COMPARISON OF FUEL PROPERTIES OF PETROLEUM COKES AND COALS USED IN POWER GENERATION

Jun M. Lee, James J. Baker, Jeffrey G. Rolle, Robert Llerena,
A. J. Edmond Co.
1530 West 16th Street, Long Beach, CA 90813

Keywords: petroleum coke, coal, fuel properties

INTRODUCTION

U.S. petroleum coke production is projected to continue to increase, reaching 90,000 st/cd (short tons per calendar day) by the year 2000, primarily due to refining heavier and higher sulfur content crudes [1]. In 1996 the coke production was 86,805 st/cd and 65.7% of the annual production was exports. Green (raw) petroleum cokes are mostly used as utility fuels (about 73% for fuel grade) combining with coal to make fuel in processing industries. Petroleum cokes are produced at refineries using three different types of coking processes: delayed, fluid, and flexicoking. The delayed coker is mostly used at forty-eight refineries. The other fluid coker (4 units) and flexicoker (2 units) are less utilized. Coke products from a delayed coker are classified as shot, sponge or needle coke depending on their chemical and physical characteristics.

Utility companies used 3,852 st/cd of petroleum coke (less than 5% of annual production) as a power plant supplemental fuel blending with coal in 1996, because petroleum coke has advantages of low price (36% lower at $/st or 46% lower at $/MMBtu), high heating value, and low ash content [1]. The disadvantages of petroleum coke as a fuel are expense of a dual solid fuel handling and crushing system, high sulfur, high nickel and vanadium content. Normally cokes are blended with coals at 10-20% before burning in boilers because of their low volatile matter and high sulfur content. Average quality of coke burned is: on as-received basis, 13,930-14,820 Btu/lb, 5.5% sulfur, and 0.5-3.8% ash.

Some refineries consume a portion or all of the coke they produce as a solid fuel to generate steam, and more recently, as fuel for cogeneration facilities. An average of 1,767 st/cd of petroleum coke was used within refineries in 1996. Texaco cogeneration power plant at El Dorado refinery, Kansas gasifies a delayed coke to produce syn-gas for a combustion turbine fuel [2]. Typical composition of the delayed coke is: on dry basis, 90% carbon, 4% hydrogen, 4% sulfur, 1.5% nitrogen, 0.5% oxygen, and 0.5% ash. Other coke-fueled cogeneration plants burn 100% delayed coke [3] or 100% fluid coke [1] in a circulating fluidized bed (CFB) steam generator. Delayed coke fines sized to 0.25 in. (6 mm) is fed to the CFB furnace along with crushed limestone. Typical composition of the delayed coke feed is: on dry basis, 89.2% carbon, 3.7% hydrogen, 5% sulfur, 1.8% nitrogen, 0.3% ash, and 15,050 Btu/lb of high heating value (HHV). The coke contains approximately 10.6% moisture.

Cement industry consumes a large portion of fuel-grade petroleum coke (35.5% of world demand) to combust in kilns [1]. The addition of cokes can constitute up to 50% of the fuel mixture and is carefully controlled conducting test burn due to detrimental effects of high sulfur and vanadium content to concrete quality. Sulfur contamination can cause cement cracking and preheater plugging-fouling due to combination with alkalies, and high vanadium content above 500 ppm can cause cement to lose strength. The cement kilns operate as scrubbers, absorbing sulfur and other contaminants into finished cement.

U.S. utility companies consume about 80% of annual coal production (approximately 1,000 million short tons in 1995) burning in boilers to generate electricity [4]. The coal production consists of 60% bituminous, 30% subbituminous, 8% lignite and small percentage of anthracite. U.S. exports annually about 90-110 millions tons (9-11% of total production).

Coal gasification process technologies have been extensively tested in conjunction with integrated gasification combined cycle (IGCC) systems to improve efficiency, environmental performance, and overall cost effectiveness in electric power generation [5]. Several successful demonstration projects are: British Gas/Lurgi gasifier, Texaco Cool Water gasification plant, Shell Coal Gasification Process, Dow Coal Gasification Process (Destec), etc. Full-scale projects are now proceeding in The Netherlands, Germany, Spain and Italy on a commercial basis. Utah (SUFCO) coal, an export western bituminous coal, was the predominate coal gasified at the Texaco Cool Water plant [6] and also tested in the Shell demo-plant [5]. Typical coal properties are: 0.4% sulfur, 8.8% ash, 12,360 Btu/lb (HHV), and 2,200 deg F of ash fusion temperature. The SUFCO Utah coal has low sulfur, low iron and high sodium content. Shell demo-plant tested a delayed coke which has low ash, high sulfur, low oxygen, low calcium, high vanadium, and high nickel content. Feed properties of the delayed coke are: on dry basis, 10.6% volatile matter, 0.5% ash, 5.2% sulfur, 89.3% carbon, 3.6% hydrogen, 1.35% nitrogen, 0.03% chlorine, 0.1% oxygen, 15,350 Btu/lb (HHV), and 61 hardgrove grindability index (HGI). The coke contains 9.3% moisture and ash mineral analysis shows 0.8% lime, 1.2% sodium oxide, 71.8% vanadium pentoxide, and 7.4% nickel oxide. Texaco and Kellogg (KRW) gasification processes also extensively tested petroleum cokes as raw material to gasifier [7,8].

