EXPLOSIBILITY OF VICTORIAN BROWN COAL DUST

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ABSTRACT

The explosibility of Victorian brown coal dusts has been investigated in a wide range of equipment, including the 1.2 dm^3 Hartmann bomb and the 20 litre spherical bomb. The Hartmann bomb seriously underestimates the severity of brown coal dust explosions and empirical relations between Hartmann bomb and Spherical bomb results cited in the literature are not valid for brown coal. Explosibility increases with decreasing moisture content and particle size and increases with increasing volatile matter content.

1 INTRODUCTION

Dust explosions can occur in any industry that handles fine-particulate combustible material and the coal industry is no exception. In the period 1972 to 1977 there were 39 major coal mine explosions throughout the world and these caused 1901 deaths (1).

In Victoria, Australia, brown coal is mined at a rate of about 38 million tonnes per annum, about 90% of this is used to generate power and about 10% is briquetted. There have been many examples of minor brown coal dust explosions (2), fortunately, so far there has been only one fatality.

For a dust explosion to occur the following conditions must prevail:

- The dust must be combustible and be suspended in an atmosphere capable of supporting flame.
- The dust must have a particle size distribution capable of propagating flame.
- The concentration of dust must be within its explosible range.
- An ignition source of sufficient energy to initiate flame propagation must be present.

The only explosibility work previously reported for Victorian brown coal was carried out by Allardice (3) who used a modified Hartmann apparatus (1.2 dm^3 bomb). This work was of a preliminary nature and was necessarily limited in scope. More importantly, it has since been demonstrated that small explosibility-testing apparatus, such as the Hartmann bomb, significantly underestimate explosion severity (4). Therefore, this investigation was undertaken to obtain sufficient quantitative explosibility data to design and operate plant for handling Victorian brown coal.

2 EXPERIMENTAL

A wide range of explosibility tests were carried out on dusts prepared from Morwell run-of-mine coal and the two extremes in coal type from the Yallourn field, viz., Yallourn pale and dark lithotypes. Air-dry samples were exhaustively ground to yield dust at least as fine as that which accumulates on ledges in coal preparation plant. Standard SECV procedures were employed to obtain complete proximate, ultimate, minerals-inorganics, physico-chemical and particle size analyses for all dust samples. Some of the key analytical data are shown in Table 1, whilst complete analyses are available elsewhere (2).

The apparatus used in the explosibility tests included : 1.2 dm^3 vertical tube (VT), modified Godbert-Greenwald furnace (GGF), 1.2 dm^3 Hartmann bomb (HB) and 20 dm^3 spherical bomb (SB) (Figure 1).

The explosibility parameters measured and the apparatus used were : Tmin - minimum ignition temperature (GGF), Emin - minimum ignition energy (VT), Cmax - maximum explosible concentration (SB), $[O_2]$lim - limiting oxygen concentration to prevent ignition (VT), Pmax - maximum explosion pressure (HB and SB) and (dP/dt)max - maximum rate of pressure rise (HB and SB). Most of these parameters are self explanatory, however, full details of the apparatus, procedures and parameter definitions are available in the literature (2, 5, 6). Many of the pressure rise tests were carried out both in the HB and SB in order to establish whether for brown coal there is a quantitative relationship between the results obtained from these bombs.

3 RESULTS AND DISCUSSION

The two parameters used to measure explosion severity (Pmax and (dP/dt)max) are readily obtained from a pressure-time curve as in Figure 2. The bulk of the results of this investigation are discussed in terms of these two parameters and the explosibility dust constant (K_{St}).

3.1 Explosibility Dust Constant

From extensive gas and dust cloud explosibility tests carried out in vessels ranging in volume from 1×10^{-3} to 60 m^3, Bartknecht (4) has shown that, provided conditions such as concentration, pressure and ignition characteristics remain constant, as the volume of the bomb increases the maximum explosion pressure is essentially constant, but the maximum rate of pressure rise is related to bomb volume by the following equation:

$$(dP/dt)max.V^{1/3} = K_{St} \qquad 1)$$

where V = volume of vessel (m^3)
K_{St} = explosibility dust constant ($bar.m.s^{-1}$)

