Coal Resources of the United States January 1, 1967

By PAUL AVERITT

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A summary and analysis of information concerning the quantity and distribution of coal in the United States. Supersedes Bulletin 1136

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By Paul Averitt

ABSTRACT

The coal resources of the United States remaining in the ground on January 1, 1967, are estimated to total 3,210 billion tons, of which about half may be considered recoverable. The distribution of this tonnage in three major categories is shown below.

Estimated total remaining coal resources of the United States, January 1, 1967

[Figures are for resources in the ground, about half of which may be considered recoverable]

Category	*Billions of short tons*
Resources determined from mapping and exploration, 0–3,000 ft overburden	1, 560
Probable additional resources in unmapped and unexplored areas:	
0–3,000 ft overburden	1, 313
3,000–6,000 ft overburden	337
Estimated total resources	3, 210

The new total is based on new, detailed, conservative estimates of resources determined from mapping and exploration in 17 States prepared in recent years by the U.S. Geological Survey; on provisional, but equally conservative, estimates for four States based on previous work of the U.S. Geological Survey and other agencies; on estimates for eight States prepared by the geological surveys of those States; and on generalized estimates prepared for areas omitted during the course of the above-mentioned studies by many individuals familiar with the local coal geology. The new estimate is an improvement on and a replacement for an older estimate prepared by M. R. Campbell in the period 1909–29, which should no longer be cited.

The resources determined from mapping and exploration in 21 States have been classified in considerable detail according to thickness of overburden, thickness of beds, and order of reliability of the estimates. These 21 States are well distributed in all coal provinces, and the classified tonnage provides a representative sample of about 55 percent of the coal resources as determined from mapping and exploration. An analysis of this classified tonnage shows that 44.5 percent is bituminous coal, 89 percent is generally less than 1,000 feet below the surface, and 29 percent is in thick beds. A choice fraction of 24 percent is classed as measured and indicated in beds 28 inches or more thick and generally less than 1,000 feet below the surface.

The United States contains about 17 percent of the world's coal resources as determined by mapping and exploration, and about 20 percent of the world's estimated total resources. In 1966, the United States contributed about 18 percent of the world's total coal production. About 75 percent of United States production is obtained from 19 thick and continuous beds.

A comparison on a uniform British thermal units basis of resources of coal and other fossil fuels in the United States shows that coal constitutes 73 percent of the total estimated recoverable fossil fuel resources, petroleum and natural gas together constitute only 9 percent, and oil in oil shale, which is not currently used as a fuel, constitutes only 17 percent. The disparity in amount of these fossil fuel resources is sharply emphasized by the fact that petroleum and natural gas together are being produced and consumed at a rate 2½ times that of coal.

Disparate trends of this order of magnitude are certain to reverse with the passage of time. The past familiar pattern in the use of fuel in the United States seems to be at the threshold of a period of massive change that will continue and intensify for many generations. The emerging pattern is characterized by (1) greatly increased total use of energy, (2) greatly increased use of atomic energy, coal, oil shale, and bituminous sandstone, and (3) use of each fuel to the fullest extent possible for the purpose or purposes for which it is best fitted. Increased reliance on these new or previously subordinate sources of energy will broaden the base of supply, and ensure that the energy needs of our growing economy can be met for many generations to come.

INTRODUCTION

Coal, petroleum, and natural gas are widely distributed and abundant in most parts of the United States, and they have contributed substantially to our industrial and economic growth. Of the three fuels, coal is by far the most abundant. On the basis of information accumulated to January 1, 1967, the total estimated recoverable resources of coal in the United States to an overburden depth of 3,000 feet seem to contain about eight times as much energy as the combined ultimately recoverable resources of petroleum and natural gas. (See table 9.) This relation may change with the passage of time, with the development of improved techniques of exploration, beneficiation, and use, and with the gradual introduction of other sources of energy; but it is an important relation that deserves recognition and examination.

Although markedly less abundant, petroleum and natural gas do not at present differ greatly in unit Btu cost from coal, and they are generally more convenient to use. As a result, the fourfold increase in use of energy in the United States that has taken place during the last 50 years has been met largely by an increase in the use of petroleum and natural gas. The increase has been accelerated since World War II by a prolonged period of industrial and economic growth, and by a considerable increase both in population and in per capita use of energy.

The increase in use of petroleum and natural gas has been accomplished without diminution of proved or ultimate resources of these fuels, which attests to the aggressiveness, ingenuity, and ability of the petroleum industry. Nevertheless, petroleum and natural gas are nonrenewable resources. Like other minerals, the ultimate resources of these fuels have finite limits. Regardless of where the limits may be established, or when they may be reached, the continued upward trend in use of petroleum and natural gas serves as a sobering reminder that these fuels will not continue indefinitely in their present abundance.

It seems most likely that over the years the recovery of petroleum and natural gas will gradually become more difficult and expensive. As this change takes place, the large consumers of energy will turn to the most economical fuel available, and coal, oil shale, and atomic energy will become more important contributors to the total energy economy. As an economical, abundant, widespread, and highly versatile chemical, coal will be in a particularly favorable position.

Although coal is abundant and widespread in the United States (figs. 1 and 2), resources of coal also have limits. In the extensively mined eastern coal fields, new areas containing thick beds of high-rank and high-quality coal are becoming increasingly difficult to locate. This is particularly true for low-volatile bituminous coal, which is the most important ingredient in the manufacture of coke and which constitutes only about 1 percent of the total resources. Furthermore, a large part of the total resources of coal in the United States consists of coal of lignite and subbituminous ranks, which yield less heat than bituminous coal. Another large part is contained in thin beds and in deeply buried beds that can be mined only with great difficulty and expense.

The U.S. Geological Survey has been engaged in a modest continuing program of geologic mapping in the coal-field areas of the United States for many years. Following World War II, when it became apparent that much more information would be needed about the occurrence and distribution of coal in the United States than had been available in the past, the Geological Survey expanded this program of geologic mapping and at the same time started preparation of State-by-State estimates of coal resources. Several State geological surveys also expanded coal investigations programs. The increased volume of geologic data now available on the occurrence of coal permits a much more reliable and useful estimate of the coal resources of the United States than has previously been available, but even this estimate is subject to improvement in the future as detailed mapping and exploration are continued.

This report supersedes Bulletin 1136, which included data as of January 1, 1960 (Averitt, 1961).

ACKNOWLEDGMENTS

Many individuals have contributed substantially to the accuracy and completeness of this report by contribution and review of material on individual States. The list of these contributors include F. F. Barnes (Alaska), H. M. Beikman (Washington), H. L. Berryhill, Jr. (Virginia and Wyoming), R. A. Brant (Ohio and North Dakota), W. C. Culbertson (Alabama and general), K. J. Englund (Kentucky), B. R. Haley (Arkansas), A. L. Hornbaker (Kansas), E. R. Landis (Colorado and Iowa), E. T. Luther (Tennessee), R. S. Mason (Oregon), F. C. Peterson (Utah), P. H. Price (West Virginia), W. V. Searight (Missouri), J. A. Simon (Illinois), A. A. Socolow (Pennsylvania), J. V. A. Trumbull (Oklahoma), and C. E. Wier (Indiana). The section on minor elements in coal was prepared with help from N. M. Denson and G. N. Pipiringos. Tables and illustrations were prepared with the invaluable assistance of Flora K. Walker.

TOTAL COAL RESOURCES

Coal-bearing rocks are widely distributed and abundant in most parts of the United States. (See Trumbull, 1960; Barnes, 1961; figs. 1 and 2, this report.)

These coal-bearing rocks range in thickness from a few hundred feet to somewhat more than 10,000 feet, but in most coal-bearing areas they are typically less than 3,000 feet thick. Coal beds are distributed irregularly, but in substantial number, throughout the sequences of coal-bearing rock. The following table shows the approximate total

Number of coal beds in selected Eastern and Central States

State	*Approximate number of named and described coal beds*	*Number of coal beds used in resource calculations, or known to be of minable thickness*
Alabama	80+	41
Arkansas	19	4
Illinois	40+	20
Indiana	16+	16
Iowa	24	19
Kansas	53	15
Kentucky (eastern)	60	33
North Carolina	2	2
Ohio	67	24
Oklahoma	20+	18
Pennsylvania	36	19
Tennessee	45	27
Virginia	60+	60
West Virginia	117	62

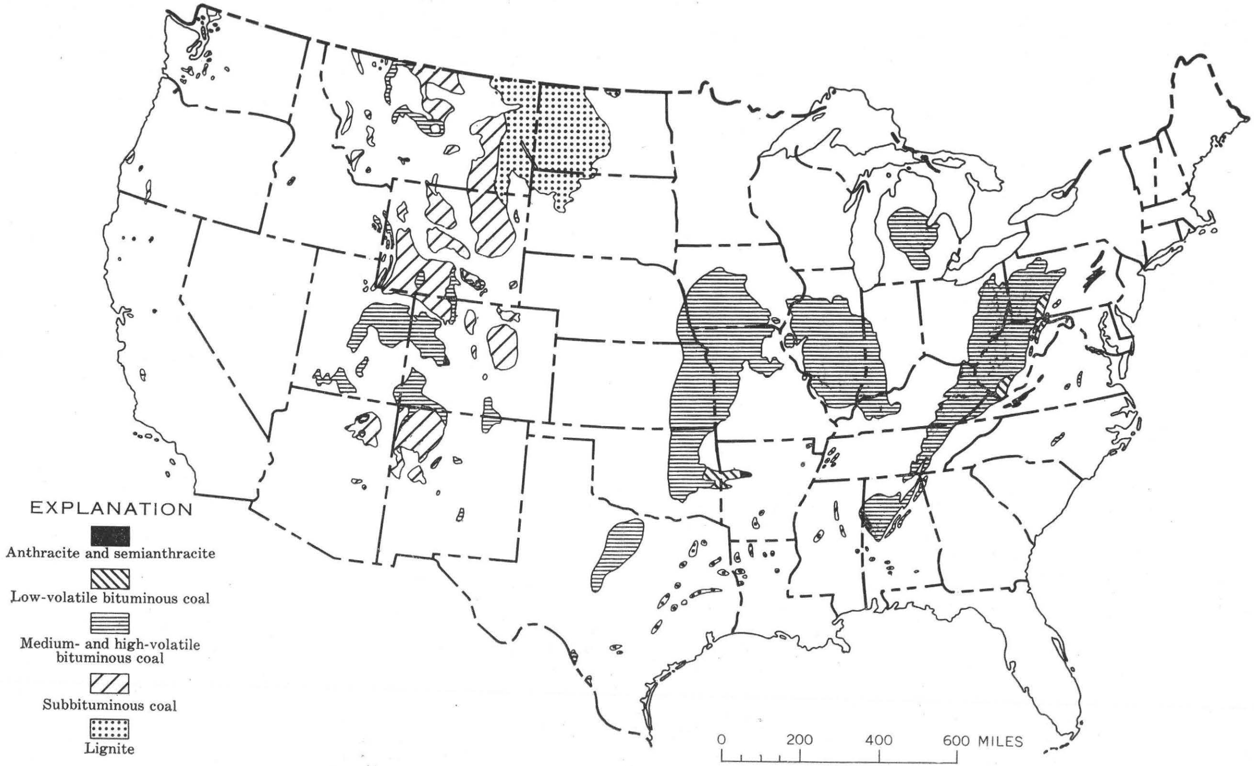
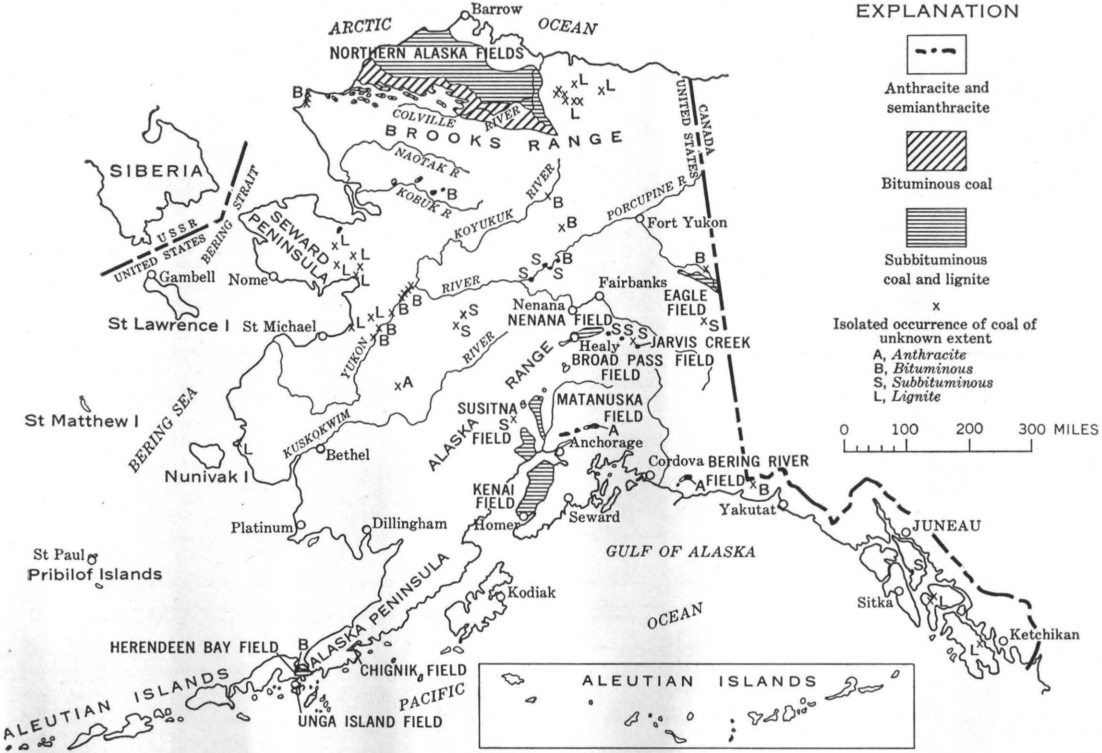


FIGURE 1.—Coal fields of the conterminous United States.



Prepared by F. F. Barnes, 1959

FIGURE 2.—Coal fields of Alaska.

number of named and described coal beds, and the number of beds known to be of minable thickness in various Eastern and Central States. The Rocky Mountain and Pacific Northwest States are not represented in this table because the Cretaceous and younger coal beds in these States are discontinuous and overlapping, and statewide correlations and nomenclature cannot be established. However, the number of coal beds present at any one locality in the Western States is comparable to the number present at any one locality in the Eastern States.

In most coal-field areas the coal-bearing rocks and the enclosed coal beds lie in structural basins, or synclines, the largest of which are broad and shallow. In the huge Appalachian basin, for example, the bulk of the coal is generally less than 3,000 feet below the surface. In the Eastern and Western Interior basins, the coal is generally less than 2,000 feet below the surface. In the vast Northern Great Plains region, the bulk of the coal is less than 1,500 feet below the surface. In the San Juan Basin of northwestern New Mexico, the bulk of the coal is less than 4,000 feet below the surface.

Other coal basins, particularly those in the Rocky Mountain region and in the Pacific Northwest, are characterized by steep dips and narrow marginal belts of accessible coal. In the Uinta Basin, for example, the coal-bearing rocks are more than 6,000 feet below the surface only a few miles from the outcrops. The geologic relation of many large, shallow coal basins and a few very deep ones accounts for the fact that United States coal resources are concentrated in the shallower overburden categories, and are successively smaller in the deeper overburden categories. Within this fixed distribution pattern the large area and volume of coal-bearing rock in the United States and the substantial number of coal beds in these rocks provide convincing evidence that the coal resources are very large.

An analysis of accumulated detailed and general information on coal from many sources permits the conclusion that the estimated total remaining coal resources of the United States as of January 1, 1967, total 3,210 billion tons, distributed in three major categories, as follows:

Estimated total remaining coal resources of the United States, January 1, 1967

[Figures are for resources in the ground, about half of which may be considered recoverable]

Category	Billions of short tons (from tables 1 and 2)
1. Resources determined from mapping and exploration, 0–3,000 ft overburden	1, 560
2. Probable additional resources in unmapped and unexplored areas:	
A. 0–3,000 ft overburden	1, 313
B. 3,000–6,000 ft overburden	337
Estimated total resources	3, 210

The tonnage recorded in category 1 is presented in greater detail by States and by rank in table 1; the methods and procedures employed to arrive at the individual figures are described on pages 14–31; and the distribution of the tonnage according to various subcategories is discussed on pages 31–39. The tonnages recorded in categories 2A and 2B are given in greater detail by States in table 2, and discussed on pages 43–45.

RESOURCES DETERMINED FROM MAPPING AND EXPLORATION

The estimate of 1,559,875 million tons for remaining resources determined from mapping and exploration is given by States and by ranks of coal in table 1. Most of the estimates in table 1 were obtained from summary reports on coal in the individual States as cited in the right-hand column of the table. These reports present data on the occurrence and distribution of coal in many resource categories, and they also contain information on the stratigraphy of coal-bearing rocks and the thickness, continuity, and composition of coal beds. Most of them include bibliographies to sources of more detailed information. These summary reports are invaluable in the beginning or overall study of coal in any State, but they are not substitutes for the larger number of detailed reports on which they are based.

For a few States, particularly Maryland and Utah, the estimates are less detailed, and the methods by which they were obtained are discussed under "Estimates for States Not Covered by Cited Reports" (p. 39–43).

TABLE 1.—*Coal resources of the United States as determined by mapping and exploration, January 1, 1967*

[In millions of short tons. Figures are for resources in the ground, about half of which may be considered recoverable. Includes beds of bituminous coal and anthracite 14 in. or more thick and beds of subbituminous coal and lignite 2.5 ft or more thick. Maximum overburden thickness is 3,000 ft. Of the total estimated tonnage, 89 percent is less than 1,000 ft below the surface, 9.5 percent is 1,000–2,000 ft below, and only 1.5 percent is 2,000–3,000 ft below. (See fig. 6.)]

State	Type of estimate [1]	Estimated original or remaining resources	Resources depleted to Jan. 1, 1967		Remaining resources, Jan. 1, 1967	Source of estimate
			Production [2]	Production plus loss in mining [3]		
Bituminous coal						
Alabama	R–1958	13, 754	[4] 118	236	13, 518	Culbertson (1964).
Alaska	Orig.	19, 429	7	14	19, 415	Barnes (1967).
Arkansas	Orig.	1, 816	88	176	1, 640	Haley (1960).
Colorado	Orig.	63, 203	407	814	62, 389	Landis (1959).
Georgia	R–1945	24	[4] 3	6	18	Johnson (1946).[5]
Illinois	R–1965	[6] 140, 000	[4] 122	244	139, 756	Simon (1965).[5]
Indiana	Orig.	37, 293	1, 257	2, 514	34, 779	Spencer (1953).
Iowa	Orig.	7, 237	359	718	6, 519	Landis (1965).
Kansas	R–1957	18, 706	[4] 10	20	18, 686	Schoewe (1958).[5]
Kentucky	Orig.	72, 318	3, 183	6, 366	65, 952	Huddle and others (1963).
Maryland	R–1950	1, 200	[4] 14	28	1, 172	This report.
Michigan	Orig.	297	46	92	205	Cohee and others (1950).
Missouri	Orig.	23, 977	309	618	23, 359	Searight (1967).[5]
Montana	Orig.	2, 363	32	64	2, 299	Combo and others (1949; 1950).
New Mexico	Orig.	10, 948	94	188	10, 760	Read and others (1950).
North Carolina	Orig.	112	1	2	110	Reinemund (1949; 1955).
Ohio	Orig.	46, 488	2, 312	4, 624	41, 864	Brant and DeLong (1960).
Oklahoma	Orig.	3, 673	187	374	3, 299	Trumbull (1957).
Oregon	Orig.	50	1	2	48	R. S. Mason (written commun., 1965).[5]
Pennsylvania	Orig.	75, 093	8, 780	17, 560	57, 533	Reese and Sisler (1928).
Tennessee	R–1959	2, 748	[4] 48	96	2, 652	E. T. Luther (1959; written commun., 1965).
Texas	Orig.	6, 100	26	52	6, 048	Mapel (1967).
Utah	Orig.	32, 678	289	578	32, 100	This report.
Virginia	Orig.	11, 696	993	1, 986	9, 710	Brown and others (1952).
Washington	R–1960	1, 869	[4] 1	2	1, 867	Beikman and others (1961).