Coal ash is classified into two categories: lignitic ash is defined as having more (CaO+MgO) than ferric oxide; and bituminous ash is defined as having more ferric oxide than the sum of CaO and MgO. The Utah coal is classified a western high volatile bituminous coal, but has lignitic ash. Ash characterization methods such as slagging and fouling indices are different in calculation depending upon bituminous or lignitic ash [9]. Chemical composition of coal ash affects slag viscosity, which is an important criterion for determining the suitability of a coal ash for use in a slag-tap cyclone furnace. Slag flow readily at or below a viscosity of 250 poise. The temperature at which this viscosity of ash occurs is called T_{250} temperature. The preferred maximum T_{250} for wet-bottom applications is 2,450 deg F.

The alkali metals, sodium and potassium, have long been associated with the fouling tendencies of coal ash. Correlations in fouling index have been developed using various parameters such as strength of sintered fly ash and total alkali content for bituminous ash, and sodium content alone for lignitic ash. All bituminous coals contain enough sulfur and alkali metals to produce corrosive ash deposits on superheaters and reheaters, and those containing more than 3.5% sulfur and 0.25% chlorine may be particularly troublesome. The elements in coal ash corrosion are sodium, potassium, aluminum, sulfur and iron, which are derived from the mineral matter in coal. Fouling observed in a CFBC boiler firing coal and petroleum coke was attributed to agglomeration of sulfate and carbonate, not due to high concentration of nickel and vanadium present in petroleum coke (306 and 870 ppm, respectively) [10].

The objective of this study is to evaluate and compare various fuel properties of petroleum cokes and bituminous coals used in power generation, comparing different cokes produced from several refineries in U.S. and export western coals sampled at the Los Angeles Export Terminal (LAXT). Four fluid cokes, fourteen delayed cokes and five export coals are included for evaluation based on recent analysis data accumulated for the past two years (1997-1998).

SAMPLING, PREPARATION AND ANALYTICAL METHODS

Representative samples of petroleum cokes and coals have been obtained from various refineries located in California, Texas, Louisiana, Kansas, Illinois and other states, and storage facilities at numerous national ports. Laboratory samples are prepared for fuel properties analysis following the procedures and principles in handling listed in the ASTM Methods D 346, D 2013 and D 2234. Laboratory test methods using various advanced analytical instruments are described in the Quality Assurance Manual of A. J. Edmond Company [11].

RESULTS AND DISCUSSION

Important fuel properties of three significantly different types, delayed coke, fluid coke and export western coal are presented for comparison in Tables 1-3. Petroleum cokes evaluated for this study are produced in various U.S. refineries located in west coast (WC), Gulf coast (GC), mid west (MW), and south east (SE), which are primarily consumed in export to foreign countries (65.7%) and in smaller extent (less than 10%) used in domestic power generation and cement kiln fuel mix. Export western coals sampled at the LAXT are high volatile bituminous coals with low sulfur and iron content. They are primarily produced in Utah and Colorado for power generation. The throughput capacity of LAXT is 10 million metric tons per year, which is correspondent to about 10% of current coal export to foreign countries.

Based on data presented in Tables 1-3, five different arbitrary groups of concentration or value of several primary fuel properties are used as indicators of different levels of properties as follows:

Fuel Property	Very Low	Low	Medium	High	Very High
Sulfur, wt%		1-2	2-4	4-6	
Ash, wt%	0.5	1-2		9-10	
Volatile Matter, wt%		2.5-6.1	9.5-13	40.2-41.1	
Btu/lb		12600-13400	14200-14600	15200-15600	
Nitrogen, wt%		1.2-2.2		2.8-3.2	
Vanadium, ppm		270-400	500-800	900-1400	2300-2900
Nickel, ppm		25-200	400-500	700+	

Fluid Coke Fuel for Cogeneration Plants

Table 1 summarizes analysis results of fuel properties of petroleum cokes used in power generation. Three fluid cokes (WC-1, WC-2 and WC-3), one bed coke (WC-4) and six delayed cokes (WC-5, SW/MW-1, SW/MW-2, SE, SE/GC, E/MW) are included for comparison. Fluid and bed cokes (WC-1 to WC-4) have been extensively used in circulating fluidized bed combustors at cogeneration power plants. WC-2 and WC-3 fluid cokes also represent export quality to foreign countries.

Fluid coke generated from a fluidized bed reactor is a solid, spherical particulate normally smaller than 8 mesh (98% for WC-2 and WC-3, and 74% for WC-4, as shown in Table 1). The coke is very hard and abrasive, suitable for direct use in a circulating fluidized bed combustor, and generally have lower HGI than delayed coke and coal. Typical moisture content is very low in the range of 0.3 to 1.2% except for export cokes having 7-11.5% which increased to control dust during transportation. Sulfur content for fluid cokes, WC-1, WC-3 and WC-4, is low in the range of 1.0 to 2.1%; and WC-2 coke has medium sulfur with 3.3%, somewhat lower than other delayed cokes listed in Table 1 (4-6%). Ash content of WC-1 and WC-2 cokes is very low in the range of 0.35 to 0.46%, and WC-1 and WC-2 cokes have a little higher ash from 1.1 to 1.5%. These ash values are significantly lower compared to coals (9.2-10%), which is normally claimed as an advantage as fuel.

