

# PHYSICAL AND CHEMICAL CHARACTERISTICS OF CCB

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## Abstract

The chemical and physical characteristics of fly ash particles are determined by the mineral matter in the original coal, combustion conditions in the boiler, and post combustion cooling conditions. Syngenetic minerals were present in the coal forming swamp and are more closely associated with the coal's organic matrix. Epigenetic minerals were deposited in a coal seam's pores and fractures after coal formation was complete. During combustion, inorganic minerals become fluid or volatile and react with oxygen. In the post-combustion portion of the boiler, they form crystalline minerals, spherical amorphous particles, or condense as coatings on particles. Size and shape are the primary physical characteristics of fly ash particles. Chemical characteristics include mineral speciation, elemental concentration, and solubility. Major elements (iron, calcium, aluminum, and silicon) are those that have a concentration in fly ash greater than 2 percent as oxides. The concentration of oxides of minor elements (sodium, magnesium, manganese, and potassium) is between 2 and 0.2 percent. Other cations are considered trace elements at concentrations generally less than 200 ppm. The effect of the formation conditions is evident from the variability of the fly ash. Examples of physical and chemical characteristics are taken from information in EPRI's 1987 report, the 1997 CIBO report, analyses of CCB samples in the NETL inventory, and other sources in the literature.

## Introduction

Coal Combustion By-Products (CCB) are the non-combustible mineral portion of coal that has been subjected to temperatures above 500°C. This heat-treated residue is commonly referred to as ash. In modern combustion systems, a variety of ashes is produced, and there is generally a serious effort to market the ash. Removing the onus of a waste has provided the impetus for a change in terminology from ash to coal combustion residue to coal combustion by-product and coal combustion product. Whatever it's called, the origin is related to the formation of coal.

The formation of coal has been described as "an inefficiency in the carbon cycle," (Barghoorn, 1952) when the carbon in plants remains in terrestrial sediments and is not recycled to the atmosphere (Figure 1). It can be considered one of the geologic mechanisms of carbon sequestration. Coal is, by definition, a readily combustible rock containing more than 50 percent by weight and 70 percent by volume of carbonaceous material (Schopf, 1966). Another definition describes coal as a combustible solid, usually stratified, which originated from the accumulation, burial, and compaction of partially decomposed vegetation in previous geologic ages (Hendricks, T.A. 1945). On an elemental basis, the carbonaceous structure is composed of carbon, hydrogen, oxygen, and small amounts of organically bound sulfur, nitrogen, phosphorous, chlorine, and other elements.

On a proximate basis, coal is composed of moisture, mineral matter, volatile matter, and fixed carbon (Hessley *et al.*, 1986). Although one of the first effects of coalification is removal of water, some physically and chemically bound water remains in the coal. The mineral matter in coal is determined by low temperature ashing or by dissolution in HF. Volatile matter includes gases that are released by thermal decomposition (pyrolysis) of coal, such as hydrogen, carbon monoxide, hydrocarbons, tar vapors, ammonia, carbon dioxide, and water vapor other than residual moisture. The fixed carbon is the solid combustible material and the non-volatile organics in coal. It is estimated by subtracting the percentages of moisture, ash, and volatile matter from 100. The heating value and rank of the coal increase with increased fixed carbon content (Figure 2). On a practical basis, coals are usually compared on a moisture and mineral matter free basis (mmmf).

Ultimate analysis of coal is the determination of the carbon and hydrogen, sulfur, nitrogen, and oxygen (Hessley *et al.*, 1986). Carbon includes organic and any mineral carbonate. Hydrogen is part of the organic portion of the coal and in the moisture. Nitrogen is assumed to be part of the organic matter. Sulfur occurs as organically bound in

pyrites and in inorganic sulfates. Oxygen, which can be in the organic and inorganic portions of the coal, is determined by difference. The ultimate coal composition on an mmmf basis is the hypothetical pure coal substance.

## **Minerals in Coal and Ash**

Coal ash originates from the inorganic portion of the coal. Inorganic compounds are added during deposition and metamorphism, but are not necessarily an integral part of the coal structure. Combustion and post combustion cooling also have a significant effect on the mineral phases in CCBs.

## **Minerals in Coal**

A variety of minerals have been identified in coal. Although some of the inorganic compounds originate in the plant material, most are deposited during (syngenetic) or after (epigenetic) coalification. Syngenetic minerals can be formed by precipitation in an aqueous medium during early stages of coalification or they may be detrital clastics transported into the peat swamp by wind or water. Epigenetic minerals are deposited within the coal seam, in cracks, fractures and bedding planes, by ascending or descending solutions. They also may be produced from syngenetic minerals by increased temperature and pressure. Minerals associated with the coal matrix are sometimes denoted as included minerals, while minerals that are independent of the organic portion may be called excluded minerals. Mackowsky (1968) indicated that most of the silicates, quartz, and phosphates had been transported into the peat swamp. Carbonates, sulfides, chalcedony, and quartz from the weathering of feldspar and mica were formed within the swamp. These minerals tend to be intimately intergrown with the organic matrix. Some carbonates, sulfides, and oxides were deposited in cleats and fractures. Illite, chlorite, and some pyrite were formed by the transformation of syngenetic minerals.

