CHAPTER 48

COALS, LIGNITE, PEAT

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48.1 INTRODUCTION

48.1.1 Nature

Coal is a dark brown to black sedimentary rock derived primarily from the unoxidized remains of carbon-bearing plant tissues. It is a complex, combustible mixture of organic, chemical, and mineral materials found in strata, or "seams," in the earth, consisting of a wide variety of physical and chemical properties.

The principal types of coal, in order of metamorphic development, are lignite, subbituminous, bituminous, and anthracite. While not generally considered a coal, peat is the first development stage in the "coalification" process, in which there is a gradual increase in the carbon content of the fossil organic material, and a concomitant reduction in oxygen.

Coal substance is composed primarily of carbon, hydrogen, and oxygen, with minor amounts of nitrogen and sulfur, and varying amounts of moisture and mineral impurities.

48.1.2 Reserves—Worldwide and United States

According to the World Coal Study (see Ref. 3), the total geological resources of the world in "millions of tons of coal equivalent" (mtce) is 10,750,212, of which 662,932, or 6%, is submitted as "Technically and Economically Recoverable Resources."

Millions of tons of coal equivalent is based on the metric ton (2205 lb) with a heat content of 12,600 Btu/lb (7000 kcal/kg).

A summary of the percentage of technically and economically recoverable reserves and the percentage of total recoverable by country is shown in Table 48.1.

As indicated in Table 48.1, the United States possesses over a quarter of the total recoverable reserves despite the low percentage of recovery compared to other countries.

It is noted that the interpretation of "technical and economic" recovery is subject to considerable variation and also to modification, as technical development and changing economic conditions dictate. It should also be noted that there are significant differences in density and heating values in various coals, and, therefore, the mtce definition should be kept in perspective.

In 1977, the world coal production was approximately 2450 mtce,[3] or about $\frac{1}{270}$th of the recoverable reserves.

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Table 48.1

	Percentage of Recoverable[a] of Geological Resources	Percentage of Total Recoverable Reserves
Australia	5.5	4.9
Canada	1.3	0.6
Peoples Republic of China	6.8	14.9
Federal Republic of Germany	13.9	5.2
India	15.3	1.9
Poland	42.6	9.0
Republic of South Africa	59.7	6.5
United Kingdom	23.7	6.8
United States	6.5	25.2
Soviet Union	2.2	16.6
Other Countries	24.3	8.4
		100.0

[a] Technically and economically recoverable reserves. Percentage indicated is based on total geological resources reported by country.

Source: World Coal Study, *Coal—Bridge to the Future,* 1980.

Table 48.2 Demonstrated Reserve Base[a] of Coal in the United States on January, 1980, by Rank (Millions of Short Tons)

State[b]	Anthracite	Bituminous	Subbituminous	Lignite	Total[c]
Alabama[d]	—	3,916.8	—	1,083.0	4,999.8
Alaska	—	697.5	5,443.0	14.0	6,154.5
Arizona	—	410.0	—	—	410.0
Arkansas	96.4	288.7	—	25.7	410.7
Colorado[d]	25.5	9,086.1	3,979.9	4,189.9	17,281.3
Georgia	—	3.6	—	—	3.6
Idaho	—	4.4	—	—	4.4
Illinois[d]	—	67,606.0	—	—	67,606.0
Indiana	—	10,586.1	—	—	10,586.1
Iowa	—	2,197.1	—	—	2,197.7
Kansas	—	993.8	—	—	993.8
Kentucky					
Eastern[d]	—	12,927.5	—	—	12,927.5
Western	—	21,074.4	—	—	21,074.4
Maryland	—	822.4	—	—	822.4
Michigan[d]	—	127.7	—	—	127.7
Missouri	—	6,069.1	—	—	6,069.1
Montana	—	1,385.4	103,277.4	15,765.2	120,428.0
New Mexico[d]	2.3	1,835.7	2,683.4	—	4,521.4
North Carolina	—	10.7	—	—	10.7
North Dakota	—	—	—	9,952.3	9,952.3
Ohio[d]	—	19,056.1	—	—	19,056.1
Oklahoma	—	1,637.8	—	—	1,637.8
Oregon	—	—	17.5	—	17.5
Pennsylvania	7,092.0	23,188.8	—	—	30,280.8
South Dakota	—	—	—	366.1	366.1
Tennessee[d]	—	983.7	—	—	983.7
Texas[d]	—	—	—	12,659.7	12,659.7
Utah[d]	—	6,476.5	1.1	—	6,477.6
Virginia	125.5	3,345.9	—	—	3,471.4
Washington[d]	—	303.7	1,169.4	8.1	1,481.3
West Virginia	—	39,776.2	—	—	39,776.2
Wyoming[d]	—	4,460.5	65,463.5	—	69,924.0
Total[c]	7,341.7	239,272.9	182,035.0	44,063.9	472,713.6

[a] Includes measured and indicated resource categories defined by USBM and USGS and represents 100% of the coal in place.

[b] Some coal-bearing states where data are not sufficiently detailed or where reserves are not currently economically recoverable.

[c] Data may not add to totals due to rounding.

[d] Data not completely reconciled with demonstrated reserve base data.

According to the U.S. Geological Survey, the remaining U.S. Coal Reserves total almost 4000 billion tons,[4] with overburden to 6000 ft in seams of 14 in. or more for bituminous and anthracite and in seams of 2½ ft or more for subbituminous coal and lignite. The U.S. Bureau of Mines and U.S. Geological Survey have further defined "Reserve Base" to provide a better indication of the technically and economically minable reserves, where a higher degree of identification and engineering evaluation is available.

