO, % [ash]	2.58 ± 1.48	18.11 ± 6.56	4.35 ± 1.61
MgO, % [ash]	1.05 ± 0.31	3.86 ± 1.35	1.99 ± 0.65
Na ₂ O, % [ash]	0.58 ± 0.27	1.93 ± 1.04	1.06 ± 0.81
K ₂ O, % [ash]	2.26 ± 0.53	0.54 ± 0.31	1.47 ± 0.77

Table 10: Comparison between mean ash compositional data for the U.S. coals included in the EPRI database and typical coals fired in Denmark. [ash]: ash (oxide) basis. The number of observations, i.e. coals included: 1) 61, 2) 22, 3) 8.

In Table 10, it is seen that the mean bulk ash composition of coals utilized in Danish power stations are comparable to the mean composition of U.S. coals with a bituminous type of ash, although the Fe-content is somewhat lower in the former.

In Table 11, boiler size data from the EPRI database (EPRI (1987a,b)) are listed for boilers designed to burn coal with a bituminous respectively lignitic ashes.

Boiler Parameter:	U.S. Boilers designed for BITUMINOUS Ash	U.S. Boilers designed for LIGNITIC Ash	All U.S. Boilers
MW _{th}	1623 ± 618(64)	1465 ± 384(23)	1582 ± 557(87)
MW _{el}	610 ± 244(67)	518 ± 135(21)	589 ± 218(88)
G (kg/s)	533 ± 220(68)	466 ± 116(23)	516 ± 194(91)
Width (m)	20.21 ± 5.56(68)	18.81 ± 5.16(23)	19.86 ± 5.46(91)
Depth (m)	13.10 ± 3.13(68)	14.08 ± 2.00(23)	13.34 ± 4.30(91)
Height (m)	50.34 ± 7.55(68)	53.16 ± 3.85(19)	50.93 ± 6.77(87)

Table 11: Mean size data for the U.S. boilers in the EPRI database. Numbers in parantheses indicate the number of observations, i.e. of boilers included. G: Superheater steam production rate.

In Table 12, boiler size data for a number of Danish boilers are listed.

Parameter	Boiler A	Boiler B	Boiler C	Boiler D	Boiler E
MW _{th}	1500	971	714	330	380
MW _{el}	630	427	300	131	160
G (kg/s)	542	328	253	110	139
Width (m)	22.3	15.1	13.0	10.0	11.0
Depth (m)	12.2	15.1	13.0	6.5	8.1
Height (m)	48.6	54.6	48.0	33.0	29.5

Table 12: Mean size data for a number of Danish boilers. G: Superheater steam production rate.

When comparing Tables 11 and 12 it is obvious that the thermal and electrical effect of the U.S. boilers in the EPRI Database is significantly higher than for the Danish boilers. Although the mean size (especially the width and the depth) of the U.S. boilers are also bigger than the mean size of the Danish boilers, this could indicate problems, when comparing the plant parameters as calculated for U.S. and Danish boilers. This problem is illustrated in Figure 1, where the Danish coal chemistry -boiler operational window appear outside the expectational data range.