Calorific value for all fluid cokes studied is medium in the range of 14,200-14,400 Btu/lb (dry basis), relatively high compared to coals (12,600-13,400 Btu/lb dry basis). Volatile matter content is low in the range of 2.5 to 6.1% for all fluid cokes, compared to delayed cokes (9.5-13%) and coals (40.2-41.1%). Power plant startup is easier with fuels having higher volatile matter. However, serious operational problems in burning petroleum cokes as 100% or 10-20% blend mix have not been reported. Fluid cokes, WC-2, WC-3 and WC-4, have relatively low nitrogen content in the range of 1.4 to 2.2%, while WC-1 has a higher nitrogen of 3%, similarly observed with some delayed cokes (2.8-3.2%). Coals evaluated for this study have a low nitrogen of 1.2 to 1.5%.

Vanadium content for WC-1 and WC-2 is medium in the range of 650 to 850 ppm, near concentration used in the cement kiln fuel mix (530-760 ppm for SW/MW-1 and SW/MW-2), but higher than that for good anode-grade cokes (270-400 ppm). WC-3 and WC-4 cokes show the highest V content in the range of 2300 to 2900 ppm among petroleum cokes and coals evaluated for this study. Detrimental affects with this high V content (as much as 10,000 ppm) have not been reported in the operation of steam generating combustors [12]. Sodium content for WC-1 and WC-2 cokes is low in the range of 80 to 180 ppm, which is similarly observed in good anode-grade sponge cokes (25-200 ppm). WC-3 and WC-4 cokes have a higher Na content of 480 to 500 ppm compared to WC-1 and WC-2. Most of delayed cokes studied have a low Na content (50-160 ppm) except for WC-5 and WC-E4 (380-450 ppm).

Delayed Coke Fuel for Utility and Cement Plants

Six delayed cokes in Table 1 (WC-5, SW/MW-1, SW/MW-2, SE, SE/GC, E/MW) have been used as fuel blend mix in pulverized coal combustors for steam generation and cement kilns. These cokes are fuel grade, green (raw) cokes with high ash, high sulfur and high metal content ranging sponge to shot coke. Typical ash content is in the range of 0.25 to 0.65%; sulfur content in the range of 3.1 to 6%; vanadium from 530 to 1700 ppm; nickel from 190 to 600 ppm; and sodium from 80 to 380 ppm. Calorific value is high in the range of 15,000 to 15,580 Btu/lb (HHV, dry basis), producing more heat during combustion than fluid cokes and coals. Size distribution covers wide range of particle size from -6 mm to +40 mm depending on fines, lump or ROC (run of coker) delivered from refineries. Typical HGI is in the range of 35 to 60, mostly higher than coal HGI (45), with shot content varying from 0 to 80%. Typical moisture content is in the range of 5 to 9%, and volatile matter varies from 9.5 to 13%.

Two delayed cokes, SW/MW-1 and SW/MW-2 have been frequently used in cement kiln operation, as fuel mix (up to 50%). Typical sulfur and vanadium content (controlled quality parameters for cement application) of these cokes vary in the range of 3.1 to 3.8% and 530 to 760 ppm, respectively. Sulfur and vanadium content are higher than those required for good anode-grade sponge coke (3% and 400 ppm, respectively).

Quality of Export Petroleum Cokes

Table 2 presents analysis results from eight export delayed cokes. These cokes have been mostly used as utility fuels combining with coal to make fuel in processing industries. Fuel property data in the table update export quality analysis of petroleum cokes previously reported [11]. Export quality criteria of green (raw), fuel-grade cokes are dependent upon buyer's requirements of coke specifications. As shown in the following for west coast cokes, primary criteria frequently used are: size distribution, moisture, sulfur, ash, volatile matter, fixed carbon content and calorific value; and secondary criteria are: nitrogen, vanadium and sodium content. In addition, complete ash mineral analysis is sometimes required to report.

Fuel Property	Criteria Specified
Size, mm	0x6, 0x10 or lump -2 & +25
Moisture, wt% (dry basis)	8-12, 9-12 or 9 max
Sulfur, wt%	1 max, 2 max or 3 max
Ash, wt%	0.5 max, 1 max or 1.5 max
Volatile Matter, wt%	9-13, 11-12.5 or 14 max
Fixed Carbon, wt%	88-90 or 87 min
HGI	45-50 or 50 min
Btu/lb	15,000 min
Nitrogen, wt%	2, 2.5-3.5 or 2.9 max
Vanadium, ppm	500-800 or 700 max
Sodium, ppm	200-300 or 700 max