See footnotes at end of table.

TABLE 1.—*Coal resources of the United States as determined by mapping and exploration, January 1, 1967*—Continued

[In millions of short tons. Figures are for resources in the ground, about half of which may be considered recoverable. Includes beds of bituminous coal and anthracite 14 in. or more thick and beds of subbituminous coal and lignite 2.5 ft or more thick. Maximum overburden thickness is 3,000 ft. Of the total estimated tonnage, 89 percent is less than 1,000 ft below the surface, 9.5 percent is 1,000–2,000 ft below, and only 1.5 percent is 2,000–3,000 ft below. (See fig. 6.)]

State	Type of estimate [1]	Estimated original or remaining resources	Resources depleted to Jan. 1, 1967		Remaining resources, Jan. 1, 1967	Source of estimate
			Production [2]	Production plus loss in mining [3]		
Bituminous coal—Continued						
West Virginia	Orig.	116, 618	7, 292	14, 584	102, 034	Headlee and Nolting (1940).
Wyoming	Orig.	13, 235	268	536	12, 699	Berryhill and others (1950; 1951).
Other States [7]	Orig.	620	1	2	618	This report.
Total		723, 545	26, 248	52, 496	671, 049	
Subbituminous coal						
Alaska	Orig.	[8] 110, 696	11	22	110, 674	Barnes (1967).
Colorado	Orig.	18, 492	122	244	18, 248	Landis (1959).
Montana	Orig.	132, 151	137	274	131, 877	Combo and others (1949; 1950).
New Mexico	Orig.	50, 801	43	86	50, 715	Read and others (1950).
Oregon	Orig.	290	3	6	284	R. S. Mason (written commun., 1965).[5]
Utah	Orig.	156	3	6	150	This report.
Washington	R–1960	4, 194	[4] Neg.	Neg.	4, 194	Beikman and others (1961).
Wyoming	Orig.	[8] 108, 319	154	308	108, 011	Berryhill and others (1950; 1951).
Other States [9]	Orig.	4, 065	4	8	4, 057	This report.
Total		429, 164	477	954	428, 210	
Lignite						
Alabama	Orig.	20	0	0	20	Culbertson (1964).
Alaska	Orig.	([8])				Barnes (1967).
Arkansas	Orig.	350			350	Haley (1960).

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Kansas		[10]				Schoewe (1952; 1958).
Montana	Orig.	87, 533	4	8	87, 525	Combo and others (1949; 1950).
North Dakota	Orig.	350, 910	115	230	350, 680	Brant (1953).
Oklahoma		[10]				Trumbull (1957).
South Dakota	Orig.	2, 033	1	2	2, 031	D. M. Brown (1952).
Texas	Orig.	7, 070	96	192	6, 878	Perkins and Lonsdale (1955).
Washington	R–1960	117	0		117	Beikman and others (1961).
Wyoming	Orig.	[8]				Berryhill and others (1950; 1951).
Other States [11]	Orig.	50	2	4	46	This report.
Total		448, 083	218	436	447, 647	
Anthracite and semianthracite						
Alaska		[12]				Barnes (1951).
Arkansas	Orig.	456	13	26	430	Haley (1960).
Colorado	Orig.	90	6	12	78	Landis (1959).
New Mexico	Orig.	6	1	2	4	Read and others (1950).
Pennsylvania	Orig.	[13] 22, 805	5, 344	10, 688	12, 117	Ashley (1945).[5]
Virginia	Orig.	355	10	20	335	Brown and others (1952).
Washington	R–1960	5	0	0	5	Beikman and others (1961).
Total		23, 717	5, 374	10, 748	12, 969	
Total, all ranks		1, 624, 509	[14] 32, 317	64, 634	1, 559, 875	

[1] R, remaining resources in the ground as of Jan. 1 of the year indicated; Orig., original resources in the ground before the advent of mining.

[2] Production data, 1800–85, from Eavenson (1942); 1886–1923, from U.S. Geological Survey (1886–1923); 1924–65, from U.S. Bureau of Mines (1924–65); 1967, from U.S. Bureau of Mines Weekly Coal Report 2609. For a few States, production data are augmented by records of State mine inspectors; neg., negligible.

[3] Past losses assumed to equal past production; neg., negligible.

[4] Production from year that remaining resources were estimated through 1966.

[5] See other summary reports on coal resources in individual States, as follows: Georgia (Butts and Gildersleeve, 1948; Sullivan, 1942), Illinois (Cady, 1952), Kansas (Abernathy and others, 1947), Missouri (Hinds, 1913), Oregon (Mason anid Erwin, 1955), and Pennsylvania Anthracite (Ashmead, 1926; Rothrock, 1950).

[6] Includes beds to a minimum thickness of 18 in., but most is 28 in. or more thick. The thinner coal is strippable.

[7] Arizona, California, Idaho, Nebraska, and Nevada.

[8] Small resources and production of lignite included under subbituminous coal.

[9] Arizona, California, and Idaho.

[10] Small resources of lignite in beds generally less than 30 in. thick.

[11] California, Idaho, Louisiana, Mississippi, and Nevada.

[12] Small resources of anthracite in the Bering River field believed to be too badly crushed and faulted to be economically recoverable. (See Barnes, 1951.)

[13] Includes beds to a minimum thickness of about 2 ft. On the basis of recent work in the Western Middle and Southern Anthracite fields, Arndt has stated (Arndt, Averitt, Dowd, Frendzel, and Gallo, 1968, p. 132) that when modern geologic mapping can be extended into the Eastern Middle and Northern Anthracite fields, and when the original resources can be recalculated using a minimum bed thickness of 14 in., the total original resources might be increased about 30 percent.

[14] Less than total recorded cumulative production of about 38 billion tons. See footnotes 1 and 4.

TABLE 2.—*Total estimated remaining coal resources of the United States, January 1, 1967*

[In millions of short tons. Figures are for resources in the ground, about half of which may be considered recoverable. Includes beds of bituminous coal and anthracite 14 in. or more thick and beds of subbituminous coal and lignite 2.5 ft or more thick]

State	Overburden 0–3,000 ft thick							Overburden 3,000–6,000 ft thick	Estimated total remaining resources in the ground, 0–6,000 ft overburden
	Resources determined by mapping and exploration (from table 1)					Estimated additional resources in unmapped and unexplored areas [1]	Estimated total remaining resources in the ground	Estimated resources in deeper structural basins [1]	
	Bituminous coal	Subbituminous coal	Lignite	Anthracite and semianthracite	Total				
Alabama	13, 518	0	20	0	13, 538	20, 000	33, 538	6, 000	39, 538
Alaska	19, 415	110, 674	([2])	([3])	130, 089	130, 000	260, 089	5, 000	265, 089
Arkansas	1, 640	0	350	430	2, 420	4, 000	6, 420	0	6, 420
Colorado	62, 389	18, 248	0	78	80, 715	146, 000	226, 715	145, 000	371, 715
Georgia	18	0	0	0	18	60	78	0	78
Illinois	139, 756	0	0	0	139, 756	100, 000	239, 756	0	239, 756
Indiana	34, 779	0	0	0	34, 779	22, 000	56, 779	0	56, 779
Iowa	6, 519	0	0	0	6, 519	14, 000	20, 519	0	20, 519
Kansas	18, 686	0	([4])	0	18, 686	4, 000	22, 686	0	22, 686
Kentucky	65, 952	0	0	0	65, 952	52, 000	117, 952	0	117, 952
Maryland	1, 172	0	0	0	1, 172	400	1, 572	0	1, 572
Michigan	205	0	0	0	205	500	705	0	705
Missouri	23, 359	0	0	0	23, 359	0	23, 359	0	23, 359
Montana	2, 299	131, 877	87, 525	0	221, 701	157, 000	378, 701	0	378, 701
New Mexico	10, 760	50, 715	0	4	61, 479	27, 000	88, 479	21, 000	109, 479

North Carolina	110	0	0	0	110	20	130	5	135
North Dakota	0	0	350, 680	0	350, 680	180, 000	530, 680	0	530, 680
Ohio	41, 864	0	0	0	41, 864	2, 000	43, 864	0	43, 864
Oklahoma	3, 299	0	(4)	0	3, 299	20, 000	23, 299	10, 000	33, 299
Oregon	48	284	0	0	332	100	432	0	432
Pennsylvania	57, 533	0	0	12, 117	69, 650	[5] 10, 000	79, 650	0	79, 650
South Dakota	0	0	2, 031	0	2, 031	1, 000	3, 031	0	3, 031
Tennessee	2, 652	0	0	0	2, 652	2, 000	4, 652	0	4, 652
Texas	6, 048	0	6, 878	0	12, 926	14, 000	26, 926	0	26, 926
Utah	32, 100	150	0	0	32, 250	48, 000	80, 250	35, 000	115, 250
Virginia	9, 710	0	0	335	10, 045	3, 000	13, 045	100	13, 145
Washington	1, 867	4, 194	117	5	6, 183	30, 000	36, 183	15, 000	51, 183
West Virginia	102, 034	0	0	0	102, 034	0	102, 034	0	102, 034
Wyoming	12, 699	108, 011	(2)	0	120, 710	325, 000	445, 710	100, 000	545, 710
Other States	[6] 618	[7] 4, 057	[8] 46	0	4, 721	1, 000	5, 721	0	5, 721
Total	671, 049	428, 210	447, 647	12, 969	1, 559, 875	1, 313, 080	2, 872, 955	337, 105	3, 210, 060

1 Estimates by H. M. Beikman (Washington), H. L. Berryhill, Jr. (Virginia and Wyoming), R. A. Brant (Ohio and North Dakota), W. C. Culbertson (Alabama), K. J. Englund (Kentucky), B. R. Haley (Arkansas), E. R. Landis (Colorado and Iowa), E. T. Luther (Tennessee), R. S. Mason (Oregon), F. C. Peterson (Kaiparowits Plateau, Utah), J. A. Simon (Illinois), J. V. A. Trumbull (Oklahoma), C. E. Wier (Indiana), and the author for the remaining States.

2 Small resources and production of lignite included under subbituminous coal.

3 Small resources of anthracite in the Bering River field believed to be too badly crushed and faulted to be economically recoverable. (See Barnes, 1951.)

4 Small resources of lignite in beds generally less than 30 in. thick.

5 After Ashley (1944).

6 Arizona, California, Idaho, Nebraska, and Nevada.

7 Arizona, California, and Idaho.

8 California, Idaho, Louisiana, Mississippi, and Nevada.

The information on which most of the States estimates in table 1 are based is from zones along outcrops of coal beds and from zones downdip from the outcrops, most generally to about the 1,000-foot overburden level, but locally to greater depths. Most mining and most coal of current interest is in these zones.

The estimates of resources based on mapping and exploration are, therefore, of great interest and importance for several reasons: (1) they are based firmly on factual information, (2) they include accessible coal of current economic interest, (3) they aid in selecting areas favorable for further exploration and development and in planning industrial expansion, and (4) they provide data from which estimates of coal in the deeper and less accessible parts of the coal basins may be obtained by extrapolation.

Based as they are on detailed information that is accumulated slowly by the laborious processes of mapping outcrops of coal beds and drilling holes to test coal thickness, the estimates in table 1 are minimum estimates and are subject to increase in the future as mapping, prospecting, and development are continued.

METHODS OF PREPARING AND REPORTING ESTIMATES

As a first step in preparing statewide estimates of the type presented in table 1, all available information is gathered and recorded on individual coal bed maps. Sources of information include the publications and records of the U.S. Geological Survey and State geological surveys, maps and drill records of coal mining companies, information in the files of State mine inspectors and railroad companies, records of exploration for petroleum and natural gas, records of water-well drilling companies, and, occasionally, private records obtained from individuals. To translate this information into estimates of tonnage, a series of definitions and standardized procedures must be employed.

First, two cutoff points must be established—one at the minimum thickness of coal included in the estimate, and the other at the maximum thickness of overburden allowed above the coal. A very conservative estimate may include only resources in thick beds and under slight overburden—in other words, resources that could be recovered profitably under current mining conditions. A more inclusive estimate, on the other hand, may consider thinner, more impure, and more deeply buried coal as recoverable by improved methods when more easily mined deposits have been exhausted.

Next, the weight or specific gravity of the coal must be determined or assumed, and where the continuity of a coal bed is unknown a method must be selected to estimate its probable extent, based on the available outcrop, mine, or drill data.

The way in which these and other factors are treated can vary greatly with individual estimators. For this reason, an estimate of coal resources has meaning only when considered in relation to the methods used in obtaining it.

To produce reasonably uniform results in preparing coal-resource estimates, the U.S. Geological Survey adopted a set of definitions and standardized procedures, which have been followed in preparing most of the estimates in table 1. These definitions and procedures, which are discussed in the following paragraphs, were prepared jointly by members of the Geological Survey and the Bureau of Mines, and include recommendations of the former National Bituminous Coal Advisory Council.

CLASSIFICATION ACCORDING TO CHARACTERISTICS OF THE COAL

RANK OF COAL

Coal is classified by rank according to percentage of fixed carbon and heat content, calculated on a mineral-matter-free basis. As shown in figure 3, the percentage of fixed carbon and the heat content, except in anthracite, increase from the lowest to the highest rank of coal as the percentages of volatile matter and moisture decrease. This change took place progressively during the slow process by which plant material deposited as peat in swamps and marshes in the geologic past was transformed into coal. The lower layers of plant material in the swamps were first compacted under successive layers of vegetation. Later, as marine or continental deposits covered the coal swamps,

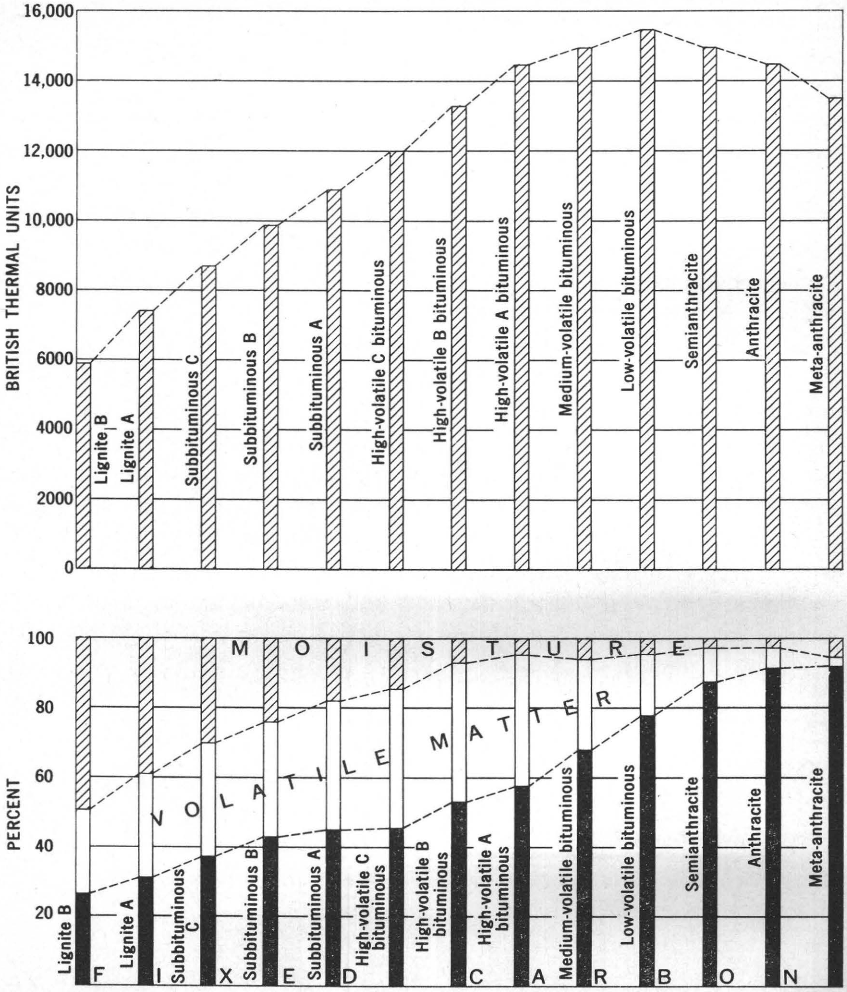

FIGURE 3.—Comparison on moist, ash-free basis of heat values and proximate analyses of coal of different ranks.

the accumulated weight of sediment further compressed the plant material and caused a progressive decrease in the amounts of volatile matter and moisture. It has been estimated that a foot of bituminous coal contains plant material accumulated over a period of several centuries.

The progressive devolatilization and consequent increase in rank of coal are produced primarily by heat and time, and secondarily by structural deformation. These factors have been carefully evaluated by Teichmüller and Teichmüller (1966). On a regional scale, the required amount of heat is produced by the normal geothermal gradient accompanying depth of burial. In the Ruhr coal district of western Germany, the correlation between increase in rank and depth of burial is well established and widely understood. In southwestern West Virginia, the observed increase in rank from west to east across the State has been studied by Heck (1943), who concluded that the progressive west-to-east increase in thickness of the overlying rocks, and the consequent increase in depth of burial, is the single factor of greatest importance.

The coal-forming process may be speeded up or intensified locally by structural deformation of the coal-bearing rocks, or by heat from nearby masses of igneous rock. In a study of coal metamorphism in the Crested Butte district, Gunnison and Pitkin Counties, Colo., Dapples (1939) has presented evidence of depth of burial, heat from nearby intrusive masses, and local deformation of rock and coal to account for observed differences in rank ranging from anthracite to high-volatile bituminous coal. On the west side of this complexly disturbed area, a deeply buried deposit of high-rank and high-quality coking coal has been delineated by Toenges and others (1952). In a study of coal metamorphism in Alaska, Barnes (1962) has presented quantitative data demonstrating the effects of age, depth of burial, and regional metamorphism on the rank of coals of Tertiary age.

The regional effects of structural deformation on rank are well displayed on Trumbull's (1960) coal map of the conterminous United States, which shows anthracite in the complexly folded and faulted Pennsylvania anthracite fields; low-volatile bituminous coal on the east, moderately deformed edge of the Appalachian coal basin; anthracite and low-volatile bituminous coal in the folded belt of the Arkansas and Oklahoma coal fields; and bituminous coal in the tightly folded synclines of Tertiary rocks of the State of Washington.