Inorganic matter in coal includes a variety of minor or trace elements. The concentration of these elements in coal may be greater than their average concentration in the earth's crust (Table 1). When compared to the overlying carbonaceous shale (Table 2), coal has a lower concentration of trace elements, reflecting the influx of detrital inorganic sediments in the shale. The distribution of trace elements varies too widely to be described by a general statement. Coals from different areas may show distinctive trace element characteristics and, within a single coal seam, the trace element distribution may not be consistent. This suggests that no single process has been responsible for the accumulation of trace elements in coal.

In a study of 35 coal samples from eight countries, Vassilev and Vassileva (1996a) identified approximately 100 minerals. The minerals were characterized as major (> 1% by wt), minor (.1><1% by wt), and trace (<0.1 % by wt). On a semi-quantitative basis, the mineral groups in decreasing order of importance are: silicates, carbonates, oxyhydroxides, sulfides, sulfates, phosphates, others.

In another study of 41 coals, Vassilev *et al.* (1996) relate mineral assemblages to the rank of the coal. The coals were divided according to rank based on dry ash free carbon concentration ( $C_{daf}$ ). The lower rank coals are enriched in mineral matter including calcium and magnesium oxides. The highest rank coals have increased contents of silica, aluminum, iron, potassium, sodium, and titanium.

The quartz in 40 samples of a Powder River Basin (PRB) coal was primarily detrital, but trace amounts of Beta-form quartz, with apatite and zircon, was attributed to air-fall and reworked volcanic ash deposited in the peat swamp (Brownfield *et al.*, 1999). In a study of Gulf Coast lignites, enrichment of some elements was attributed to proximity of igneous rocks or to deposition of volcanic ash (Warwick *et al.*, 1997). The mineral composition of the coal seam also can be modified by post-coalification circulation of geothermal fluids (Kolker, 1999; Daniels *et al.*, 1990).

The minerals phases identified in various coals are summarized in Table 3 and the modes of occurrence and maximum concentration of selected elements listed in Table 4.

## Combustion System

The generation of coal combustion by-products depends on the combustion system, boiler and its operating conditions, and post-combustion parameters (Figure 3). In pulverized coal (PC) fired power stations, the furnace operating temperature is typically above 1400 degrees C (~2500 degrees F). The finely divided coal particles are injected into the furnace and ignited while suspended in air. The volatile matter and organic matrix react with air to produce heat, CO<sub>2</sub>, H<sub>2</sub>O, SO<sub>2</sub>, and NO<sub>x</sub>. At these temperatures, minerals may oxidize, decompose, fuse, disintegrate, or agglomerate (Clarke and Sloss, 1992). For instance, although some SO<sub>2</sub> is produced from the sulfur in the organic matrix, most is the result of the oxidation of pyrite. Another product of pyrite oxidation is iron oxide that is found in ash particles as hematite or magnetite. Discrete mineral particles may undergo fusion and partial melting in the boiler. Depending on the temperature conditions in the post combustion zone, the particles may cool slowly and develop a characteristic crystalline structure (Figure 4). If cooling is rapid, the minerals may condense to a spherical, glassy particle. If mineral grains originate within the coal matrix, they can become liquid during combustion while volatile elements enter the vapor phase. As they cool, these gaseous compounds may condense to very small particles (aerosols) or coalesce to slightly larger spherical particles. They also may condense on the surface of other particles, leading to surface enrichment of volatile species. Non-volatile compounds will agglomerate to form fly ash particles. Expansion of trapped volatile matter may cause the particle to expand, forming a hollow, low-density cenosphere. Residence time within the boiler is relatively short and some minerals, especially those with high melting points, are transported through the combustion zone almost unchanged.

Based on their boiling points and the phase change temperature of their oxides, several authors have described the partitioning of trace elements in CCBs (Germani and Zoller, 1988; Meij, 1989; Yokoyama *et al.*, 1991). The first group of elements, which are concentrated in bottom ash or equally distributed between bottom ash and fly ash, includes typically lithophile elements: Ba, Mg, and Mn. In a second group, trace elements enriched in the fine particulate fraction are usually chalcophile elements such as As, Cd, Pb, Se, and Zn. Group 3 includes volatile elements that remain in the vapor state: Hg and Br. Several elements partition between the groups (Figure 5).

According to Davison *et al.* (1974), the concentration of the elements Pb, Sb, Cd, Se, As, Ni, Cr, and Zn increased with decreasing particle size. The concentration of the elements Fe, Mn, V, Si, Mg, C, Be, and Al increased with decreased particle size only for particles with a diameter less than 11 μm. These elements showed no size dependence for larger particles. The concentrations of Bi, Sn, Cu, Ti, Ca, and K showed no dependence on particle size.