A summary of the reserve base of U.S. coal is provided in Table 48.2.[5]

48.1.3 Classifications

Coals are classified by "rank," according to their degree of metamorphism, or progressive alteration, in the natural series from lignite to anthracite. Perhaps the most widely accepted standard for classification of coals is ASTM D388, which ranks coals according to fixed carbon and calorific value (expressed in Btu/lb) calculated to the mineral-matter-free basis. Higher-rank coals are classified according to fixed carbon on the dry basis; the lower-rank coals are classed according to calorific value on the moist basis. Agglomerating character is used to differentiate between certain adjacent groups. Table 48.3 shows the classification requirements.

Agglomerating character is determined by examination of the residue left after the volatile determination. If the residue supports a 500-g weight without pulverizing or shows a swelling or cell structure, it is said to be "agglomerating."

The mineral-matter-free basis is used for ASTM rankings, and formulas to convert Btu, fixed carbon, and volatile matter from "as-received" bases are provided. Parr formulas—Eqs. (48.1)–(48.3) are appropriate in case of litigation. Approximation formulas—Eqs. (48.4)–(48.6) are otherwise acceptable.

Parr formulas

$$\text{Dry, MM-Free } FC = \frac{FC - 0.15S}{100 - (M + 1.08A + 0.55S)} \times 100 \tag{48.1}$$

$$\text{Dry, MM-Free } VM = 100 - \text{Dry, MM-Free } FC \tag{48.2}$$

$$\text{Moist, MM-Free Btu} = \frac{\text{Btu} - 50S}{100 - (1.08A + 0.55S)} \times 100 \tag{48.3}$$

Approximation formulas

$$\text{Dry, MM-Free } FC = \frac{FC}{100 - (M + 1.1A + 0.1S)} \times 100 \tag{48.4}$$

$$\text{Dry, MM-Free } VM = 100 - \text{Dry, MM-Free } FC \tag{48.5}$$

$$\text{Moist, MM-Free Btu} = \frac{\text{Btu}}{100 - (1.1A + 0.1S)} \times 100 \tag{48.6}$$

where MM = mineral matter
Btu = British thermal unit
FC = percentage of fixed carbon
VM = percentage of volatile matter
A = percentage of ash
S = percentage of sulfur

Other classifications of coal include the International Classification of Hard Coals, the International Classification of Brown Coals, the "Lord" value based on heating value with ash, sulfur, and moisture removed, and the Perch and Russell Ratio, based on the ratio of Moist, MM-Free Btu to Dry, MM-Free *VM*.

Table 48.3 ASTM (D388) Classification of Coals by Rank[a]

Class	Group	Fixed Carbon Limits, Percent(Dry, Mineral-Matter-Free Basis)		Volatile Matter Limits, Percent (Dry, Mineral-Matter-Free Basis)		Calorific Value Limits, Btu/lb Moist,[b] Mineral-Matter-Free Basis)		Agglomerating Character
		Equal to or Less Than	Less Than	Greater Than	Equal to or Less Than	Equal to or Less Than	Less Than	
I Anthracitic	1. Metaanthracite	98	—	—	2	—	—	
	2. Anthracite	92	98	2	8	—	—	Nonagglomerating
	3. Semianthracite[c]	86	92	8	14	—	—	
II Bituminous	1. Low-volatile bituminous	78	86	14	22	—	—	
	2. Medium-volatile bituminous	69	78	22	31	—	—	Commonly agglomerating[e]
	3. High-volatile A bituminous	—	69	31	—	14,000[d]	—	
	4. High-volatile B bituminous	—	—	—	—	13,000[d]	14,000	
	5. High-volatile C bituminous	—	—	—	—	11,500	13,000	
						10,500	11,500	Agglomerating
III Subbituminous	1. Subbituminous A	—	—	—	—	10,500	11,500	
	2. Subbituminous B	—	—	—	—	9,500	10,500	
	3. Subbituminous C	—	—	—	—	8,300	9,500	
IV Lignitic	1. Lignite A	—	—	—	—	6,300	8,300	
	2. Lignite B	—	—	—	—	—	6,300	

[a] This classification does not include a few coals, principally nonbanded varieties, that have unusual physical and chemical properties and that come within the limits of fixed carbon or calorific value of the high-volatile bituminous and subbituminous ranks. All of these coals either contain less than 48% dry, mineral-matter-free fixed carbon or have more than 15,500 moist, mineral-matter-free British thermal units per pound.

[b] Moist refers to coal containing its natural inherent moisture but not including visible water on the surface of the coal.

[c] If agglomerating, classify in the low-volatile group of the bituminous class.

[d] Coals having 69% or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of calorific value.

[e] It is recognized that there may be nonagglomerating varieties in these groups of the bituminous class and that there are notable exceptions in the high-volatile C bituminous group.

48.2 CURRENT USES—HEAT, POWER, STEELMAKING, OTHER

According to statistics compiled for the 1996 Keystone Coal Industry Manual, the primary use of coals produced in the United States in recent years has been for Electric Utilities; comprising almost 90% of the 926 million tons consumed in the U.S. in 1993. Industry accounted for about 8% of the consumption during that year in a variety of Standard Industrial Classification (SIC) Codes, replacing the manufacturing of coke (now about 3%) as the second largest coal market from the recent past. Industrial users typically consume coal for making process steam as well as in open-fired applications, such as in kilns and process heaters.

It should be noted that the demand for coal for coking purposes was greater than the demand for coal for utility use in the 1950's, and has steadily declined owing to more efficient steelmaking, greater use of scrap metal, increased use of substitute fuels in blast furnaces, and other factors. The production of coke from coal is accomplished by heating certain coals in the absence of air to drive off volatile matter and moisture. To provide a suitable by-product coke, the parent coal must possess quality parameters of low ash content, low sulfur content, low coking pressure, and high coke strength. By-product coking ovens, the most predominant, are so named for their ability to recapture otherwise wasted by-products driven off by heating the coal, such as coke oven gas, coal-tar, ammonia, oil, and useful chemicals. Beehive ovens, named for their shape and configuration, are also used, albeit much less extensively, in the production of coke.