Eight delayed cokes in Table 2 (WC-E1 to WC-E8) are produced in refineries located in west coast. These cokes are good quality, fuel-grade green (raw) cokes, which generally have lower ash, sulfur and metal content than six delayed cokes in Table 1 used in domestic power generation. Typical ash content is in the range of 0.18 to 0.45%; sulfur content in the range of 0.8 to 4%; vanadium from 270 to 1150 ppm; nickel from 180 to 550 ppm; and sodium from 50 to 450 ppm. Calorific value is high in the range of 15,300 to 15,520 Btu/lb (HHV, dry basis), as similarly observed with delayed cokes in Table 1. Size distribution covers wide range of particle size from -6 mm (30-99%) with fines, to +40 mm (3-47%) with lump or ROC (run of coker) depending on delivery from refineries. Typical HGI is in the range of 35 to 80, mostly higher than coal HGI (45), with shot content varying from 0 to 60%. Typical moisture content is in the range of 7 to 12%, and volatile matter varies from 10 to 12.5%.

Quality of Export Western Coals

Table 3 summarizes analysis results from five export western coals (type I to V). These coals sampled at the LAXT are high volatile bituminous coals with low sulfur and iron content. They are primarily produced in Utah and Colorado and used as utility fuels for power generation. Coal quality specifications for export were previously reported [11]. Primary fuel properties of coal are: proximate, ultimate, calorific value, HGI, size distribution, ash mineral analysis and ash fusion temperatures.

Typical ash content of export western coals is high in the range of 9.2 to 10%; sulfur content is very low in the range of 0.45 to 0.6%. These coals are classified as western high volatile bituminous coal, but have lignitic ash having more (CaO+MgO) than ferric oxide [9]. Primary constituents of coal ash are silica (52.3-58.6%), alumina (11.6-21%) and lime (5-13.1%). Ferric oxide content in ash is low from 4.4 to 5.9% compared to eastern bituminous coal (20-30%); sodium oxide content is high from 1.8 to 4.2%. Calorific value is low in the range of 12,640 to 13,360 Btu/lb (HHV, dry basis), compared to fluid cokes and delayed cokes in Tables 1 and 2. Size distribution shows top size of 2 inches having 92-100% 50 mm x 0 mm and 11.6-33% 2 mm x 0 mm. Typical HGI is in the range of 43 to 46. Typical moisture content is in the range of 7.7 to 10.3%, and volatile matter varies from 40.2 to 41.1%.

Data for coal ash characteristics used for selection of feed coal and boiler design criteria are also presented in Table 3. Ash and slag viscosity plot parameters are: silica ratio, base-to-acid (B/A) ratio, T_{250}, and slagging index. Fouling plot parameters are: alkalies as sodium oxide and fouling index [9]. Typical silica ratio is in the range of 0.712 to 0.828; B/A ratio from 0.2 to 0.386; T_{250} from 2,420 to 2,760 deg F; and slagging index is medium to high in the range of 2,114 to 2,263. Typical alkalies as sodium oxide is high in the range of 2.5 to 4.5; and fouling index is high from 1.8 to 4.2. Very low sulfur content with theses coals may lower corrosive ash deposits caused by reacting with sodium, potassium, aluminum and iron, but addition of high sulfur petroleum cokes as fuel mix may increase corrosion reactions with alkali metals. Coal type III and V with high B/A ratio of 0.386 and 0.372 have low T_{250} (2,420 and 2,450 deg F, respectively) meeting requirement for operation of slag-tap cyclone furnace.

SUMMARY

Various fuel properties of four fluid cokes, fourteen delayed cokes and five export western coals were analyzed and are compared for use in power generation. Important fuel quality parameters (typical and range) are tabulated for comparison, using recent analysis data accumulated for the past two years (1997-1998). Primary properties evaluated are: heating value, sulfur, nitrogen, ash, moisture, volatile matter content, hardgrove grindability index, size distribution, and mineral analysis. In addition, coal ash characteristics such as silica ratio, base-to-acid ratio, ash fusibility, alkalies, T_{250}, slagging index, fouling index, etc. are discussed.

Petroleum cokes as 100% fuel or 10-20% fuel mix with coal have been used in power generation without serious operational problems reported, even burning with some cokes of high vanadium content (1,000-3,200 ppm). Some cokes have high sulfur content up to 7%, high nitrogen content up to 3.5%, and low HGI down to 25 (for delayed coke). Typical sulfur content of most cokes studied varies in the range of 0.8 to 4.1%; nitrogen varies in the range of 1.3 to 3.2%; and HGI varies from 40 to 80 (for delayed coke), mostly higher than coal HGI (45).

Petroleum cokes as fuel mix (up to 50%) have been used in cement kiln operation. Typical sulfur and vanadium content (controlled quality parameters for cement application) of delayed cokes mixed in kiln vary in the range of 3.1 to 3.8% and 530 to 760 ppm, respectively.

Export delayed cokes are good quality, fuel-grade green (raw) cokes, which generally have lower ash, sulfur and metal content than delayed cokes used in domestic power generation. Typical ash content is in the range of 0.18 to 0.45%; sulfur content from 0.8 to 4%; vanadium from 270 to 1,150 ppm; nickel from 180 to 550 ppm; and sodium from 50 to 450 ppm. Calorific value is high in the range of 15,300 to 15,520 Btu/lb (HHV, dry basis).