Equation 1 is known as the cube-root law and it applies to spherical vessels that have a capacity of at least 16 dm^3 and a strong ignition source. The German dust explosibility classification system is based on K_{St} values as follows:

K_{St} ($bar.m.s^{-1}$)	Dust Explosion Class (St)	
0	St 0	Non-explosive
0 - 200	St 1	Explosive
200 - 300	St 2	Strongly explosive
> 300	St 3	Extremely explosive

3.2 The Model

A quantitative model of the combustion process in a brown coal dust explosion is beyond the scope of this study. However, the following simplified sequence of events in a coal dust explosion, which is based on a model proposed by Hertzberg (7, 10), will be used to rationalise the results obtained in this study:

- Removal of adsorbed water from surface.
- Devolatilisation of the particle.
- Mixing of volatiles with air.
- Combustion of air/volatile mixture.
- Oxidation of char substrate.

The processes which quench propogation are a complex combination of convective, conductive and radiative heat transfer from the burnt products to the unburnt particles and the surrounding gases.

3.3 The Effect of Coal Dust Concentration on Explosibility

Dust/air mixtures, like gas/air mixtures, are only explosible within a certain concentration range, i.e. there is a minimum and a maximum explosible concentration. The values of the explosibility limits for a dust depend mainly on its chemical composition, but also on the particle size distribution, ignition energy, moisture content and particle structure - porosity, surface area and shape. The effect of dust concentration on Pmax and (dP/dt)max for air-dry Morwell coal is shown in Figure 3.

At concentrations below Cmin, the heat liberated from the combustion of the particles near the ignition source is not sufficient to ignite adjacent particles; consequently flame propagation does not occur. For the dusts tested, Cmin ranged between 0.09 and 0.20 kg m^{-3} for the pale (60% volatiles) and dark (51% volatiles) lithotypes respectively (Table 3). Once the dust concentration exceeds Cmin, flame propagation is favoured and the flame speed increases with coal dust concentration (Figure 3). The explosion severity peaks at a dust concentration (Cex) of 0.50 kg m^{-3}. The stoichiometric ratios of total fuel/oxygen and volatile matter*/ oxygen are 0.15 and 0.20 kg m^{-3} respectively, i.e. a significant quantity of fuel is not consumed in the explosion. With gas mixtures, which are homogeneous at a molecular level, the explosion severity peaks at the stoichiometric ratio. However, for the two phase dust dispersions the rate of oxidation is limited by the rate at which the particles are heated and devolatilised, thus Cex occurs at a concentration above the stoichiometric ratio.

At fuel concentrations above Cex the severity of the explosion decreases since the excess fuel acts as a heat sink and reduces the maximum temperature rise. The quenching effect of the excess fuel increases as the dust concentration increases until at the upper explosible limit no flame propagation occurs. In practice it is very difficult to measure Cmax owing to the difficulty of obtaining a uniform, dust concentration throughout the vessel. Agglomeration of the dust inhibits dispersion, whilst turbulence results in concentration stratification (9). Therefore, the upper explosibility limit should be regarded as a guide to Cmax and not an absolute measurement. For air-dry Morwell coal Cmax was found to be 7.0 kg m^{-3}, whilst the zero moisture coal was still explosible at the maximum concentration achievable in the apparatus (10 kg m^{-3}).

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* For rapid heating rates ($\sim 10^4\,°C\,s^{-1}$), such as these experienced in a dust explosion, Victorian brown coal produces about 70% volatile matter (8).

3.4 Ignition of Brown Coal Dust Clouds

Ignition and flame propagation in a dust cloud may take place if the temperature of the cloud is raised above Tmin or if there is a local input of high energy, for example a spark with an energy greater than Emin. For air-dry Morwell coal Tmin and Emin were determined to be 390°C and 50 mJ respectively.

Since explosibility is dependent upon the type of ignition source and its energy the HB tests were carried out with high energy spark ignition (∿ 10 J) and hot coil ignition. The results shown in Figure 4 are typical for the HB tests; it is clear that within the experimental scatter the two types of ignition yield the same results. With the SB two 5 KJ chemical igniters were used since it has been demonstrated that this yields the same results as high energy spark ignition (4).

A technique commonly employed in industry to prevent dust cloud ignition is gas inertion. With brown coal this may be achieved by the introduction of N_2 or CO_2 or by self-inertion in a sealed silo. For Morwell air-dry coal $[O_2]$lim is 13% Vol.