Vaporization and condensation form an ultra fine aerosol during PC combustion (Senior *et al.*, 2000a). Factors such as residence time, temperature history, and level of turbulence control the size and morphology of the aerosol particles. Fly ash particles with aerodynamic diameters less than 0.4 μm were attributed to condensation. Non-volatile elements, such as Fe, were found to concentrate in larger ash particles. Between 10 and 30 pct of the volatile elements As, Sb, Se, and Zn are in the condensed fly ash particles. Arsenic and Sb are soluble in silicate glass and may be retained by glassy particles that form by coalescence of minerals. Correlations between the concentrations of arsenic and calcium in fly ash are assumed to indicate the formation of calcium arsenate.

## Minerals in Ash

Volatilization, melting, decomposition, and formation of new minerals, as well as oxidation, are the mechanisms that transform the minerals in coal. The transition of minerals in coal to those found in combustion by-products is related to the high temperature oxidation and to the rate of cooling of the inorganic melt. There is a significant difference between the minerals in coal and those in the ash produced from the same coals. The inclusion of heavy metals or hazardous air pollutants (HAPs) in the ash and their solubility are the primary determinants of toxicity. Concentration is not the only factor; volatility, toxicity, and solubility determine the potential for health and environmental effects. These factors are functions of speciation within the ash. A summary of the minerals identified in coal ash is given in Table 7. Because different authors use different methods of mineral identification and different concentration units, some degree of interpretation was necessary to assemble the comparative table. The mineral association of trace elements is summarized in Table 8.

## Chemical Composition of Coal Ash

The Electric Power Research Institute (EPRI) conducted a study of the composition of 39 fly ash samples and 40 bottom ash samples from power plants in the United States (EPRI, 1987a). The trace element composition indicated that more volatile elements (As, B, Cl, F, S, and Se) were preferentially partitioned to the fly ash and their concentrations were higher in fly ash derived from bituminous coal. The mean and range of concentrations for major elements is shown in Table 5. Maximum trace element concentrations are given in Table 6. EPRI also conducted an extensive literature search on the inorganic and organic constituents of fossil fuel combustion residues (EPRI, 1987b; EPRI, 1987c). They concluded that the inorganic composition was highly variable. Some non-volatile elements were evenly distributed between fly ash and bottom ash, while volatile elements tend to be concentrated in fly ash.

The Council of Industrial Boiler Owners (CIBO) conducted a survey of operators of FBC units, requesting information on the physical and chemical characteristics of FBC fly ash (CIBO, 1997). Trace elements were found to be concentrated in the smaller ash particles. The composition of the FBC fly ash, as provided by respondents to the CIBO survey, is given in Table 5. Trace element data is given in Table 6.

The Pennsylvania Department of Environmental Protection (PADEP) allowed DOE personnel to copy applications and reports relative to placement of CCBs at surface mine sites (Kim and Cardone, 1997). The information included analyses of 99 fly ash samples. A summary of the major element and trace element data is given in tables 5 and 6. The mean concentration of major and trace elements in ash from Bulgarian power plants, as reported by Vassilev and Vassileva (1997), is in the same range as the data reported in tables 5 and 6.

In evaluating the chemical composition of fly ash in tables 5 and 6, it must be recognized that the data provided by several entities has limitations. First, ash is a non-homogeneous material, and it must be assumed that the sample was representative. In the data submitted, blanks are not always identified as values below detection limits or as elements not included in the analysis. Also, detection limits may vary, which makes comparing analyses difficult. It's also possible to dissolve solid samples by several methods (metaborate fusion, aqua regia, and hydrofluoric acid for example) and the method used may affect the analytical results. Therefore, compilations of fly ash analyses give good indications of the range of compositions, but are not reliable indicators of concentration of elements in an "average" fly ash.

## Physical Properties

The physical characteristics of combustion residues include particle size, particle shape or morphology, hardness, and density. These properties are a function of the particle size of the feed coal, the type of combustion, and the particulate control device. PC boilers typically use fuel that is ground to a diameter of less than 0.075 mm (CIBO, 1997). The fly ash has a particle diameter less than 0.010 mm. Due to the high temperature of PC combustion, fly ash particles tend to melt and condense as spheres. Fly ash particles from FBC boilers, although having similar diameters and density, tend to have a less regular shape. Armesto and Merino (1999) also found that residues from PC systems are smaller than those generated in FBC systems.

The particle size distribution is considered an important parameter in the utilization of fly ash. Sized fractions of fly ashes were found to have similar mineral compositions (Erdogdu and Turker, 1998). However, when used as a cement replacement in concrete, higher strengths were correlated with smaller particle size. The effect was attributed to the decreased porosity due to small particles filling a higher percentage of concrete pores.

Comparing the size distribution of minerals in fly ash with that in the original coal showed that both types of particles are larger than 1Fm, but fly ash particles are larger with a median diameter of 20Fm and a maximum diameter in the range of 150 to 200 Fm (Wigley and Williamson, 1998). The larger size of fly ash particles is attributed to coalescence of mineral grains during cooling. In a random population of fly ash samples from PC combustion, the median particle diameter was 27 Fm (Kim, 2002).