Price of fuel grade petroleum coke is normally below 5 $/ton at refinery, however, transportation cost significantly increases the price at power plant (21 $/ton, 1996 annual average delivered). Demand and supply of petroleum coke are dictated by three important factors such as refinery cost, coke quality and transportation cost. Location of refinery and power plant seems an important factor to be considered.

Export western coals are high volatile bituminous coals with low sulfur and iron content, and are used as utility fuels for power generation. Typical ash content is high in the range of 9.2 to 10%; sulfur content is very low in the range of 0.45 to 0.6%. Ash from these coals are defined as lignitic ash having more (CaO+MgO) than ferric oxide. Ferric oxide content in ash is low from 4.4 to 5.9% compared to eastern bituminous coal (20-30%); sodium oxide content is high from 1.8 to 4.2%. Calorific value is low in the range of 12,640 to 13,360 Btu/lb (HHV, dry basis), compared to petroleum cokes. Coal ash characteristics used for selection of feed coal and boiler design criteria are discussed relating to slag viscosity, fouling, and corrosion. Coal type III and V have low T_{250}, meeting requirement for operation of slag-tap cyclone furnace.

The SUFCO Utah coal, one of five export western bituminous coals evaluated for this study, was extensively tested at several gasification demonstration plants for IGCC systems in addition to variety of petroleum cokes as feed material to gasifiers.

REFERENCES

1. E. J. Swain, Oil & Gas Journal, Nov. 10, 1997, 79-82; May 20, 1991, 49-52.
2. A. K. Rhodes, Oil & Gas Journal, Aug. 5, 1996, 31-35.
3. K. W. Richardson and F. D. Taibi, Oil & Gas Journal, Apr. 5, 1993, 38-42.
4. R. Graham, ASTM Standardization News, Mar. 1998, 36-43.
5. Kerk-Othmer Encyclopedia of Chemical Technology, Volume 6, 4th Ed., Gasification, 541-568 (1993).
6. D. H. Watts, Sixth Annual International Pittsburgh Coal Conference, Sep. 25-29, 1989, 569-581.
7. A. M. Robin, et. al., Sixth Annual International Pittsburgh Coal Conference, Sep. 25-29, 1989, 244-254.
8. F. M. Floyd and R. K. Agrawal, Sixth Annual International Pittsburgh Coal Conference, Sep. 25-29, 1989, 559-568.
9. Babcock & Wilcox Company, "Steam - Its Generation and Use: Steam 40", Chap. 20, Fuel Ash Effects on Boiler Design and Operation (1992).
10. E. J. Anthony, et. al., 215th ACS National Meeting, Dallas, Preprints of Symposia, Division of Fuel Chemistry, Vol. 43, No. 1, 163-166 (1998).
11. J. M. Lee, J. J. Baker, R. Llerena, J. G. Rolle, 214th ACS National Meeting, Las Vegas, Preprints of Symposia, Division of Fuel Chemistry, Vol. 42, No. 3, 844-853 (1997).
12. R. W. Bryers, ACS National Meeting, Preprints of Symposia, Division of Fuel Chemistry, Vol. 38, No. 4, 1237-1244 (1993).

Table 1. FUEL PROPERTIES OF FLUID AND DELAYED COKES USED IN POWER GENERATION

Industry Location	WC-1		WC-2		WC-3		WC-4		WC-5	
Process	Cogeneration		Cogeneration/Export		Cogeneration/Export		Cogeneration		PCC	
	CFBC		CFBC		CFBC		CFBC		Cement Kiln	
Coke Type	Fluid		Fluid		Fluid		Bed		Delayed (Blend)	
Properties	*Typical*	*Range*	*Typical*	*Range*	*Typical*	*Range*	*Typical*	*Range*	*Typical*	*Range*
(as-received)										
Moisture, wt%	0.5	0.2-1.4	0.3	0.02-0.8	11.5	10-15	1.2	0.2-2.5	9	4-13
(dry-basis)			(Export: 6-8%)							
Proximate, wt%										
VCM	6.1	5-7	5.3	4-7	4.6	2.9-7.5	2.5	1.6-3.1	13	11-15
Ash	0.46	0.3-0.6	0.35	0.25-0.5	1.1	0.7-1.2	1.5	1.2-1.9	0.65	0.3-0.7
FC (by diff.)	93.4	93-94.5	94.3	93.4-95.2	94.3	91.5-96.5	95.6	-	86.5	85-88
Ultimate, wt%										
Sulfur	2.1	1.5-2.5	3.3	3.0-3.6	1.2	0.8-2.5	1.0	-	4.6	3.8-5.5
Carbon	92.2	91.6-93	91.7	91-92.5	94.8	-	94.6	-	86.5	-
Hydrogen	1.7	1.3-2.2	2.0	1.8-2.2	1.0	-	0.8	-	3.8	-
Nitrogen	3.0	2.7-3.4	2.2	1.8-2.4	1.4	-	1.7	-	2.9	2.8-3.1
Oxygen (by diff.)	0.54	-	0.45	-	0.5	-	0.4	-	1.55	-
Chlorine (ppm)	-	-	160	70-260	-	-	-	-	265	-
Metals, ppm										
Silicon	150	80-200	150	60-230	350	100-570	400	230-530	150	100-210
Iron	380	230-500	150	110-240	1600	1080-2060	1600	1120-2060	170	80-290
Vanadium	650	430-860	850	700-1130	2300	1940-2750	2900	2670-3200	1700	1400-2100
Nickel	620	480-700	450	400-540	2200	2050-2840	2350	2050-2630	600	490-730
Aluminum	45	10-95	80	40-200	90	50-180	100	30-160	70	20-170
Calcium	210	160-290	120	40-210	800	420-1140	800	500-1030	200	140-360
Sodium	180	90-250	80	40-170	480	340-740	500	290-740	380	200-510
Calorific Value										
Btu/lb	14540	14280	14550	14300	14330	14200	14200	-	15000	14900
		-14700		-14750		-14460		-		-15150
HGI	-	-	-	-	-	-	-	-	60	50-67
Shot, %	-	-	-	-	-	-	-	-	0	0-5
Size, wt%										
-6 mm	-	-	98.6	-	97.7	-	-	-	-	-
+4 mesh	-	-	-	-	-	0	-	-	-	-
+8 mesh	-	-	-	1.5	-	2	-	-	-	-
-50 mesh	-	-	-	94	-	-	-	74	-	-
-100 mesh	-	-	-	52	-	38	-	24	-	-
-200 mesh	-	-	-	4	-	7	-	7	-	-
Fuel Ratio	15.3	-	17.8	-	20.5	-	38.2	-	6.7	-

