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Title:	Steam: It Generation And Use, 38th Edition, Babcock and Wilcox, New York, 1975.

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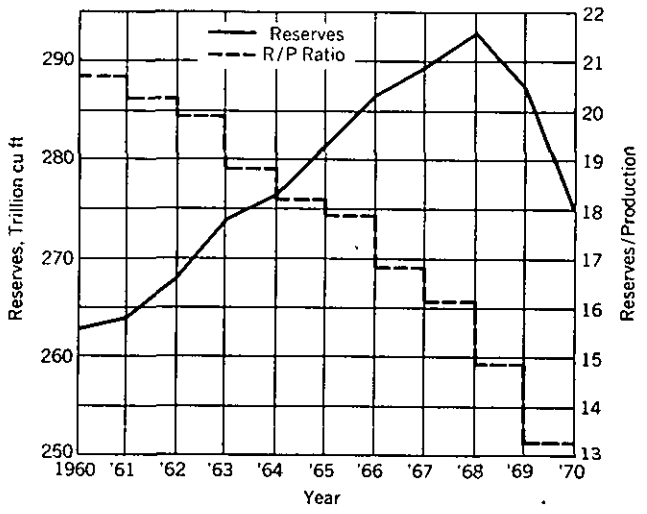


Fig. 4 Recoverable reserves and the reserves-production ratio of natural gas in the United States. *(Source, Bureau of Mines.)*

Table 13
Recoverable natural gas reserves and production in the ten leading states of the U.S.
(Trillion cu ft)

	Reserves Jan. 1, 1970	Production 1969
Texas	112.4	4.6
Louisiana	85.1	7.28
Oklahoma	17.6	1.68
New Mexico	14.3	1.09
Kansas	14.1	0.89
California	6.9	0.64
Alaska	5.2	—
Wyoming	3.9	0.32
Arkansas	2.6	0.17
West Virginia	2.4	0.21
Mississippi	—	0.17
Total	264.5	20.11
Total in the U.S.	275.1	20.72

Source, American Gas Association, Inc.

in circumstances which prevented the free access of air. At intervals, wind and water covered this mass with sediment, sand and dirt to form the overburden now found above coal seams. During millions of years, these layers of vegetation were subjected to moisture, heat and pressure, and portions of the cellulose and other organic materials were converted to carbon and hydrocarbons. In this manner wood and vegetation were changed, perhaps progressively, to peat, brown coals and lignite, subbituminous and bituminous coals, and finally to anthracite.

The intrinsic ash of coal was largely in the vegetation from the beginning. The extraneous ash came from mud deposits of shale and pyrites that filled the cracks and crevices caused by the movement of the earth's crust.

Most of the coal mined in the U.S. comes from seams 3 to 6 ft thick, with the average about 5.5 ft. One seam near Lake De Smet, Johnson County, Wyoming, averages more than 100 feet in thickness and acquires a maximum thickness of 220 ft. The thickest known seam in the world, 425 ft, is in Manchuria.

Sampling of coal

Although the coal consumption in a central station may be measured in thousands of tons per day, the samples used for laboratory analysis are measured in grams. It is therefore important and difficult to obtain representative samples of coal. B&W played a prominent part in resolving this difficulty, and the first ASTM Standard for Sampling Coal (D 21) was based largely on the work of B&W personnel.

ASTM Standard D 492 now in use was developed, adopted in 1948, and reapproved in 1958. In this standard, which is less laborious than the original, allowances are made for the probable ash content of the coal, permitting the use of smaller gross samples for the coals of lower ash content.

Two sampling procedures are recognized in the present standard.

1. Commercial-Sampling Procedure.
2. Special-Purpose Sampling Procedure.

The "Commercial-Sampling Procedure" applies to the average commercial sampling of coal. This procedure is designed to measure the average ash content of a large number of samples within ± 10% to a 95% probability.

The "Special-Purpose-Sampling Procedure" applies to the sampling of coal when special accuracy is required. This procedure should be used to supply samples for the classification of coals and the establishment of design or performance parameters. The special-purpose sample can be one of two sizes, either 4 times that of the commercial sample, giving an accuracy of ± 5% of the ash content of the coal samples, or 9 times that of the commercial sample, giving an accuracy of ± 3.33% of the ash content of the coal sampled.

Standard D 492 also sets procedures for reducing gross samples and for obtaining samples for standard and special moisture determinations. Two additional pertinent publications by the ASTM are: *Symposium on Bulk Sampling* (STP 242, 1958) and *Symposium on Coal Sampling* (STP 162, 1955). A new method has also been adopted in 1968 covering the mechanical sampling of coal, D 2234.

Careful coal sampling is of prime importance since any data resulting from subsequent analyses are only as representative as the sample provided.

Coal analysis

Customary practice in reporting the components of a coal is to use two different analyses, known as "proximate" and "ultimate." The proximate analysis is defined as the determination of moisture, volatile matter, and ash, and the calculation of fixed carbon by difference. The ultimate analysis from a dried sample is defined as the determination of carbon, hydrogen, sulfur, nitrogen and ash, and the estimation of oxygen by difference. The scope of each is indicated in the following analyses of a West Virginia coal, in which the ultimate analysis has been converted to the as-received basis.

The analysis on the as-received basis includes the total moisture content of coal received at the plant. Similarly, the as-fired basis includes the total moisture content of the coal as it enters the boiler furnace or pulverizers. The various values from such analyses are needed to imple-

Coal analyses
On as-received basis
(Pittsburgh Seam Coal, West Virginia)

Proximate Analysis		Ultimate Analysis	
Component	Weight,%	Component	Weight,%
Moisture	2.5	Moisture	2.5
Volatile matter	37.6	Carbon	75.0
Fixed carbon	52.9	Hydrogen	5.0
Ash	7.0	Sulfur	2.3
Total	100.0	Nitrogen	1.5
		Oxygen	6.7
Heating value,		Ash	7.0
Btu/lb	13,000	Total	100.0

ment the formulas in this chapter and in Chapter 6. Standard laboratory procedures for making these analyses appear in ASTM D 271. A list of other testing standards is given in Table 14.

ASTM classification by rank

Coals are classified in order to identify end use and also to provide data useful in specifying and selecting burning and handling equipment and in the design and arrangement of heat transfer surfaces. Methods and principles of burning are closely associated with specific types of equipment, and reference should be made to Chapters 9, 10 and 11. The nature and effects of impurities in coal are discussed in Chapter 15.

One classification of coal is by rank, i.e., according to the degree of metamorphism, or progressive alteration, in the natural series from lignite to anthracite. Volatile matter, fixed carbon, inherent or bed moisture (equilibrated moisture at 30C and 97% humidity), and oxygen are all indicative of rank, but no one item completely defines it. In the ASTM classification, the basic criteria are the fixed carbon and the calorific values calculated on a mineral-matter-free basis.

It is necessary, in establishing the rank of coals, to use information showing an appreciable and systematic variation with age. For the older coals, a good criterion is the "dry, mineral-matter-free fixed carbon or volatile." However, this value is not suitable for designating the rank of the younger coals. A dependable means of classifying the latter is the "moist, mineral-matter-free Btu," which varies little for the older coals but appreciably and systematically for younger coals.

Table 14
ASTM standards for testing coal, specifications and definitions of terms

ASTM Standards for Testing Coal

°D 1756	Carbon Dioxide in Coal
°D 2361	Chlorine in Coal
°D 291	Cubic Foot Weight of Crushed Bituminous Coal
°D 440	Drop Shatter Test for Coal
°D 547	Dustiness, Index of, of Coal and Coke
°D 1857	Fusibility of Coal Ash
°D 1412	Equilibrium Moisture of Coal at 96 to 97% Relative Humidity and 30C
°D 2014	Expansion or Contraction of Coal by the Sole-Heated Oven
°D 720	Free-Swelling Index of Coal
D 409	Grindability of Coal by the Hardgrove-Machine Method
°D 2015	Gross Calorific Value of Solid Fuel by the Adiabatic Bomb Calorimeter
D 1812	Plastic Properties of Coal by the Gieseler Plastometer
D 2639	Plastic Properties of Coal by the Automatic Gieseler Plastometer
D 197	Sampling and Fineness Test of Powdered Coal
°D 271	Sampling and Analysis, Laboratory, of Coal and Coke
D 492	Sampling Coals Classified According to Ash Content
°D 2234	Sampling, Mechanical, of Coal
°D 2013	Samples, Coal, Preparing of Analysis
°D 410	Screen, Analysis of Coal
D 311	Sieve Analysis of Crushed Bituminous Coal
D 310	Size of Anthracite
°D 431	Size of Coal, Designating from its Screen Analysis
°D 1757	Sulfur in Coal Ash
°D 2492	Sulfur, Forms of, in Coal
°D 441	Tumbler Test for Coal

Specifications

°D 388	Classification of Coals by Rank
°E 11	Wire-Cloth Sieves for Testing Purposes
E 323	Perforated-Plate Sieves for Testing Purposes

Definitions of Terms

°D 121	Coal and Coke
D 2796	Lithological Classes and Physical Components of Coal
°D 407	Gross Calorific Value and Net Calorific Value of Solid and Liquid Fuels

° Approved as American National Standard by the American National Standards Institute.

Table 15, ASTM D 388, is used for classification according to rank or age. Older coals are classified by dry, mineral-matter-free fixed carbon, and younger coals by moist, mineral-matter-free Btu. These terms are defined by the Parr formulas (1), (2) and (3). Formulas (4), (5) and (6) are approximate forms of the Parr formulas. Proximate analyses and higher heating values are used in making the calculations.