3.5 The Effects of Moisture Content, Particle Size

It is clearly established from the literature that explosibility increases as the dust particle size or moisture content decreases. These tests were carried out with ultrafine dust, mass-median diameters (Dm) of 13 and 21 μm, in order to obtain the data for the most hazardous industrial situation. Moisture contents were varied between the equilibrium (14% H_2O) and 0% H_2O. The results of the HB and SB explosibility tests are shown in Figure 5 and Table 3.

The following conclusions can be drawn:

- The HB seriously underestimates the severity of brown coal dust explosions. Over the moisture range tested Pmax is underestimated by 2.0 to 2.5 bar, whilst the "apparent" HB K_{St} is under-estimated by factors of 6 to 13.

- Pmax increases marginally as the moisture content decreases.

- The explosion severity increases linearly with decreasing moisture content. The transition from the explosive (St1) to the strongly explosive (St2) category occurs at about 4% moisture.

- The explosion severity increases marginally when Dm is reduced from 21.4 to 13.2 μm, i.e. for these very small particle sizes moisture content has a much greater impact on explosibility than does particle size.

The rate of devolatilisation and combustion of brown coal is dependent on the effective surface area of the dust, which in turn is dependent on particle size, porosity, moisture content and internal surface area. For these extremely fine dusts the moisture content is the dominant factor. Hertzberg (7, 10) claims that for mass-median diameters of less than 40 μm the explosibility-particle size dependence disappears and that the gas phase combustion of the volatiles is the rate controlling step. The coal moisture reduces flammability in a number of ways, it acts as a fuel dilutant and as an inertant, but more importantly it reduces the effective solid-air interfacial surface area. The dry Morwell coal has a porosity of 41% and a surface area of 213 m^2g^{-1}, however, at equilibrium moisture content the coal has an adsorbed multilayer of water which is 3-4 molecules thick, i.e. the micropores are completely water filled. Clearly this water has to be desorbed prior to devolatilisation and oxidation and will thus reduce the coal flammability.

Complete removal of the equilibrium moisture was found to increase the explosible concentration range from 0.16 - 7.0 to 0.10 - >10 kg m^{-3}. The fuel dilution effect only accounts for 0.01 kg m^{-3} of the difference in Cmin and only about 3% of the heat liberated in combustion is absorbed by the water vapour. Since the equilibrium moisture does not significantly alter the dust dispersion characteristics the major impact of the moisture is to reduce ignition sensitivity.

3.6 Effect of Bomb Size

From Equation 1 it can be seen that for vessels larger than 16 dm^3 explosion severity (dP/dt)max) decreases as the bomb size increases. Small bombs, such as the Hartmann apparatus, have a large surface area to volume ratio and there are large heat losses at the walls of the bomb. Consequently, small bombs underestimate explosion severity. The data obtained from the HB are frequently used to determine explosion relief vent areas by the vent ratio method (10). However, in recent times there have been a number of attempts to obtain a quantitative relationship between 1.2 and 20 dm^3 bomb data (e.g. References 11 and 12). The ultimate objective of such studies is to develop procedures which allow the Nomograph method of venting (11) to be applied to Hartmann bomb data. The relationship proposed in References 11 and 12 is shown in Figure 6. From this figure it can be seen that for the various moisture content Morwell coal dusts there is a linear relationship between (dP/dt)max HB and K_{St} SB, however it is clear that the more explosible brown coal dusts do not conform to the proposed (11, 12) limit.

The brown coal results show that for a single material of the same particle size the "apparent" K_{St} HB is underestimated by factors of ranging from 13 to 6 as the moisture content decreases (i.e. as the explosibility increases). However, at this stage, there is insufficient brown coal data to establish a reliable correlation between SB and HB results. These brown coal results highlight the fact that there is no one simple correlation between 1.2 and 20 dm^3 bomb results for dusts of different chemical or physical composition. It should be stressed that the proposed St1 explosibility limit based on the Hartmann data (11, 12) are not valid for Victorian brown coal. Moreover, extrapolation of the brown coal data shown in Figure 6 suggests that a more explosible brown coal (e.g. zero moisture pale lithotype) may in actual fact fall into the upper St2 or lower St3 range and yet the proposed HB limit could classify such a dust as St1; an incorrect classification such as this could have catastrophic consequences in an industrial application.