Table 1. FUEL PROPERTIES OF FLUID AND DELAYED COKES USED IN POWER GENERATION *(Continued)*

Industry Location	SW/MW-1		SW/MW-2		SE		SE/GC		E/MW	
Process	PCC		PCC		PCC		PCC		PCC	
	Cement Kiln		Cement Kiln		Cement Kiln		Cement Kiln		Cement Kiln	
Coke Type	Delayed (Blend)		Delayed (Blend)		Delayed (Blend)		Delayed (Blend)		Delayed (Blend)	
Properties	*Typical*	*Range*	*Typical*	*Range*	*Typical*	*Range*	*Typical*	*Range*	*Typical*	*Range*
(as-received)										
Moisture, wt%	5	2-10	5	1-10	7	1-24	8	5-14	8	7-13
(dry-basis)										
Proximate, wt%										
VCM	10.5	9.8-11.1	11	9-14	11	7-13	10.5	9-12	9.5	8.6-10.5
Ash	0.25	0.21-0.32	0.28	0.2-0.4	0.45	0.3-0.6	0.52	0.35-0.65	0.32	0.2-0.53
FC (by diff.)	89.2	88.7-90	88.6	87-90	88.5	87-92	89.0	87-91	90.2	89.3-91.2
Ultimate, wt%										
Sulfur	3.1	2.8-3.6	3.8	2.9-4.9	5	3.5-6.5	6.0	5-7	4.1	3.3-5.8
Carbon	-	-	89.8	-	-	-	86.8	85-89	89.9	89-91
Hydrogen	-	-	3.9	-	-	-	3.8	3.6-4.0	3.6	3.4-3.9
Nitrogen	-	-	1.3	-	1.8	1.4-2.2	1.7	1.5-1.8	1.5	1.1-2.2
Oxygen (by diff.)	-	-	0.92	-	-	-	1.2	-	0.58	-
Chlorine (ppm)	-	-	130	50-200	-	-	200	100-300	270	-
Metals, ppm										
Silicon	60	-	85	-	150	50-310	140	50-300	80	-
Iron	300	-	650	-	200	50-550	200	100-400	230	-
Vanadium	530	450-610	760	540-860	1400	1100-1900	1100	530-1650	730	600-890
Nickel	190	-	240	220-280	350	260-450	300	250-350	350	210-550
Aluminum	10	-	30	-	70	-	100	50-200	40	-
Calcium	80	-	90	-	-	-	150	50-300	160	-
Sodium	130	-	100	-	100	-	80	50-150	130	-
Calorific Value										
Btu/lb	15580	15360	15500	15350	15350	15170	15240	15050	15450	15350
		-15710		-15750		-15480		-15400		-15600
HGI	50	41-56	50	40-70	50	30-80	48	35-70	35	26-51
Shot, %	80	40-100	50	0-100	60	0-100	75	40-100	60	5-90
Size, wt%							(ROC)			
+40 mm	-	-	-	-	-	-	+30 mm	7-11	-	-
40x30 mm	-	-	-	-	-	-	30x15	7-82	-	-
20x12 mm	-	-	-	-	-	-	-15	10-85	-	-
12x6 mm	-	-	-	-	-	-	-	-	-	-
-6 mm	-	-	-	-	-	-	-	-	-	-
-200 mesh	-	-	-	-	-	-	-	-	-	-
Fuel Ratio	8.5	-	8.1	-	8.1	-	8.5	-	9.5	-