Parr formulas

$$\text{(1)}\qquad \text{Dry, } Mm\text{-free } FC = \frac{FC - 0.15\,\text{S}}{100 - (M + 1.08A + 0.55\,\text{S})} \times 100,\ \%$$

$$\text{(2)}\qquad \text{Dry, } Mm\text{-free } VM = 100 - \text{Dry, } Mm\text{-free } FC,\ \%$$

$$\text{(3)}\qquad \text{Moist, } Mm\text{-free Btu} = \frac{\text{Btu} - 50\,\text{S}}{100 - (1.08A + 0.55\,\text{S})} \times 100,\ \text{per lb}$$

Approximation formulas

$$\text{(4)}\qquad \text{Dry, } Mm\text{-free } FC = \frac{FC}{100 - (M + 1.1A + 0.1\,\text{S})} \times 100,\ \%$$

$$\text{(5)}\qquad \text{Dry, } Mm\text{-free } VM = 100 - \text{Dry, } Mm\text{-free } FC,\ \%$$

$$\text{(6)}\qquad \text{Moist, } Mm\text{-free Btu} = \frac{\text{Btu}}{100 - (1.1A + 0.1\,\text{S})} \times 100,\ \text{per lb}$$

where:

Mm = mineral matter
Btu = heating value per lb
FC = fixed carbon, %
VM = volatile matter, %
M = bed moisture, %
A = ash, %
S = sulfur, %

All for coal on a moist basis.

The term "moist" refers to bed moisture only, and analyses of constituents must be of bed samples collected as prescribed by ASTM D 388. Agglomerating and weathering (or slacking) indices are used to differentiate between certain adjacent groups and are defined in this standard.

Table 16 lists 17 selected U.S. coals, arranged in the order of the ASTM classification. The basis for the two ASTM criteria (the fixed carbon and the calorific values calculated on a moist, mineral-matter-free basis) are shown in Fig. 5 for over 300 typical coals of the U.S. The classes and groups of Table 15 are indicated in Fig. 5. For the anthracitic and low- and medium- volatile bituminous coals, the moist, mineral-matter-free calorific value changes very little; hence the fixed-carbon criterion is used. Conversely, in the case of the high-volatile bituminous, subbituminous and lignitic coals, the moist, mineral-matter-free calorific value is used, since the fixed carbon is almost the same for all classifications.

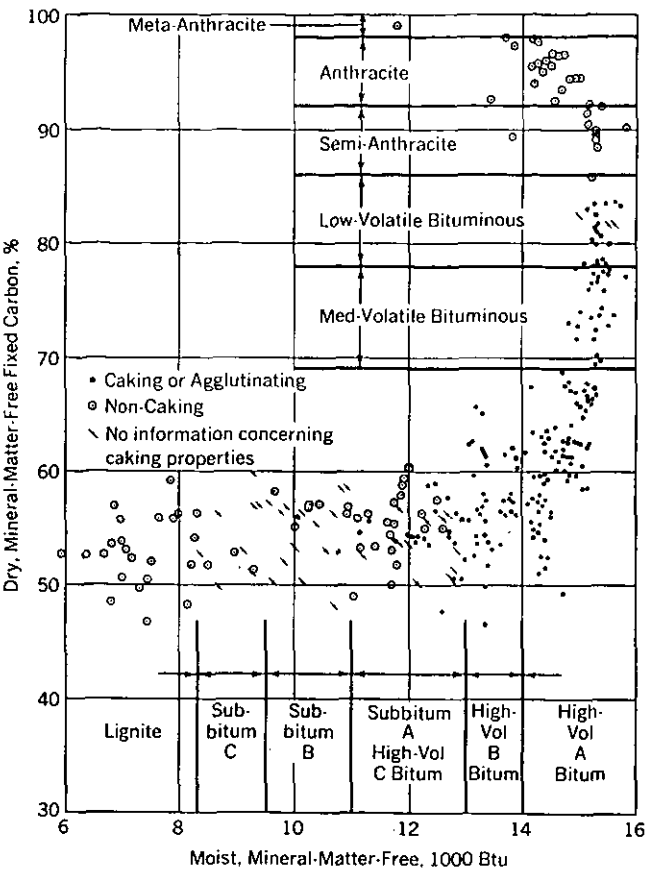


Fig. 5 Distribution plot for over 300 coals of the United States, illustrating ASTM classification by rank as defined in Table 15.

Other classifications of coal by rank

There are classifications of coal by rank (or type) which are currently in limited use on the European Continent. These are the *International Classification of Hard Coals by Type*, and the *International Classification of Brown Coals*. The systems were developed by a Classification Working Party established in 1949 by the Coal Committee of the Economic Commission for Europe.

The classification system of hard coals, which also includes a simplified statistical grouping combining coals having the same general characteristics, appears in Table 17. The term "hard coal" is based on European terminology and is defined as coal with a calorific value of more than 10,260 Btu/lb on the moist, ash-free basis. The term "type" is equivalent to rank in American coal classification terminology and the term "class" approximates the ASTM rank.

The nine classes of coal, based on dry, ash-free volatile matter content and moist, ash-free calorific value, are divided into groups according to their caking properties. Either the free-swelling test or the Roga test may be used to determine caking properties (a measure of the behavior of coal when heated rapidly).

The coal groups are further subdivided into subgroups according to their coking properties, which are a measure of the behavior of the coal when heated slowly. Either the Audibert-Arnu test or the Gray-King coking test may be used to determine these coking properties.

A three-figure code number is used to express coal

Table 15
Classification of coals by rank[a] (ASTM D 388)

Class	Group	Fixed Carbon Limits, % (Dry, Mineral-Matter-Free Basis)		Volatile Matter Limits, % (Dry, Mineral-Matter-Free Basis)		Calorific Value Limits, Btu/lb (Moist,[b] Mineral-Matter-Free Basis)		Agglomerating Character
		Equal or Greater Than	Less Than	Greater Than	Equal or Less Than	Equal or Greater Than	Less Than	
I. Anthracitic	1. Meta-anthracite	98	—	—	2	—	—	Nonagglomerating
	2. Anthracite	92	98	2	8	—	—	
	3. Semianthracite[c]	86	92	8	14	—	—	
II. Bituminous	1. Low volatile bituminous coal	78	86	14	22	—	—	Commonly agglomerating[e]
	2. Medium volatile bituminous coal	69	78	22	31	—	—	
	3. High volatile *A* bituminous coal	—	69	31	—	14,000[d]	—	
	4. High volatile *B* bituminous coal	—	—	—	—	13,000[d]	14,000	
	5. High volatile *C* bituminous coal	—	—	—	—	11,500	13,000	
						10,500[e]	11,500	Agglomerating
III. Subbituminous	1. Subbituminous *A* coal	—	—	—	—	10,500	11,500	Nonagglomerating
	2. Subbituminous *B* coal	—	—	—	—	9,500	10,500	
	3. Subbituminous *C* coal	—	—	—	—	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, which have unusual physical and chemical properties and which 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 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 there are notable exceptions in high volatile *C* bituminous group.

Table 16
Seventeen selected U.S. coals arranged in order of ASTM classification

No.	Coal Rank		State	County	Coal Analysis, Bed Moisture Basis						Rank	Rank
	Class	Group			*M*	*VM*	*FC*	*A*	S	Btu	*FC*	Btu
1	I	1	Pa.	Schuylkill	4.5	1.7	84.1	9.7	0.77	12,745	99.2	14,280
2	I	2	Pa.	Lackawanna	2.5	6.2	79.4	11.9	0.60	12,925	94.1	14,880
3	I	3	Va.	Montgomery	2.0	10.6	67.2	20.2	0.62	11,925	88.7	15,340
4	II	1	W.Va.	McDowell	1.0	16.6	77.3	5.1	0.74	14,715	82.8	15,600
5	II	1	Pa.	Cambria	1.3	17.5	70.9	10.3	1.68	13,800	81.3	15,595
6	II	2	Pa.	Somerset	1.5	20.8	67.5	10.2	1.68	13,720	77.5	15,485
7	II	2	Pa.	Indiana	1.5	23.4	64.9	10.2	2.20	13,800	74.5	15,580
8	II	3	Pa.	Westmoreland	1.5	30.7	56.6	11.2	1.82	13,325	65.8	15,230
9	II	3	Ky.	Pike	2.5	36.7	57.5	3.3	0.70	14,480	61.3	15,040
10	II	3	Ohio	Belmont	3.6	40.0	47.3	9.1	4.00	12,850	55.4	14,380
11	II	4	Ill.	Williamson	5.8	36.2	46.3	11.7	2.70	11,910	57.3	13,710
12	II	4	Utah	Emery	5.2	38.2	50.2	6.4	0.90	12,600	57.3	13,560
13	II	5	Ill.	Vermilion	12.2	38.8	40.0	9.0	3.20	11,340	51.8	12,630
14	III	1	Mont.	Musselshell	14.1	32.2	46.7	7.0	0.43	11,140	59.0	12,075
15	III	2	Wyo.	Sheridan	25.0	30.5	40.8	3.7	0.30	9,345	57.5	9,745
16	III	3	Wyo.	Campbell	31.0	31.4	32.8	4.8	0.55	8,320	51.5	8,790
17	IV	1	N.D.	Mercer	37.0	26.6	32.2	4.2	0.40	7,255	55.2	7,610

Notes: For definition of Rank Classification according to ASTM requirements, *see Table 15.*

Data on Coal (Bed Moisture Basis)

M = equilibrium moisture, %; *VM* = volatile matter, %; *FC* = fixed carbon, %; *A* = ash, %; S = sulfur, %; Btu = Btu per lb, high heating value.

Rank *FC* = dry, mineral-matter-free fixed carbon, %.
Rank Btu = moist, mineral-matter-free Btu per lb.
Calculations by Parr formulas.