48.3 TYPES

Anthracite is the least abundant of U.S. coal forms. Sometimes referred to as "hard" coal, it is shiny black or dark silver-gray and relatively compact. Inasmuch as it is the most advanced form in the coalification process, it is sometimes found deeper in the earth than bituminous. As indicated earlier, the ASTM definition puts upper and lower bounds of dry, mineral-matter-free fixed carbon percent at 98% and 86%, respectively, which limits volatile matter to not more than 14%. Combustion in turn is characterized by higher ignition temperatures and longer burnout times than bituminous coals.

Excepting some semianthracites that have a granular appearance, they have a consolidated appearance, unlike the layers seen in many bituminous coals. Typical Hardgrove Grindability Index ranges from 20 to 60 and specific gravity typically ranges 1.55 ± 0.10.

Anthracite coals can be found in Arkansas, Colorado, Pennsylvania, Massachusetts, New Mexico, Rhode Island, Virginia, and Washington, although by far the most abundant reserves are found in Pennsylvania.

Bituminous coal is by far the most plentiful and utilized coal form, and within the ASTM definitions includes low-, medium-, and high-volatile subgroups. Sometimes referred to as "soft" coal, it is named after the word bitumen, based on general tendency toward forming a sticky mass on heating.

At a lower stage of development in the coalification process, carbon content is less than the anthracites, from a maximum of 86% to less than 69% on a dry, mineral-matter-free basis. Volatile matter, at a minimum of 14% on this basis, is greater than the anthracites, and, as a result, combustion in pulverized form is somewhat easier for bituminous coals. Production of gas is also enhanced by their higher volatility.

The tendency of bituminous coals to produce a cohesive mass on heating lends them to coke applications. Dry, mineral-matter-free oxygen content generally ranges from 5% to 10%, compared to a value as low as 1% for anthracite. They are commonly banded with layers differing in luster.

The low-volatile bituminous coals are grainier and more subject to size reduction in handling.

The medium-volatile bituminous coals are sometimes distinctly layered, and sometimes only faintly layered and appearing homogeneous. Handling may or may not have a significant impact on size reduction.

The high-volatile coals (A, B, and C) are relatively hard and less sensitive to size reduction from handling than low- or medium-volatile bituminous.

Subbituminous coals, like anthracite and lignite, are generally noncaking. "Caking" refers to fusion of coal particles after heating in a furnace, as opposed to "coking," which refers to the ability of a coal to make a good coke, suitable for metallurgical purposes.

Oxygen content, on a dry, mineral-matter-free basis, is typically 10–20%.

Brownish black to black in color, this type coal is typically smooth in appearance with an absence of layers.

High in inherent moisture, it is ironic that these fuels are often dusty in handling and appear much like drying mud as they disintegrate on sufficiently long exposure to air.

The Healy coal bed in Wyoming has the thickest seam of coal in the United States at 220 ft. It is subbituminous, with an average heating value of 7884 Btu/lb, 28.5% moisture, 30% volatile matter, 33.9% fixed carbon, and 0.6% sulfur. Reported strippable reserves of this seam are approximately 11 billion tons.[4]

Lignites, often referred to as "brown coal," often retain a woodlike or laminar structure in which wood fiber remnants may be visible. Like subbituminous coals, they are high in seam moisture, up to 50% or more, and also disintegrate on sufficiently long exposure to air.

Both subbituminous coals and lignites are more susceptible than higher-rank coals to storage, shipping, and handling problems, owing to their tendency for slacking (disintegration) and spontaneous ignition. During the slacking, a higher rate of moisture loss at the surface than at the interior may cause higher rates and stresses at the outside of the particles, and cracks may occur with an audible noise.

Peat is decaying vegetable matter formed in wetlands; it is the first stage of metamorphosis in the coalification process. Development can be generally described as anaerobic, often in poorly drained flatlands or former lake beds. In the seam, peat moisture may be 90% or higher, and, therefore, the peat is typically "mined" and stacked for drainage or otherwise dewatered prior to consideration as a fuel. Because of its low bulk density at about 15 lb/ft^3 and low heating value at about 6000 Btu/lb (both values at 35% moisture), transportation distances must be short to make peat an attractive energy option.

In addition, it can be a very difficult material to handle, as it can arch in bins, forming internal friction angles in excess of 70°.

Chemically, peat is very reactive and ignites easily. It may be easily ground, and unconsolidated peat may create dusting problems.

48.4 PHYSICAL AND CHEMICAL PROPERTIES—DESCRIPTION AND TABLES OF SELECTED VALUES

There are a number of tests, qualitative and quantitative, used to provide information on coals; these tests will be of help to the user and/or equipment designer. Among the more common tests are the following, with reference to the applicable ASTM test procedure.

A. "*Proximate*" analysis (D3172) includes moisture, "volatile matter," "fixed carbon," and ash as its components.

Percent moisture (D3173) is determined by measuring the weight loss of a prepared sample (D2013) when heated to between 219°F (104°C) and 230°F (110°C) under rigidly controlled conditions. The results of this test can be used to calculate other analytical results to a dry basis. The moisture is referred to as "residual," and must be added to moisture losses incurred in sample preparation, called "air-dry losses" in order to calculate other analytical results to an "as-received" basis. The method which combines both residual and air dry moisture is D3302.

Percent volatile matter (D3175) is determined by establishing the weight loss of a prepared sample (D2013) resulting from heating to 1740°F (950°C) in the absence of air under controlled conditions. This weight loss is corrected for residual moisture, and is used for an indication of burning properties, coke yield, and classification by rank.