The effect of geologic age on rank of coal is exhibited in a gross way by the overall distribution of coal by rank and age in the conterminous United States. As shown on the map by Trumbull (1960), coal of Pennsylvanian age is entirely bituminous coal and anthracite, whereas coal of Cretaceous and Tertiary ages, with a few exceptions, is subbituminous coal and lignite. This relation is well displayed on Trumbull's map by the distinction between the high-rank coal of Pennsylvanian age in the eastern half of the conterminous United States, and the lower rank coal of Cretaceous and Tertiary ages in the Rocky Mountain region.

The highly significant relation between depth of burial and increase in rank suggests that some Cretaceous and Tertiary coal of very high rank is present in the deeper parts of the deep Rocky Mountain coal basins.

To a very minor extent, local differences in rank can be attributed only to differences in composition of the original coal-forming materials. In the Black Mesa field, northeast Arizona, where the coal-bearing rocks are flat lying and near the surface, the rank relations are the reverse of the normal observed elsewhere. In this field, coal beds in the Dakota Sandstone are of subbituminous B rank, whereas coal beds in the overlying Mesaverde Formation are of high-volatile B bituminous rank.

Rank of coal is thus a way of expressing successive stages in the formation of coal. It is quite independent of grade, or quality, which is in part a function of the amount of ash and sulfur in the coal.

The standard classification of coal by rank in use in the United States is that established by the American Society for Testing and Materials (1966). This classification, which is shown in table 3, is used uniformly in classifying all coal-resource estimates. As coals of different rank are adaptable to different uses, rank is the major basis of differentiation used in figures 1 and 2 and in tables 1 and 2.

Most of the tables and illustrations in this report show resources of all ranks of coal in short tons as computed. In terms of ultimate usefulness, however, comparison of the resources of lignite and subbituminous coal, which have relatively low heat values, with resources of bituminous coal and anthracite, which have higher heat values, can best be made on a uniform Btu basis. Such a comparison is presented in figure 4, which shows the remaining resources in each State as of January 1, 1967, on both a tonnage and a Btu basis.

GRADE OF COAL

Coal is classified by grade, or quality, largely according to the content of ash, sulfur, and other deleterious constituents. Thus far in work on coal resources it has not been possible to report on resources in categories according to grade because coal analyses tend to be for samples from areas of active mining, or from a few thick, continuous, and well-exposed beds.

Although the definitions and procedures used in calculating coal resources generally permit the inclusion of beds containing as much as 33 percent ash, very little coal of such high ash content is included in modern estimates, in part because of the natural conservatism of the estimators, and in part because all layers of parting and bone more than three-eighths of an inch thick are excluded in determining the thickness of the beds. On the other hand, resource estimates obviously include beds containing higher ash and sulfur contents than most beds now being actively mined.

TABLE 3.—*Classification of coals by rank*

[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 these coals either contain less than 48 percent dry, mineral-matter-free fixed carbon, or have more than 15,500 British thermal units per pound, calculated on the moist, mineral-matter-free basis. Modified from American Society for Testing and Materials (1966)]

Class	Group	Fixed carbon limits, in percent (Dry, mineral-matter-free basis)		Volatile matter limits, in percent (Dry, mineral-matter-free basis)		Calorific value limits, in Btu per pound (Moist, mineral-matter-free basis)[1]		Agglomerating character
		Equal or greater than	Less than	Equal or greater than	Less than	Equal or greater than	Less than	
I. Anthracitic	1. Meta-anthracite	98			2			Nonagglomerating.[2]
	2. Anthracite	92	98	2	8			
	3. Semianthracite	86	92	8	14			
II. Bituminous	1. Low-volatile bituminous coal	78	86	14	22			Commonly, agglomerating.[4]
	2. Medium-volatile bituminous coal	69	78	22	31			
	3. High-volatile *A* bituminous coal		69	31		[3]14,000		
	4. High-volatile *B* bituminous coal					[3]13,000	14,000	
	5. High-volatile *C* bituminous coal					11,500	13,000	
						10,500	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	

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

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

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

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

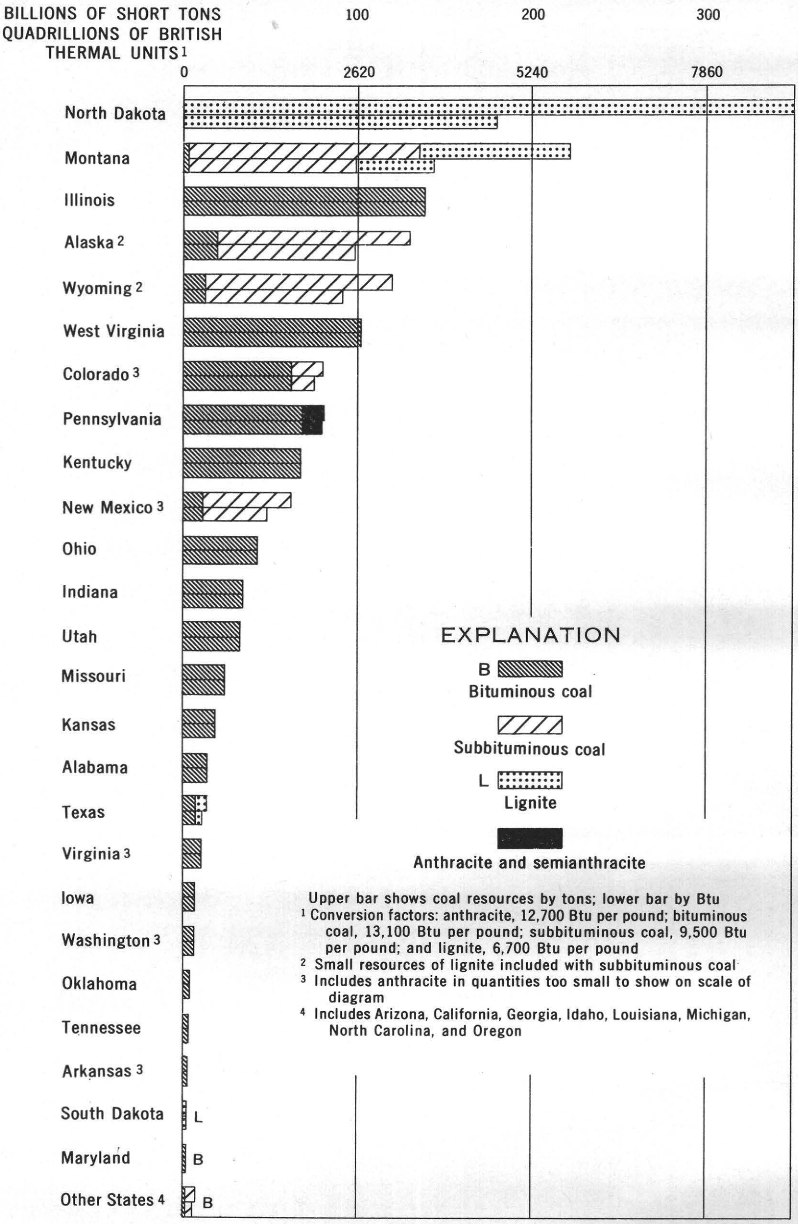

FIGURE 4.—Remaining coal resources of the United States as determined by mapping and exploration, January 1, 1967, by States, according to tonnage and heat value.

Fieldner, Rice, and Moran (1942) have prepared a list of 642 typical mine, tipple, and delivered samples of coal from beds in all parts of the United States. In these samples the ash content ranged from 2.5 to 32.6 percent and averaged 8.9 percent. The sulfur content ranged from 0.3 to 7.7 percent and averaged 1.9 percent.

The maximum ash and sulfur contents of beds included in the estimated resources are probably about the same as the maximum figures shown in the list of typical analyzed samples, whereas the average ash and sulfur contents of the estimated resources are probably higher than the averages derived from the list.

SPECIFIC GRAVITY OF COAL

The specific gravity of coal varies significantly with rank and with differences in ash content. The following values, however, conform closely to the average of the recorded specific gravities of unbroken coal in the ground in each of the four major rank categories:

Specific gravity and weight of coal of different ranks

Rank	Specific gravity	Tons per acre-foot	Tons per square mile-foot
Anthracite and semianthracite	1. 47	2, 000	1, 280, 000
Bituminous coal	1. 32	1, 800	1, 152, 000
Subbituminous coal	1. 30	1, 770	1, 132, 560
Lignite	1. 29	1, 750	1, 120, 000

Where more precise data are not available, these values are assigned as the weight of the coal in the ground in most estimates of coal resources.

Persons closely associated with individual mining operations may employ lower weight factors to allow for anticipated losses in mining. Such a practice is not suitable for use in a general report, however, for recoverability may vary greatly in different areas, in different beds, and with different methods of mining. The selected weight factors, therefore, are intended to yield resources of coal in the ground without regard to ultimate recoverability.

THICKNESS OF BEDS

According to the recommended procedures of the U.S. Geological Survey, coal resources should be calculated and reported by beds in three categories of thickness as follows:

Thickness categories used in calculating resources of coal of different ranks

Rank	Thickness categories		
	Thin	Intermediate	Thick
Anthracite, semianthracite, and bituminous coal, in inches	14–28	28–42	>42
Subbituminous coal and lignite, in feet	2½–5	5–10	>10

The thickness categories for anthracite and bituminous coal were selected to conform with present mining practices and past procedures in estimating resources. The 14- to 28-inch category represents coal that in the present economy is unsuitable for mining except for small-scale local use. Coal in this category is of little present economic interest and is, therefore, segregated in most estimates. The category is retained, however, because (1) prudence dictates that occurrences of marginal resources of coal should be recorded for possible future use, just as marginal resources of other useful minerals are recorded; (2) some coal in this category is mined; (3) the information is obtained with little additional effort during work with the thicker coals and aids in studies of coal-bed continuity and correlations; and (4) the minimum of 14 inches permits comparison with older estimates, which generally employed this same figure.

The 28- to 42-inch category represents coal that can be mined using certain types of underground mechanical loading machinery.

The category of more than 42 inches represents coal that can be mined by all types of mechanical cutting and loading machinery.

The thickness categories for subbituminous coal and lignite are somewhat broader, to conform with occurrences of coal in these ranks and with present interest in such coal.

For a few States the thickness categories and the minimum thicknesses differ from the recommended standards. In Montana, the bituminous coal categories are 14–24 inches, 24–36 inches, and more than 36 inches, whereas, in North Carolina, the categories are 14–28 inches, 28–36 inches, and more than 36 inches. In Ohio, the bituminous coal categories are 14–28 inches, 28–54 inches, and more than 54 inches. In Illinois, 18 inches has been used as the minimum thickness for bituminous coal. In Kansas, a minimum of 16 inches has been used for bituminous coal to a maximum depth of 100 feet, and 18 inches for coal to a maximum depth of 150 feet.

The average thickness of coal beds used in coal-resource calculations is determined in two ways. Where information on thickness is abundant and points of information are well spaced, lines of equal coal thickness are drawn and used to determine the average thickness. Where information on thickness is less abundant and points of information are poorly spaced, weighted average figures are used. The weighing is accomplished by assigning intermediate values for the thickness at points where information is needed to fill out a system of evenly spaced points, and using both the direct measurements and the assigned figures in determining a simple average. Where this procedure is followed to obtain the weighted average thickness along the outcrop of a persistent bed, the two end points of minimum thickness are included in the average.

Partings more than three-eighths of an inch thick are disregarded in determining the thickness of individual beds. Beds and parts of beds made up of alternating layers of thin coal and partings are omitted if the partings make up more than half the total thickness or if the ash content exceeds 33 percent. Benches of coal of less than the minimum thickness stated, which lie above or below thick partings and which normally would be left in mining, are also omitted.

Occasionally, in older coal-resource estimates, a formula termed "the modulus of irregularity" has been used to determine the probable minimum thickness of a coal bed. According to this formula, the probable minimum thickness is obtained by multiplying the average of the measurements of bed thickness by $(1-\frac{SD}{S})$, in which S is the sum of all the thickness measurements and SD is the sum of the differences between each individual thickness measurement and the average of all the thickness measurements.

The modulus of irregularity was originally adopted by the U.S. Geological Survey as a mechanism in establishing the value of coal lands (Smith and others, 1913, p. 88), but it is no longer used for this purpose. It was devised as a safeguard for the buyer of coal lands in areas where the coal beds vary widely in thickness. As stated by Smith and others, computation of the thickness of the coal by using the modulus of irregularity permitted the

> thickness of the coal under any tract of land to be considered as less than the average of the measurements. For while the coal is as likely to be just above the average as just below, and mathematically, is more likely to be just the average thickness than any other, yet a cautious buyer bargaining for coal would always want to discount the probability a little as a matter of safety.

The modulus of irregularity is no longer used in preparing estimates of coal resources.

AREAL EXTENT OF BEDS

The areal extent of coal beds included in modern classified coal-resource estimates is determined in several ways. Where the continuity of a bed is well established from maps of the outcrop, from mine workings, and from drill holes, the entire area of the known occurrence of the bed is taken, even though points of observation are widely spaced. Persistent beds that have been traced around a basin or spur are considered to underlie the area enclosed by the outcrop. Otherwise, the length of outcrop within the thickness limits listed is considered to determine the presence of coal in a semicircular area having a radius equal to half the length of the outcrop. The total area of coal is considered to extend beyond such a semicircle if mine workings or drill holes so indicate, in which case coal is considered to extend no more than 1 mile beyond the limiting point of information. An isolated drill hole farther from the area thus defined is considered to determine the area of coal extending for a maximum radius of half a mile around the hole.

These conservative procedures have been followed in preparing most of the estimates presented in table 1.

THICKNESS OF OVERBURDEN

Wherever possible, coal-resource data are divided into three major categories according to thickness of overburden, in feet, as follows: 0–1,000, 1,000–2,000, and 2,000–3,000. In a few States where the overburden is thin the resources have been calculated in several subcategories within the 0- to 1,000-foot category; and in others, where the overburden is thicker or where information is inadequate, one or more of the major categories may be combined.

In Indiana, for example, where all the estimated resources are less than 1,000 feet below the surface and where a large part of the production is by strip mining, the coal considered to be suitable for strip mining is divided into three categories as follows:

Overburden range (feet)	*Thickness of beds included (inches)*
0–40	14–28
0–60	28–42
0–90	>42

The remainder, which is considered suitable primarily for underground mining, is in a single category.

In Arkansas, the resources are divided into five categories according to the thickness of overburden, in feet, as follows: 0–60, 60–500, 500–1,000, 1,000–2,000, and 2,000–3,000.

In Michigan, where all the coal is less than 400 feet below the surface, the resources are divided into four categories according to thickness of overburden in feet, as follows: 50–100, 100–200, 200–300, and 300–400.

In several States no overburden categories were employed, but in each of these States the coal included in the estimated resources is significantly less than 3,000 feet below the surface. In Illinois and Montana, the maximum overburden on the coal is 2,000 feet. In Kentucky, Ohio, Virginia, and North Dakota, the maximum overburden is a little more than 1,000 feet, but the great bulk of the estimated resources is less than 1,000 feet. In Iowa the maximum overburden is 1,000 feet.

CLASSIFICATION ACCORDING TO RELIABILITY OF ESTIMATES

Wherever possible, coal-resource estimates are divided into three categories according to the relative abundance and reliability of data used in preparing the estimates. These classes are termed "measured," "indicated," and "inferred."

MEASURED RESOURCES

Measured resources are resources for which tonnage is computed from dimensions revealed in outcrops, trenches, mine workings, and drill holes. The points of observation and measurement are so closely spaced, and the thickness and extent of the coal are so well defined, that the computed tonnage is judged to be accurate within 20 percent of the true tonnage. Although the spacing of the points of observation necessary to demonstrate continuity of coal differs from region to region according to the character of the coal beds, the points of observation are, in general, about half a mile apart.

INDICATED RESOURCES

Indicated resources are resources for which tonnage is computed partly from specific measurements and partly from projection of visible data for a reasonable distance on the basis of geologic evidence. In general, the points of observation are about 1 mile apart, but they may be as much as 1½ miles apart for beds of known continuity.

In several States, particularly Alabama, Colorado, Iowa, Montana, and Washington, where the amount of measured resources is very small, the measured and indicated categories have been combined.

INFERRED RESOURCES

Inferred resources are resources for which quantitative estimates are based largely on broad knowledge of the geologic character of the bed or region and for which few measurements of bed thickness are available. The estimates are based primarily on an assumed continuity in areas remote from outcrops of beds, which in areas near outcrops were used to calculate tonnage classed as measured or indicated. In the interest of conservatism, the areas in which the coal is classed as inferred are restricted as described under the heading "Areal Extent of Beds." In general, inferred coal lies more than 2 miles from the outcrop or from points for which mining or drilling information is available.

UNCLASSIFIED RESOURCES

In a few States, particularly Georgia, Maryland, Pennsylvania, Utah, and West Virginia, the calculated resources have not been divided into the measured, indicated, and inferred categories.

DISTINCTION BETWEEN ORIGINAL, REMAINING, AND RECOVERABLE RESOURCES

Coal resources may be calculated and presented according to one or all of three different points of view as defined below.

ORIGINAL RESOURCES

Original resources are resources in the ground before the beginning of mining. Although subject to revision with new mapping and exploration, an estimate of original resources is essentially a constant, needing no date nor explanation to make it understandable. From this estimate the figures for remaining and recoverable resources, which must be dated, can be determined annually, if desired, from available information on production and losses or from surveys of mined-out areas.

All older estimates and most modern estimates, particularly those for Western States where relatively little mining has been done, are for original resources.

REMAINING RESOURCES

Remaining resources are unmined resources remaining in the ground, as of the date of the estimate. Where adequate records have been kept of mined-out areas, estimates of remaining resources can be calculated without reference to original resources, and estimates for Illinois, Kansas, Maryland, Tennessee, and Washington have been made on this basis. Where records of mined-out areas are not available, remaining resources can be calculated by subtracting past cumulative production and estimated losses in mining from original resources.

In tables 1 and 2, all estimates have been reduced by the amount of production and losses from the dates of the estimates to January 1, 1967, so that figures in the remaining resources columns are on a comparable basis.

RECOVERABLE RESOURCES

Recoverable resources are resources in the ground, as of the date of the estimate, that past experience suggests can actually be produced in the future. Much coal thus classified can be mined at or near present costs, measured in man-hours and equipment. The remainder, in thinner and less accessible beds, can be mined either at gradually increased cost according to the present mining technology, or possibly with little or no increase in cost according to a future, improved mining technology. Recoverable resources may be obtained by subtracting estimated future losses in mining from remaining resources.

Because recoverability differs in different areas and with different methods of mining, most of the tables and diagrams in this report are set up on the basis of original or remaining resources. For this tonnage as a whole and for the United States as a whole, only about half of the tonnage discussed and analyzed is potentially recoverable.