Table 2. FUEL PROPERTIES OF EXPORT DELAYED COKES USED IN POWER GENERATION

Industry Location	WC-E1		WC-E2		WC-E3		WC-E4		WC-E5	
Process	Export		Export		Export		Export		Export	
	PCC, etc.		PCC, etc.		PCC, etc.		PCC, etc.		PCC, etc.	
Coke Type	Delayed (Blend)		Delayed (Blend)		Delayed (Blend)		Delayed (Blend)		Delayed (Blend)	
Properties	*Typical*	*Range*	*Typical*	*Range*	*Typical*	*Range*	*Typical*	*Range*	*Typical*	*Range*
(as-received)										
Moisture, wt%	9	5-13	7	5-11	10	8-14	10	6-14	10	7-14
(dry-basis)										
Proximate, wt%										
VCM	11.5	10-13	10	9-11.5	11.5	10-13	11.5	10-13.5	10	9-12
Ash	0.2	0.1-0.4	0.4	0.3-0.5	0.35	0.3-0.6	0.45	0.3-0.6	0.35	0.25-0.45
FC (by diff.)	88.3	-	89.6	-	88.1	-	88.0	-	89.6	-
Ultimate, wt%										
Sulfur	0.8	0.7-1.1	1.2	0.9-1.4	1.3	1-1.8	2.7	2.5-3.1	2.9	2.3-3.4
Carbon	90.5	89.5-91.6	90.5	89.8-91.7	90.2	89-91	89.0	88.8-89.3	89.4	88.5-89.9
Hydrogen	4.1	3.9-4.3	3.9	3.8-4	4.0	3.8-4.2	3.9	3.8-4.1	3.9	3.7-4.1
Nitrogen	3.2	3-3.5	3.1	2.7-3.3	3.2	2.7-3.4	2.8	2.7-3.0	2.8	2.5-3.2
Oxygen (by diff.)	1.20	-	0.9	-	0.95	-	1.15	-	0.65	-
Chlorine (ppm)	150	90-280	180	110-320	-	-	-	-	200	90-270
Metals, ppm										
Silicon	80	20-240	110	60-260	150	50-360	100	30-200	70	40-220
Iron	230	120-380	340	290-430	270	180-400	300	170-500	350	160-640
Vanadium	270	230-330	600	450-720	550	470-720	900	690-1200	900	780-1060
Nickel	540	480-640	550	490-720	500	440-610	500	430-560	520	400-650
Aluminum	40	10-100	100	40-210	120	40-220	50	20-150	40	10-110
Calcium	50	20-110	190	170-220	230	90-400	150	90-300	100	50-210
Sodium	70	40-140	110	80-160	160	80-210	450	360-670	140	90-220
Calorific Value										
Btu/lb	15450	15300	15450	15350	15500	15400	15350	15200	15350	15200
		-15650		-15650		-15650		-15500		-15450
HGI	60	50-70	40	30-52	50	40-65	55	45-75	35	25-40
Shot, %	40	5-80	60	20-100	20	5-60	30	0-80	60	10-90
Size, wt%	(Fines)	(ROC)	(Fines)	(ROC)	(ROC)	(Lump)	(Fines)	(Lump)	(Fines)	(Lump)
+40 mm	-	-	-	2-6	-	-	-	13-47	-	3-17
40x30 mm	-	-	-	0-9	0-28	21-54	4-19	13-45	0	5-25
20x12 mm	-	-	0-1	9-26	0-15	10-36	7-32	10-34	3	11-89
12x6 mm	-	-	1-4	2-9	3-22	1-19	22-55	1-23	6	5-26
-6mm	-	-	96-99	65-98	39-88	1-49	30-61	1-39	91	11-55
-200 mesh	9	-	-	-	8	-	9	-	9	-
Fuel Ratio	7.7	-	9.0	-	7.7	-	7.7	-	9.0	-

Table 2. FUEL PROPERTIES OF EXPORT DELAYED COKES USED IN POWER GENERATION (Continued)