Percent ash (D3174) is determined by weighing the residue remaining after burning a prepared sample under rigidly controlled conditions. Combustion is in an oxidizing atmosphere and is completed for coal samples at 1290–1380°F (700–750°C).

Fixed carbon is a calculated value making up the fourth and final component of a proximate analysis. It is determined by subtracting the volatile, moisture, and ash percentages from 100.

Also generally included with a proximate analysis are calorific value and sulfur determinations.

B. *Calorific value,* Btu/lb (J/g, cal/g), is most commonly determined (D2015) in an "adiabatic bomb calorimeter," but is also covered by another method (D3286), which uses an "isothermal jacket bomb calorimeter." The values determined by this method are called gross or high heating values and include the latent heat of water vapor in the products of combustion.

C. *Sulfur* is determined by one of three methods provided by ASTM, all covered by D3177: the Eschka method, the bomb washing method, and a high-temperature combustion method.

The Eschka method requires that a sample be ignited with an "Eschka mixture" and sulfur be precipitated from the resulting solution as $BaSO_4$ and filtered, ashed, and weighed.

The bomb wash method requires use of the oxygen-bomb calorimeter residue, sulfur is precipitated as $BaSO_4$ and processed as in the Eschka method.

The high-temperature combustion method produces sulfur oxides from burning of a sample at 2460°F (1350°C), which are absorbed in a hydrogen peroxide solution for analysis. This is the most rapid of the three types of analysis.

D. *Sulfur forms* include sulfate, organic, and pyritic, and rarely, elemental sulfur. A method used to quantify sulfate, pyritic sulfur, and organic sulfur is D2492. The resulting data are sometimes used to provide a first indication of the maximum amount of sulfur potentially removable by mechanical cleaning.

E. *Ultimate analysis* (D3176) includes total carbon, hydrogen, nitrogen, oxygen, sulfur, and ash. These data are commonly used to perform combustion calculations to estimate combustion air requirements, products of combustion, and heat losses such as incurred by formation of water vapor by hydrogen in the coal.

Chlorine (D2361) and phosphorus (D2795) are sometimes requested with ultimate analyses, but are not technically a part of D3176.

F. *Ash mineral analysis* (D2795) includes the oxides of silica (SiO_2), alumina (Al_2O_3), iron (Fe_2O_3), titanium (TiO_2), phosphorus (P_2O_5), calcium (CaO), magnesium (MgO), sodium (Na_2O), and potassium (K_2O).

These data are used to provide several indications concerning ash slagging or fouling tendencies, abrasion potential, electrostatic precipitator operation, and sulfur absorption potention.

See Section 48.8 for further details.

G. *Grindability* (D409) is determined most commonly by the Hardgrove method to provide an indication of the relative ease of pulverization or grindability, compared to "standard" coals having grindability indexes of 40, 60, 80, and 110. As the index increases, pulverization becomes easier, that is, an index of 40 indicates a relatively hard coal; an index of 100 indicates a relatively soft coal.

Standard coals may be obtained from the U.S. Bureau of Mines.

A word of caution is given: grindability may change with ash content, moisture content, temperature, and other properties.

H. *Free swelling index* (D720) also referred to as a "coke-button" test, provides a relative index (1–9) of the swelling properties of a coal. A sample is burned in a covered crucible, and the resulting index increases as the swelling increases, determined by comparison of the button formed with standard profiles.

I. *Ash fusion temperatures* (D1857) are determined from triangular-core-shaped ash samples, in a reducing atmosphere and/or in an oxidizing atmosphere. Visual observations are recorded of temperatures at which the core begins to deform, called "initial deformation"; where height equals width, called "softening"; where height equals one-half width, called "hemispherical"; and where the ash is fluid.

The hemispherical temperature is often referred to as the "ash fusion temperature."

While not definitive, these tests provide a rough indication of the slagging tendency of coal ash.

Analysis of petrographic constituents in coals has been used to some extent in qualitative and semiquantitative analysis of some coals, most importantly in the coking coal industry. It is the application of macroscopic and microscopic techniques to identify maceral components related to the plant origins of the coal. The macerals of interest are vitrinite, exinite, resinite, micrinite, semifusinite, and fusinite. A technique to measure reflectance of a prepared sample of coal and calculate the volume percentages of macerals is included in ASTM Standard D2799.

Table 48.4 shows selected analyses of coal seams for reference.

48.5 BURNING CHARACTERISTICS

The ultimate analysis, described in the previous section, provides the data required to conduct fundamental studies of the air required for stoichiometric combustion, the volumetric and weight amounts of combustion gases produced, and the theoretical boiler efficiencies. These data assist the designer in such matters as furnace and auxiliary equipment sizing. Among the items of concern are draft equipment for supplying combustion air requirements, drying and transporting coal to the burners and exhausting the products of combustion, mass flow and velocity in convection passes for heat transfer and erosion considerations, and pollution control equipment sizing.

The addition of excess air must be considered for complete combustion and perhaps minimization of ash slagging in some cases. It is not uncommon to apply 25% excess air or more to allow operational flexibility.

As rank decreases, there is generally an increase in oxygen content in the fuel, which will provide a significant portion of the combustion air requirements.

The theoretical weight, in pounds, of combustion air required per pound of fuel for a stoichiometric condition is given by

$$11.53\mathrm{C} + 34.34\,[\mathrm{H}_2 - \tfrac{1}{8}\mathrm{O}_2] + 4.29\mathrm{S} \tag{48.7}$$

where C, H_2, O_2, and S are percentage weight constituents in the ultimate analysis.