PERCENTAGE OF COAL RECOVERED IN MINING

In estimating remaining and recoverable resources, it is necessary to take into account not only past production, but also both past and estimated future losses in mining. Reasonably accurate figures for past production can be obtained from the annual statistics of production published by the U.S. Bureau of Mines and by various State agencies. The figures for past and estimated future losses in mining are less easily obtained, partly because the percentages of coal recovered and lost in mining differ considerably in different areas and mines, for different operators, and under different methods of mining. In localities covered by detailed mine maps, past losses in mining can be determined by comparing production figures with measurements of areas known to be mined out. The necessary detailed maps are not available, however, for many of the coal-mining areas in the United States, and the estimates of individuals familiar with local mining operations provide, in general, the only indication of the relative tonnages of coal that are recovered and lost in mining.

In calculating remaining and recoverable resources on a regional or national scale, therefore, an average and rounded figure for the estimated percentage of recovery in the past and in the future must be derived from a consideration of the relatively few detailed studies available.

UNDERGROUND MINING

Most studies of recoverability in underground mining involve consideration of individual mines or small areas and typically indicate a higher recoverability than studies of larger areas. In some individual mines, for example, as much as 90 percent of the coal in the block actually being mined may be recovered. From the total-resource point of view, however, recoverability seems to be only about 50 percent of the coal in the ground. This marked difference arises because studies of recoverability in larger areas include consideration of coal that is left in barrier pillars, in restricted areas around oil and gas wells, under towns, railroads, roads, and streams, in rider beds, and in local areas of complex faulting and folding, as well as the more conspicuous losses in the block or blocks of coal actually being mined. Furthermore, few studies of recoverability take into account the lower recoverability that will probably be experienced as underground mining progresses into the deeper overburden coals.

In a special study of the No. 6 coal bed in Franklin County, Ill., for example, Cady (1949, p. 67–69) determined that when barrier pillars and coal left to protect oil and gas wells are taken into account, underground mining operations to the date of his study recovered only 33–35 percent of the coal originally present in the mined areas.

In a similar study in Perry County, Ohio, Flint (1951, p. 100) calculated that during 1938–48 the recovery from all beds was only 43 percent of the coal originally present in the mined areas.

In Michigan, the recovery of coal has averaged about 60 percent of the total in the ground, according to estimates by individuals familiar with mining operations in the State (Cohee and others, 1950, p. 5).

In Utah, past recovery in underground mining operations in all beds has resulted in recovery not exceeding 50 percent, according to B. W. Dyer (oral commun., 1949).

Eavenson (1946) has estimated that the actual recovery from the Pittsburgh bed in Pennsylvania is no more than 50–60 percent because of the large amount of coal that is left in the barriers, in reservations for oil and gas wells, under buildings, and in the rider above the main bed. In calculating the remaining resources of bituminous coal in Pennsylvania, Ashley (1944, p. 79–83) assumed a recovery of 50 percent for all coal in the State with the exception of that in the Pittsburgh bed, for which he assumed a recovery of 66.6 percent. Ashley's figures were based on the percentage recovery of coal in Fayette County, Pa., as determined by Moyer (Hickok and Moyer, 1940, p. 359, 417–420).

The weighted averages of recovery in mining bituminous coal in 44 counties in the Appalachian region, as determined by the U.S. Bureau of Mines, ranged from 45.4 to 65.4 percent and averaged about 54 percent (Dowd and others, 1950–52c; 1955–56; Wallace and others, 1952–55b; Williams and others, 1954–56; Hershey and others, 1955, 1956; Blaylock and others, 1955, 1956; Travis and others, 1956; Lowe and others, 1956; Provost and others, 1956; Tavenner and others, 1956).

Trumbull (1957, p. 367) has estimated that in Oklahoma recoverability in past mining operations has averaged only 39 percent.

In Washington, Beikman, Gower, and Dana (1961, p. 4) have estimated that recoverability in past mining operations in southwest Washington has averaged about 40 percent. In the Roslyn field, however, recoverability has averaged about 80 percent.

In a very careful study of 200 selected underground mines, which in 1963 accounted for nearly half of the Nation's underground production of bituminous coal, Lowrie (1968, p. 14) concluded that the recovery within the mined areas ranged from 29 to 91 percent, and averaged 57 percent. In all these mines overburden was less than 1,000 feet.

Inasmuch as the recovery figures determined in these studies cluster around 50 percent, the estimated remaining resources of coal shown in tables 1 and 2 are based on the assumption that past mining operations have recovered only 50 percent of the coal in the ground and that this rate will be applicable in the future. As noted above, however, many individual operations recover more than 50 percent of the coal in the ground, and it is to be hoped that the gradual introduction of more efficient mining methods will ultimately result in a higher average recoverability.

As production statistics of separate States generally include only the output of the larger mines, the recorded production figures used in tables 1 and 2 are somewhat less than actual production. Thus, the past losses in mining, which are assumed in tables 1 and 2 to be equal to past production, are also somewhat less than actual losses. Therefore, the remaining resources as reported in tables 1 and 2 are somewhat higher than they would be if complete data were available for the amounts of coal mined and lost in mining.

A considerable amount of the coal recovered in mining is ultimately lost in the process of mechanical cleaning. In 1966, for example, 64 percent of the bituminous coal and lignite produced was cleaned mechanically, and an average of 21.7 percent of this amount was discarded as refuse (U.S. Bur. Mines, 1966, p. 666).

STRIP MINING

According to Koenig (1950, p. 28), recoverability in strip mining may, under favorable conditions, be as much as 90 percent of the coal originally in the ground. Most strip-mine operators agree that the average recoverability in strip mining is on the order of 80 percent, and this figure is used in preparing many estimates of recoverable strip-mining resources. Because strippable coal constitutes only a small part of the total resources and only a modest part of past total production, the use in tables 1 and 2 of the 50-percent recoverability factor for all coal seems to be justified.

AUGER MINING

In auger mining the maximum possible recovery is about 75 percent, but when many operations are considered, the actual average recovery is probably no more than about 50 percent—the same recovery assumed for other methods of underground mining. Actual recovery in auger mining is less than the possible maximum because the auger holes are generally smaller in diameter than the thickness of the bed being mined, and because spaces several inches wide are routinely left between adjacent auger holes.

COMPUTER METHODS OF ESTIMATING RESOURCES

For three States—Illinois, Oklahoma, and eastern Kentucky—the estimates discussed herein were prepared through use of computers. In each of these studies, the individual punched card represented a block of coal of known average thickness, areal extent, and resource classification. The machine then performed the basic calculation—area × thickness × specific gravity—and printed out the total with other totals on the same resource classification. As the amount of data on coal increases, the use of computer techniques will certainly increase. But even this efficient electronic aid will not relieve the geologist of the strictly geologic problems of coal-bed correlations, interpretations of centers and trends of coal deposition, probable position of ancient shore lines, and subsequent channeling and postdepositional erosion that have reduced the tonnage formerly present in many beds.

STATISTICAL METHODS OF ESTIMATING RESOURCES

In recent years several engineers closely associated with the coal-mining industry have applied sophisticated statistical methods to the estimation of resources in areas of closely spaced exploratory drilling. (See Koch and Gomez, 1966; Pundari, 1966.) The chief virtue of these methods is to provide management with figures representing the maximum and minimum possible recovery in terms of tons and Btu content from the bed or beds being considered. The statistical methods work best when the geology of the coal and the enclosing rocks is fully understood.

DISTRIBUTION OF RESOURCES IN SELECTED CATEGORIES

The resources determined by mapping and exploration have been classified in considerable detail in several major resources categories. The distribution according to State and rank have been presented in tables 1 and 2 and in figure 4. Some broader aspects of the distribution according to coal basins or regions and rank are discussed under separate headings below.

About 60 percent of the estimated original resources as determined by mapping and exploration has been classified according to thickness of overburden, reliability of estimates, and thickness of beds. The distribution of this tonnage in these three categories is also discussed under separate headings below. This classified tonnage is fairly large and it is widely distributed in 21 States.[1] If comparable information were available for the entire United States, it is likely that the overall distribution patterns would not differ significantly from those based on current information.

DISTRIBUTION ACCORDING TO REGION

Coal-bearing rocks underlie about 13 percent of the land area of the 50 United States, and about 14 percent of the land area of the 48 conterminous States. (See figs. 1 and 2, table 4; Trumbull, 1960; Barnes, 1961.) These rocks are present in 37 States, including a few, such as Mississippi, New York, and Nevada, in which the coal-bearing areas are small or the resources insignificant, and others, such as Illinois and West Virginia, in which the coal-bearing areas represent more than half of the total area of the State. The wide distribution of accessible coal has contributed greatly to the industrial growth of the United States.

The distribution of resources on a tonnage basis is roughly proportional to the areal distribution of coal-bearing rocks, although in a few large areas of coal-bearing rocks, such as those in Michigan and the bituminous-coal areas of Texas, the resources are relatively small; whereas in other areas, such as some in the Rocky Mountain region, the coal-bearing rocks are deeply buried, and the contained coal is relatively inaccessible.

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[1] Alabama, Arkansas, Colorado, Illinois, Indiana, Iowa, eastern Kentucky, Michigan, Missouri, Montana, New Mexico, North Carolina, North Dakota, Ohio, Oklahoma, South Dakota, Tennessee, Texas, Virginia, Washington, and Wyoming.

TABLE 4.—*Size and percentage distribution of coal-bearing areas in the United States*

State	Total area of State (square miles)[1]	Area underlain by coal-bearing rocks	
		Square miles	Percent
Alabama	51, 609	9, 700	19
Alaska	586, 400	35, 000	6
Arizona	113, 909	3, 040	3
Arkansas	53, 104	1, 700	3
California	158, 693	230	. 1
Colorado	104, 247	29, 600	28
Georgia	58, 876	170	. 2
Idaho	83, 557	500	. 6
Illinois	56, 400	37, 700	67
Indiana	36, 291	6, 500	18
Iowa	56, 290	20, 000	36
Kansas	82, 264	18, 800	23
Kentucky	40, 395	14, 600	36
Louisiana	48, 523	1, 360	3
Maryland	10, 577	440	4
Michigan	58, 215	11, 600	20
Mississippi	47, 716	1, 000	2
Missouri	69, 686	24, 700	35
Montana	147, 138	51, 300	35
Nebraska	77, 227	300	. 4
Nevada	110, 540	50	--------
New Mexico	121, 666	14, 650	12
New York	49, 576	10	--------
North Carolina	52, 712	155	. 3
North Dakota	70, 665	32, 000	45
Ohio	41, 222	10, 000	24
Oklahoma	69, 919	14, 550	21
Oregon	96, 981	600	. 6
Pennsylvania	45, 333	15, 000	33
South Dakota	77, 047	7, 700	10
Tennessee	42, 246	4, 600	11
Texas	267, 339	16, 100	6
Utah	84, 916	15, 000	18
Virginia	40, 815	1, 940	5
Washington	68, 192	1, 150	2
West Virginia	24, 181	16, 800	69
Wyoming	97, 914	40, 055	41
Other States	312, 821	0	0
United States total	3, 615, 202	458, 600	13

[1] U.S. Bureau of the Census, 1966, Statistical abstract of the United States; 87th ed., p. 171.

The distribution of resources according to eight major coal basins or comparable large regions is given in table 5. These subdivisions provide a natural breakdown of data, and they can be considered separately or combined in various ways for study and analysis. Region 1, for example, represents coal available to the densely populated, highly industrialized northeastern States. Regions 1 and 2 combined represent the Appalachian coal basin, which provides coal to the eastern seaboard, and coal that is exported to Europe, Canada, and elsewhere. Regions 1, 2, 3, and 4 combined represent all coal east of the Mississippi River, whereas regions 5, 6, 7, and 8 combined represent all coal west of the Mississippi. Regions 1, 2, 3, 4, and 5 lie east of, and regions 6, 7, and 8 lie west of, an imaginary northeast-trending line extending from the panhandle of Texas to Minnesota, which marks an important division of regions and resources according to age and rank of coal. Regions 6 and 7 combined represent the Rocky Mountain and northern Great Plains provinces. Region 8 represents the west coast and Alaska.

TABLE 5.—*Distribution by basin or region, and by thickness of beds, of remaining coal resources of the United States as determined by mapping and exploration, January 1, 1967*

[In billions of short tons. Figures are for resources in the ground, about half of which may be considered recoverable. Neg., negligible]

Basin or region	Overburden 0–3,000 ft thick			
	Resources in thick beds[1] generally less than 1,000 ft below the surface		Resources in thinner beds less than 1,000 ft below the surface, and in all beds 1,000–3,000 ft below the surface	Total remaining resources (from table 1)
	Tons	Percent of total		
1. Northern Appalachian basin (Pa., Ohio, W. Va., and Md.)	58	27	157	215
2. Southern Appalachian basin (eastern Ky., Va., Tenn., N.C., Ga., and Ala.)	12	21	44	56
3. Michigan basin	Neg.	Neg.	Neg.	Neg.
4. Illinois basin (Ill., Ind., and western Ky.)	107	50	104	211
5. Western Interior basin (Iowa, Kans., Mo. Okla., Ark., and Tex.)	11	16	56	67
6. Northern Rocky Mountains (N. Dak., S. Dak., Mont., Wyo., and Idaho)	152	22	544	696
7. Southern Rocky Mountains (Colo., Utah, Ariz., and N. Mex.)	36	20	142	178
8. West coast (Alaska, Wash., Oreg., and Calif.)	24	18	113	137
Total	400	25	1,160	1,560

[1] Includes bituminous coal and anthracite in beds 42 in. or more thick, and subbituminous coal and lignite in beds 10 ft or more thick.

The amount of thick, accessible coal as determined from mapping and exploration is much larger in some regions than in others because of differences in the thickness and number of coal beds, and differences in the structure and topography of the major coal-bearing basins.

The larger amount and percentage of thick coal in region 1, the northern Appalachian basin, as compared with the smaller amounts in region 2, the southern Appalachian basin, reflect the fact that the center of coal deposition was in the northern part of the Appalachian basin; hence, coal beds are thicker, more continuous, and more numerous in region 1. Also, the bulk of the coal-bearing sequence in the northern Appalachian basin is preserved in a geosyncline, whereas in the southern Appalachian basin the entire upper part of the coal-bearing sequence was eroded in post-Pennsylvanian time.

The very large amount and percentage of thick coal in region 4, the Illinois basin, result from the fact that the Illinois basin is relatively shallow and the topography is relatively flat, so that coal is less than 1,000 feet below the surface over thousands of square miles. However, much of this coal can be reached only by vertical shafts.

The relatively small amount and percentage of thick coal in region 5, the Western Interior basin, result from the fact that the coal-bearing rocks are thin; the coal beds are few in number and, in general, are less than 42 inches thick. This region contains much larger resources of coal in the 28- to 42-inch thickness category.

The very large amount of thick coal and of total coal in region 6, the Northern Rocky Mountains, reflects the fact that coal beds are very thick, numerous, and closely spaced; the coal-bearing rocks are nearly flat lying; and the topography is relatively flat over thousands of square miles in North Dakota, eastern Montana, and northeastern Wyoming.

The modest amount of thick accessible coal in region 7, the Southern Rocky Mountains, as compared with that in region 6, reflects the fact that in most of region 7 the coal-bearing rocks are on the edges of moderately to steeply dipping structural basins. In parts of the region, particularly in the Wasatch Plateau and Book Cliffs of central Utah, the moderately dipping coal crops out at the bases of nearly vertical cliffs, and thus passes below 1,000 feet of overburden a short distance from the outcrops. All the coal occurring in this topographic setting can be reached by drift mines, and even larger tonnages with overburden more than 1,000 feet thick can be reached conveniently through the same openings.

DISTRIBUTION ACCORDING TO RANK

United States coal is distributed quite unequally among five categories of rank. As determined from the totals in the third column of table 1, 44.5 percent of the original resources as determined by mapping and exploration is bituminous coal, including 1.2 percent of low-volatile bituminous coal. By comparison, 26.5 percent is subbituminous coal, 27.5 percent is lignite, and only 1.5 percent is anthracite. This percentage distribution is shown graphically in figure 5*A*. It should be noted that the comparison shown in figure 5*A* is based on weight in tons. A comparison based on the contained heat value would show longer columns for bituminous and anthracite, and progressively shorter columns for subbituminous coal and lignite.

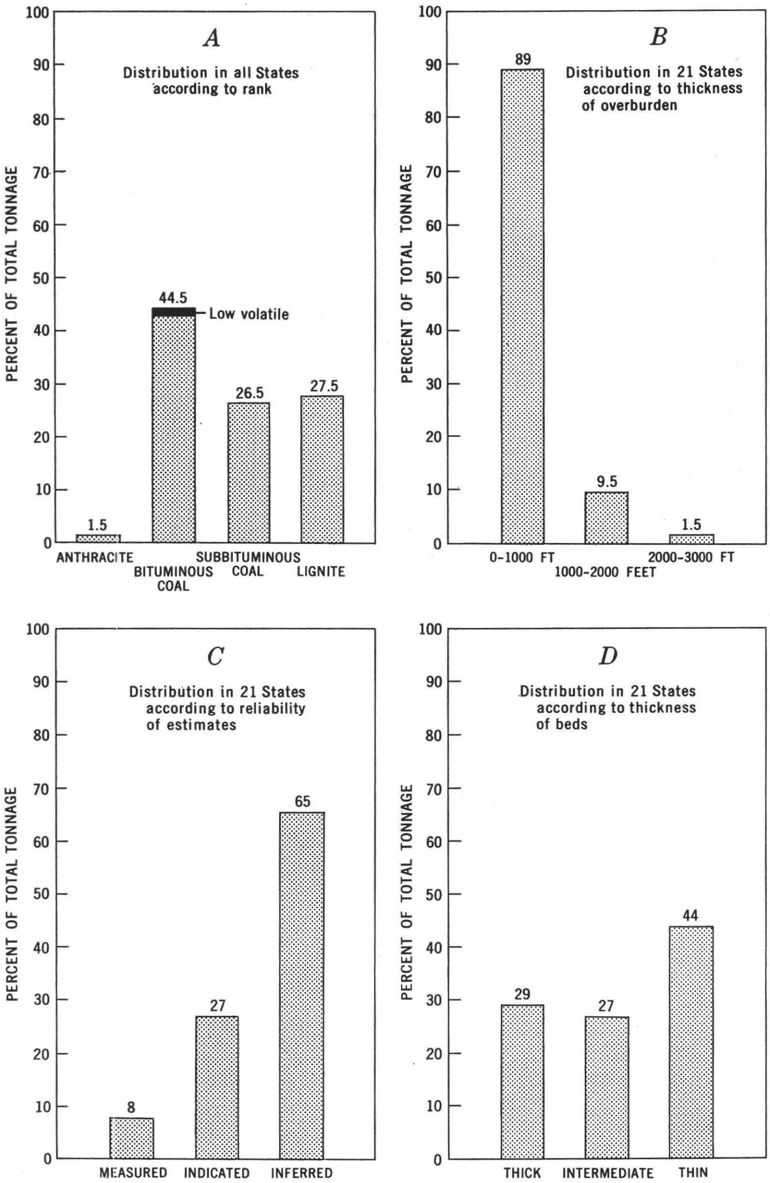

FIGURE 5.—Percentage distribution of estimated original coal resources as determined by mapping and exploration (*A*) in all States according to rank; and in 21 States according to (*B*) thickness of overburden, (*C*) reliability of estimates, and (*D*) thickness of beds.