Table 17
International classification of hard coals by type and their statistical grouping

Groups (Determined by Caking Properties)			Code Numbers										Subgroups (Determined by Coking Properties)		
Group Number	Alternative Group Parameters: Free swelling Index (Crucible Swelling Number)	Alternative Group Parameters: Roga Index	The first figure of the code number indicates the class of the coal, determined by volatile-matter content up to 33% volatile matter and by calorific parameter above 33% volatile matter. The second figure indicates the group of coal, determined by caking properties. The third figure indicates the subgroup, determined by coking properties.										Sub-Group Number	Alternative Subgroup Parameters: Audibert-Arnu Dilatometer	Alternative Subgroup Parameters: Gray-King
	*						435	535	635 (VC)				5	>140	$>G_8$
						334 (VA)	434 (VB)	534	634				4	>50-140	G_5-G_8
3	>4	>45				333	433	533	633	733 (VD)			3	>0-50	G_1-G_4
						332a 332b	432	532	632	732	832		2	≷0	E-G
						323	423	523	623	723 (VIA)	823		3	≷0-50	G_1-G_4
2	2½-4	>20-45				322 (IV)	422	522	622	722	822		2	≷0	E-G
						321	421	521	621	721 (VIB)	821		1	Contraction only	B-D
1	1-2	>5-20			212	312	412	512	612	712	812		2	≷0	E-G
					211	311 (III)	411	511	611 (VII)	711	811		1	Contraction only	B-D
0	0-½	0-5		100 (IA / IB)	200 (II)	300	400	500	600	700	800	900	0	Nonsoftening	A
Class Number →			0	1	2	3	4	5	6	7	8	9	As an indication, the following classes have an approximate volatile-matter content of: Class 6 33-41% Volatile Matter; Class 7 33-44% Volatile Matter; Class 8 35-50% Volatile Matter; Class 9 42-50% Volatile Matter		
Class Parameters	Volatile Matter (Dry, ash-free) →		0-3	>3-10 (>3-6.5 / >6.5-10)	>10-14	>14-20	>20-28	>28-33	>33	>33	>33	>33			
	Calorific Parameter* →		–	–	–	–	–	–	>13,950	>12,960-13,950	>10,980-12,960	>10,260-10,980			
Classes: (Determined by volatile matter up to 33% volatile matter and by calorific parameter above 33% volatile matter)															

Notes:

(1) Where the ash content of coal is too high to allow classification according to the present systems, it must be reduced by laboratory float-and-sink method (or any other appropriate means). The specific gravity selected for flotation should allow a maximum yield of coal with 5-10% of ash.

(2) 332a >14-16% volatile matter. 332b >16.20% volatile matter.

* Gross calorific value on moist, ash-free basis (86 F/96% relative humidity) Btu/lb.

(Source: Bureau of Mines)

Table 18
Grouping of American coals in international system of classification

Groups (Determined by Caking Properties)			Code Numbers										Subgroups (Determined by Coking Properties)		
Group Number	Alternative Group Parameters: Free-swelling Index (Crucible-Swelling Number)	Alternative Group Parameters: Roga Index	The first figure of the code number indicates the class of the coal, determined by volatile-matter content up to 33% volatile matter and by calorific parameter above 33% volatile matter. The second figure indicates the group of coal, determined by caking properties. The third figure indicates the subgroup, determined by coking properties.										Sub-Group Number	Alternative Subgroup Parameters: Audibert-Arnu Dilatometer	Alternative Subgroup Parameters: Gray-King
3	>4	>45					435	535	635				5	>140	$>G_8$
						334	434	534	634	734			4	>50-140	G_5-G_8
						333	433	533	633	733			3	>0-50	G_1-G_4
						332a / 332b	432	532	632	732	832		2	≷0	E-G
2	2½-4	>20-45				323	423	523	623	723	823		3	>0-50	G_1-G_4
						322	422	522	622	722	822		2	≷0	E-G
						321	421	521	621	721	821		1	Contraction only	B-D
1	1-2	>5-20			212	312	412	512	612	712	812		2	≷0	E-G
					211	311	411	511	611	711	811		1	Contraction only	B-D
0	0-½	0-5	000	100 A / 100 B	200	300	400	500	600	700	800	900	0	Nonsoftening	A
Class Number →			0	1	2	3	4	5	6	7	8	9	As an indication, the following classes have an approximate volatile-matter content of: Class 6 33-41% Volatile Matter; Class 7 33-44% Volatile Matter; Class 8 35-50% Volatile Matter; Class 9 42-50% Volatile Matter		
Class Parameters	Volatile Matter (Dry, ash-free) →		0-3	>3-10 (>3-6.5 / >6.5-10)	>10-14	>14-20	>20-28	>28-33	>33	>33	>33	>33			
	Calorific Parameter* →		—	—	—	—	—	—	>13,950	>12,960-13,950	>10,980-12,960	>10,260-10,980			
Classes: (Determined by volatile matter up to 33% volatile matter and by calorific parameter above 33% volatile matter)															

Notes:

(1) Where the ash content of coal is too high to allow classification according to the present systems, it must be reduced by laboratory float-and-sink method (or any other appropriate means). The specific gravity selected for flotation should allow a maximum yield of coal with 5-10% of ash.

(2) 332a >14-16% volatile matter. 332b >16.20% volatile matter.

(3) From information available, American coals are represented by open-faced blocks. There are probably no commercial deposits of American coals represented by dotted blocks.

* Gross calorific value on moist, ash-free basis (86 F/96% relative humidity) Btu/lb.

(Source: Bureau of Mines)

classification. The first figure indicates the class of the coal, the second figure the group, and the third figure the subgroup. For example, a 635 coal would be a class 6 coal with a free-swelling index greater than 4 and expansion (dilatation) greater than 140.

The rank classification is about the same as ASTM classification except for determination of calorific-value correction. The International system uses the ash-free basis, whereas the ASTM system uses the mineral-matter-free basis. American coals fit in the International classification as shown by the open faced blocks in Table 18. A general comparison of the systems with several American coals is shown in Table 19.

Table 19
System comparison of selected American coals

State	County	Seam	Classification ASTM	Classification International
W.Va.	McDowell	Pocahontas #3	lvb	333
Pa.	Clearfield	Lower Kittaning	mvb	435
W.Va.	Monongalia	Pittsburgh	hvAb	635
Ill.	Williamson	No. 6	hvBb	734
Ill.	Knox	No. 6	hvCb	821

lvb = low-volatile bituminous
mvb = medium-volatile bituminous
hvAb = high-volatile *A* bituminous
hvBb = high-volatile *B* bituminous
hvCb = high-volatile *C* bituminous

Source, Bureau of Mines.

The International Classification of Brown Coals is shown in Table 20, where the term "brown coal" refers to coal containing less than 10,260 Btu/lb on the moist, ash-free basis. The six classes of coal, based on the ash-free equilibrium-moisture content, are divided into groups according to their tar yield on a dry, ash-free basis. This grouping indicates the value of these low-rank coals as fuel and as raw material for chemical purposes. Brown coals with high tar content are generally used as raw material in the chemical industry rather than as fuel.

Other criteria for the classification of coal by rank have been proposed by various authorities.

A method of classifying, by computing the heating value of the residual coal with moisture (M), ash (A), and sulfur (S) removed, has been used by Lord. This is called the "H" value.

$$(7) \qquad H = \frac{\text{Btu} - 4050\ \text{S}}{100 - (M + A + \text{S})} \times 100$$

While the H values as listed in Table 21 are of interest, they do not arrange the 17 coals in the same order as the ASTM classification.

Another classification method, reported by Perch and Russell, is based on the following ratio:

$$(8) \qquad \text{Ratio} = \frac{\text{Moist, } Mm\text{-free Btu}}{\text{Dry, } Mm\text{-free } VM}$$

Values of this ratio for the 17 coals listed in Table 16 arrange these coals in Table 21 in exactly the same order as the ASTM method. The very high ratio for coal No. 1 is not shown, since it is of little importance. It is said that this Perch and Russell ratio is closely related to the coking properties of coals used in coke-oven practice.

It may be of interest to consider the validity of other criteria in the classification of coal by rank based on the dry, ash-free analyses appearing in Table 21. Carbon (C) comes close to lining up the coals in the same order as the ASTM rank. As a criterion, the carbon content would be quite simple, but it cannot be used as a suitable basis for classification. Oxygen (O_2) generally decreases with the age of coals, but it is not consistent. The volatile matter (VM), fixed carbon (FC), hydrogen (H_2), and the Btu do not follow the same order as the ASTM method. Nitrogen (N_2) varies little for all ranks.

Since the quality of the volatile matter in coal is an index of the extent of the conversion of the original carbohydrates to hydrocarbons, studies have been made suggesting that the heating value of the volatile matter will serve as an accurate criterion for classification by rank. This criterion, developed on a "pure coal" basis as calculated in equation (12), is listed in Table 21 under Btu per lb VM_{pc}.

Composition of the fixed carbon in all types of coal is substantially all carbon. The variable constituents of coals can, therefore, be considered as concentrated in the volatile matter. One index of the quality of the volatile matter, its heating value, is perhaps the most important property as far as combustion is concerned and bears a direct relation to the properties of the pure coals (dry, mineral-matter-free). The volatile matter in coals of lower rank, where the conversion of carbohydrates to hydrocarbons has not progressed far, is relatively high in water and CO_2 and, consequently, low in heating value. The volatile matter, in coals of higher rank, is relatively high in hydrocarbons, such as methane (CH_4), and, consequently relatively high in heating value.