Industry Location	WC-E6		WC-E7		WC-E8	
Process	Export		Export		Export	
	PCC, etc.		PCC, etc.		PCC, etc.	
Coke Type	Delayed (Blend)		Delayed (Blend)		Delayed (Blend)	
Properties	*Typical*	*Range*	*Typical*	*Range*	*Typical*	*Range*
(as-received)						
Moisture, wt%	11.5	9-15	8	5-13	12	8-20
(dry-basis)						
Proximate, wt%						
VCM	11.5	10-13	10	8-11	12.5	11.4-14.4
Ash	0.2	0.18-0.33	0.18	0.08-0.41	0.31	0.26-0.44
FC (by diff.)	88.3	87.2-89.8	89.8	88.4-91.3	87.2	86.2-88.3
Ultimate, wt%						
Sulfur	3.5	2.4-5	2.9	2.6-3.2	4	2.7-5.2
Carbon	89.7	88.5-90.8	90.7	89.8-91.4	89.5	88.5-90.5
Hydrogen	3.9	3.7-4.1	3.8	3.7-3.9	3.8	3.6-3.9
Nitrogen	2.0	1.7-2.4	1.6	1.4-1.8	2.1	1.7-2.4
Oxygen (by diff.)	0.7	-	0.82	-	0.29	-
Chlorine (ppm)	-	-	220	-	-	-
Metals, ppm						
Silicon	70	20-230	60	20-190	70	40-130
Iron	220	110-320	70	30-180	130	100-180
Vanadium	370	300-560	370	300-440	1150	960-1280
Nickel	310	250-400	180	130-230	460	430-600
Aluminum	45	20-100	30	30-90	20	10-40
Calcium	80	30-200	40	20-100	80	40-140
Sodium	80	40-160	50	30-90	110	100-130
Calorific Value						
Btu/lb	15520	15350	15500	15400	15400	15330
		-15620		-15630		-15460
HGI	80	60-96	55	35-75	70	54-83
Shot, %	0	0-5	30	0-70	20	0-60
Size, wt%	(Fines)	(ROC)	(Fines)	(Lump)	(Fines)	(Lump)
+40 mm	8-18	3-15	0	13-30	-	-
40X30mm	4-9	2-42	0	7-58	-	5-16
20x12mm	9-13	3-20	1-4	4-30	-	15-25
12x6mm	6-15	1-20	7-92	6-23	-	16-35
-6mm	31-47	2-55	4-92	1-41	-	3-32
-200 mesh	11	-	5	-	9	-
Fuel Ratio	7.7	-	9.0	-	7.3	-

Table 3. FUEL PROPERTIES OF EXPORT WESTERN COALS USED IN POWER GENERATION

Coal Source	I		II	III		IV	V
Process	Export		Export	Export		Export	Export
	PCC, etc.		PCC, etc.	PCC, etc.		PCC, etc.	PCC, etc.
Coal Type	Bituminous		Bitumin.	Bituminous		Bitumin.	Bitumin.
Properties	*Typical*	*Range*	*Typical*	*Typical*	*Range*	*Typical*	*Typical*
(as-received)							
Moisture, wt%	9.4	8.4-10.4	10.1	10.3	9.2-11.2	7.7	9.8
(dry-basis)							
Proximate, wt%							
VCM	41.1	39.5-42.7	40.8	40.3	39.8-41.2	41	40.2
Ash	10	8.6-10.9	9.8	9.7	8.6-10.8	9.2	9.9
FC (by diff.)	48.9	-	49.4	50		49.8	49.9
Ultimate, wt%							
Sulfur	0.53	0.43-0.62	0.52	0.42	0.36-0.52	0.5	0.6
Carbon	72.2	71.2-72.3	72.1	72.1	71.1-73.7	73.3	72.3
Hydrogen	5.4	5-5.5	5.3	5.0	4.7-5.2	5.5	5.2
Nitrogen	1.33	1.15-1.54	1.47	1.17	1.02-1.22	1.28	1.3
Oxygen (by diff.)	10.54	10.4-12	10.81	11.61	11.4-12.4	10.22	10.75
Chlorine (ppm)	150	10C-300	100	100	-	150	120
Mineral of Ash, wt%							
Silica	58.6	52.5-61.7	56.7	52.3	50.4-54.1	58.6	56.1
Alumina	14.5	12-16.5	21	13.7	11.9-14.7	14.7	11.6
Ferric Oxide	5	2.9-7	4.9	5.9	5.3-6.2	4.4	5.7
Lime	10	7.7-14	5	13.1	10.7-15.3	8.9	13.1
Magnesia	1.8	1.6-2.1	1.9	2.2	2-2.5	2.4	2.4
Sodium Oxide	1.8	0.8-3	2.9	4.2	3.5-4.9	1.8	3.6
Potassium Oxide	1.2	0.5-1.5	1	0.4	0.2-0.8	1.1	0.7
Titania	0.7	0.5-0.9	0.8	0.9	0.8-0.9	0.7	0.8
Manganese Oxide	0.04	0.01-0.05	0.03	0.04	0.03-0.05	0.03	0.09
Calorific Value							
Btu/lb	12870	12750	12870	12640	12580	13360	12800
		-12990			-12700		
HGI	44	-	46	43	-	44	46
Size, wt%							
50 mm x 0 mm	100	-	100	100	-	96	92
2 mm x 0 mm	30.3	-	-	11.6	-	33	32.6
Fuel Ratio	1.2	-	1.2	1.2	-	1.2	1.2
Silica Ratio	0.777	-	0.828	0.712	0.68-0.75	0.789	0.726
B/A Ratio	0.268	0.18-0.4	0.2	0.386	0.34-0.45	0.251	0.372
Alkalies (Na2O), wt%	2.6	-	3.6	4.5	3.5-5.1	2.5	4.1
T250, deg F	2600	-	2760	2420	2400-2475	2700	2450
Ash Fusion T, deg F (Reduction/Oxidation)							
IDT	2192/2228		2221	2117/2149		2160	-
ST	2237/2291		2320	2128/2174		2250	-
HT	2300/2354		2383	2179/2220		2310	-
FT	2390/2444		2421	2294/2340		2410	-
Slagging Index	2147	2114-2224	2263	2114	2098-2180	2200	-
Fouling Index	1.8	0.8-3	2.9	4.2	3.5-4.9	1.8	3.6