The resulting products of combustion, again at a stoichiometric condition and complete combustion, are

$$\mathrm{CO}_2 = 3.66\mathrm{C} \tag{48.8}$$

$$\mathrm{H_2O} = 8.94\mathrm{H}_2 + \mathrm{H_2O}\ (\text{wt\% } \mathrm{H_2O} \text{ in fuel}) \tag{48.9}$$

$$\mathrm{SO}_2 = 2.00\mathrm{S} \tag{48.10}$$

$$\mathrm{N}_2 = 8.86\mathrm{C} + 26.41\,(\mathrm{H}_2 - \tfrac{1}{8}\mathrm{O}_2) + 3.29\mathrm{S} + \mathrm{N}_2\ (\text{wt\% nitrogen in fuel}) \tag{48.11}$$

The combustion characteristics of various ranks of coal can be seen in Fig. 48.1, showing "burning profiles" obtained by thermal gravimetric analysis. As is apparent from this figure, ignition of lower rank coals occurs at a lower temperature and combustion proceeds at a more rapid rate than higher rank coals. This information is, of course, highly useful to the design engineer in determination of the size and configuration of combustion equipment.

The predominant firing technique for combustion of coal is in a pulverized form. To enhance ignition, promote complete combustion, and, in some cases, mitigate the effects of large particles on

Table 48.4 Selected Values—Coal and Peat Quality

Parameter	East Kentucky, Skyline Seam (Washed)	Pennsylvania, Pittsburgh #8 Seam (Washed)	Illinois, Harrisburg 5 (Washed)	Wyoming, Powder River Basin (Raw)	Florida Peat, Sumter County	
					In situ	Dry
Moisture % (total)	8.00	6.5	13.2	25.92	86.70	—
Ash %	6.48	6.5	7.1	6.00	0.54	4.08
Sulfur %	0.82	1.62	1.28	0.25	0.10	0.77
Volatile %	36.69	34.40	30.6	31.27	8.74	65.73
Grindability (HGI)	45	55	54	57	36	69[a]
Calorific value (Btu/lb, as received)	12,500	13,100	11,700	8,500	1,503	11,297
Fixed carbon	48.83	52.60	49.1	37.23	4.02	30.19
Ash minerals						
SiO_2	50.87	50.10	48.90	32.02	58.29	
Al_2O_2	33.10	24.60	25.50	15.88	19.50	
TiO_2	2.56	1.20	1.10	1.13	1.05	
CaO	2.57	2.2	2.90	23.80	1.95	
K_2O	1.60	1.59	3.13	0.45	1.11	
MgO	0.80	0.70	1.60	5.73	0.94	
Na_2O	0.53	0.35	1.02	1.27	0.40	
P_2O_5	0.53	0.38	0.67	1.41	0.09	
Fe_2O_3	5.18	16.20	12.20	5.84	14.32	
SO_3	1.42	1.31	1.96	11.35	2.19	
Undetermined	0.84	1.37	1.02	1.12	0.16	
Ash	7.04	7.0	8.23	7.53	4.08	
Hydrogen	5.31	5.03	4.95	4.80	4.59	
Carbon	75.38	78.40	76.57	69.11	69.26	
Nitrogen	1.38	1.39	1.35	0.97	1.67	
Sulfur	0.89	1.73	1.47	0.34	0.77	
Oxygen (by difference)	9.95	6.35	7.03	17.24	19.33	
Chlorine	0.05	0.10	0.40	0.01	0.30	
Ash Fusion Temperatures (°F)						
Initial deformation (reducing)	2800+	2350	2240	2204	1950	
Softening ($H = W$) (reducing)	2800+	2460	2450	2226	2010	
Hemispherical ($H = \frac{1}{2}W$) (reducing)	2800+	2520	2500	2250	2060	
Fluid (reducing)	2800+	2580	2700+	2302	2100	

[a] At 9% H_2O.

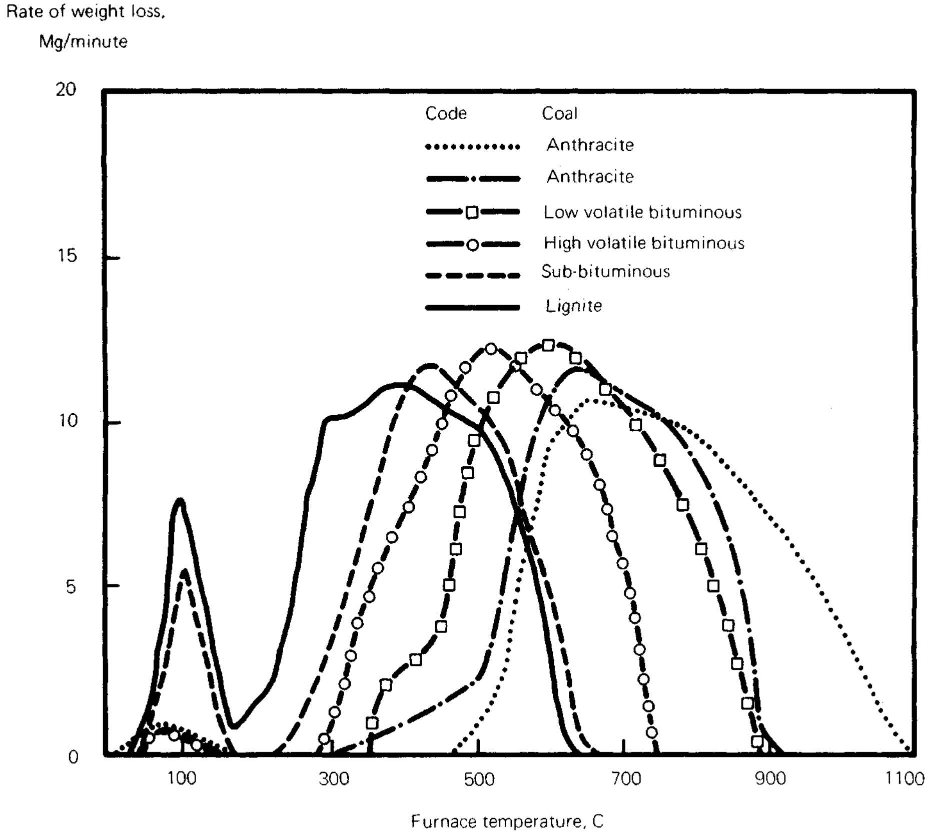

Fig. 48.1 Comparison of burning profiles for coals of different rank (courtesy of The Babcock and Wilcox Company).

slagging and particulate capture, guidelines are generally given by the boiler manufacturer for pulverizer output (burner input).