The geographic distribution of resources of the different ranks of coal is also very unequal. In the counterminous United States, about 83 percent of the bituminous coal and anthracite as determined by mapping and exploration lies east of an imaginary northeast-trending line extending from the panhandle of Texas to Minnesota (fig. 1), and about 99 percent of the subbituminous coal and lignite lies west of the line.

The geographic distribution of the different ranks of coal is related principally to differences in geologic age. Nearly all the coal in States east of the imaginary line from the panhandle of Texas to Minnesota is of Pennsylvanian age, whereas nearly all the coal west of the line is of much younger age—Cretaceous or Tertiary. The younger, western coal attains high rank only where it has been deformed and altered by the forces that accompanied mountain building and by the intrusion of igneous rock.

The resources of subbituminous coal and lignite in the West have only local value at present. Coals of these ranks tend to crumble during transportation and to ignite by spontaneous combustion if stored for too long a period without special precautions. They also have lower heat values than other coals. On the other hand the low-rank coals are well suited for the production of electric power and the production of synthetic gas and liquid fuels, and in many parts of the West they can be mined efficiently by stripping methods. With these advantages, the low-rank coals in the West are certain to receive increased attention in the future.

DISTRIBUTION ACCORDING TO THICKNESS OF OVERBURDEN

Figure 5*B* shows the percentage distribution of resources in the 21 States classified in three categories according to thickness of overburden, in feet, as follows: 0–1,000, 1,000–2,000, and 2,000–3,000. It is noteworthy that 89 percent of the classified resources is less than 1,000 feet below the surface, and that only 9.5 percent and 1.5 percent, respectively, are present in the 1,000- to 2,000-foot and 2,000- to 3,000-foot categories. The impressive concentration of resources in the 0- to 1,000-foot category is due in part to the fact that coal-bearing rocks lie near the surface in many places and in part to the fact that less information is available for the more deeply buried beds. Most of the coal mined in the United States today, for example, is taken from beds less than 1,000 feet below the surface, and only a small amount is mined from beds 1,000–2,000 feet below the surface. In the United States no significant amount of coal is mined from beds more than 2,000 feet below the surface, though in Great Britain and Belgium mining has been carried to depths of 4,000 feet. As exploration and development are carried to greater depths, it is certain that the estimated resources as determined by mapping and exploration will be considerably increased by the addition of tonnage in the deeper overburden categories.

DISTRIBUTION ACCORDING TO RELIABILITY OF ESTIMATES

Figure 5*C* shows the percentage distribution of classified resources in the 21 States in the measured, indicated, and inferred categories, as previously defined. Of the large tonnage of classified resources, 8 percent is classed as measured, 27 percent as indicated, and 65 percent as inferred. The larger figure for inferred resources reflects the lack of precise data for many of the coal-bearing areas. It is, however, a convenient method of expressing the amount of coal that can be inferred with confidence to be present on the basis of current geologic information. Additional geologic mapping and exploration in any of the coal-bearing areas included in this distribution study would undoubtedly serve to increase the tonnage of measured and indicated resources.

DISTRIBUTION ACCORDING TO THICKNESS OF BEDS

The terms "thick," "intermediate," and "thin," as used in figure 5*D*, refer to beds of coal in three thickness categories, which differ for the different ranks of coal. Defined as "thick" are beds of bituminous coal and anthracite more than 42 inches thick and beds of subbituminous coal and lignite more than 10 feet thick. Defined as "intermediate" are beds of anthracite and bituminous coal 28–42 inches thick and beds of subbituminous coal and lignite 5–10 feet thick. Defined as "thin" are beds of anthracite and bituminous coal 14–28 inches thick and beds of subbituminous coal and lignite 2½–5 feet thick.

As recorded in the diagram, coal in thick beds makes up 29 percent of the total, coal in beds of intermediate thickness makes up 27 percent, and coal in thin beds makes up 44 percent. The relatively low percentage of resources in beds of intermediate thickness is probably due in part to a human tendency to assign minimum thicknesses to beds in the inferred category and thus increase the percentage of coal in the thin category.

DISTRIBUTION ACCORDING TO COMBINED CATEGORIES OF OVERBURDEN, RELIABILITY, AND THICKNESS OF BEDS

Figure 6 summarizes the distribution of resources in the three major categories presented in figure 5(*B*, *C*, *D*). Figure 6 clearly shows the preponderance of resources in the 0- to 1,000-foot category and the relatively small quantities of measured resources in all categories. Resources are present in each of the 27 possible categories in figure 6, except the one representing measured resources in thin beds 2,000–

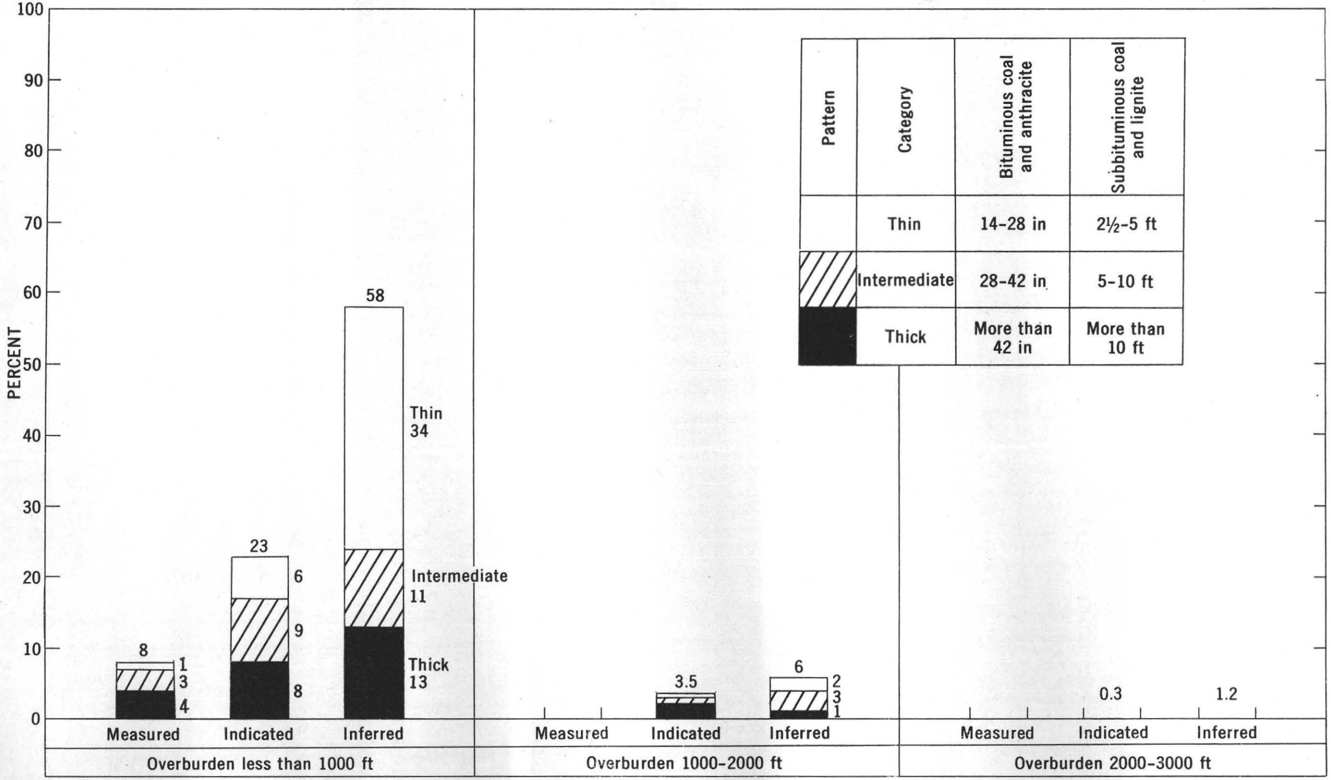

FIGURE 6.—Summary of percentage distribution by major resource categories of estimated original coal resources as determined by mapping and exploration in 21 States.

3,000 feet below the surface. The amounts in several categories are less than 1 percent of the total and could not be shown on a diagram at this scale.

Like figure 5*B–D*, figure 6 shows the conservative character of the estimates for the resources in the 21 selected States. The relatively large percentages of resources in the indicated and inferred categories and the small percentages in the measured category are due to a lack of data—not a lack of coal. The relatively small percentage of coal in the 1,000- to 2,000-foot category as compared with that in the 0- to 1,000-foot category is also due primarily to lack of data. The deeper overburden categories obviously contain additional coal that could not be included in estimates based on existing mapping and exploration. This additional tonnage is discussed under a separate heading below.

ESTIMATES FOR STATES NOT COVERED BY CITED REPORTS

The estimates for Maryland, Utah, and "Other States" used in table 1 are not taken from summary reports on coal like those cited for all other States, but, instead, are based on a review and synthesis of data in detailed coal reports as explained below.

MARYLAND

The coal-bearing rocks in Maryland cover an area of about 440 square miles in three parallel structural troughs that extend northeastward across Garrett and Allegany Counties in the western part of the State. The easternmost trough is divided by the Potomac and Savage Rivers into the Georges Creek basin to the north and the upper Potomac basin to the south. The central trough is divided into the Castleman basin to the north and the upper Youghiogheny basin to the south. The westernmost trough is known as the lower Youghiogheny basin.

The remaining coal resources in Maryland, as determined by mapping and exploration to January 1, 1950, are here estimated to total approximately 1.2 billion tons. This estimate is based in part on two reports by Toenges and others (1949, 1952) describing the results of investigations by the U.S. Bureau of Mines, the Maryland Department of Geology, Mines, and Water Resources, and the U.S. Geological Survey in the Georges Creek basin, the northern half of the upper Potomac basin, and the central part of the Castleman basin.

The remaining resources in the Georges Creek basin and the northern half of the upper Potomac basin, as of January 1, 1947, were estimated to total 627 million tons (Toenges and others, 1949). The estimate comprises resources in 10 beds, 18 inches or more thick, lying below the Pittsburgh bed. The Pittsburgh bed and the overlying Sewickley bed have been mined extensively and are now nearly depleted. The resources are classified according to the measured, indicated, and inferred categories, and according to four thickness categories. The coal is of low-volatile bituminous rank and is strongly coking.

The remaining resources in the central part of the Castleman basin, as of January 1, 1950, were estimated to total 232 million tons (Toenges and others, 1952). The estimate comprises resources in six beds 14 inches or more thick. The resources are classified according to the measured, indicated, and inferred categories, and according to three thickness categories. The coal is of low- to medium-volatile bituminous rank and in general is strongly coking.

The estimates in the two reports were based on a substantial amount of data obtained from measurements in drill holes and at the outcrops, and are of a high order of accuracy. A minimum coal thickness of 18 inches was used in the report on the Georges Creek and upper Potomac basins, whereas a minimum of 14 inches was used in the report on the Castleman basin and elsewhere.

In the areas covered by the two reports, the estimated remaining resources as of the period January 1, 1947, to January 1, 1950, total 859 million tons. The larger figure of 1.2 billion tons as the remaining resources of the State as of January 1, 1950, is derived from the 859-million-ton figure by a process of extrapolation, as summarized below.

The areas of the five coal basins in Maryland and the number and thickness of the contained coal beds suggest that the resources should be distributed about as follows: Georges Creek basin, 50 percent; upper Potomac basin, 20 percent; Castleman basin, 15 percent; upper Youghiogheny basin, 5 percent; and the lower Youghiogheny basin, 10 percent.

The areas considered by Toenges and others (1949, 1952) in the Georges Creek, upper Potomac, and Castleman basins is about 84 percent of the total area of the three basins. If we assume that the estimate by Toenges and others represents 84 percent of the total resources of the three basins, and that the percentage distribution of resources in the five basins is correct, then the figure of 859 million tons represents about 70 percent of the total resources of the State (84 percent × 85 percent). Therefore, the remaining resources of Maryland as of January 1, 1950, should total about 1.2 billion tons.

Based as it is upon a broad extrapolation of data from several sources, this figure is subject to modification as more information becomes available about Maryland coal resources. It is, however, of the proper order of magnitude for comparison with estimates from other States where reestimates of resources on the basis of mapping and exploration have been prepared.

UTAH

The original coal resources of Utah as determined by mapping and exploration are here estimated to be 32,678 million tons, comprising 32,522 million tons of bituminous coal and 156 million tons of subbituminous coal. This estimate is a summation of 12 estimates of resources in individual fields. Of these 12 estimates, nine are contained in previous publications of the Geological Survey, and three were prepared by the writer and associates for use in this summary. The accompanying table shows the amount and source of each individual estimate.

For eight of the areas summarized in the table, the estimates are based on detailed information on resources in individual beds and townships or in individual townships. Additional information on the distribution of resources is contained in the publications cited in the table.

The nine previously published estimates that make up the greater part of the total shown in the table were prepared by various individuals during the period from 1912 to the present and, as a result, show some individual variation. Following a pattern that has been characteristic of coal resource estimates, the older estimates tend to be larger than recent estimates. This is particularly well illustrated by the difference between the comparatively large Lupton estimate of 1912 for the Blacktail (Tabby) Mountain field and the comparatively small Kinney estimate of 1955 for the nearby Vernal field. The two fields are about the same size, and the coal is contained in rocks of the same age. On this basis of appraisal the Lupton estimate of 1916 for the relatively small Castle Valley field also may be high as compared with the author's estimate for the larger, nearby Henry Mountains field, which is presented in the accompanying table.

In spite of these discrepancies, the total obtained by adding all documented figures, regardless of date or method of preparation, indicates the order of magnitude of resources determinable from existing information.

OTHER STATES

The coal resources of Arizona, California, Idaho, Louisiana, Mississippi, Nebraska, and Nevada are combined in table 1 under "Other States." In each of these States the resources are small or information about the occurrence and distribution of coal is so scanty that preparation of a meaningful estimate is impossible.

The accompanying table gives the estimated resources, and the source of the estimate used, for each State. The individual figures, however, have a very low order of accuracy and are presented only to show how the totals by rank in table 1 were obtained.

Estimated original coal resources of Utah as determined by exploration and mapping

[In millions of short tons]

Field and county	Estimated resources	Source of estimate	Remarks
		Bituminous coal	
Henrys Fork field, Daggett County.			Insignificant resources in Frontier Formation and Mesaverde Group. (See Gale, 1910, p. 233–239.)
Blacktail (Tabby) Mountain field, Duchesne and Wasatch Counties.	1,858	Lupton (1912, p. 628)[1]	Estimate is high as compared to recent estimate for the similar-sized Vernal field.
Vernal field (west end only), Uintah County.	143	Kinney (1955, p. 143–149)[2].	Insignificant additional resources in east end of field. (See Gale, 1910, p. 204–219.)
Book Cliffs field, Carbon, Emery, and Grand Counties:			
Castlegate quadrangle	1,275	Clark (1928, p. 100–103)[2].	Resource area covers 43 sq. mi.
Wellington and Sunnyside quadrangles.	2,629	Clark (1928, p. 159–162)[2].	Resource area covers 237 sq. mi.
Book Cliffs south and east of Sunnyside quadrangle.	518	Fisher (1936, p. 56)[2]	Resources within 2 miles of outcrop.
Wasatch Plateau field, Emery and Sevier Counties.	13,000	Spieker (1931, p. 201–206).[2]	Includes 7,800 million tons in beds more than 30 in. thick.
Mount Pleasant field, Sanpete County.			Modest resources 1,000 ft. below surface. (See Duncan, 1944.)
Wales field, Sanpete County			Small resources. (See Clark, 1914.)
Salina Canyon field, Sevier County.	170	Spieker and Baker (1928, p. 151–152)[2].	Resource area covers 30 sq. mi.
Castle Valley or Emery field, Emery and Sevier Counties.	1,429	Lupton (1916, p. 86)[1]	Coal in Ferron Sandstone Member of Mancos Shale. Estimate may be high.
Henry Mountains field, Wayne and Garfield Counties.	200	Provisional gross estimate by writer.	Data from Hunt, Averitt, and Miller (1953, p. 216–217, pl. 22).
Kolob Terrace field, Iron, Washington, and Kane Counties.	4,000	Estimate by W. B. Cashion and writer by extrapolation from work in two parts of the field.	(See Cashion, 1961; Averitt, 1962, p. 61–63.)
Kaiparowits Plateau field, Garfield and Kane Counties.	7,300	Estimate by F. C. Peterson, based on recent detailed mapping.	Potential total is much larger (F. C. Peterson, oral commun., 1967).
San Juan River field, San Juan County.			Small resources. (See Gregory, 1938, p. 110.)
Total, bituminous coal	32,522		
		Subbituminous coal	
Lost Creek field, Morgan County.			Insignificant resources. (See Clark, 1918.)
Coalville field, Summit County.	156	Campbell (1917)	Data from Wegemann (1915).
		Semianthracite	
Harmony field, Iron and Washington Counties.			Insignificant resources of high-ash coal. (See Richardson, 1909, p. 384–388.)
Total, all ranks	32,678		

[1] Report contains breakdown of resources by townships only.
[2] Report contains breakdown of resources by beds and by townships.

Estimated original coal resources of Arizona, California, Idaho, Louisiana, Mississippi, Nebraska, and Nevada

[In millions of short tons]

State and field	Bituminous coal	Subbituminous coal	Lignite	Total	Source of estimate
Arizona:					
Black Mesa		[1] 4,000		4,000	Based on statements by G. A. Williams (1951) and Kiersch (1956).
Pinedale		25		25	Provisional, gross estimate by author, based on data from Veatch (1911).
Deer Creek	10			10	Campbell (1929).
Total	10	4,025		4,035	
California:					
Amador County			50	50	Total estimate of 100 million tons by Karp (1949). Also see Jennings (1957). Provisional breakdown, according to rank, by author.
Mount Diablo		40		40	Do.
Stone Canyon	10			10	Do.
Total	10	40	50	100	
Idaho	600	(2)	(2)	600	Campbell (1929).
Louisiana			(2)		
Mississippi			(3)		See C. S. Brown (1907).
Nebraska	(3)				See Pepperberg (1910).
Nevada	(3)		(3)		See Hance (1913), Toenges and others (1946), Bowen (1913), Mapel and Hail (1959).
Total, all States	620	4,065	50	4,735	

[1] Includes bituminous coal in the Mesaverde Group of the Black Mesa field.
[2] Small.
[3] Insignificant.

PROBABLE ADDITIONAL RESOURCES IN UNMAPPED AND UNEXPLORED AREAS

The preceding analysis of data on resources as determined from mapping and exploration provides convincing evidence that unmapped and unexplored areas contain additional resources in widespread abundance. An estimate of the probable tonnage in these areas is presented in table 2. It is noteworthy that the probable additional tonnage is essentially the same as the tonnage determined from existing mapping and exploration. The evidence on which the additional tonnage is based is summarized in the following paragraphs.

In most States for which modern estimates of coal resources based on existing mapping and exploration have been prepared, substantial areas of coal-bearing rock were omitted from consideration because of lack of specific information about the occurrence and thickness of the coal. In Colorado, for example, 75 percent of the coal-bearing area was thus omitted; in eastern Kentucky, 13 percent was omitted; in Montana, 9.3 percent; in North Dakota, 1.7 percent; in Washington, 66 percent; and in Wyoming, 53.5 percent. A part of the assumed additional tonnage is present in such areas.