In a study of 27 samples of pulverized fuel ash from Australian and Japanese coals, Nagataki *et al.*, (1995) determined that specific gravity of the samples varied from 2.01 to 2.31. The maximum bulk density was between 0.7 and 1.4 g/cm<sup>3</sup>, while the surface area varied between 0.7 and 37 m<sup>2</sup>/g. The average specific gravity of fly ash particles used in the NETL leaching experiments was 2.32 (Kim, 2002).

The morphology of fly ash grains is determined by the heating and cooling regimes in the PC boiler. Micro spheres, typically between 30 and 100 Fm in diameter, can be described as hollow cenospheres or noncrystalline glass beads (Shao *et al.*, 1997). Unburned carbon particles, irregular partially melted minerals, particle fragments, and agglomerated particles tend to be slightly larger.

## Summary

Inorganic compounds in coal may originate in plant material, but most are deposited during (syngenetic) or after (epigenetic) coalification. Syngenetic minerals are either chemical precipitates or detrital clastics. Epigenetic minerals are deposited within the coal seam after coalification is complete. Minerals identified in coal include silicates, carbonates, oxides, oxyhydroxides, sulfides, sulfates, and phosphates. In coal, the more volatile elements (As, Hg, Mo, Pb, Sb, and Se) are usually associated with pyrite. The elements Cd and Cu are associated with sulfides, possibly with Pb and Zn sulfide. The carbonates are apparently limited to Ca, Mg, and Mn. Several elements are associated with the organic matrix or with silicates.

During combustion, minerals in coal become fluid, are subjected to high temperature oxidation, and then cooled. The maximum temperature and the rate of cooling influence the morphology and composition of the ash. Generally, more than 50 percent of fly ash is composed of spherical amorphous particles. Inorganic compounds also may be present in fly ash as crystals or as surface coatings on other particles. In fly ash, the major cations are Si, Al, Fe, and Ca with lesser amounts of Na, Mg, K, Sr, and Ti. Trace elements include As, B, Ba, Cd, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Se, V, and Zn. The primary minerals are quartz, mullite, hematite, clays, and feldspars. Volatilization and condensation are believed to be primary determinants of trace element partitioning in fly ash, but there is limited data on trace element associations.

Physical characteristics of combustion residues, including particle size, particle shape or morphology, hardness, and density, are a function of the particle size of the feed coal, type of combustion, and particulate control device. About 50 percent of fly ash particles are glassy spheres.

The chemical and physical properties of fly ash particles are a function of the mineral matter in the coal, combustion conditions, and post-combustion cooling.

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Table 1. Distribution of trace elements in coal ash compared to the average concentration in the earth's crust, ppm. (After Nicholls, 1968).

Element	Crust	Coal ash, minimum	Coal ash, maximum
Ag	0.7	1	10
As	1.8	100	900
B	10	86	5,800
Ba	425	300	3,500
Be	2.8	1	30
Co	25	30	300
Cr	100	50	400
Cu	55	20	500
Mn	950	200	1,000
Mo	1.5	10	200
Ni	75	50	800
Pb	12.5	5	700
Sr	375	80	3,500
V	135	100	1,000
Zn	70	100	1,000

Table 2. Trace elements in whole coal compared to concentration in shales, ppm (After Nicholls, 1968).

Element	Shale	Coal, Minimum	Coal, Maximum
Ag	.07		<0.05
As	13		100
B	100	12	145
Ba	580	35	170
Be	3	<1	2
Co	19	2	20
Cr	90	5	38
Cu	45	3	15
Mn	830	20	150
Mo	2.6	<0.5	7
Ni	68	6	35
Pb	20	8	80
Sr	300	26	250
Zn	95	25	100



Table 3. Minerals Identified in Coal.

Sample	B <sup>1</sup>	PRB <sup>1</sup>	PRB <sup>2</sup>	Various <sup>3</sup>	Lignite <sup>4</sup>	UK <sup>5</sup>	B <sup>6</sup>
Units	wt%/mm	wt%/mm	Ma/ Mi/ T	vol%/mm	NA	NA	Frequency
# of Samples	3	1	40	34	48	?	75
Quartz	12	27	$\alpha$ Ma	33	U	U	63
			$\beta$ T		crystalobolite U		
Kaolinite	13	19	Ma	10		U	73
Illite	13	8		4		U	9
Montmorillonite	<1	2		1			
Feldspar	<1	2		4	U		
Silicates	27	29		2	U		15
Pyrite	16	1	T	4	U	U	18
Sulfides	<1	1					2
Siderite	<1	<1					15
Calcite	3		Mi	6	U		62
Carbonates	2	<1		6	U		56
Rutile/Anatase	<1	3	T				0
Phosphates	<1	6	T	3		U	47
Other	9						
Micas			Mi	3			
Zeolites					U		
Barite			T	1			
Zircon			T				
Plagioclase			T				12
Sulfates				10	U	U	17
Oxides & Hydroxides				11			1

<sup>1</sup>Senior *et al*, 2000b<sup>2</sup>Brownfield *et al*, 1999<sup>3</sup>Vassilev *et al*, 1997<sup>4</sup>Karayigit *et al*, 2001<sup>5</sup>Spears *et al*, 1999<sup>6</sup>Kimura, 1998

Table 4. Modes of Occurrence and Maximum Concentration (ppm) of Elements in Coal.