The analyses and heating values of the coal must be converted to the mineral-matter-free ("pure coal") basis

Table 20
International classification of brown coals
(Gross calorific value below 10,260 Btu/lb)*

Group No.	Group Parameter Tar Yield (dry, ash free), %	Code Number					
40	>25	1040	1140	1240	1340	1440	1540
30	>20-25	1030	1130	1230	1330	1430	1530
20	>15-20	1020	1120	1220	1320	1420	1520
10	>10-15	1010	1110	1210	1310	1410	1510
00	10&less	1000	1100	1200	1300	1400	1500
	Class Number	10	11	12	13	14	15
	Class Parameter, i.e., Total Moisture, (ash free), %	20 and less	20 to 30	30 to 40	40 to 50	50 to 60	60 to 70

Notes: The total-moisture content refers to freshly mined coal. For internal purposes, coals with a gross calorific value over 10,260 Btu/lb (moist, ash-free basis), considered in the country of origin as brown coals but classified as hard coals for international purposes, may be classified under this system, to ascertain, in particular, their suitability for processing.

When the total-moisture content is over 30%, the gross calorific value is always below 10,260 Btu/lb.

* Moist, ash-free basis (86F/96% relative humidity).

Source, Bureau of Mines.

Table 21
Study of the suitability of other criteria in the classification of coals

Coals Table 16 No.	Btu Lord's H Value	Perch & Russell Ratio	Btu per lb VM_{pc}	Coal Analysis, Dry, Ash-Free Basis							Grindability
				VM	FC	C	H_2	O_2	N_2	Btu	
1	14,950	—	—	2.0	98.0	93.9	2.1	2.3	0.3	14,850	37
2	15,180	2520	25,685	7.3	92.7	93.5	2.6	2.3	0.9	15,100	26
3	15,410	1358	23,330	13.6	86.4	90.7	4.2	3.3	1.0	15,325	83
4	15,765	907	21,750	17.7	82.3	90.4	4.8	2.7	1.3	15,670	100
5	15,840	834	21,155	19.8	80.2	89.4	4.8	2.4	1.5	15,615	112
6	15,765	688	19,785	23.5	76.5	88.6	4.8	3.1	1.6	15,540	105
7	15,930	611	19,570	26.5	73.5	87.6	5.2	3.3	1.4	15,630	95
8	15,500	445	17,230	35.2	64.8	85.0	5.4	5.8	1.7	15,265	88
9	15,460	389	16,930	39.0	61.0	85.5	5.5	6.7	1.6	15,370	56
10	15,230	322	15,430	45.8	54.2	80.9	5.7	7.4	1.4	14,730	57
11	14,800	320	14,875	43.8	56.2	80.5	5.5	9.1	1.6	14,430	60
12	14,359	318	14,200	43.2	56.8	79.8	5.6	11.8	1.7	14,260	50
13	14,830	300	14,690	49.3	50.7	79.2	5.7	9.5	1.5	14,400	61
14	14,170	295	13,885	40.8	59.2	80.9	5.1	12.2	1.3	14,110	55
15	13,145	229	11,435	42.8	57.2	75.9	5.1	17.0	1.6	13,100	43
16	13,055	181	11,570	49.0	51.0	74.0	5.6	18.6	0.9	12,970	52
17	12,400	170	9,945	45.3	54.7	72.7	4.9	20.8	0.9	12,330	45

Notes:

For calculations of Lord's H Value and the Perch & Russell ratio, and the heating value of the volatile matter (pure-coal basis) refer to equations 7 to 12, inclusive, this chapter.

The subscript pc means on a "pure coal" basis. The dry, ash-free VM may be used, instead of the VM_{pc}, without appreciable error. Grindability is determined by ASTM Method D 409.

in order to establish reasonably accurate heating values for volatile matter. The only difference in the conversion used for this method and the conversion used in the ASTM Standard D 388 is that half the sulfur is assumed to be pyritic on the pure-coal basis. The assumption that only half the sulfur is pyritic and the remainder organic is in closer agreement with the average for a large number of U.S. coals. The formulas for converting the analyses and coal heating values to the "pure coal" basis and for calculating the heating value of the volatile matter are as follows:

$$(9)\quad VM_{pc} = \frac{VM - (0.08A + 0.2\ \mathrm{S})}{100 - (1.08A + 0.2625\ \mathrm{S} + M)} \times 100,\ \%$$

$$(10)\quad FC_{pc} = \frac{FC - 0.0625\ \mathrm{S}}{100 - (1.08A + 0.2625\ \mathrm{S} + M)} \times 100,\ \%$$

$$(11)\quad \mathrm{Btu}_{pc} = \frac{\mathrm{Btu} - 26.2\ \mathrm{S}}{100 - (1.08A + 0.2625\ \mathrm{S} + M)} \times 100,\ \mathrm{Btu/lb}$$

$$(12)\quad \mathrm{Btu/lb}\ VM_{pc} = \frac{\mathrm{Btu}_{pc} - \left(\frac{14{,}460}{100} FC_{pc}\right)}{VM_{pc}} \times 100,\ \mathrm{Btu/lb}$$

where:

VM, FC, A, S, M, and Btu are the same as noted previously for the Parr formulas. Subscript $_{pc}$ denotes "pure coal" basis.

The Btu per lb volatile matter, calculated from the above formulas, is given in Table 21 for 16 of the 17 coals listed, covering the entire range of rank. The order of these values follows generally the ASTM classification of the coals, although the correlation is not as good as with the Perch and Russell ratio. The range of values of Btu per lb volatile matter, from about 8000 to 28,000 (Fig. 6), is large and may serve as a useful classification.

The relation of the heating value of the volatile matter and the heating value of the pure coal is shown in Fig. 6 for a large number of coals. It is evident that a fair line could be drawn, without serious error, to indicate the path of this relationship.

Commercial sizes of coal

Bituminous. Sizes of bituminous coal are not well standardized, but the following sizings are common:

Run of mine. This is coal shipped as it comes from the mine without screening. It is used for both domestic heating and steam production.

Run of mine (8 in.). This is run of mine with oversize lumps broken up.

Lump (5 in.). This size will not go through a 5-in. round hole. It is used for hand firing and domestic purposes.

Egg (5 in. × 2 in.). This size goes through 5 in. and is

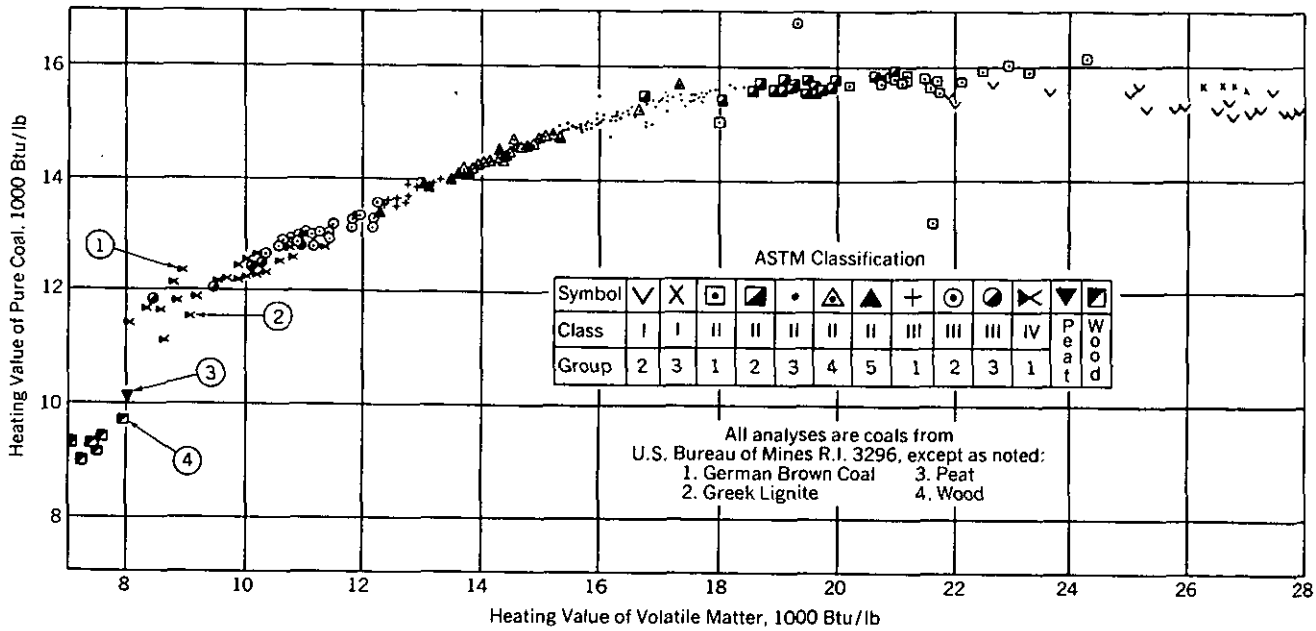


Fig. 6 To illustrate a suggested coal classification using the relationship of the respective heating values of "pure coal" and the volatile matter.

retained on 2-in. round-hole screens. It is used for hand firing, gas producers, and domestic firing.

Nut (2 in. × 1¼ in.). This size is used for small industrial stokers, gas producers, and hand firing.

Stoker coal (1¼ in. × ¾ in.) is used largely for small industrial stokers and domestic firing.

Slack (¾ in. and under) is used for pulverizers, Cyclone Furnaces, and industrial stokers.

Several other sizes of bituminous coal are prepared by different producers especially for domestic stoker requirements.

Anthracite. Definite sizes of anthracite are standardized in Table 22. The broken, egg, stove, nut and pea sizes are largely used for hand-fired domestic units and gas producers. Buckwheat and rice are used in mechanical types of firing equipment.

Table 22
Commercial sizes of anthracite (ASTM D 310)
(Graded on round-hole screens)

Trade Name	Diameter of Holes, Inches Through	Retained On
Broken	4-3/8	3-1/4 to 3
Egg	3-1/4 to 3	2-7/16
Stove	2-7/16	1-5/8
Nut	1-5/8	13/16
Pea	13/16	9/16
Buckwheat	9/16	5/16
Rice	5/16	3/16

Moisture determination

Moisture in coal is determined quantitatively by definite prescribed methods. It is preferable to determine the moisture in two steps: 1) prescribed air drying to equilibrium at 10-15C above room temperature, and 2) prescribed oven drying for one hr at 104-110C, after pulverizing (*see also ASTM Standard D 271*).