Because most mining and prospecting in the United States are done along outcrops, very little information is available about the occurrence of coal at depth or at a distance of more than a few miles from the outcrops, and no information is available about resources in the centers of the large coal basins. Therefore, most of the estimated resources based on mapping and exploration are confined to a narrow zone a few miles wide parallel to the outcrops of the individual coal beds. This is well illustrated by the fact that 89 percent of the resources classified in figure 5*B* are less than 1,000 feet below the surface. A large part of the estimated additional resources is assumed to be covered by more than 1,000 feet of overburden.

Many coal-bearing areas, particularly those remote from present means of transportation or centers of use, have been mapped or examined only in reconnaissance. In such areas, information is generally available only for the thicker and higher quality beds, and, as a result, resource estimates tend to be small. The estimated additional resources include an allowance for coal that should be discovered when detailed geologic mapping is extended into such areas.

In areas covered by reconnaissance mapping, and in many others as well, data on the coal-bearing rocks and on individual coal beds are generally insufficient to permit the establishment of correlations between coal beds in all parts of the areas. Where correlations cannot be established, the estimated resources are restricted to the vicinity of known outcrops. Where correlations can be established, resources can be inferred to exist at greater distances between outcrops, and the total estimated resources tend to be larger. The estimated additional tonnage presented in table 2 includes an allowance for coal that may be delineated as a result of improved knowledge of stratigraphy and of coal bed correlations.

From the foregoing discussion and from the distribution pattern shown in figure 6 it is apparent that the bulk of the estimated additional resources in unmapped and unexplored areas is in the 1,000- to 2,000-foot overburden zone, and that smaller amounts are present in other overburden zones. The probable distribution, according to thickness of overburden, of the total estimated coal resources of the United States both in mapped and explored areas and in unmapped and unexplored areas is shown in figure 7.

The estimated additional resources in unmapped and unexplored areas are, of course, only an approximation, based primarily on extrapolation from the more reliable and more useful estimates determined from mapping and exploration. Although large, the estimated additional resources are, for the most part, relatively inaccessible for mining at present. Furthermore, the exact size, distribution, and future

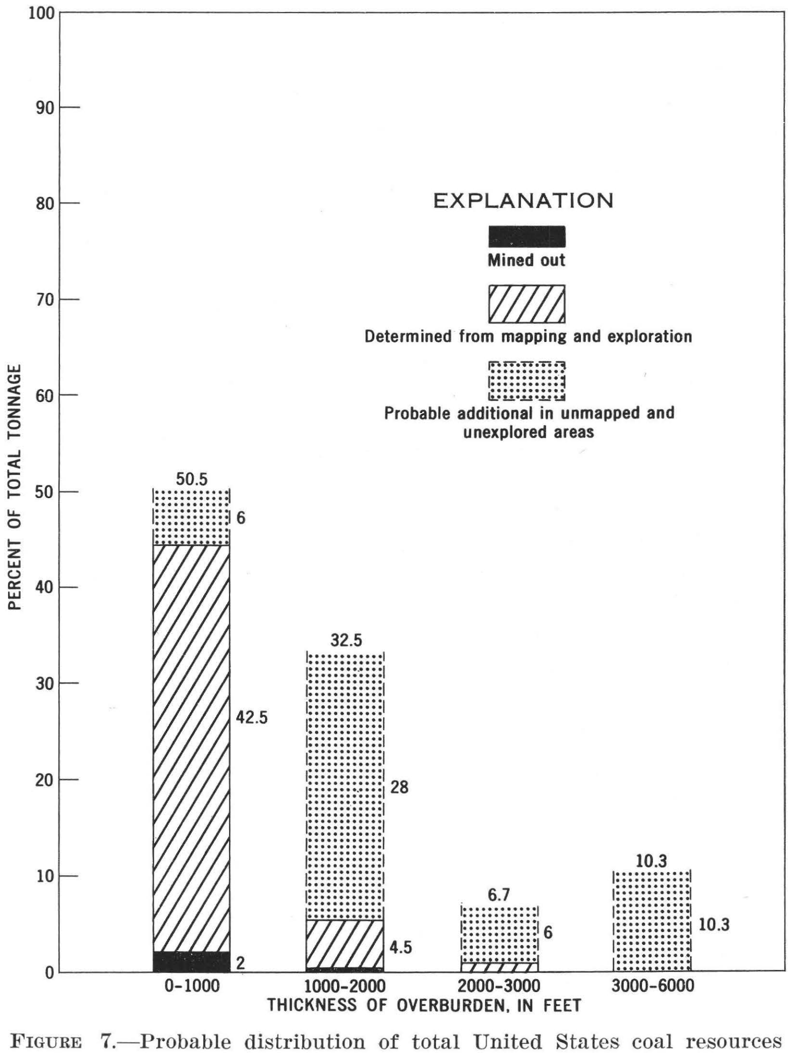

FIGURE 7.—Probable distribution of total United States coal resources according to thickness of overburden.

utility of such resources can be ascertained only by detailed mapping, exploration, and study over a long period. Nevertheless, the estimated additional resources in unmapped and unexplored areas constitute an important part of the total resource that needs to be considered in advanced planning for the utilization of all energy resources.

NEED FOR ADDITIONAL WORK

This summary study of coal resources has revealed many obvious deficiencies in knowledge of the distribution, extent, and correlation of coal beds:

1. Substantial areas had to be omitted from consideration in preparing estimates based on mapping and exploration.
2. A very large percentage of coal had to be classified as inferred (fig. 5*C*).
3. Very little information is available on coal in overburden zones deeper than 1,000 feet (fig. 5*B*).
4. In many areas, particularly the eastern coal fields, where information is generally considered to be more abundant, much of the geologic mapping was done in the period 1900–20 and does not provide the data necessary for modern needs.

Full knowledge about coal in the United States is thus dependent on a continuing, active program of detailed geologic mapping and exploratory drilling in the coal-field areas, accompanied by periodic inventories of resources.

The cooperation between Government and industry in the accumulation, preservation, and analysis of coal-resource data, which has been so effective in the preparation of recent resource estimates, should be strengthened and improved at every opportunity.

PREVIOUS ESTIMATES OF UNITED STATES COAL RESOURCES

Three estimates of United States coal resources have been prepared in previous years to serve specialized needs. These estimates were based on different assumptions and procedures, and thus differ considerably in magnitude. However, when the points of difference are taken into account these older estimates are found to be in reasonably good accord with each other and with the improved and more detailed estimate presented in this report. Pertinent information about each of the older estimates is summarized in the following paragraphs.

M. R. CAMPBELL, 1909–29

The first considered estimate of the total coal resources of the United States was prepared by M. R. Campbell of the U.S. Geological Survey and published with successive revisions several times between 1909 and 1929. (See Campbell and Parker, 1909; Campbell, 1913, 1917, 1929.) For more than 40 years this estimate served as the principal reference on United States coal resources. It has been cited or republished many times by other individuals and organizations.

The Campbell estimate was a pioneer attempt to estimate the total resources originally present in the ground before mining began. With the limited data then available, Campbell made statistical allowance for coal in all unmapped and unexplored areas, and primarily for this reason the estimate could not be classified according to thickness of beds and overburden.

In the Campbell estimate the following minimum thicknesses were used for the several ranks of coal:

Rank	*Minimum thickness (inches)*
Bituminous coal and anthracite	14
Subbituminous coal	24
Lignite	36

Except for this major breakdown of resources according to rank, all coal above the stated minimum thicknesses was included in a single category. The estimate was based on an assumed average specific gravity of 1.3, which is equivalent to a weight of 1,770 tons per acre-foot, for coal of all ranks.

The estimate prepared by Campbell and Parker (1909) included data by States in the 0- to 3,000-foot overburden category only. Estimates prepared by Campbell in the period 1913–22 (Campbell, 1913, 1917) included data by major coal basins or regions only, and included coal in both the 0- to 3,000-foot and the 3,000- to 6,000-foot overburden categories. A later estimate prepared by Campbell (1929), and estimates by Hendricks (1939), and Buch, Hendricks, and Toenges (1947) included data by States only, and did not include coal in the 3,000- to 6,000-foot overburden category.

The table on page 48 shows all estimates for the conterminous United States prepared by Campbell and adopted or adjusted by subsequent writers. The Campbell estimate has been accepted and reprinted by many writers, most of whom have cited estimates prepared in the period 1913–22 (Campbell, 1913, 1917), apparently unaware of the improvements introduced by Campbell (1929), updated and reprinted by Hendricks (1939), and further improved by Buch, Hendricks, and Toenges (1947).

COMPARISON BETWEEN THE CAMPBELL ESTIMATE AND THE PRESENT ESTIMATE

The table below includes for purpose of comparison the new estimate presented in detail in tables 1 and 2 and in earlier pages of this report. This new estimate is a summation of the work and experience of many specialists on coal in individual States, as cited in table 1. It is based on a review and analysis of about twice as much information as was available to Campbell, and is intended to replace the

Campbell estimate and all derivatives of the Campbell estimate. Because the new estimate is for remaining resources as of January 1, 1967, and includes data on Alaska, and the previous estimates were for original resources, and do not include Alaska, the new estimate had to be adjusted downward as explained in footnotes 1, 2 and 3 of the table. With this adjustment to a common basis, the new estimate is seen to be slightly smaller than any previous estimate.

In the 0- to 3,000-foot overburden category, for example, the new estimate is 14 percent smaller than the estimate by Buch, Hendricks, and Toenges (1947), and 17 percent smaller than the estimate by Campbell (1929). In the 3,000- to 6,000-foot overburden category it is only half of the previous estimate of Campbell 1917. In total, it is 20 percent less than the estimate of Buch, Hendricks, and Toenges (1947), and 22 percent less than the estimate of Campbell (1929).

A discussion of the reasons for these minor differences follows.

Total original coal resources of the conterminous United States as estimated by M. R. Campbell and subsequent writers

[In billions of short tons]

Source of estimate	Original resources in the ground		
	Overburden 0–3,000 ft	Overburden 3,000–6,000 ft	Total
Campbell and Parker (1909)	3, 076	[1] 667	3, 743
Campbell (1913, 1917)	3, 554	667	4, 221
Campbell (1922, see Campbell, 1917)	3, 553	667	4, 220
Campbell (1929); Hendricks (1939)	3, 215	[1] 667	3, 882
Buch, Hendricks, and Toenges (1947)	3, 144	[1] 667	3, 811
This report, adjusted	[2] 2, 689	[3] 332	3, 021

[1] No estimate in this category in cited report. Campbell estimate of 667 billion tons for Rocky Mountain States presented in reports of 1913–22 inserted for purpose of obtaining a total.

[2] Remaining resources of 2,873 billion tons as of Jan. 1, 1967, from table 2, minus 260 billion tons for Alaska, which was not included in previous estimates; plus 76 billion tons, representing past production and assumed losses from beginning of mining to Jan. 1, 1967.

[3] Original resources of 337 billion tons from table 2, minus 5 billion tons for Alaska, which was not included in previous estimates.

REASONS FOR DIFFERENCE IN THE 0- TO 3,000-FOOT OVERBURDEN CATEGORY

In the 0- to 3,000-foot overburden category, the difference between the Campbell estimate and the new estimate is explained primarily by a fundamental difference in point of view and method of work. Campbell and associates assumed that coal beds are continuous tabular bodies. They established the total cumulative thickness of coal above the minimum permissible thickness in the full thickness of coal-bearing rocks at the outcrop, and, using a suitable weight factor, multiplied this cumulative thickness by the total area of coal-bearing rocks. This method tends to yield totals somewhat larger than the totals actually present because it does not take into account the vagaries of coal occurrence, such as the lenticularity of beds, the normal thinning that occurs away from old shorelines, stream channels that locally cut out coal beds, and changes in sedimentation that produced environments unfavorable for coal deposition and preservation. The present generation of estimators have taken these factors into account, and, in general, have based estimates on consideration of individual beds.

Although modern concepts concerning the nature of coal deposition tend to produce smaller and more accurate estimates, the newer estimates are larger than the Campbell estimates for Arkansas, Illinois, Indiana, North Carolina, South Dakota, and Utah. The increases in these States were brought about by much additional positive information on coal occurrence, thickness, continuity, and correlation accumulated since Campbell's time.

In Kentucky, Montana, and North Dakota, the newer estimates are only slightly smaller than the Campbell estimates. In these States the sequences of coal-bearing rock are thick, and coal beds are both numerous and thick. Mapping and exploration in these States since Campbell's time have clearly revealed the presence of coal in quantities about as estimated on less certain evidence by Campbell.

For the remainder of the States (except Alaska, which Campbell did not consider) the newer estimates are smaller than the Campbell estimates. For many States in this category, the sequence of coal-bearing rocks is thin and coal beds are few or thin, or both. In such States, Campbell and associates saw only localities where the thicker beds and parts of beds had been prospected and mined at the outcrops, and they did not see or take into account areas where the coal is thin or absent. In Iowa, Kansas, Missouri, Michigan, and Tennessee, for example, extensive mapping and prospecting since Campbell's day have located large areas in which the coal is thin or absent. Findings in Michigan and Tennessee are typical.

For Michigan, the Campbell estimate of 2,000 million tons for original resources has been replaced by a smaller estimate of 705 million tons for remaining resources as of January 1, 1967, on the basis of a study by Cohee, Burns, Brown, Brant, and Wright (1950). In an examination of subsurface data in 33 townships (1,188 square miles) in the more heavily explored and developed part of the Michigan coal field, Cohee and colleagues found that only 41 square miles was underlain by continuous, correlated coal beds more than 14 inches thick. For this smaller area they estimated the original resources to have been 297 million tons. Of this total, 92 million tons has been mined and lost in mining to January 1, 1967, so that 205 million tons remains in the ground.

In considering the possibility of finding additional coal outside this selected area, Cohee and colleagues stated that scattered areas totaling 1,900 square miles in 70 townships are underlain by black shale that could contain coal beds. On the assumption that prospecting in these areas will disclose coal in the same ratio as the 1,188 square miles previously examined, the additional potential resources would be about 500 million tons. Thus, as here estimated, the remaining resources of Michigan as of January 1, 1967, would be 205 million tons, plus 500 million tons, for a total of 705 million tons. This smaller estimate is considered generous in the light of existing information.

In Tennessee, the Campbell estimate of 25,665 million tons for original resources would require an average of about 4.5 feet of coal over the entire Plateau coal field. According to E. T. Luther, Assistant State Geologist of Tennessee (written commun., Apr. 1965), mapping and exploration in Tennessee since the Campbell estimate was prepared has shown "that great stretches of the Plateau are underlain by no coal, even as thick as 16 inches * * * and that no seams exist whose continuity and uniform thickness may be assumed more than a few miles from information points." Luther's estimate of 4,652 million tons as the remaining resources January 1, 1967, is more accurate than the Campbell estimate.

In addition to lack of continuity of coal beds, other aspects of coal geology, as cited in examples below, have contributed to the smaller modern estimates.

For Alabama, Campbell estimated 67 billion tons for original resources to a depth of 3,000 feet, whereas the new estimate sets the figure at about 34 billion tons. A major part of the difference is found in the Warrior coal basin. Campbell, of necessity, assumed that the basin was underlain by coal in beds comparable in number and thickness to those exposed on the eastern and northern edges of the basin. Since Campbell's time, however, a large amount of mapping and exploratory drilling has shown that the coal beds thin and pinch out basinward, and that the amount of sandstone in the sequence of coal-bearing rocks also increases in this direction. For an area of 2,600 square miles in the more accessible and better explored part of the basin where Campbell estimated about 44 billion tons, Culbertson (1964, p. B66), using more abundant and more reliable data, estimated 11.9 billion tons. Evidence of a similar nature can be cited for other Alabama coal fields, thereby confirming that the newer and smaller estimate is more accurate than the older one.

REASONS FOR DIFFERENCE IN THE 3,000- TO 6,000-FOOT OVERBURDEN CATEGORY

For coal in the 3,000- to 6,000-foot overburden category the new estimate is significantly smaller than the Campbell estimate, primarily because of improved knowledge of the structure of the deeper coal basins in the Rocky Mountain region. Campbell and his associates assumed that these basins were relatively shallow, and that the coal-bearing rocks were structurally depressed in the centers no more than about 6,000 feet. This interpretation permitted the assumption of substantial resources in the central parts of these basins, both in the 0- to 3,000-foot overburden category and in the 3,000- to 6,000-foot overburden category. Recent oil and gas exploration in the Rocky Mountains has shown that most of these basins are very deep. The coal-bearing rocks of the Uinta Basin, for example, are 6,000 feet below the surface only a few miles from the outcrops. In marked contrast, the coal-bearing rocks of the San Juan Basin, northwestern New Mexico, are structurally depressed only to about 4,000 feet in the deepest central parts.

These revised structural interpretations required a significant reduction in the estimated resources in the 3,000- to 6,000-foot overburden category—from 667 billions tons in the Rocky Mountain States as estimated by Campbell (1917 [1922 repr.]) to 337 billion tons for all States as shown in table 2. Although Campbell considered deeply buried coal only in the Rocky Mountain region, the new estimate presented in table 2 of this report records modest additional amounts of such coal in Alabama, Alaska, Oklahoma, Virginia, and Washington, which were not considered by Campbell.

The points of difference between the two estimates and the reasons therefor, as summarized above, permit several broad generalizations:

1. The Campbell estimate was an adequate extrapolation of the data available in the period 1909–29.
2. The Campbell estimate is somewhat too large for the stated parameters. It cannot be supported by examination and interpretation of the more abundant data now available.
3. In the present new estimate, the figures for individual States range more widely than they did in the outdated Campbell estimate. Thus, in the present estimate, figures for six States are larger than those in the Campbell estimate; figures for three States are nearly the same; and the remainder are smaller, all of which results in a smaller total.
4. As additional information is accumulated about coal in the United States, and as new State estimates are prepared in the future, the spread between State estimates is more likely to increase than to decrease. This is to say, opportunities for increasing resource estimates are best in States that are estimated to contain the largest resources, and the possibility of reducing estimates is most likely in States that are estimated to contain the smallest resources.

5. The new State estimates are much more useful than the older, Campbell estimates because about half of the total included in the estimates is based on a bed-by-bed analysis of coal in the immediately accessible parts of the coal-field areas, and the results of this analysis have been published in considerable detail in the many State summary coal reports cited in table 1.

UNITED STATES COAL COMMISSION COMMITTEE REPORT, 1922

The recoverable coal resources of the United States as of January 1, 1922, were estimated to be 1,634 billion tons by a committee established by the United States Coal Commission. This committee, known at that time as the Engineers' Advisory Valuation Committee, was requested to estimate the market value of coal mines and of the coal in the ground. The Coal Commission did not accept the estimate of the valuation committee for use in the Commission reports, but permission was given for separate publication by the committee (Am. Inst. Mining Metall. Engineers, 1924).

The committee's estimate of recoverable resources, now largely of historic value, was based on estimates of original resources in individual States prepared by Campbell and by several State surveys. These estimates were reduced to allow for future mining losses and to exclude "thin and unavailable coal." No specific information as to the criteria used in reducing the basic original-resource figures is contained in the committee report. It is interesting to note, however, that if future recoverability is assumed to be 50 percent, the recoverable resources of coal in the United States as of January 1, 1919, based on the Campbell estimate of that period, totaled 1,768 billion tons, whereas the recoverable resources as of January 1, 1922, suggested by the valuation committee, totaled 1,634 billion tons.