Reference	<i>Senior et al</i>		<i>Shao et al</i>		<i>Hower et al</i>		<i>Palmer et al</i>	
Element	Mode	Max	Mode	Max	Mode	Max	Mode	Max
As	Py	250	S	25	Py	1156a	Py, Sl	45
B	Cly,O	500						
Ba			O, SO <sub>4</sub>	500				
Be	Cly,O	30					Sl, O	2
Cd	ZnS	10					S	2.5
Co			S	25			Sl, O	12
Cr	Cly, Fe, OOH	100	O	80		401a	Sl, O	97
Cu	S,O	200						
Fe			S	2,000			Py, Sl	2.6 %
Hg	S,E	10					Py, O	0.50
K			O	14,000				
Mn	O, CO <sub>3</sub>	1,000				563a	Sl, CO <sub>3</sub>	230
Mo	Py, O	50						
Na			O, SO <sub>4</sub>	4,500				
Ni	S,O	100	S			131a	Sl, O	48
Pb	Py, S	100			Py	193a	O, S, Py	25
Sb	S, Py	40					Sl, O	2.1
Se							Py	6.1
Sn	Ox, S	20						
Sr			O, SO <sub>4</sub>	300				
Zn	S, O	300	O, SO <sub>4</sub>	50			Sl, S, Py	190

Py = Pyrite    S = Sulfide    Cly = Clay    CO<sub>3</sub> = Carbonate    Sl = Silicate  
O = Organic    OOH = Oxyhydroxide    Ox = Oxide    E = Elemental  
SO<sub>4</sub> = Sulfate    a = ash

Table 5. Minerals Identified in Fly Ash

Reference	Vassilev & Vassileva, 1996	Yamashita <i>et al</i> , 1998	Hower <i>et al</i> , 1999	McCarthy <i>et al</i> , 1999	
				Class F	Class C
Units	M-m-T-a	wt%	wt %	wt%	wt %
Quartz	M	5 - 40	<0.5	7.1	
Cristobalite	a-M				
Kaolinite					
Illite	M				
Plagioclase	m-M	1 - 20			
K-feldspar	m-M	1 - 10			
Micas	m-M				
Mullite	a-M		<1	13.3	
Hematite	m-M	1 - 10		4.1	
Magnetite	a			7.0	2.5
Goethite	a-M				
Spinel	a-m				
Gypsum		1 - 20			
Calcite				0.5	5.7
Ettringite				3.5	7.8
Alumino-Silicates		20 - 70			
Corundum	a-M				
Gibbsite	a-M				
Rutile	a-m				
Lime	a-M				
Portlandite	a-M				
Anhydrite	M				
Amorphous	50 - 90 vol %		75-86	64.5	74.8

M-m-T-a = Major, minor, Trace, accessory

Table 6. Trace Element Association in Fly Ash

Reference	
Huggins <i>et al</i> , 1997	As in FA is As (V); 25% of As in BA is As(III), < 5% of Cr is toxic Cr(VI); Ni is +2 valence and Se may be selenide or selenate.
Finkelman <i>et al</i> , 1997	As = 170 ppm in FA from high S coal and 54 ppm in FA from low S, primarily condensed on ash surfaces. Cr enriched in the Fe-oxide phases, such as spinel. 70 pct of Cr in the glassy silicate. Similar results for Ni and Co. Sb and Zn present in more than one ash phase.
Senior <i>et al</i> , 2000	Elements vaporized during combustion: 40 to 80 % of As & Sb, residual may dissolve in silicates or form Ca compounds; > 80 % Se and Zn volatilized; < 40 % Cr in vapor state.
Furminsky, 2000	Most As, Pb, and Cd in FA; Se and Hg vaporized. Air/coal ratio affects partitioning of elements in vapor and solid phases, shifts condensation to lower temperature.
Hulett <i>et al</i> , 1980	Ba, Sr, Ti, As, Se concentrated in amorphous phase. V, Cr, Mn, Ni, Zn and Cu concentrated in Fe oxide/spinel

Table 7. Major element concentrations in fly ash samples, g/kg.

Element	EPRI Data			CIBO Data			PADEP Data		
	n	Mean	Range	n	Mean	Range	n	Mean	Range
Al	39	113	46-152	14	29.9 <sup>1</sup>	.02 - 176	89	30	.012 - 140
Ca	39	62	7.4-223	2	56	37 - 74	19	50	.003 - 265
Fe	39	76	25-177	18	31 <sup>1</sup>	.02 - 81	89	35	.009 - 675
K	39	14.3	3-25.3	13	1.5 <sup>1</sup>	.001 - 15			
Mg	39	11.8	1.6-41.8	1	10		22	139	.005 - 4
Na	39	9.1	1.3-62.5	1	5				
P	24	3	1.1-10.3	1	0.5 <sup>1</sup>				
S	39	12.6	1.3-64.4	2	15	8 - 21			
Si	39	209	90-275	2	115	90 - 115			
Sr	39	1.3	.2 - 7	1	0.3				
Ti	39	7	1.3 - 10	1	2				

Median

Table 8. Trace element concentration in fly ash, mg/kg.