3.7 Effect of Coal Type

Owing to differences in hardness, porosity, and equilibrium moisture content (Table 1) it was not possible, or desirable, to test the different air-dry coal types at precisely the same conditions. Despite the above differences it was found that the differences in the explosibility parameters were too large to be attributed to the effects of moisture and particle size alone. In terms of each of the parameters Cmin, Pmax, (dP/dt)max and K_{St}, the explosibility increased going from dark lithotype to ROM to pale lithotype coal. This trend can be attributed to a combination of physico-chemical factors, however, the major factor is high liptinite content of the pale lithotype. The liptinite content of the pale and dark lithotypes is 26.4 and 2.2% respectively, consequently the pale lithotype coal has a high volatile matter content and specific energy (Table 2). Furthermore, although the dark lithotype coal has the highest surface area, it has the lowest porosity and the highest equilibrium moisture content. This increase in explosibility with increasing volatile matter content is consistent with the literature (e.g. 13) and this is the keystone to many of the postulated dust explosibility models. In these models (e.g. 7, 10) it is presumed that only the volatile matter is consumed in an explosion and that the role of the less reactive material, the char, is that of a heat sink. Such models fail to recognise the importance of the phyaical structure of the particle. The physical structure of the coal has two main effects on combustion. Firstly, the rate of devolatilisation, and ultimately the rate of combustion, is dependent upon the pore size distribution of the coal. For example, combustion ignition tests on single particles of brown coal have shown that for a single coal sample the ignition time is inversely related to porosity (14). Secondly, the reactivity of the char substrate to direct oxidation increases markedly as the porosity or surface area increases. For example, both the brown coal char and anthracite listed in Table 3 are essentially composed of carbon (> 90% C, ∿ 1% volatiles) and yet in all respects the char is much more explosible. The reactivity of the char is much higher than that of the anthracite because of its higher porosity (∿ 40% cf 10%) and surface area (∿ 600 cf 400). It is therefore not unreasonable to suppose that oxidation of the char is the initial flame front may contribute to the explosibility of brown coal. However, this has yet to be experimentally verified. It is concluded that the explosibility of brown coal increases as the porosity increases due to the enhanced rate of volatile release and the possibility of an increase in the rate of oxidation of the resulting char in the flame front.

3.8 Hazard Rating of Victorian Brown Coals

The explosibility parameters for a wide range of coal based dusts are as given in Table 3, the dusts have been ranked in terms of their explosibility dust constants K_{St} or their Hartmann (dP/dt)max values. In terms of these explosion severity parameters the Victorian brown coal dusts are the most hazardous of the dusts listed.

The US Bureau of Mines has developed a series of empirical explosibility indices based on the explosibility parameters of Standard Pittsburgh Coal (SPC) (Table 3). These indices take into account both ignition sensitivity and explosion severity. The indices enable qualitative comparisons of explosibility hazards to be made, however, they are limited in their usefulness since they are based on HB data. The indices for air-dry Morwell and Yallourn pale lithotype* coal are given below.

	MORWELL ROM	YALLOURN PALE LITHOTYPE
Ignition sensitivity	Weak	Moderate
Explosion severity	Moderate	Severe
Explosibility index	Moderate	Moderate

It is concluded that at equilibrium moisture content Morwell brown coal is at least as hazardous as SPC and German brown coals, whilst the pale lithotype or oven dried coals are significantly more hazardous than SPC.

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* Emin and Tmin assumed to be the same as that for Morwell coal.

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TABLE 1 : EXTRACT OF PHYSICO-CHEMICAL ANALYSES

Sample Designation	EMC	Dm (μm)	Ash (% d.b.)	HI	P (% Vol)	S (m^2/g)	I
Morwell - ROM (1)	14.1	21.7	2.8	113	40.9	213	1.3
Yallourn - PL	11.4	19.5	1.4	97	50.1	175	1.5
Yallourn - DL	14.8	36.4	0.9	47	35.8	304	3.9

EMC - Equilibrium moisture content, HI - Hardgrove index, P - Total porosity, S - Surface area, I - Ignition index, ROM (1) - Morwell Run Of Mine Coal Sample 1, PL - Pale Lithotype, DL - Dark Lithotype.