Typical guidelines are as follows:

Coal Class/Group	Percentage Passing a 200 Mesh Sieve	Percentage Retained on a 50 Mesh Sieve	Allowable Coal/Air Temperature (°F)
Anthracite	80	2.0	200
Low-volatile bituminous	70–75	2.0	180
High-volatile bituminous A	70–75	2.0	170
High-volatile bituminous C	65–72	2.0	150–160
Lignite	60–70	2.0	110–140

It is noted that these guidelines may vary for different manufacturers, ash contents, and equipment applications and, of course, the manufacturer should be consulted for fineness and temperature recommendations.

The sieve designations of 200 and 50 refer to U.S. Standard sieves. The 200 mesh sieve has 200 openings per linear inch, or 40,000 per square inch. The ASTM designations for these sieves are 75 and 300 micron, respectively.

Finally, agglomerating character may also have an influence on the fineness requirements, since this property might inhibit complete combustion.

48.6 ASH CHARACTERISTICS

Ash is an inert residue remaining after the combustion of coal and can result in significant challenges for designers and operators of the combustion, ash handling, and pollution control equipment. The quantity of ash in the coal varies widely from as little as 6% or less to more than 30% by weight. Additionally, diverse physical and chemical properties of ashes can pose substantial problems, with slagging, abrasion, and fouling of boilers. Electrostatic precipitators, used for pollution control, can experience material changes in collection efficiency depending on the mineral constituents of the ash.

"Slagging" is a term that generally refers to the formation of high-temperature fused ash deposits on furnace walls and other surfaces primarily exposed to radiant heat.

"Fouling" generally refers to high-temperature bonded ash deposits forming on convection tube banks, particularly superheat and reheat tubes.

Indication of ash-slagging tendencies can be measured by tests such as viscosity–temperature tests or by ash-softening tests. In addition, there are many empirical equations that are used to provide information as to the likelihood of slagging and fouling problems.

ASTM Standard number D1857 is the most common test used for slagging indication. In this test, ash samples are prepared as triangular cones and then are heated at a specified rate. Observations are then made and recorded of temperatures at prescribed stages of ash deformation, called initial deformation, softening temperature, hemispherical temperature, and fluid temperature. These tests are conducted in reducing and/or oxidizing atmospheres.

Another method used, although far more costly, involves measurement of the torque required to rotate a platinum bob suspended in molten slag. A viscosity–temperature relationship is established as a result of this test, which is also conducted in reducing and/or oxidizing atmospheres. A slag is generally considered liquid when its viscosity is below 250 poise, although tapping from a boiler may require a viscosity of 50–100 poise. It is plastic when its viscosity is between 250 and 10,000 poise. It is in this region where removal of the slag is most troublesome.

Ash mineral analyses are used to calculate empirical indicators of slagging problems. In these analyses are included metals reported as equivalent oxide weight percentages of silica, alumina, iron, calcium, magnesium, sodium, potassium, titania, phosphorous, and sulfur, as follows:

$$\mathrm{SiO_2 + Al_2O_3 + Fe_2O_3 + CaO + MgO + Na_2O + K_2O + TiO_2 + P_2O_5 + SO_3 = 100\%}$$

Some ratios calculated using these data are:

Base: Acid Ratio, B/A

$$\frac{B}{A} = \frac{\text{base}}{\text{acid}} = \frac{\mathrm{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}}{\mathrm{SiO_2 + Al_2O_3 + TiO_2}}$$

It has been reported[1] that a base/acid ratio in the range of 0.4 to 0.7 results typically in low ash fusibility temperatures and, hence, more slagging problems.

Slagging Factor, R_s

$$R_s = B/A \times \%\ \text{sulfur, dry coal basis}$$

It has been reported[15] that coals with bituminous-type ashes exhibit a high slagging potential with a slagging factor above 2 and severe slagging potential with a slagging factor of more than 2.6. Bituminous-type ash refers to those ashes where iron oxide percentage is greater than calcium *plus* magnesium oxide.

Silica/Alumina Ratio

$$\frac{\text{silica}}{\text{alumina}} = \frac{\mathrm{SiO_2}}{\mathrm{Al_2O_3}}$$

It has been reported[1] that the silica in ash is more likely to form lower-melting-point compounds than is alumina and for two coals having the same base/acid ratio, the coal with a higher silica/alumina ratio should result in lower fusibility temperatures. However, it has also been reported[2] that for low base/acid ratios the opposite is true.

Iron/Calcium Ratio

$$\frac{\text{iron}}{\text{dolomite}} = \frac{\mathrm{Fe_2O_3}}{\mathrm{CaO + MgO}}$$

This ratio and its use are essentially the same as the iron/calcium ratio.