Element	EPRI Data			CIBO Data			PADEP Data		
	n	Mean	Maximum	n	Median	Maximum	n	Median	Maximum
Ag				19	1	39	78	0.4	22
As	39	156	385	23	12	46	92	20	21,030
Ba	39	1,880	10,850	20	320	7,700	93	212	2,960
Be				13	2	12			
B				11	90	652	80	50	3,995.4
Cd	2	12	17	23	.6	13	81	1	30
Co				16	14	179	30	28	83
Cr	29	247	651	23	29	141	92	40	360
Cu	39	185	1,452	20	43	99	91	41	474
Hg				22	.3	7	84	0.4	5.44
Mn	39	357	1,332	15	126	57,700	86	79	27,614
Mo	36	44	236	21	6	61	79	12	108
Ni	39	141	353	22	35	1,020	91	39	752
Pb	39	171	2,120	24	15	73	93	33	225
Sb	7	43	131	17	5	1,370	64	27	140
Se	30	14	49	22	5	46	77	3	201
Sn	18	44	56						
Th				12	3	25			
V	35	272	652	13	61	1,120			
Zn	39	449	2,880	22	36	105	93	41	1,196

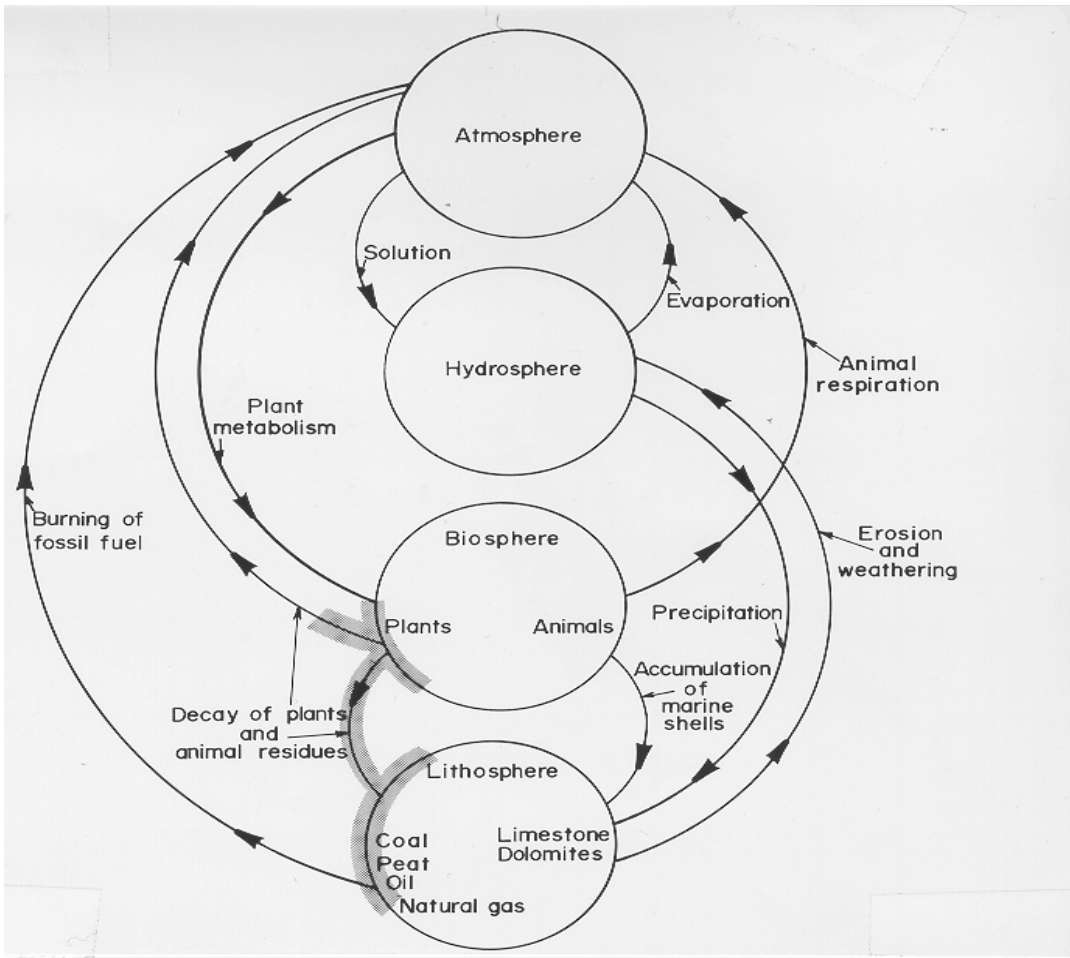


Figure 1. The generation of fossil fuel resources due to the migration of carbon from the biosphere to the lithosphere within the carbon cycle.