TABLE 2 : EXTRACT OF CHEMICAL ANALYSES (DRY MINERAL AND INORGANIC FREE BASIS)

Sample Designation	Volatile Matter (%)	Specific Energy (MJ/kg)	C	H	So	N	O
Morwell - ROM (1)	49.5	27.6	69.9	5.0	0.28	0.66	24.2
Yallourn - PL	59.7	28.8	70.2	6.0	0.25	0.51	23.0
Yallourn - DL	50.6	26.7	68.2	4.8	0.25	0.49	26.3

So - organic sulphur.

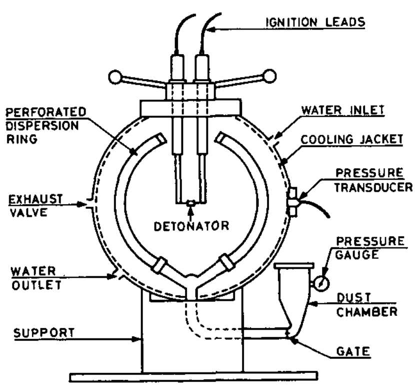


Figure 1 - Twenty litre spherical bomb.

TABLE 3 : SUMMARY OF COAL EXPLOSIBILITY RESULTS

Coal Classification	% H_2O	Dm (μm) or %<x μm	Bomb Size (dm^3)	Cmin ($kg\ m^{-3}$)	Tmin (°C)	Emin (mJ)	$[O_2]$lim % Vol	Pmax (bar)	(dP/dt)max ($bar.s^{-1}$)	¶ K_{St} $bar.m\ s^{-1}$	Ref No
Morwell brown coal	0	22	20 1.2	$1.0x10^{-1}$	-	-	-	7.62 5.82	812 351	220 NA	PS PS
Yallourn pale	11.4	19.5	1.2	$9.0x10^{-2}$	-	-	-	5.61	225	NA	PS
Morwell brown#	14.1	22	20 1.2	$1.6x10^{-1}$	390	190	13	7.47 5.19	598 167	162	PS PS
Peat	15	58	$1x10^3$	$6.0x10^{-2}$	480	-	-	10.9	157	157	15
Standard Pittsburgh Coal, 37% Volatiles	2.0	100% < 74 μm	1.2	$5.5x10^{-2}$	610	60	-	5.7	159	NA	16
Brown coal	~10*	32	$1x10^3$	$6.0x10^{-2}$	380	-	-	10.0	151	151	15
Brown coal 5% Ash, 44% Volatiles	11	57% < 90 μm	$1x10^3$	$6.0x10^{-2}$	450	-	12	9.0	150	150	15
Bituminous/ coking coal	-	24	$1x10^3$	$6.0x10^{-2}$	590	-	~14	9.2	129	129	15
Yallourn dark lithotype	14.8	36.4	20 1.2	$2.0x10^{-1}$	-	-	-	6.67 4.95	337 69	91 NA	PS PS
Brown-coal char	~2*	16	$1x10^3$	$3.0x10^{-2}$	680	-	-	8.4	64	64	15
Anthracite	-	30	$1x10^3$	$2.0x10^{-1}$	710	-	-	0.6	<1	1	15

¶ - coals listed in order of decreasing explosion severity; # - more hazardous result of two series of tests cited; * - moisture contents not given in original reference approximate values estimated; NA - not applicable to 1.2 dm^3 bomb data; PS - present study.

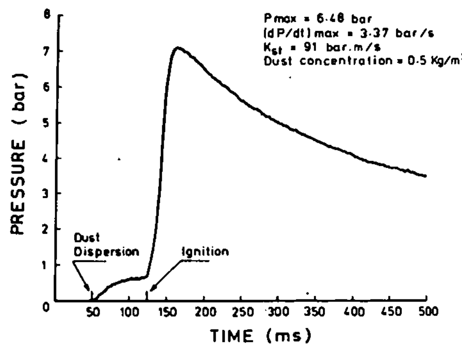


Figure 2 - Typical pressure-time curve for Yallourn dark lithotype coal dust.