A few writers have implied that the estimate of the valuation committee differed significantly from the Campbell estimate because these writers failed to recognize that the Campbell estimate was for original coal resources in the ground, whereas the committee's estimate was for recoverable resources as of January 1, 1922. The two estimates are in close accord when they are adjusted to the same basis of comparison.

UNITED STATES ARMY CORPS OF ENGINEERS, 1952

A survey of the United States to determine general areas suitable for the location of synthetic liquid-fuel plants was completed in 1952 by Ford, Bacon and Davis under the auspices of the U.S. Army Corps of Engineers (1952, p. 17, 18). The estimated recoverable coal resources, as of January 1, 1949, considered during the survey, totaled about 170 billion tons, of which a maximum of 126 billion tons was deemed suitable for immediate large-scale use in the manufacture of synthetic liquid fuels.

The major objective of the Corps of Engineers survey was to outline large blocks of coal that would be immediately available for large-scale mining to supply hypothetical synthetic liquid fuel plants. The maximum depth of coal considered in the Corps of Engineers estimate, for example, is 1,500 feet, whereas in the Geological Survey estimate the resources of coal are computed in three categories: 0–1,000 feet, 1,000–2,000 feet, and 2,000–3,000 feet. The minimum thickness of coal considered for underground mining in the Corps of Engineers estimate is 24 inches for bituminous coal and 48 inches for lignite, whereas the Geological Survey estimate includes in several categories of thickness bituminous coal in beds as thin as 14 inches and lignite in beds as thin as 30 inches.

The Corps of Engineers figure of 170 billion tons is thus a very conservative statement of recoverable coal known to be available for immediate use under present mining conditions. If, for the moment, this figure is doubled to 340 billion tons to represent coal in the ground so that it can be compared with U.S. Geological Survey data summarized in this report, it is found to be 22 percent of the total of 1,560 billion tons recorded in table 1. This is comparable with the estimate for measured, indicated, and inferred resources in thick beds and less than 1,000 feet below the surface, which is shown in table 5 and figure 6 to be 25 percent of the total.

The larger figure presented in this report includes, in separate categories, resources of both present economic interest and possible future usefulness, and thus provides a more comprehensive statement of information available about the total coal resources of the United States.

COKING-COAL RESOURCES

Coke is usually manufactured from blends of two or more coals of different composition and may incorporate small amounts of other ingredients such as anthracite fines, petroleum coke, or low-temperature char. In spite of the common use of the term "coking coal," very little coal can be used alone to produce coke suitable for metallurgical processes. When a single coal is used, it is of medium-volatile bituminous rank and reasonably free of ash and sulfur. Resources of such coal are small and are rapidly being depleted. The desired properties are more readily obtained by blending two or more coals of different rank and composition. Generally, 15–30 percent of low-volatile bituminous coal, which is very strongly coking, is blended with 85–70 percent of high-volatile bituminous coal, which is weakly coking. In 1966 high-volatile bituminous coal constituted 65 percent of the total coal made into coke, medium-volatile constituted 11 percent, and low-volatile constituted 24 percent (U.S. Bur. Mines, 1966, p. 751). The nature of the original plant constituents also is a factor in determining coking properties, as are the deleterious constituents, ash, sulfur, and phosphorus. With these several variables to be taken into account, modern coking-coal blends have become complex mixtures of carbonaceous material.

Most of the areas of high-rank and high-quality coal best suited for the manufacture of coke and coke chemicals are in the northern part of the Appalachian basin, principally in West Virginia, Pennsylvania, eastern Kentucky, and Virginia. Substantial amounts of coal suitable for the manufacture of coke are also present in Alabama in the southern end of the Appalachian basin. Bibliographies accompanying summary reports on various Appalachian basin States as cited in table 1 contain information on the occurrence and composition of coking coal in the respective States. Additional information is contained in reports by Dowd and others (1950–52c; 1955–56), Wallace and others (1952–55), Williams and others (1954–56), Hershey and others (1955–56), Blaylock and others (1955, 1956), Travis and others (1956), Lowe and others (1956), Provost and others (1956), and Tavenner and others (1956).

Coal in the Illinois basin is weakly coking, but because of its proximity to the steel manufacturing center at the southern end of Lake Michigan small amounts of it are used in this area in coking-coal blends that incorporate higher rank coal from the Appalachian basin. (See Jackman and Helfinstine 1967.)

In a few areas in the West, principally in Colorado, Utah, Oklahoma, Arkansas, Washington, and New Mexico, coal is produced that is satisfactory for the manufacture of coke when used in blends. The most important areas are the Raton Mesa region, Colorado–New Mexico; the Sunnyside field, Utah; and the Somerset–Crested Butte–Carbondale region, Colorado. These areas stand out prominently in plans for the industrial development of the West. Summary information about resources of coking coal in the West is contained in reports by Averitt (1966), Haley (1960), R. B. Johnson (1961), Landis (1959), and Trumbull (1957).

Because of the almost limitless possibilities of blending coals and hydrocarbons in the manufacture of coke, and because of the certainty that the acceptable amounts of impurities in coke will be allowed to increase and coking properties to decrease as the higher rank and higher grade coals are depleted, the resources of bituminous coal that can be used in the manufacture of coke are very large. Of the remaining bituminous coal resources as determined by mapping and exploration to January 1, 1967 (table 1), about 40 percent, or about 270 billion tons, is high enough in rank, quality, and composition to be used if required in major or minor proportions in coking-coal blends.

LOW-VOLATILE BITUMINOUS COAL

Of all coal used in the manufacture of coke, low-volatile bituminous coal is the most important and most valuable, because (1) it is very strongly coking and can be used in coking-coal blends to upgrade larger resources of high-volatile bituminous coal, which is less strongly coking; (2) most areas of low-volatile bituminous coal are on the east edge of the Appalachian coal basin near centers of population and industry on the eastern seaboard; (3) it contributes less to air pollution than lower rank coal; and (4) it is in relatively short supply. An analysis of data on the occurrence of low-volatile bituminous coal in State summary reports on Pennsylvania, West Virginia, Maryland, Virginia, Alabama, Oklahoma, Arkansas, and Colorado, suggests that the original resources of low-volatile bituminous coal in the ground totaled about 20,000 million tons. This figure is about 1.2 percent of the total original coal resources of the United States as determined by mapping and exploration. This proportion will not change significantly because any change in the figure for resources of low-volatile bituminous coal is likely to be accompanied by a comparable change in the figure for total resources.

Mining has been carried on extensively in areas containing low-volatile bituminous coal because the same properties that render it important in the manufacture of coke—high heat value, low volatile-matter content, and low ash and sulfur contents—also render it desirable to the manufacturing industries and to the electric utilities, particularly those operating in areas where the abatement of air pollution is a municipal objective.

In many areas of less desirable and less readily accessible coal in the United States, the remaining resources are very nearly equal to the original resources because little mining has been done. The areas containing low-volatile bituminous coal, on the other hand, are rapidly being mined out, and the remaining resources of this coal are now less than 1 percent of the total coal remaining in the United States, of which no more than half can be regarded as recoverable. With only a limited supply of low-volatile bituminous coal available, it is apparent that coking operations and metallurgical processes must ultimately be adjusted to permit increasing use of lower rank coal.

STRIPPING-COAL RESOURCES

The amount of coal mined and potentially minable by strip-mining methods has increased steadily throughout the years, concomitant with an impressive increase in the size and efficiency of strip-mining machinery. In 1917, strip mining accounted for only 1 percent of total United States production of bituminous coal and lignite as compared with 33.7 percent in 1966. In 1920 there were 312 power shovels and draglines in operation, whereas by 1966 there were 3,366; most of these machines were far larger and more efficient than their 1920 predecessors. In 1957 the largest shovel in operation had a capacity of 70 cubic yards, or 105 tons; in 1965 the largest shovel had a capacity of 180 cubic yards; and in 1966 shovels in the planning and construction stage had capacities of 200 cubic yards.

The gradual introduction of larger and more efficient strip-mining machinery has permitted increases over the years in the maximum economical ratio of overburden thickness to coal thickness, in the average thickness of overburden removed, and in the maximum thickness of overburden removed. In 1955, for example, the maximum economical ratio of overburden thickness to coal thickness was roughly 20:1 for most existing strip-mining machinery; in 1965 the ratio was 30:1. In 1955, the average thickness of overburden removed was 42 feet; in 1965, about 50 feet. In 1955, the maximum thickness of overburden removed was in the 70-foot range; in 1965, it was in the 125-foot range.

At the present level of technologic development and knowledge of coal resources, the original stripping-coal resources of the United States with overburden in the range of 0–100 feet are estimated to be 139,969 million tons (table 6). This figure is 9.6 percent of the estimated original coal resources of the United States thus far determined by mapping and exploration in the 0- to 1,000-foot overburden category, which suggests that it is a reasonable maximum.

If the 139,969-million-ton figure is reduced to allow for past production and losses in mining to January 1, 1967, and for estimated future losses in mining, the recoverable stripping-coal resources of the United States as of this date total 108,095 million tons. This figure is too large to be appreciated except by comparison with smaller and more meaningful numbers. It is, for example, 28 times the cumulative strip-coal production of 3,876 million tons from the beginning of strip mining to January 1, 1967, and it is 600 times the 1966 strip-coal production of 179 million tons. These comparisons do not represent life expectancy because the rate of production and the estimated size of the resource will surely change in the future. A more detailed account of the stripping-coal resources of the United States, including a comprehensive bibliography, is contained in another bulletin (Averitt, 1968).

TABLE 6.—*Estimated original resources of stripping coal in the United States in beds generally less than 100 feet below the surface*

[Figures are for resources in the ground, of which about 80 percent may be considered recoverable]

State	Millions of short tons	State	Millions of short tons
Alabama	800	North Dakota	50, 000
Alaska	2, 000	Ohio	5, 000
Arizona	100	Oklahoma	500
Arkansas	263	Pennsylvania	8, 000
Colorado	1, 200	South Dakota	400
Illinois	[1] 23, 000	Tennessee	200
Indiana	3, 524	Texas	3, 282
Iowa	600	Utah	300
Kansas	600	Virginia	1, 000
Kentucky	6, 000	Washington	100
Maryland	100	West Virginia	6, 000
Missouri	1, 000	Wyoming	10, 000
Montana	15, 000		
New Mexico	1, 000	Total	139, 969

[1] Overburden 0–150 ft.

PEAT RESOURCES

Peat, the first stage in the alteration of plants to coal, is the partly carbonized remains of roots, trunks of trees, twigs, seeds, shrubs, grasses, and mosses that have been covered or saturated with water so that decomposition is retarded. It contains a large proportion of the carbon of the original vegetable matter, and the plant structures of which it is composed generally are visible without the aid of a microscope. In general, peat accumulates on poorly drained land in regions of cool climate or high humidity, where evaporation is slow, and plants may flourish.

Peat is an important fuel in Europe, but only small quantities have been produced as commercial fuel in the United States because of the abundance and superiority of coal. The United States contains large deposits of peat, however, and it is produced commercially for a variety of purposes other than as fuel. Air-dried peat is a source of concentrated organic matter, and it contains about 2 percent nitrogen. It is used in the United States principally for soil improvement and as an ingredient in commercial fertilizers. According to the U.S. Bureau of Mines (1966, p. 803) the use of peat in the United States has increased steadily over the years, and has essentially doubled during the last decade. During 1966, production of peat in the United States totaled 611,085 tons, and imports, obtained mostly from Canada, totaled 293,412 tons. Of the peat produced and sold in the United States, about 96 percent was used directly for soil improvement. The remaining 4 percent was used principally as an ingredient in commercial fertilizers and potting soils, and for packing flowers, shrubs, and bulbs. Small amounts were used in the culture of mushrooms and earthworms. The imported peat was also used primarily for soil improvement.

The peat resources of the conterminous United States have been described in considerable detail in a report by Soper and Osbon (1922), who estimated that the original peat resources totaled 13,827 million tons, calculated on an air-dried basis. Of this total only about 8 million tons was mined between 1922 and January 1, 1967.

The peat resources occur primarily in local deposits distributed throughout two general regions. The northern peat region, which contains about 80 percent of the total resources, comprises Minnesota, Wisconsin, Michigan, eastern South Dakota, the northern parts of Iowa, Illinois, Indiana, Ohio, and Pennsylvania, and New York, New Jersey, and the New England States. The Atlantic coastal region, which contains approximately 19 percent of the total resources, comprises the southern part of Delaware, the eastern parts of Maryland, Virginia, North Carolina, South Carolina, and Georgia, and all of Florida. Small deposits of peat also occur in a narrow belt of land adjoining the Gulf Coast; in the valleys of the Sacramento and San Joaquin Rivers and in Siskiyou, Los Angeles, Orange, and San Bernardino Counties, Calif.; and in the basins of lakes and rivers in Oregon, Washington, and the Rocky Mountain States.

Table 7, taken from Soper and Osbon (1922, p. 92–93) shows the original resources of peat in the United States, calculated on an air-

TABLE 7.—*Estimated original resources of peat in the conterminous United States, calculated on an air-dried basis, by regions and States*

[From Soper and Osbon (1922, p. 92–93). In millions of short tons]

Region and State	Resources	Region and State	Resources
Northern region:		Atlantic coastal region:	
Minnesota	6, 835	Virginia and North Carolina	700
Wisconsin	2, 500	Florida	2, 000
Michigan	1, 000	Other States [1]	2
Iowa	22	Total	2, 702
Illinois	10	Other regions:	
Indiana	13	Gulf Coast [2]	2
Ohio	50	California	72
Pennsylvania	1	Oregon and Washington	1
New York	480	Total	75
New Jersey	15	Total, all regions	13, 827
Maine	100		
New Hampshire	1		
Vermont	8		
Massachusetts	12		
Connecticut	2		
Rhode Island	1		
Total	11, 050		

[1] Includes Delaware, Georgia, Maryland, and South Carolina.
[2] Exclusive of Florida.

dried basis, by regions and States. The report by Soper and Osbon also includes tables of resources classified by counties for the States having important peat resources, as well as detailed descriptions of individual peat deposits.

PRODUCTION OF COAL IN THE UNITED STATES [1]

The cumulative production of coal in the United States to January 1, 1967, totals about 38 billion tons, which is equivalent to about 10 cubic miles of broken coal. Half of this huge total had been mined since January 1, 1930.

The accompanying diagram (fig. 8) shows the distribution by States of the cumulative production in the United States to January 1, 1967.

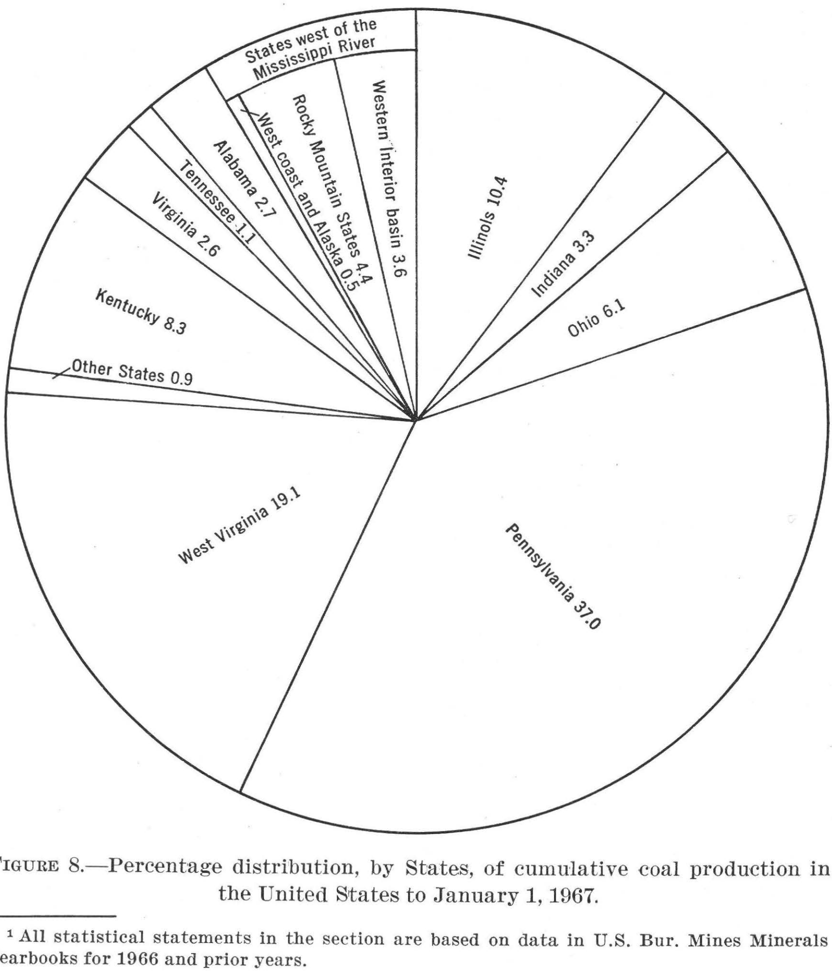

FIGURE 8.—Percentage distribution, by States, of cumulative coal production in the United States to January 1, 1967.

[1] All statistical statements in the section are based on data in U.S. Bur. Mines Minerals Yearbooks for 1966 and prior years.

Most conspicuous in the diagram is the preponderance of production from Pennsylvania and West Virginia, and the fact that more than 90 percent of production came from coal fields east of the Mississippi River.

Before the Revolutionary War, coal was mined only in a very small way by the American colonists, and was used mostly in blacksmith forges. With increased industrialization and growth in population that characterized the 1800's, coal production increased very rapidly, and more than doubled in some decades in the first half of the century. Production continued to double every 10 years or so until about the time of World War I. An early peak in coal production was reached in 1918 when 678 million tons was mined. Following World War I, coal production began a long irregular decline, due in part to the great expansion in use of petroleum and natural gas, which began in the 1920's and has continued until the present time, and in part to the business depression of the 1930's. An unprecedented low of 359 million tons was recorded in 1932.

Following the 1932 depression, coal production increased slowly and irregularly until the outbreak of World War II, which brought about a rapid increase in production. A second, alltime peak of 688 million tons was reached in 1947. Following World War II, coal production again declined as railroads turned almost 100 percent to diesel-powered locomotives, and as oil and natural gas became the preferred fuels for household heating and for other purposes formerly served by coal. This decline continued until 1961, when a new low of 420 million tons was mined. Since 1961, coal production has increased dramatically in response to increased demands by the electric utility industry (see p. 73, and to the lower cost coal made possible by the continued improvement in strip-mining machinery (see p. 56). The 549 million tons of bituminous coal and anthracite produced in 1966 was the highest figure reported since 1951. This amount would fill a continuous line of coal cars extending three times around the circumference of the earth.[2]

The mining and distribution of coal is the second largest mineral industry in the United States. The coal produced in 1966 had an estimated value at the mine mouth or tipple of $2,521 million. This is more than the value of any other mineral or fuel commodity except petroleum and natural gas, and is more than the value of all metallic minerals combined.