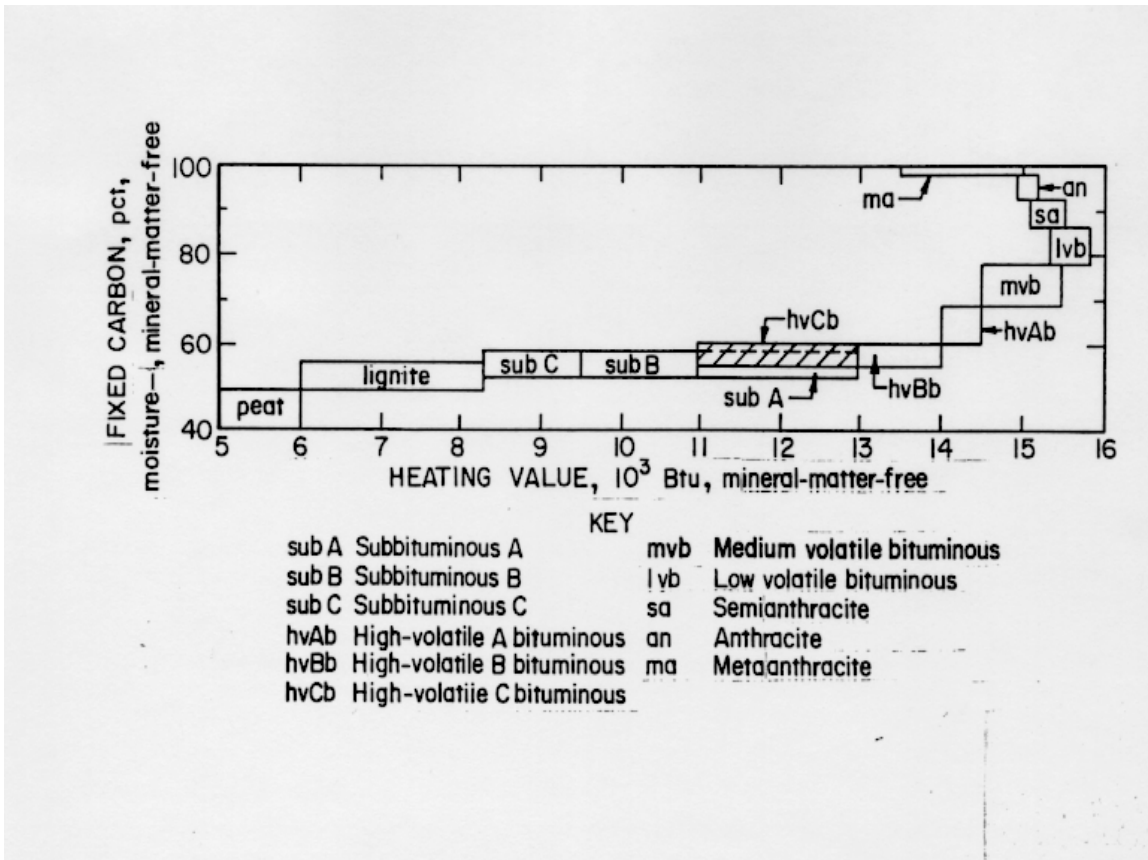


Figure 2. Variation in heating value and rank with increased concentration of fixed carbon.