Silica Percentage (*SP*)

$$SP = \frac{SiO_2 \times 100}{SiO_2 + Fe_2O_3 + CaO + MgO}$$

This parameter has been correlated with ash viscosity. As silica ratio increases, the viscosity of slag increases. Graphical methods[2] are used in conjunction with this parameter to estimate the T_{250} temperature—the temperature where the ash would have a viscosity of 250 poise. Where the acidic content is less than 60% and the ash is lignitic, the *dolomite percentage* (*DP*) is used in preference to the silica percentage, along with graphs to estimate the T_{250}:

$$DP = \frac{(CaO + MgO) \times 100}{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}$$

where the sum of the basic and acidic components are adjusted, if necessary, to equal 100%. For bituminous ash or lignitic-type ash having acidic content above 60%, the base/acid ratio is used in conjunction with yet another graph.

Fouling Factor (R_F)

$$R_F = \text{acid base} \times \%\ Na_2 \text{ (bituminous ash)}$$

or

$$R_F = \%\ Na_2O \text{ (lignitic ash)}$$

For bituminous ash, the fouling factor[17] is "low" for values less than 0.1, "medium" for values between 0.1 and 0.25, "high" for values between 0.25 and 0.7, and "severe" values above 0.7. For lignitic-type ash, the percentage of sodium is used, and low, medium, and high values are <3.0, 3.0–6.0, and >6.0, respectively.

The basis for these factors is that sodium is the most important single factor in ash fouling, volatilizing in the furnace and subsequently condensing and sintering ash deposits in cooler sections.

Chlorine has also been used as an indicator of fouling tendency of eastern-type coals. If chlorine, from the ultimate analysis, is less than 0.15%, the fouling potential is low; if between 0.15 and 0.3, it has a medium fouling potential; and if above 0.3, its fouling potential is high.[1]

Ash resistivity can be predicted from ash mineral and coal ultimate analyses, according to a method described by Bickelhaupt.[24] Electrostatic precipitator sizing and/or performance can be estimated using the calculated resistivity. For further information, the reader is referred to Ref. 14.

48.7 SAMPLING

Coals are by nature heterogeneous and, as a result, obtaining a representative sample can be a formidable task. Its quality parameters such as ash, moisture, and calorific value can vary considerably from seam to seam and even within the same seam. Acquisition of accurate data to define the nature and ranges of these values adequately is further compounded by the effects of size gradation, sample preparation, and analysis accuracy.

Inasmuch as these data are used for such purposes as pricing, control of the operations in mines, and preparation plants, determination of power plant efficiency, estimation of material handling and storage requirements for the coal and its by-products, and in some cases for determination of compliance with environmental limitations, it is important that samples be taken, prepared, and analyzed in accordance with good practice.

To attempt to minimize significant errors in sampling, ASTM D2234 was developed as a standard method for the collection of a gross sample of coal and D2013 for preparation of the samples collected for analysis. It applies to lot sizes up to 10,000 tons (9080 mg) per gross sample and is intended to provide an accuracy of ± $\frac{1}{10}$th of the average ash content in 95 of 100 determinations.

The number and weight of increments of sample comprising the gross sample to represent the lot, or consignment, is specified for nominal top sizes of $\frac{5}{8}$ in. (16 mm), 2 in. (50 mm), and 6 in. (150 mm), for raw coal or mechanically cleaned coal. Conditions of collection include samples taken from a stopped conveyor belt (the most desirable), full and partial stream cuts from moving coal consignments, and stationary samples.

One recommendation made in this procedure and worth special emphasis is that the samples be collected under the direct supervision of a person qualified by training and experience for this responsibility.

This method does not apply to the sampling of reserves in the ground, which is done by core drilling methods or channel sampling along outcrops as recommended by a geologist or mining engineer. It also does not apply to the sampling of coal slurries.

A special method (D197) was developed for the collection of samples of pulverized coals to measure size consist or fineness, which is controlled to maintain proper combustion efficiency.

Sieve analyses using this method may be conducted on No. 16 (1.18 mm) through No. 200 (750 mm) sieves, although the sieves most often referred to for pulverizer and classifier performance are the No. 50, the No. 100, and the No. 200 sieves. The number refers to the quantity of openings per linear inch.

Results of these tests should plot as a straight line on a sieve distribution chart. A typical fineness objective, depending primarily on the combustion characteristics might be for 70% of the fines to pass through a 200-mesh sieve and not more than 2% to be retained on the 50-mesh sieve.

D2013 covers the preparation of coal samples for analysis, or more specifically, the reduction and division of samples collected in accordance with D2234. A "referee" and "nonreferee" method are delineated, although the "nonreferee" method is the most commonly used. "Referee" method is used to evaluate equipment and the nonreferee method.

Depending on the amount of moisture and, therefore, the ability of the coal to pass freely through reduction equipment, samples are either predried in air drying ovens or on drying floors or are processed directly by reduction, air drying, and division. Weight losses are computed for each stage of air drying to provide data for determination of total moisture, in combination with D3173 or 3302 (see Section 48.6).

Samples must ultimately pass the No. 60 (250 mm) sieve (D3173) or the No. 8 (2.36 mm) sieve (D3302) prior to total moisture determination.

Care must be taken to adhere to this procedure, including the avoidance of moisture losses while awaiting preparation, excessive time in air drying, proper use of riffling or mechanical division equipment, and verification and maintenance of crushing equipment size consist.

48.8 COAL CLEANING

Partial removal of impurities in coal such as ash and pyritic sulfur has been conducted since before 1900, although application and development has intensified during recent years owing to a number of factors, including the tightening of emissions standards, increasing use of lower quality seams, and increasing use of continuous mining machinery. Blending of two or more fuels to meet tight emissions standards, or other reasons, often requires that each of the fuels is of a consistent grade, which in turn may indicate some degree of coal cleaning.

Coal cleaning may be accomplished by physical or chemical means, although physical coal cleaning is by far the most predominant.