The air-dried component of the total moisture value should be reported separately, because this information is required in the design and selection of equipment. It is the surface moisture having normal vapor pressure that must be evaporated prior to efficient pulverizing of anthracite and bituminous coal.

ASTM Standard D 1412 provides a means of estimating the bed moisture of either wet coal showing visible surface moisture or coal that may have lost some moisture. It may be used for estimating the surface, or extraneous, moisture of wet coal, i.e., the difference between total moisture, as determined by ASTM Standard D 271, and equilibrium moisture. Also, for classification of coal by rank, the equilibrium moisture of a sample is considered to be equal to the bed or inherent moisture. (ASTM Standard D 388.)

Calorific value of coal

The calorific or heating value of coal is determined accurately in an oxygen bomb submerged in cooling water. Several acceptable makes or types of bomb calorimeters are listed in ASTM Standard D 271. A pulverized coal sample is compressed into a hard pellet and ignited in an oxygen atmosphere with a hot wire. The heating value is then determined from the rise in water temperature.

Gross (higher) heating value is defined as the heat released from combustion of unit fuel quantity (mass), with the products in the form of ash, gaseous CO_2, SO_2, N_2, and liquid water exclusive of any water added directly as vapor. The net (lower) heating value is calculated from the gross heating value as the heat produced by a unit quantity of fuel when all water in the products remains as vapor. This calculation (ASTM Standard

D 407) is made by deducting 1030° Btu/lb of water derived from the fuel, including both the water originally present as moisture and that formed by combustion. In America the gross calorific value is commonly used in heat balance calculations, while in Europe the net value is generally used.

Grindability of coal

Grindability is a term used to measure the ease of pulverizing a coal in comparison with a standard coal chosen as 100 grindability. For a description of the method of testing to determine grindability of a coal, see "Grindability Index (ASTM D 409)," Chapter 9. Fig. 6 of the same chapter shows the machine used in making the test. The grindability of the 17 representative coals in Table 16 is tabulated in the last column of Table 21.

° The value of 1030 Btu/lb of water, an average figure, corrects for both the latent heat of vaporization and conversion from constant volume conditions of the calorimeter to an equivalent constant pressure basis.

Free-swelling index

The ASTM Standard Method D 720 is used for obtaining information regarding the free-swelling property of a coal. Since it is a measure of the behavior of rapidly heated coal, it may be used as an indication of the caking characteristics of coal burned as a fuel.

Coal ash

The nature, composition, and properties of coal ash are discussed in Chapter 15.

Characteristics of fuel oil

It is common practice in refining petroleum to produce fuel oils complying with several specifications prepared by the ASTM and adopted as a commercial standard by the U.S. Bureau of Standards. These standards have been revised several times in order to meet changes in supply and demand and further changes may be expected.

The current standards are tabulated in Table 23. Fuel oils are graded according to gravity and viscosity, the lightest being No. 1 and the heaviest No. 6. Grades 5

Table 23
ASTM standard specifications for fuel oils[a]

No. 1 A distillate oil intended for vaporizing pot-type burners and other burners requiring this grade of fuel

No. 2 A distillate oil for general purpose domestic heating for use in burners not requiring No. 1 fuel oil

No. 4 Preheating not usually required for handling or burning

No. 5 (Light) Preheating may be required depending on climate and equipment

No. 5 (Heavy) Preheating may be required for burning and, in cold climates, may be required for handling

No. 6 Preheating required for burning and handling

Grade of Fuel Oil	Flash Point, F (C)	Pour Point, F (C)	Water and Sediment, % by Volume	Carbon Residue on 10% Bottoms, %	Ash, % by Weight	Distillation Temperatures, F (C)			Saybolt Viscosity, sec				Kinematic Viscosity, centistokes				Gravity, deg API	Copper Strip Corrosion
						10% Point	90% Point		Universal at 100F (38C)		Furol at 122F (50C)		At 100F (38C)		At 122F (50C)			
	Min	Max	Max	Max	Max	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
No. 1	100 or legal (38)	0	trace	0.15	–	420 (215)	–	550 (288)	–	–	–	–	1.4	2.2	–	–	35	No. 3
No. 2	100 or legal (38)	20[c] (–7)	0.10	0.35	–	[d]	540[c] (282)	640 (338)	(32.6)[f]	(37.93)	–	–	2.0[e]	3.6	–	–	30	–
No. 4	130 or legal (55)	20 (–7)	0.50	–	0.10	–	–	–	45	125	–	–	(5.8)	(26.4)	–	–	–	–
No. 5 (Light)	130 or legal (55)	–	1.00	–	0.10	–	–	–	150	300	–	–	(32)	(65)	–	–	–	–
No. 5 (Heavy)	130 or legal (55)	–	1.00	–	0.10	–	–	–	350	750	(23)	(40)	(75)	(162)	(42)	(81)	–	–
No. 6	150 (65)	–	2.00[g]	–	–	–	–	–	(900)	(9000)	45	300	–	–	(92)	(638)	–	–

[a] Recognizing the necessity for low-sulfur fuel oils used in connection with heat-treatment, nonferrous metal, glass, and ceramic furnaces and other special uses, a sulfur requirement may be specified in accordance with the following table:

Grade of Fuel Oil	Sulfur, Max, %
No. 1	0.5
No. 2	0.7
No. 4	no limit
No. 5	no limit
No. 6	no limit

Other sulfur limits may be specified only by mutual agreement between the purchaser and the seller.

[b] It is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

[c] Lower or higher pour points may be specified whenever required by conditions of storage or use.

[d] The 10% distillation temperature point may be specified at 440F (226C) maximum for use in other than atomizing burners.

[e] When pour point less than 0 F is specified, the minimum viscosity shall be 1.8 cs (32.0 sec, Saybolt Universal) and the minimum 90% point shall be waived.

[f] Viscosity values in parentheses are for information only and not necessarily limiting.

[g] The amount of water by distillation plus the sediment by extraction shall not exceed 2.00%. The amount of sediment by extraction shall not exceed 0.50%. A deduction in quantity shall be made for all water and sediment in excess of 1.0%.

Source, ASTM D 396.

and 6 generally require heating for satisfactory pumping and burning (*see Oil Burners, Chapter 7*). Analyses and relative cost of some selected fuel oils are listed in Table 24. The range of analyses and heating values of the several grades of fuel oils are given in Table 25.

The gross heating values of various fuel oils of different gravity are shown in Fig. 7. The abscissa on this figure is the API (American Petroleum Institute) gravity. Degrees API refer to a hydrometer scale with the following relation to specific gravity:

$$(13) \qquad \text{Degrees API} = \frac{141.5}{\text{sp gr @ } 60/60\text{F}} - 131.5$$

where:

sp gr @ 60/60F represents the ratio of oil density at 60F to water density also at 60F.

The heating values, as listed in Fig. 7, are closely related to the gravity of the oil. The heating value for an actual oil is obtained by correcting the Btu/lb value from Fig. 7 as follows:

$$(14) \qquad \frac{\text{Btu/lb} \times [100 - (A + M + \text{S})]}{100} + 40.5\ \text{S}$$

where:

Btu/lb is taken from Fig. 7
A = % by wt of ash
M = % by wt of water
S = % by wt of sulfur

The volume percentages of water and sediment can be used without appreciable error in place of weight percentage where the percentages by weight of water and ash are not known.

Fuel oils are generally sold on a volume basis with 60F as the base temperature. Correction factors are given in Fig. 8 for converting known volumes at other temperatures to the 60F standard base. This correction

Table 24
Selected analyses and relative cost of fuel oils

Grade of Fuel Oil	No. 1	No. 2	No. 4	No. 5	No. 6
Weight, percent					
Sulfur	0.1	0.3	0.8	1.0	2.3
Hydrogen	13.8	12.5	—	—	9.7
Carbon	86.1	87.2	—	—	85.6
Nitrogen	—	0.02	—	—	2.0
Oxygen	Nil	Nil	—	—	
Ash	Nil	Nil	0.03	0.03	0.12
Gravity					
Deg API	42	32	20	19	—
Specific	0.815	0.865	0.934	0.940	—
Lb per gal	6.79	7.21	7.78	7.83	—
Pour point, F	−35	−5	+20	+30	—
Viscosity					
Centistokes @ 100F	1.8	2.4	27.5	130	—
SUS @ 100F	—	34	130	—	—
SSF @ 122F	—	—	—	30	—
Water & sediment, vol %	Nil	Nil	0.2	0.3	0.74
Heating value Btu per lb, gross	19,810	19,430	18,860	18,760	18,300*
Relative cost per Btu	118	100	76	60	51

* Bomb calorimeter determination.