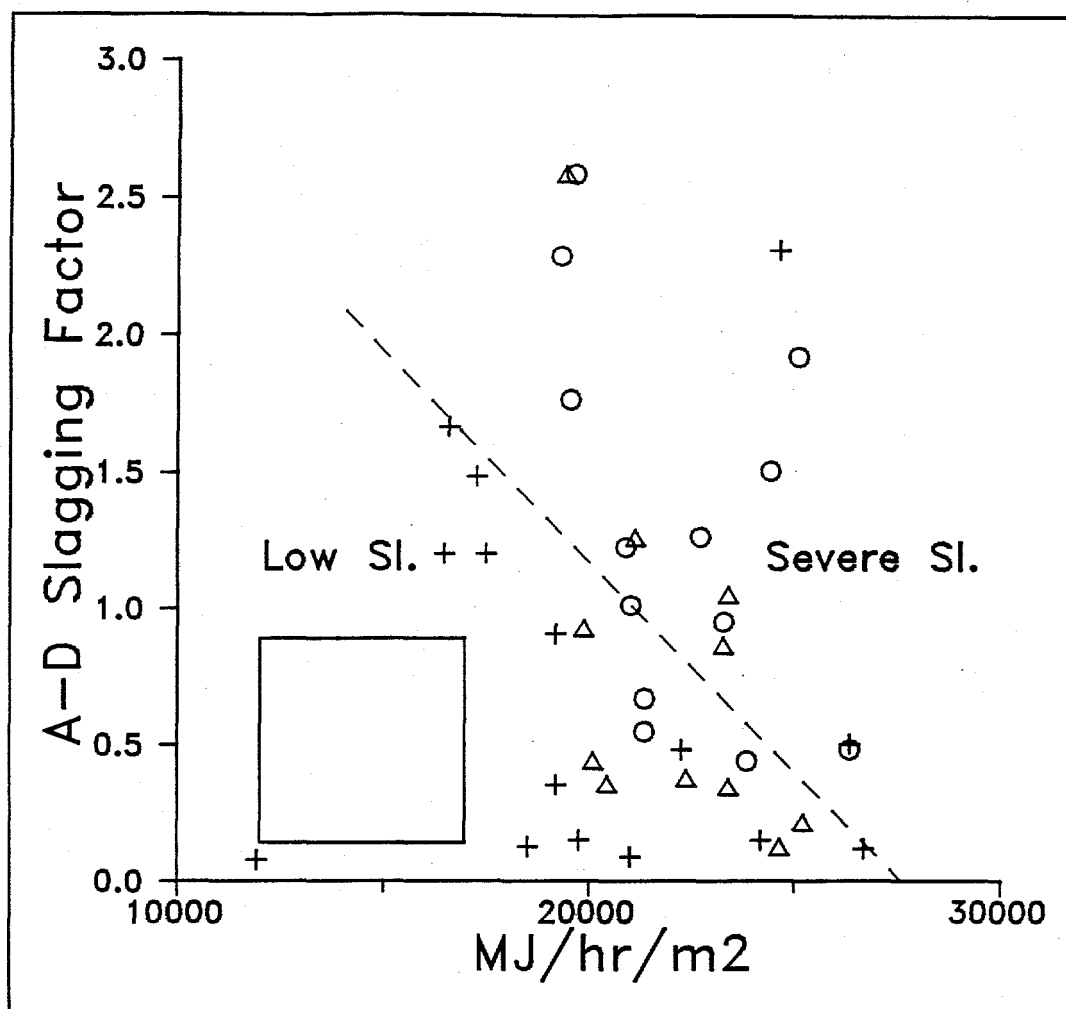


Figure 1: Diagram for 2-dimensional prediction of slagging propensities in coal-fired utilities. A-D Factor: the Attig and Duzy slagging factor (defined in eqn. (10)). The empirical data are taken from (EPRI (1987a)). The rectangle indicates the Danish coal chemistry - boiler operational window, while the dashed line indicates a best fit separation of the empirical data (low and severe slagging).

Legends: + Low slagging propensity
 Δ Medium/high slagging propensity
 ○ Severe slagging propensity

In Figure 1, a correlation can be found, dividing the figure in two areas: 1) a low slagging propensity area and 2) a severe slagging propensity area. Thus, the figure can be utilized to empirical prediction of slagging propensities in pc-fired utility boilers, provided that the actual coal chemistry - boiler operation is covered by the empirical data material. As seen in Figure 1, this is not the case for the Danish coal chemistry - boiler operational window. Thus, 2-dimensional prediction of slagging and fouling in Danish coal-fired utilities will require an extension of the empirical data material following the simple guidelines provided by Barrett et al. (1984).

At first sight, Figure 1 could lead to the conclusion, that slagging will never occur in Danish boilers. Anyhow, this conclusion is highly **WRONG**. The reader should keep in mind that the Danish and U.S. boilers have different temperature and boiler heat-uptake profiles. Thus, slagging may occur in Danish boilers although this is unlikely based on U.S. boiler experiences.

5. Conclusion

Empirical evaluation of coal ash deposition propensities based only on ash chemistry indices, as outlined above, is easy to perform and requires only a minimum of coal compositional data. The technique provides an easy and cheap qualitative indication of potential slagging/fouling problems for fuel technologists, utility managers and boiler manufacturers. Boiler configuration and operation data can be taken into account by plotting appropriate bulk ash chemistry indices vs. plant indices, but this will require an extension of the empirical data material following the simple guidelines provided by Barrett et al. (1984).

A more quantitative, mechanistic, and boiler site specific, prediction of slagging/fouling problems will require a significant increase in the amount of detailed information about the coal fired, the boiler configuration, and the operation of the boiler.

Acknowledgement:

Ms. Karin Laursen, The Geological Survey of Denmark and Greenland, GEUS, lic. techn. Ole Hede Larsen, Fælleskemikerne, Fynsværket, and Mr. Niels Bøjer Jørgensen, Elsam Fuel Department are greatly acknowledged for their positive attitude, high spirits, and numerous beneficial discussions concerning prediction of slagging and fouling in pc-fired utility boilers.

Ms. Anne-Birgitte Krusholm is also greatly acknowledged for her valuable contribution to this work, by plotting several sets of data from the EPRI empirical databank for visual evaluation.

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