Primarily, physical processes rely on differences between the specific gravity of the coal and its impurities. Ash, clay, and pyritic sulfur have a higher specific gravity than that of coal. For example, bituminous coal typically has a specific gravity in the range 1.12–1.35, while pyrite's specific gravity is between 4.8 and 5.2.

One physical process that does not benefit from specific gravity differences is froth flotation. It is only used for cleaning coal size fractions smaller than 28 mesh (½ mm). Basically the process requires coal fines to be agitated in a chamber with set amounts of air, water, and chemical reagents, which creates a froth. The coal particles are selectively attached to the froth bubbles, which rise to the surface and are skimmed off, dewatered, and added to other clean coal fractions.

A second stage of froth flotation has been tested successfully at the pilot scale for some U.S. coals. This process returns the froth concentrate from the first stage to a bank of cells where a depressant is used to sink the coal and a xanthate flotation collector is used to selectively float pyrite.

The predominant commercial methods of coal cleaning use gravity separation by static and/or dynamic means. The extent and cost of cleaning naturally depends on the degree of end product quality desired, the controlling factors of which are primarily sulfur, heating value, and ash content.

Although dry means may be used for gravity separation, wet means are by far the more accepted and used techniques.

The first step in designing a preparation plant involves a careful study of the washability of the coal. "Float and sink" tests are run in a laboratory to provide data to be used for judging application and performance of cleaning equipment. In these tests the weight percentages and composition of materials are determined after subjecting the test coal to liquid baths of different specific gravities.

Pyritic sulfur and/or total sulfur percent, ash percent, and heating value are typically determined for both the float (called "yield") and sink (called "reject") fractions.

Commonly, the tests are conducted on three or more size meshes, such as 1½ in. × 0 mesh, ⅜ in. × 100 mesh, and minus 14 mesh, and at three or more gravities of such as 1.30, 1.40, and 1.60. Percentage recovery of weight and heating value are reported along with other data on a cumulative basis for the float fractions. An example of this, taken from a Bureau of Mines study[11] of 455 coals is shown in Table 48.5.

Many coals have pyrite particles less than one micron in size (0.00004 in.), which cannot be removed practically by mechanical means. Moreover, the cost of coal cleaning increases as the particle size decreases, as a general rule, and drying and handling problems become more difficult. Generally, coal is cleaned using particle sizes as large as practical to meet quality requirements.

Table 48.5 Cumulative Washability Data[a]

Product	Recovery Weight	% Btu	Btu/lb	Ash %	Sulfur (%)		lb SO_2/MBtu
					Pyritic	Total	
Sample Crushed to Pass 1½ in.							
Float—1.30	55.8	58.8	14,447	3.3	0.26	1.09	1.5
Float—1.40	90.3	93.8	14,239	4.7	0.46	1.33	1.9
Float—1.60	94.3	97.3	14,134	5.4	0.53	1.41	2.0
Total	100.0	100.0	13,703	8.3	0.80	1.67	2.4
Sample Crushed to Pass ⅜ in.							
Float—1.30	58.9	63.0	14,492	3.0	0.20	1.06	1.5
Float—1.40	88.6	93.2	14,253	4.6	0.37	1.26	1.8
Float—1.60	92.8	96.8	14,134	5.4	0.47	1.36	1.9
Total	100.0	100.0	13,554	9.3	0.77	1.64	2.4
Sample Crushed to Pass 14 Mesh							
Float—1.30	60.9	65.1	14,566	2.5	0.16	0.99	1.4
Float—1.40	88.7	93.1	14,298	4.3	0.24	1.19	1.7
Float—1.60	93.7	97.1	14,134	5.4	0.40	1.29	1.8
Total	100.0	100.0	13,628	8.8	0.83	1.72	2.5

[a] State: Pennsylvania (bituminous); coal bed: Pittsburgh; county: Washington; raw coal moisture: 2.0%.

It is interesting to note that a 50-micron pyrite particle (0.002 in.) inside a 14-mesh coal particle (0.06 in.) does not materially affect the specific gravity of a pure coal particle of the same size.

Washability data are usually organized and plotted as a series of curves, including:

1. Cumulative float–ash, sulfur %
2. Cumulative sink ash %
3. Elementary ash % (not cumulative)
4. % recovery (weight) versus specific gravity

Types of gravity separation equipment include jigs, concentrating tables, water-only cyclones, dense-media vessels, and dense-media cyclones.

In jigs, the coal enters the vessel in sizes to 8 in. and larger and stratification of the coal and heavier particles occurs in a pulsating fluid. The bottom layer, primarily rock, ash, and pyrite, is stripped from the mixture and rejected. Coal, the top layer, is saved. A middle layer may also be collected and saved or rejected depending on quality.

Concentrating tables typically handle coals in the ⅜ in. × 0 or ¼ in. × 0 range and use water cascading over a vibrating table tilted such that heavier particles travel to one end of the table while lighter particles, traveling more rapidly with the water, fall over the adjacent edge.

In "water-only" and dense-media cyclones, centrifugal force is used to separate the heavier particles from the lighter particles.

In heavy-media vessels, the specific gravity of the media is controlled typically in the range of 1.45 to 1.65. Particles floating are saved as clean coal, while those sinking are reject. Specific gravity of the media is generally maintained by the amount of finely ground magnetite suspended in the water, as in heavy-media cyclones. Magnetite is recaptured in the preparation plant circuitry by means of magnetic separators.

Drying of cleaned coals depends on size. The larger sizes, ¼ in. or ⅜ in. and larger, typically require little drying and might only be passed over vibrating screens prior to stockpiling. Smaller sizes, down to, say, 28 mesh, are commonly dried on stationary screens followed by centrifugal driers. Minus 28 mesh particles, the most difficult to dry, are processed in vibrating centrifuges, high-speed centrifugal driers, high-speed screens, or vacuum filters.

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