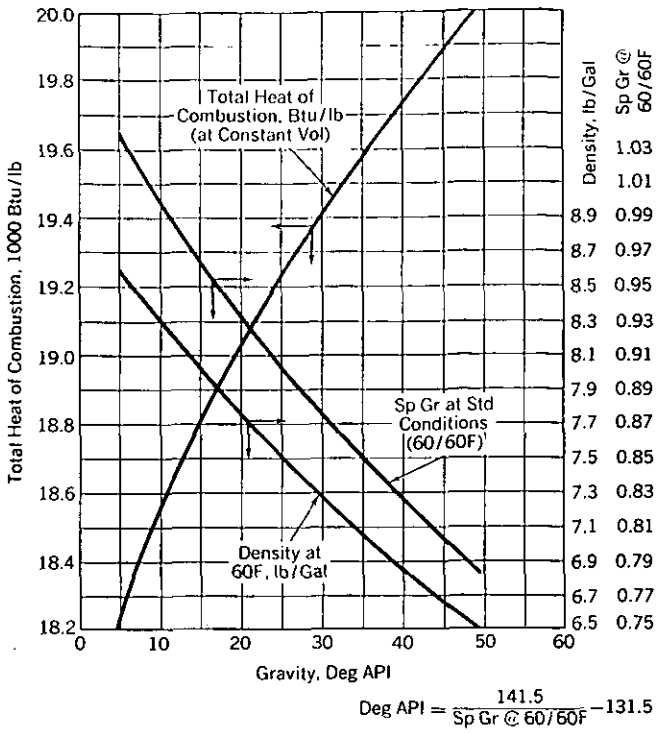


Fig. 7 Heating value, weight (lb per gal), and specific gravity of fuel oil for a range of API gravities.

is also dependent on the API (American Petroleum Institute) gravity range as illustrated by the three parametric curves of Fig. 8.

Since handling and especially burning equipment is usually designed for a maximum oil viscosity, it is necessary to know the viscosity characteristics of the fuel oil to be used. If the viscosities of heavy oils are known at two temperatures, viscosities at other temperatures can be closely predicted with negligible error by a linear interpolation between these two values located on the standard ASTM chart of Fig. 9. Viscosity variations with temperature for certain light oils can also be found with the aid of the ASTM chart but in this case knowledge of the viscosity at only one temperature is required. Viscosities of light oils at various temperatures within the region designated as No. 2 fuel oil can be found by drawing a line parallel to the No. 2 boundary lines through the point of known viscosity and temperature. Copies of the chart may be obtained from the ASTM.

Compared with coal, fuel oils are relatively easy to handle and burn. Heating is not required for the lighter oils, and even the heavier oils are relatively simple to handle. There is not as much ash-in-bulk disposal problem as there is with coal, and the amount of ash discharged from the stack is correspondingly small. In most oil burners the oil is atomized to a mist of small particles that mix with combustion air. In the atomized state, the characteristics of oil approach those of a gas, with consequent similar explosion hazards (*see Safety Precautions, Chapter 7*).

Because of its relatively low cost compared with that of lighter oils, No. 6 fuel oil is the most widely used for steam generation. It can be considered a by-product of the refining process. Its ash content ranges from about 0.01 to 0.5%, which is very low compared with coal.

Table 25
Range of analyses of fuel oils

Grade of Fuel Oil	No. 1	No. 2	No. 4	No. 5	No. 6
Weight, percent					
Sulfur	0.01-0.5	0.05-1.0	0.2-2.0	0.5-3.0	0.7-3.5
Hydrogen	13.3-14.1	11.8-13.9	(10.6-13.0)°	(10.5-12.0)°	(9.5-12.0)°
Carbon	85.9-86.7	86.1-88.2	(86.5-89.2)°	(86.5-89.2)°	(86.5-90.2)°
Nitrogen	Nil-0.1	Nil-0.1	—	—	—
Oxygen	—	—	—	—	—
Ash	—	—	0-0.1	0-0.1	0.01-0.5
Gravity					
Deg API	40-44	28-40	15-30	14-22	7-22
Specific	0.825-0.806	0.887-0.825	0.966-0.876	0.972-0.922	1.022-0.922
Lb per gal	6.87-6.71	7.39-6.87	8.04-7.30	8.10-7.68	8.51-7.68
Pour point, F	0 to −50	0 to −40	−10 to +50	−10 to +80	+15 to +85
Viscosity					
Centistokes @ 100F	1.4-2.2	1.9-3.0	10.5-65	65-200	260-750
SUS @ 100F	—	32-38	60-300	—	—
SSF @ 122F	—	—	—	20-40	45-300
Water & sediment, vol %	—	0-0.1	tr to 1.0	0.05-1.0	0.05-2.0
Heating value					
Btu per lb, gross (calculated)	19,670-19,860	19,170-19,750	18,280-19,400	18,100-19,020	17,410-18,990

° Estimated.

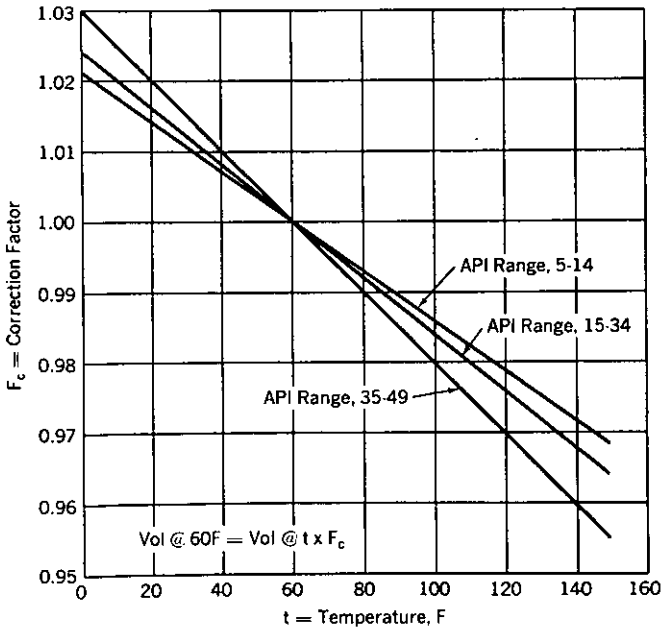
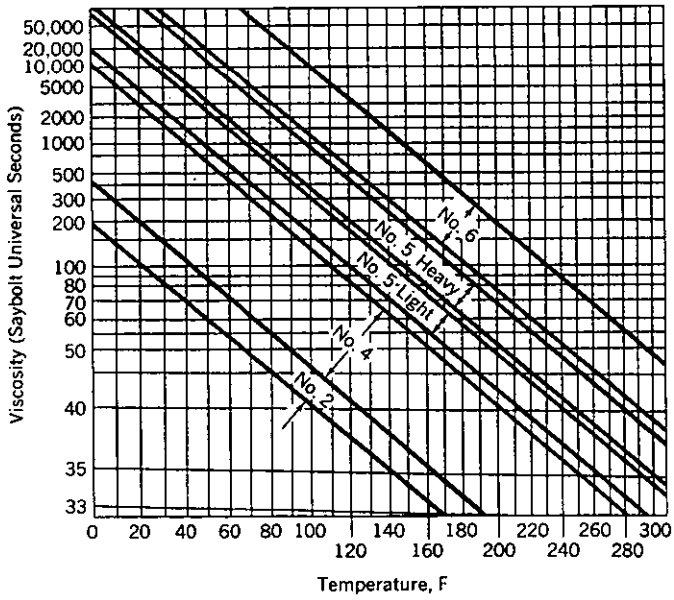


Fig. 8 Temperature-volume correction factor for fuel oil.

However, despite this low percentage content, ash containing compounds of vanadium, sodium and sulfur can be responsible for a number of serious operating problems (Chapter 15).

Fuel oils generally available on the Eastern seaboard are produced from varying amounts of Venezuelan and Middle East crudes, depending on the relative quantities of shipments and on the blending at the refineries to meet No. 6 fuel-oil viscosity specifications. Fuel oils used



Note: On the scale at the left, find the SUS viscosity at 100F (standard test temperature) for the given oil; move horizontally to the vertical line for 100F. From this intersection move parallel to the diagonal lines to the viscosity required for atomization; the temperature necessary to achieve this viscosity can be read on the bottom scale. The chart, based on U.S. Commerical Standard 12-48 has been developed from data for many fuels and should be sufficiently accurate for most applications.

Fig. 9 Approximate viscosity of fuel oil at various temperatures. *(Source, ASTM.)*

on the Gulf and West Coasts are produced largely from domestic crudes, although they may contain some Venezuelan crude. Because of this it is difficult, if not impossible, to identify the source of fuel oils as fired.

Shale oil

An analysis of a typical Green River oil shale from the Colorado-Utah-Wyoming area is given in Table 26. Fuel oils produced from refineries using shale oil feedstock on a commercial scale are unavailable. Characteristics of the fuel oil will depend on the refinery processes to be used and, also, any supplementary crude oil used in the feedstock. At the prevailing cost of producing oil from petroleum, it has not been commercially attractive to produce oil products from oil shale in the U.S.

Table 26
Analysis of a Green River oil shale

Physical properties		
Specific gravity, 60F/60F		2.3
Bulk density, 48 mesh, lb/cu ft		67.8
Oil-shale assay,* % by wt		
Oil		10.3
Gas		2.5
Water		1.4
Organic residue		3.1
Mineral residue		82.7
Yield in oil, gal per ton		26.7
Mineral residue, wt % of raw shale		
Mineral CO_2 evolved		20.0
Mineral analysis of ash		
Silica	as SiO_2	26.4
Calcium	as CaO	17.1
Magnesium	as MgO	5.4
Aluminum	as Al_2O_3	6.6
Alkalies	as Na_2O & K_2O	3.7
Iron	as Fe_2O_3	2.6
Phosphorus & Vanadium	as P_2O_5 & V_2O_5	0.4
Sulfur	as SO_3	0.5

* Modified Fischer assay.

Characteristics of natural gas

Of all chemical fuels, natural gas is considered the most desirable for steam generation. It is piped directly to the consumer, eliminating the need for storage at the consumer's plant. It is substantially free of ash, and mixes intimately with air to provide complete combustion at low excess air without smoke. Although the total hydrogen content of natural gas is high, the amount of free hydrogen is low. Because of this characteristic, natural gas is not as easy to burn as some manufactured gases with their high free hydrogen content.

The high hydrogen content of natural gas compared with that of oil or coal results in more water vapor produced in the combustion gases with a correspondingly lower efficiency of the steam generating equipment. This can readily be taken into account in the design of the equipment and evaluated in comparing the cost of gas with other fuels.