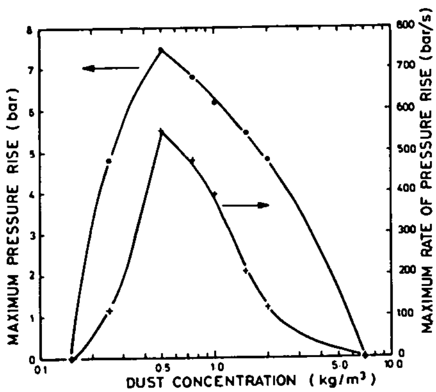
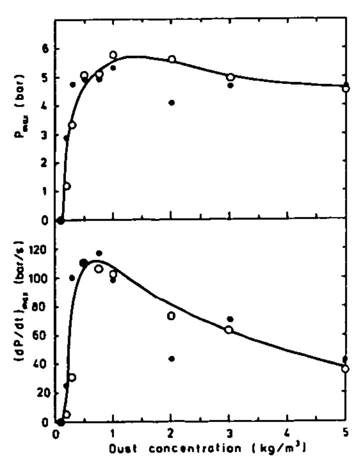


Figure 3 - The dependence of explosibility on coal dust concentration.

(Morwell air-dry coal, Dm = 21.4 μm, 20 dm³ bomb data.)

Figure 4 - The effect of ignition source on dust explosibility. (Air-dry Morwell coal, 1.2 dm³ bomb.)

o spark ignition
● hot coil ignition



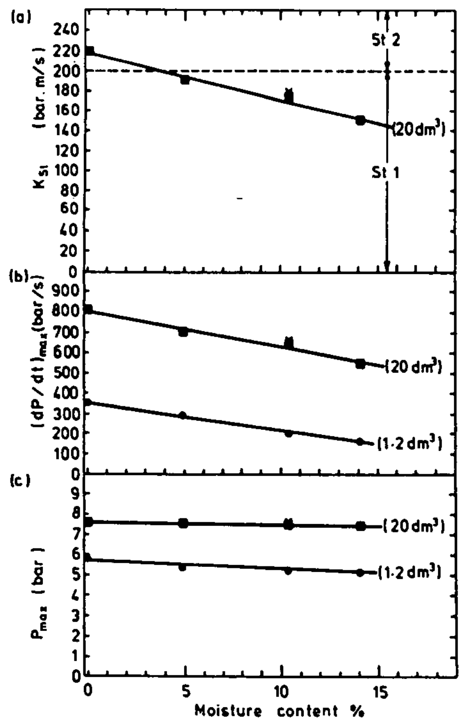


Figure 5 - The effect of moisture content on the explosibility of Morwell coal dust.

o Dm = 21.4 μm, 1.2 dm³ bomb
■ Dm = 21.4 μm, 20 dm³ bomb
x Dm = 13.2 μm, 20 dm³ bomb

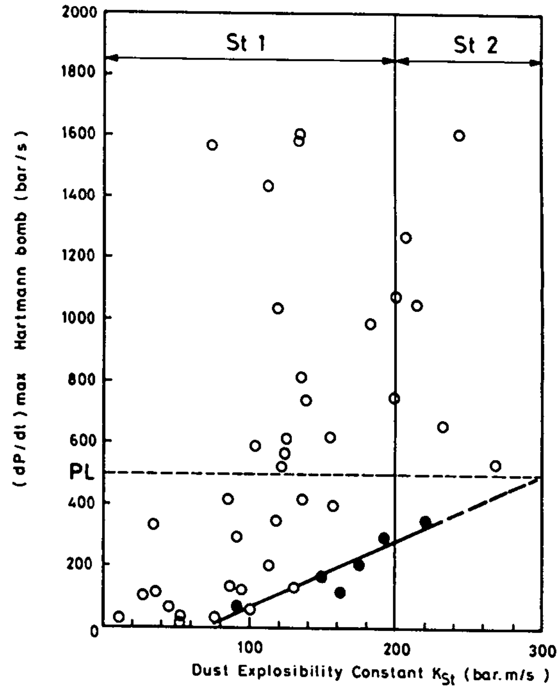


Figure 6 - Relation between SB K_{St} values and HB (dP/dt)max results.

PL Hartmann bomb St1 limit proposed in Refs 11 & 12
● Brown coal data from present study
o Non-coal data from Ref 12