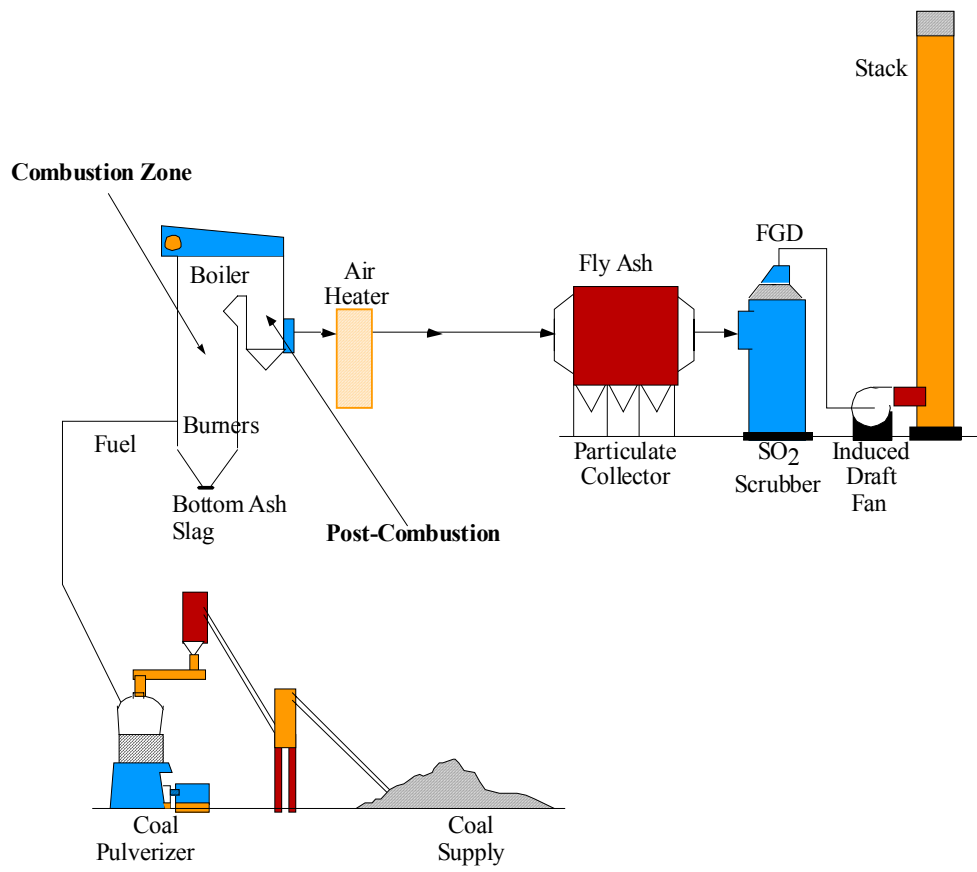


Figure 3. Generation of Coal Combustion By-Products (CCB) in a PC Utility Boiler



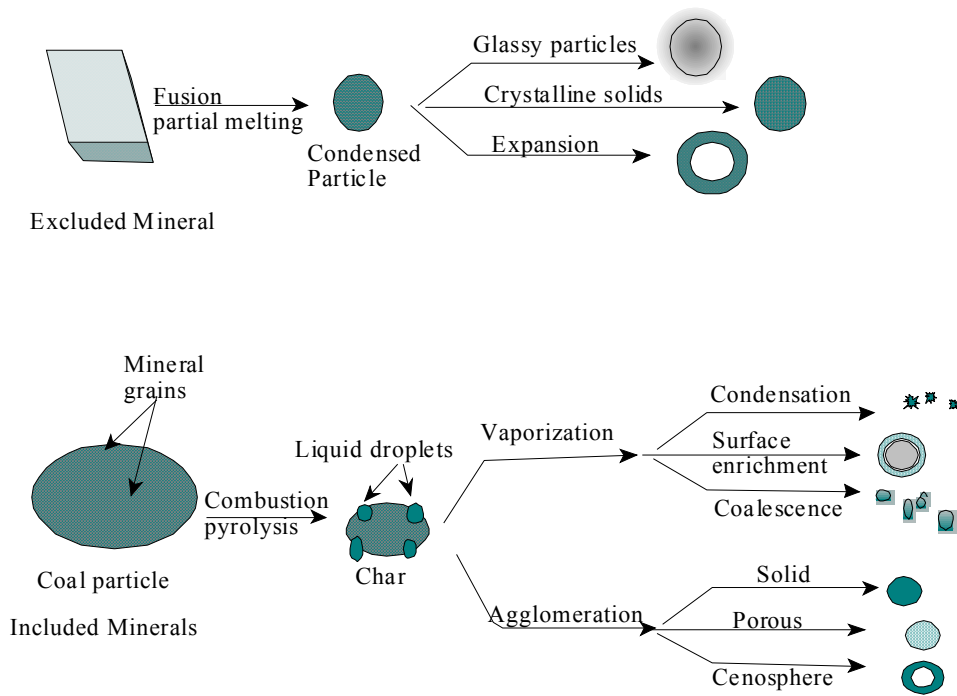


Figure 4. Transformation of mineral matter in coal to ash (After Clarke & Sloss, 1992, p.38)

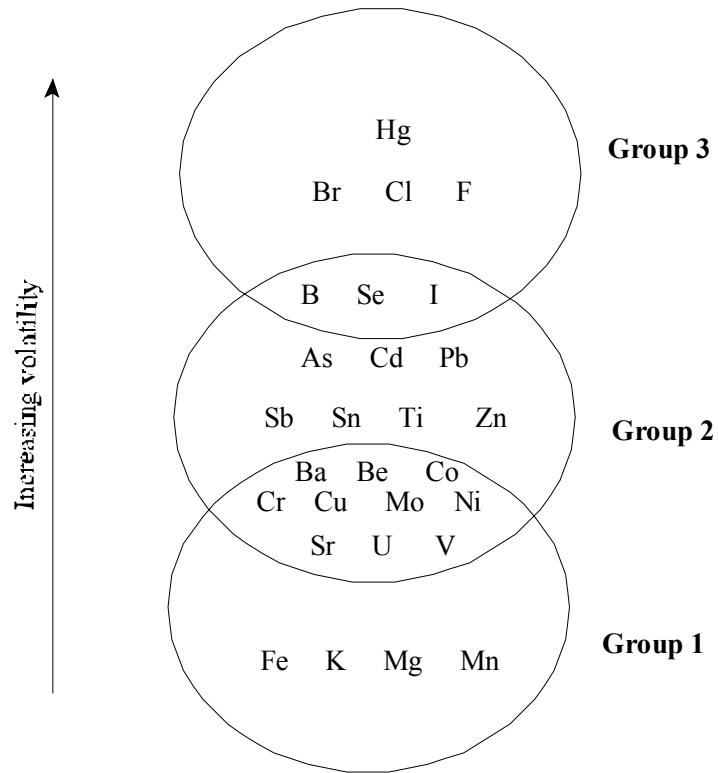


Figure 5. Classification of trace elements in coal by their relative volatility (After Clarke & Sloss, 1992, p.37).