Analyses of natural gas from several U.S. fields are given in Table 27.

Relative costs of the three major fuels

Transportation of fuels is an important factor in fuel costs, particularly in the case of coal which is not as readily pumped through pipelines as are oil and gas. A number of methods for reducing the cost of transporting coal have been or are being tried (Chapter 8). Several large electric generating plants have been built at the

Table 27
Selected samples of natural gas from United States fields

Sample No. / Source of Gas		1 Pa.	2 So. Cal.	3 Ohio	4 La.	5 Okla.
Analyses						
Constituents, % by vol						
H_2	Hydrogen	—	—	1.82	—	—
CH_4	Methane	83.40	84.00	93.33	90.00	84.10
C_2H_4	Ethylene	—	—	0.25	—	—
C_2H_6	Ethane	15.80	14.80	—	5.00	6.70
CO	Carbon monoxide	—	—	0.45	—	—
CO_2	Carbon dioxide	—	0.70	0.22	—	0.80
N_2	Nitrogen	0.80	0.50	3.40	5.00	8.40
O_2	Oxygen	—	—	0.35	—	—
H_2S	Hydrogen sulfide	—	—	0.18	—	—
Ultimate, % by wt						
S	Sulfur	—	—	0.34	—	—
H_2	Hydrogen	23.53	23.30	23.20	22.68	20.85
C	Carbon	75.25	74.72	69.12	69.26	64.84
N_2	Nitrogen	1.22	0.76	5.76	8.06	12.90
O_2	Oxygen	—	1.22	1.58	—	1.41
Specific gravity (rel to air)		0.636	0.636	0.567	0.600	0.630
Higher heat value						
Btu/cu ft @ 60F & 30 in. Hg		1,129	1,116	964	1,002	974
Btu/lb of fuel		23,170	22,904	22,077	21,824	20,160

mine site in situations where it is economical to transport electricity rather than coal.

Costs of all fuels vary from year to year and even seasonally so that, in the same locality, first one and then another fuel may be the more economical to use. In some parts of the country, steam generating equipment is arranged to burn all three fuels—coal, oil or natural gas. Table 28 shows the "as-consumed" fuel costs for the year 1968 for steam electric plants located in the Middle Atlantic and New England Coast areas. The as-consumed cost of natural gas is assumed to be the same as the delivered cost. The percent of the total energy, on a Btu basis, supplied by each fuel is also indicated.

Table 28
As-consumed fuel costs of steam-electric plants, 1968

State or City	Cents/Million Btu			Percent of Total Btu		
	Coal	Oil	Gas	Coal	Oil	Gas
Maine	—	30.4	—	0	100	0
Massachusetts	36.7	29.1	31.7	32	65	3
Connecticut	32.5	29.3	31.6	46	54	—
Rhode Island	41.0	30.8	33.6	15	77	8
New York City	38.0	34.9	37.1	30	48	22
New Jersey	33.0	35.4	31.4	46	48	6
Philadelphia	32.4	33.3	30.2	66	33	1
Delaware	31.2	61.0	31.1	81	6	13

Source, National Coal Association.

Table 24 lists relative costs for various grades of fuel oils. Because of the proportionately great variations over periods of time and in different localities, these relative costs can only serve as a rough approximation.

The cost of natural gas in the U.S. close to the source is about 12 cents per million Btu and increases up to 70 cents further from the source. Since a large percentage of natural gas is used for space heating, the demand for natural gas is considerably higher during winter months. During summer, natural gas may be available at relatively low cost for steam generation, even in areas at a considerable distance from the source. However, some natural gas is now being stored underground during the summer in consumer areas remote from gas fields to hold it for higher winter prices. More and more industrial boilers up to sizes of 250,000 lb of steam per hour are using oil and natural gas fuels year-round. The supply of natural gas is currently greater than pipeline capacity. As pipeline capacity is increased, the cost of natural gas may approach that of oil and coal, even in areas near its source. Comparative costs of coal, oil, and natural gas in cents per million Btu are shown in Fig. 10 over a wide range of costs for these three fuels.

Other fuels for combustion

Among other fuels used, those derived from coal are the most important. Also used are petroleum by-products; wood, its by-products and wastes from wood-processing industries; and certain types of vegetation, particularly bagasse.

Coke

When coal is heated in the absence of air or with a large deficiency of air, the lighter constituents are volatilized and the heavier hydrocarbons crack, liberating hydrogen and leaving a residue of carbon. Some of the volatilized

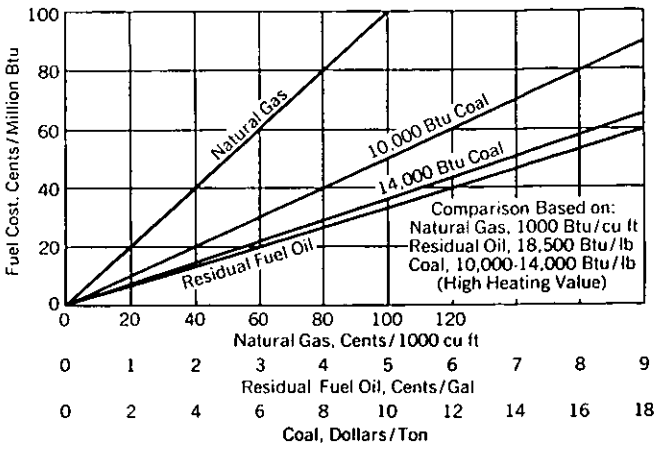


Fig. 10 Comparative fuel costs in cents per million Btu.

portions crack on contact with the hot carbon, leaving an additional quantity of carbon. The carbonaceous residue containing the ash and a part of the sulfur of the original coal is called "coke." The amount of sulfur and the amount and nature of the ash in the coke depend in large measure on the coal from which it is produced and the coking process used. The principal uses for coke are in the production of pig iron in blast furnaces and the charging of iron foundry cupolas. Because it is smokeless in combustion, considerable quantities have been used for space heating.

Coke production and consumption in millions of tons for the year 1968 are tabulated as follows:

Total coal used for coke production	91.3
Total annual coke production	63.7
Coke breeze produced	4.1
Coke breeze used for steam generation	0.5
Coke breeze used for sintering iron ore	1.6

Undersized coke called "coke breeze," usually passing a 5/8-in. screen, is unsuited for charging blast furnaces and is available for steam generation. A typical analysis of coke breeze appears in Table 29. Approximately 4.5% by weight of the coal charged into slot-type coke ovens is recovered as breeze.

Table 29
Selected analyses
—bagasse, coke breeze, and fluidized-bed char

Analyses (as fired), % by wt		Bagasse	Coke Breeze	Fluidized-Bed Char
Proximate				
Moisture		52.0	7.3	0.7
Volatile matter		40.2	2.3	14.7
Fixed carbon		6.1	79.4	70.4
Ash		1.7	11.0	14.2
Ultimate				
H_2	Hydrogen	2.8	0.3	—
C	Carbon	23.4	80.0	—
S	Sulfur	trace	0.6	4.1
N_2	Nitrogen	0.1	0.3	—
O_2	Oxygen	20.0	0.5	—
H_2O	Moisture	52.0	7.3	—
A	Ash	1.7	11.0	—
Heating value, Btu/lb		4000	11,670	12,100

Until the late 1940's, roughly three-fourths of the breeze produced at coke oven plants was used by the producing companies for steam generation. In 1968 the use of breeze for steam generation amounted to only 12.4% of the output. This reduction was, in large part, the result of increased requirements for coke breeze for sintering iron ore.

Tars and char

A portion of the coal tars produced as a by-product of the various coking processes may be burned in equipment similar to that used for heavy petroleum oil. Low temperature (900 to 1100F) carbonization processes have been developed for the extraction from coal of valuable tars, bitumens and gases for use as raw materials in the chemical industry. The by-product solid fuel from these processes is called char. Disco char, produced by low temperature carbonization has been sold for use in the domestic and small commercial fuel market. Char which appears to have the greatest commercial significance is that produced by the fluidized-bed method. At present, economics has curtailed the widespread use of any of these processes. A typical analysis of fluidized-bed char is given in Table 29.

Gaseous fuels from coal

A number of gaseous fuels are derived from coal both as by-products and from coal gasification processes. Table 30 lists selected analyses of these gases according to the various types described in the following paragraphs. At the present time they have been largely supplanted by natural gas and oil. However, improvements in coal gasification and wider use of coal in the chemical and liquid fuel industries could reverse this trend.

Table 30
Selected analyses of gaseous fuels derived from coal

Column No.		1	2	3	4
Analyses, % by vol					
H_2	Hydrogen	47.9	2.4	34.0	14.0
CH_4	Methane	33.9	0.1	15.5	3.0
C_2H_4	Ethylene	5.2	—	4.7	—
CO	Carbon monoxide	6.1	23.3	32.0	27.0
CO_2	Carbon dioxide	2.6	14.4	4.3	4.5
N_2	Nitrogen	3.7	56.4	6.5	50.9
O_2	Oxygen	0.6	—	0.7	0.6
C_6H_6	Benzene	—	—	2.3	—
H_2O	Water	—	3.4	—	—
Specific gravity (relative to air)		0.413	1.015	0.666	0.857
Higher heat value—Btu/cu ft					
@ 60F & 30 in. Hg		590	—	534	163
@ 80F & 30 in. Hg		—	83.8	—	—

Col. No.	Kind of Gas	Col. No.	Kind of Gas
1	Coke-oven gas	3	Carbureted water gas
2	Blast-furnace gas (lean)	4	Producer gas

Coke-oven gas. A considerable portion of coal is converted to gases or vapors in the production of coke. Valuable products recovered from these gaseous portions include ammonium sulfate, oils and tars. The noncondensable portion is called "coke-oven gas." Constituents depend on the nature of the coal and the coking process used (Table 30).

A part of the sulfur from coal may be present in coke-oven gas as hydrogen sulfide and carbon disulfide. These may be removed by scrubbing. Coke-oven gas often contains other impurities that deposit in lines and burners requiring the use of relatively large burner-gas-port openings to reduce plugging. Also, burners are arranged for easy access and cleaning. Coke-oven gas burns readily because of a high free-hydrogen content and presents no problems when used as fuel for steam generation except for the buildup of deposits.

Approximately 14 to 16% by weight of the coal charged into slot-type coke ovens is recovered in the form of a fuel gas. In 1968 a total of 923 billion cu ft of coke-oven gas was formed from 90.0 million tons of coal averaging 10,251 cu ft per ton of coal carbonized. A breakdown of gas produced in 1968 shows 36.0% used to heat coke ovens, 58.5% used by the producing companies in steel and allied plants and in boilers, 4.0% sold for residential, commercial, and industrial heating, and 1.5% wasted.

Blast-furnace gas. The gas discharged from steel mill blast furnaces is used at the mills in heating furnaces, gas engines, and for steam generation. This gas is quite variable in quality but is generally of high carbon monoxide content and low heating value (Table 30).

The gas is discharged from the furnace at about 500F and contains 5 to 7 grains of entrained dust per cu ft. This gas may be burned directly for steam generation. However, at many mills, entrained dust is first removed by washing or by electrostatic precipitation. Wet washed gas, from many types of washers, will have a dust loading of 0.1 to 0.2 grains per cu ft.

Both dirty and wet washed gas burned for steam generation can cause trouble by plugging gas lines and burner ports and fouling boiler heating surfaces. Blast-furnace-gas deposits adhere very firmly, and provisions must be made for cleaning boiler heating surfaces. Because of the nature of the deposits, wet washed gas is often more troublesome than hot, dry, dirty gas. Electrostatically cleaned gas may or may not cause trouble, depending on the collector efficiency.

When blast-furnace gas is used for steam generation, special safety precautions are required because of fluctuations in gas supply from variations or interruptions in blast furnace operation. Also, an alternate fuel must be immediately available in cases where the steam production rate must be maintained.

Water gas. The gas produced by passing steam through a bed of hot coke is known as water gas. Carbon in the coke combines with the steam to form hydrogen and carbon monoxide. This is an endothermic reaction which cools the coke bed. General practice is to replace steam periodically by air for combustion of coke in order to regain the required bed temperature. While the air is passing through the bed, the discharged products of combustion are diverted to the atmosphere to avoid diluting the water gas with noncombustibles.

Water gas is often enriched with oil by passing the gas through a checkerwork of hot bricks sprayed with oil

which in turn is cracked to a gas by the heat. Refinery gas is also used for enrichment. It may either be mixed with the steam and passed through the coke bed or mixed directly with the water gas. Such enriched water gas is called "carbureted water gas" (Table 30) and it is piped for relatively short distances through city mains for industrial and domestic consumption. Where it is so used, it is cleaned at the source to remove sulfur gases and other impurities. In many areas use of carbureted water gas has been replaced by natural gas.

Producer gas. When coal or coke is burned with a deficiency of air and a controlled amount of moisture (steam), a gas known as producer gas is obtained. This gas, after removal of entrained ash and sulfur compounds, is used near its source because of its low heating value.

Gasification using in-situ combustion of coal has been carried out by the Bureau of Mines on an experimental basis at Gorgas, Alabama. The purpose of these tests was to demonstrate that energy from coal in seams too thin for mining could be made available through underground gasification. Russia has made producer gas for power generation using this process. This means of gasification is not economically competitive in the U.S. at the present time.

Coke from petroleum

The heavy residuals from the various petroleum cracking processes are presently utilized in a number of ways to produce a higher yield of lighter hydrocarbons and a solid residue suitable for fuel. Characteristics of these residues vary widely, depending on the process used. Solid fuels from oil include delayed coke, fluid coke and petroleum pitch. Some selected analyses are given in Table 31.

Table 31
Selected analyses of solid fuels derived from oil

Analyses (dry basis), % by wt	Delayed Coke		Fluid Coke	
Proximate				
Volatile matter	10.8	9.0	6.0	6.7
Fixed carbon	88.5	90.9	93.7	93.2
Ash	0.7	0.1	0.3	0.1
Ultimate				
Sulfur	9.9	1.5	4.7	5.7
Heating value, Btu/lb	14,700	15,700	14,160	14,290

The delayed coking process uses residual oil heated and pumped to a reactor for coking. Coke is deposited as a solid mass and is subsequently stripped either mechanically or hydraulically, in the form of lumps and granular material. Some of these cokes are easy to burn and pulverize, while others are quite difficult.

Fluid coke is produced by spraying hot residual feed onto externally heated seed coke in a fluid bed. The fluid coke is removed as small particles, which are built up in layers similar to an onion. This coke can be pulverized and burned, or it can be burned in the as-received size in a Cyclone Furnace. Both types of firing require some supplemental fuel to aid ignition.

The process producing petroleum pitch is an alternate to the coking process and yields fuels of various characteristics. Melting points vary considerably and the physical properties vary from soft and gummy to hard and friable. The low melting point pitches may be heated and burned like heavy oil, while those with higher melting points may be pulverized and burned, or crushed and burned in the Cyclone Furnace.

Wood

Selected analyses and heating values of several types of wood (also analyses of wood ash) are given in Table 32. Wood, in common with all types of vegetation, is composed primarily of carbohydrates and consequently has a relatively low heating value compared with bituminous coal and oil.

Wood bark may pick up impurities during transportation. It is common practice to drag the rough logs to central loading points in the logging area. This results in sand pick-up. Where the logs are salt-water borne, bark will absorb sea water with its included salt. Combustion temperatures from burning dry bark may be high enough for impurities to cause fluxing of refractory furnace walls and fouling of boiler heating surfaces, unless sufficient furnace cooling surface is provided. Sand passing through the boiler banks can cause erosion of boiler

Table 32
Analyses of wood and wood ash

Wood analyses (dry basis), % by wt	Pine Bark	Oak Bark	Spruce Bark*	Redwood Bark*
Proximate				
Volatile matter	72.9	76.0	69.6	72.6
Fixed carbon	24.2	18.7	26.6	27.0
Ash	2.9	5.3	3.8	0.4
Ultimate				
Hydrogen	5.6	5.4	5.7	5.1
Carbon	53.4	49.7	51.8	51.9
Sulfur	0.1	0.1	0.1	0.1
Nitrogen	0.1	0.2	0.2	0.1
Oxygen	37.9	39.3	38.4	42.4
Ash	2.9	5.3	3.8	0.4
Heating value, Btu/lb	9030	8370	8740	8350
Ash analyses, % by wt				
SiO_2	39.0	11.1	32.0	14.3
Fe_2O_3	3.0	3.3	6.4	3.5
TiO_2	0.2	0.1	0.8	0.3
Al_2O_3	14.0	0.1	11.0	4.0
Mn_3O_4	Trace	Trace	1.5	0.1
CaO	25.5	64.5	25.3	6.0
MgO	6.5	1.2	4.1	6.6
Na_2O	1.3	8.9	8.0	18.0
K_2O	6.0	0.2	2.4	10.6
SO_3	0.3	2.0	2.1	7.4
Cl	Trace	Trace	Trace	18.4
Ash fusibility, F				
Reducing				
Initial deformation	2180	2690		
Softening	2240	2720		
Fluid	2310	2740		
Oxidizing				
Initial deformation	2210	2680		
Softening	2280	2730		
Fluid	2350	2750		

* Salt-water stored.

tubes, particularly if the sand loading of the flue gases is increased by returning collected material to the furnace from hoppers or dust collectors. Such collectors may be required with some types of bark-burning equipment to reduce the stack discharge of incompletely burned bark to acceptable limits.

Wood or bark with moisture content of 50% or less burns quite well; however, as the moisture content increases above this amount, combustion becomes more difficult. With moisture content above 65%, a large part of the heat in the wood is required to evaporate the moisture, and little remains for steam generation. Burning of this wet bark becomes a means of disposal rather than a source of energy.

"Hogged" wood and bark are very bulky and require relatively large handling and storage equipment (*see Wood Refuse, Chapter 27*). Uninterrupted flow from bunkers or bins through chutes is difficult to maintain, and available equipment for this purpose is not always satisfactory.

Wood wastes. There are several industries using wood as a raw material where combustible by-products or wastes are available as fuels. The most important of these are the pulp and turpentine industries. The nature and methods of utilization of the combustible by-product from the pulp industry are discussed in Chapter 26.

The residue remaining after the steam distillation of coniferous woods for the production of turpentine is usable as a fuel. Some of the more easily burned constituents are removed in the distillation process, with the result that the residue is somewhat more difficult to burn. Other than this, fuel properties are much the same as those of the raw wood, and the problems involved in utilization are similar.

Bagasse

Mills grinding sugar cane commonly use bagasse for steam production. The mills normally operate 24 hours per day during the grinding season. The supply of bagasse will easily equal that required to meet the plant steam demands in mills where the sugar is not refined. Consequently, where there is no other market for the bagasse, no particular effort is made to burn it efficiently, and burning equipment is provided that will burn the bagasse as received from the grinders. In plants where refining is done, supplemental fuels are required to provide the increased steam demands. Greater efforts to obtain higher efficiency are justified in these plants. A selected analysis of bagasse is given in Table 29.

Other vegetation wastes

Food and related industries produce numerous vegetable wastes that are usable as fuels. They include such materials as grain hulls, the residue from the production of furfural from corn cobs and grain hulls, coffee grounds from the production of instant coffee and tobacco stems. Fuels of this type are available in such small quantities that they are relatively insignificant in our total energy requirements.