In 1966 there were 6,749 operating bituminous coal and lignite mines in the United States, ranging from small mines producing as little as 1,000 tons per year to very large, highly mechanized mines producing

[2] A line of loaded coal cars 1 mile long is assumed to hold 7,500 tons.

more than 500,000 tons per year. About 58 percent of the 1966 production was obtained from 274 mines of the largest class.

About 72 percent of the bituminous coal and lignite mined in 1966 was shipped to its final destination by rail. The remainder was shipped by truck or water, or was used directly at the mine. Rail shipments of coal represent about 25 percent of the total freight handled by the railroads, and about 12 percent of their gross income. The percentage of coal shipped by rail is decreasing slowly through the years, and the percentage shipped by truck and by water is increasing.

Most of the coal mined in the United States is obtained from beds ranging in thickness from 3 to 6 feet, as shown in the table below, taken from a report by Young (1967, p. 2):

Thickness, in feet, of beds mined	*Percent of 1965 production*
<3	12.5
3–6	61.5
6–8	19.4
>8	6.6
Total	100.0

The substantial 12.5 percent credited to beds generally less than 3 feet thick is obtained primarily by strip- and auger-mining methods. Improvements in strip- and auger-mining machinery over the years have resulted in a modest but steady increase in the percentage of coal obtained from the thinner beds.

Coal-mining methods have changed greatly through the years; in 1920, for example, less than 1 percent of underground production of bituminous coal and lignite was mechanically loaded, whereas by 1966 a record 92 percent was mechanically loaded. In 1920, strip mining accounted for only 1.5 percent of the coal produced, whereas by 1966 strip mining accounted for a record 33.7 percent.

The pronounced trend toward mechanization in coal mining has resulted in an increase in productivity per man, and a comparable decrease in the number of men employed. In 1920, when total coal production was somewhat higher than at present, the average productivity was about 4.5 tons per man per day, whereas by 1966 the average productivity was about 18.5 tons per man per day. Over the same period the average number of men employed declined from 639,547 in 1920 to 131,752 in 1966.

CONCENTRATION OF RESOURCES AND PRODUCTION IN SELECTED BEDS

Of the many coal beds known in the United States, a few are thick and continuous over large areas, or they possess special properties that make them commercially desirable. These beds contain a significantly large part of the total resources, and they have yielded the bulk of past production. A few selected beds in this category are discussed briefly below. Most are in the eastern half of the United States because the older, Paleozoic coal beds in the East are more continuous than the younger, Cretaceous and Tertiary coal beds of the West, and because the beds in the East have been explored, mined, and studied in greater detail.

PITTSBURGH BED

The Pittsburgh bed has been described by Ashley (1938, p. 56) as the most valuable individual mineral deposit in the United States and perhaps in the world. It is of minable thickness and is remarkably uniform in character over an area of about 6,000 square miles in Pennsylvania, West Virginia, Maryland, and Ohio. It is recognizable as a stratigraphic unit over a much larger area. According to Cross (1952, p. 34) and Wanless (1956, p. 122) it attains maximum thickness in western Maryland and northeastern West Virginia, and thins in all directions from this area. It is 22 thick feet at places in Mineral County, W. Va., and almost 20 feet thick in small areas in Preston County, W. Va. Farther to the west, in southwestern Pennsylvania and northern West Virginia, it is 8–14 feet thick. In easternmost Ohio and southern West Virginia it is 4–6 feet thick. It thins to generally less than 3 feet in northwestern Pennsylvania, eastern Ohio, and northern Kentucky. Much of the thicker and more accessible coal has, of course, been mined out, but large areas of coal of minable thickness remain in the ground.

An extrapolation of data assembled by Ashley (1938) and by Latimer (1962) indicates that by January 1, 1965, the bed had yielded about 8 billion tons of coal. This is about 35 percent of the total cumulative production of the Appalachian bituminous coal basin and 21 percent of the total cumulative production of the United States to the same date.

Coal from the Pittsburgh bed has a high heat content and excellent coking properties. It was a major factor in the many decisions that led to the establishment of the iron and steel empire at Pittsburgh, Pa. (See Eavenson, 1938; Davis and Griffen, 1944.)

LOWER KITTANNING (NO. 5 BLOCK) BED

The Lower Kittanning bed is thinner than the Pittsburgh bed, but it covers a larger area and contains larger resources. The Lower Kittanning bed, together with possibly correlative beds, extends almost continuously throughout the northern part of the Appalachian bituminous coal basin in Pennsylvania, West Virginia, Ohio, and Maryland. It also extends into northern Kentucky, where it is known as the Princess (No. 6) bed, and it may have a stratigraphic equivalent in the High Splint bed of Virginia, which crops out in hilltops in southwestern Virginia.

According to Wanless (1956, p. 112), and Headlee and Nolting (1940, p. 44–49), the Lower Kittanning is thickest in central West Virginia and thins very gradually in all directions. With minor local variations, thicknesses are commonly as follows: Central West Virginia, maximum of 12 feet; northern West Virginia, 4 feet; western Pennsylvania, 2½–4 feet; Ohio, 2–4 feet; Maryland, generally less than 3 feet; and southern West Virginia, 3–7 feet.

The Lower Kittanning bed has been mined in most areas where it is more than 4 feet thick, and it is second only to the Pittsburgh bed as a major source of coal in the Appalachian bituminous coal basin.

UPPER FREEPORT BED

The Upper Freeport bed is less uniform in thickness than the overlying Pittsburgh bed or the underlying Lower Kittanning bed because it was subjected to local uplift and erosion before deposition of the overlying rocks. Nevertheless, it is a persistent bed throughout large areas in Pennsylvania, West Virginia, and Ohio, and is the third most important bed in the northern part of the Appalachian bituminous coal basin, both in production and in contained resources.

Data assembled by Wanless (1956, p. 120), Headlee and Nolting (1940, p. 33–37), and Ashley (1928, p. 112) show that the bed is thickest on the eastern edge of the basin in southwestern Pennsylvania and central West Virginia.

In Pennsylvania, the Upper Freeport bed is thick and continuous in the counties around Pittsburgh and in the southwestern part of the State, where it ranges in thickness from 2 to 10 feet, and is 4–6 feet thick over considerable areas.

In West Virginia, the Upper Freeport bed is considered to be of minable thickness and purity over an area of 1,165 square miles in a belt running north-south through the central part of the State. In the northern part of the belt it ranges in thickness from 3 to 12 feet and is 4–5 feet thick over large areas. It thins to the south and is generally less than 2 feet thick in Clay and Braxton Counties.

In Ohio, the Upper Freeport bed is very irregular in thickness. It is locally as much as 8 feet thick, but typically thins within a few miles, or tens of miles, to less than 14 inches. Nevertheless, its wide distribution makes it the fourth most important bed in Ohio in known resources.

ELKHORN NO. 3 BED

Of the many coal beds in eastern Kentucky described by Huddle, Lyons, Smith, and Ferm (1963), the Elkhorn No. 3 bed and the Fire Clay bed are the most important in terms of production and contained resources. Both beds are recognizable as stratigraphic horizons over most of eastern Kentucky and parts of adjoining States.

The Elkhorn No. 3 bed is of minable thickness over an area of 2,000 square miles in eastern Kentucky, and of 1,470 square miles in West Virginia, where it is known as the Cedar Grove bed. It has been mined extensively in southeastern Kentucky and in Logan, Mingo, Boone, and Kanawa Counties, W. Va. Where mined it is typically 3–4 feet thick, but local maximum thicknesses of 8 feet have been observed. It has yielded more coal than any other bed in eastern Kentucky, and it contains the largest remaining resources.

FIRE CLAY BED

At most exposures the Fire Clay coal bed contains in its lower part an easily recognizable parting of hard, medium-brown, flint clay, typically 4–6 inches thick. Because of this distinctive parting, the Fire Clay bed is an important unit in stratigraphic correlations and structural interpretations throughout eastern Kentucky, southern West Virginia, Virginia, and Tennessee. The bed is of minable thickness over an area of 1,800 square miles in eastern Kentucky, and of 1,170 square miles in West Virginia, where it is known as the Chilton bed. It has been mined extensively in southeastern Kentucky, and in Logan and Mingo Counties, W. Va. Where actively mined it is typically 3–4 feet thick, but locally it is as much as 8 feet thick. In eastern Kentucky, the Fire Clay bed is second only to the Elkhorn No. 3 bed in past production and in remaining resources.

POCAHONTAS BEDS

The name "Pocahontas" has been assigned to nine coal beds that crop out in the basal part of the Pennsylvanian sequence on the eastern edge of the Appalachian bituminous coal basin near the town of Pocahontas, Va. These beds extend over a relatively small area in Tazewell and Buchanan Counties, Va., and adjoining counties in West Virginia. The Pocahontas beds collectively contain relatively small remaining resources as compared with other more extensive beds in the two States, but they are mined very intensively because of their low ash, high heat content, and special coking properties. The coal in the Pocahontas area is of medium- to low-volatile bituminous rank and is very strongly coking. For this reason it can be used to upgrade blends incorporating larger amounts of high-volatile bituminous coal, which is less strongly coking. It is shipped for this purpose to major steel-manufacturing centers throughout the Eastern United States.

The Pocahontas beds are numbered from 1 to 9 beginning at the bottom of the sequence. The Pocahontas No. 3 bed is the most important of the group. As described by Headlee and Nolting (1940, p. 143–145) and by Brown, Berryhill, Taylor, and Trumbull (1952, p. 11), it extends as a minable bed over 650 square miles in West Virginia, and a somewhat smaller area in Tazewell and Buchanan Counties, Va. Within this area the coal ranges in thickness from 2 to 11 feet and is about 8 feet thick in most operating mines. The coal thins to the southwest and to the northeast and is not mined in these areas. The Pocahontas No. 3 bed has been mined intensively since 1883, and most of the thicker and more accessible coal has been mined out. Most of present mining in the area is in other Pocahontas beds, which are of similar quality but of smaller areal extent.

SEWANEE BED

Most of Tennessee coal production is obtained from six coal beds, of which the Sewanee bed is one of the best. The Sewanee bed crops out throughout the central and southern parts of the Tennessee coal field and extends into nearby parts of Georgia and Alabama. It is mined extensively in the southernmost counties in Tennessee (Luther, 1959, p. 183–184, 189–190, 197–199, and 260–262), where it is typically $2\frac{1}{2}$–$3\frac{1}{2}$ feet thick but locally is 4 feet thick.

PRATT BED

The Pratt bed was an important factor in the establishment of the iron and steel industry at Birmingham, Ala. Through the years it has yielded large amounts of excellent coking coal to support this industry, and it still contains large resources. The bed is of minable thickness over an area of 775 square miles in the Warrior coal basin. In Jefferson County, Ala., near Birmingham, it ranges in thickness from 30 to 75 inches, and averages about 45 inches. Farther to the west, in Walker County, it thins to less than 36 inches and is lower in rank and somewhat higher in ash and sulfur. (See Culbertson, 1964, p. 32.)

MARY LEE COAL ZONE

The Mary Lee coal zone, about 400 feet below the Pratt bed, covers a larger area and contains more coal than any other bed in Alabama. As described by Culbertson (1964, p. 29–31), the zone consists of five closely spaced beds that vary considerably in thickness, persistence, and spacing. At places an individual bed is thick enough to be mined separately. At other places two or more beds coalesce into one bed 10 feet thick or more, including partings. The Mary Lee zone contains at least one bed over an area of 1,500 square miles. Mines located on a bed in this zone typically recover 4–6 feet of coal and locally may recover as much as 10 feet. Coal from the Mary Lee zone is relatively high in ash and low in sulfur. It has been mined extensively in the eastern part of the Warrior basin for the manufacture of coke.

NO. 5 BED

The No. 5 bed is the most widespread and commercially valuable coal bed in the Eastern Interior coal basin. It is known in Illinois as the No. 5, Harrisburg, or Springfield bed; in Indiana as the No. V, Petersberg, or Alum Cave bed; and in western Kentucky as the No. 9 bed (Weller and Wanless, 1939, p. 1379, 1390). It is of minable thickness over an area of about 20,000 square miles in the three States, and it is recognizable as a lithologic unit over an area of about 30,000 square miles. In southeastern Illinois it is 4–5 feet thick over large areas; in Indiana it has an average thickness of 5 feet, and locally is as much as 11 feet thick; and in western Kentucky it is uniformly 4 feet 8 inches to 4 feet 10 inches thick throughout its area of occurrence. From the standpoint of resources and production it is the most important bed in Indiana and western Kentucky, and it is second only to the Herrin No. 6 bed in Illinois. It is more widespread and continuous than the Pittsburg bed and other important beds in the Appalachian basin.

HERRIN (NO. 6) BED

The Herrin (No. 6) bed is recognizable over an area of about 15,000 square miles in the Eastern Interior coal basin, where it is second in commercial importance only to the No. 5 bed. It is known in western Kentucky as the No. 11 bed, and in Indiana as the VIb bed (Weller and Wanless, 1939, p. 1379, 1391). This coal attains maximum thickness in southern Illinois, where it is locally as much as 14 feet thick. In central Illinois and in western Kentucky the Herrin (No. 6) bed is 5–7 feet thick over large areas. It thins eastward and is relatively unimportant in Indiana. It also thins toward the northwest edge of the basin. From the standpoint of resources and production it is the most important coal in Illinois, but it is followed closely by the No. 5 bed. It is the second most important bed in western Kentucky, exceeded only by the No. 5 bed (No. 9 bed of that State).

The Herrin (No. 6) bed is thin but persistent over considerable areas in the Western Interior coal basin. It is correlated with the Mystic bed of Iowa (Landis, 1965, p. 26), and with the Lexington bed of Missouri (Weller and others, 1942, p. 1591).

LOWER HARTSHORNE BED

The Lower Hartshorne bed contains the largest resources and is the most extensively mined bed in both Arkansas and Oklahoma. It is known to be 28 inches or more thick, and less than 3,000 feet below the surface over an area of 610 square miles in the two States, and it is recognizable as a stratigraphic unit over an area of about 3,000 square miles. The area of accessible coal in this bed is smaller than that of important beds in other parts of the United States because the enclosing rocks are folded and locally steeply dipping so that in Arkansas the coal is confined primarily to synclinal areas, and in Oklahoma the coal is accessible only in narrow belts parallel to steeply dipping outcrops.

The Lower Hartshorne bed attains a maximum thickness of 8 feet in Arkansas, and it ranges in thickness from 2½ to 6 feet in the mined areas in Oklahoma. The original resources in parts of the bed 28 inches or more thick total 1,864 million tons, according to data supplied by Haley (1960, p. 806, 808) and Trumbull (1957, p. 313).

LOWER SUNNYSIDE BED

The Lower Sunnyside bed is the best known and most important commercial coal bed in Utah, and perhaps in the Western United States, because it is mined extensively for the manufacture of coke, which is used by the western steel industry. As mapped by Clark (1928, pl. 22) the Lower Sunnyside bed crops out for a linear distance of about 30 miles near the base of the Book Cliffs in the Sunnyside and Wellington quadranges, Carbon County, Utah. Near the town of Sunnyside, where mining is concentrated, the bed ranges in thickness from 7 to 14 feet. It thins north and west of this area but is estimated to be at least 4 feet thick over an area of about 170 square miles in the Sunnyside quadrangle. Some of this coal is remote from the outcrop and is deeply buried. The thickest and most accessible coal is in a belt 2½ miles wide and 14 miles long near the outcrop, extending from about 4 miles south of Sunnyside to about 10 miles northwest of Sunnyside. In this restricted area of about 35 square miles the estimated original resources total about 230 million tons, according to data supplied by Clark (1928, p. 101–102). This represents an overall average coal thickness of 5.7 feet. Additional tonnage is, of course, present in the bed outside this choice belt, and in other beds in the sequence of coal-bearing rocks.

HIAWATHA BED

The Hiawatha bed, in Carbon and Emery Counties, Utah, is more extensive and contains larger accessible coal resources than the Sunnyside bed, but it is not as suitable for the manufacture of coke and is, therefore, mined for other purposes.

As mapped by Spieker (1931, pls. 31 and 32), the Hiawatha bed crops out almost continuously over a linear north-south distance of 75 miles near the base of the east-facing cliffs of the Wasatch Plateau. Because of many reentrants and topographic and structural irregularities in the cliffs, the actual outcrop distance is perhaps twice this amount. Near the town of Hiawatha, where the bed is actively mined, it is 7–20 feet thick. For 23 selected areas totaling about 220 square miles along the base of the Wasatch Cliffs, where the local average thickness of the coal is 4 feet or more, Spieker (1931, p. 204–206) estimated that the bed contains 1,546 million tons of coal. For the 23 areas, this represents an overall average thickness of 6.1 feet. The Spieker report includes data on eight additional areas totaling 20 square miles where the local average thickness of coal in the Hiawatha bed ranges from 2.2 to 3.1 feet and the estimated resources total 64 million tons. He also included data on other thick but less extensive beds.

Little is known about the thickness and continuity of the Hiawatha bed and other beds in the sequence of coal-bearing rocks downdip from the areas along the outcrop because this coal passes under the thick overburden of the Wasatch Plateau beyond the limits of present economic interest.

D-ANDERSON BED

The Powder River basin of northeastern Wyoming and southeastern Montana contains many thick, closely spaced coal beds. The concentration of coal resources in this area is larger than that in any other area of comparable size in the United States. The large number and close spacing of coal beds and accompanying irregularities in thickness of coal beds and thickness and composition of the enclosing rocks have created problems in regional correlation that have not been completely resolved.

Of the many coal beds known in this area, a bed that crops out at Minturn, Campbell County, Wyo., is perhaps the thickest and best known. This bed is strip mined on an extensive scale nearby at Wyodak, where it attains a maximum thickness of 106 feet. This bed was first mapped by Dobbin and Barnett (1928, p. 14), who termed it the D bed and assumed it to be a correlative of the Roland bed of areas to the north and west. This correlation was accepted and used for many years, and it permitted the conclusion that the D-Roland bed was persistent over a north-south distance of about 100 miles. Using this correlation, Berryhill, Brown, Brown, and Taylor (1950, p. 16) concluded that the measured, indicated, and inferred original resources in the D-Roland bed totaled 45,575 million tons.

In a more recent study of the Spotted Horse field, which covers an area north and west of Wyodak, Olive (1957, p. 13, pls. 4 and 5) concluded that the D bed at Wyodak is a correlative of the Anderson bed of the Spotted Horse field. The Anderson bed, which is about 300 feet lower stratigraphically than the Roland bed, is much thicker than the Roland bed and is continuous over a larger area. The revised correlation between the D bed at Wyodak and the Anderson bed in the Spotted Horse field extends the continuity of the D-Anderson bed over a north-south distance of about 150 miles and over an area of about 30,000 square miles. This increase in both area and thickness permits an increase in the estimated resources from the 45,575 million tons calculated for the D-Roland bed to about 60,000 million tons for the D-Anderson bed. This is the largest tonnage in a single, presumably continuous, bed anywhere in the United States.

WADGE BED

The Wadge bed has been mapped for a linear distance of about 35 miles in Routt and Moffat Counties, Colo., and it is known to underlie an area about 300 square miles to a maximum overburden depth of 3,000 feet. The original measured, indicated, and inferred resources in the bed in the known area of occurrence total 1,347 million tons (Bass and others, 1955, p. 210–223). The bed is actively mined by both underground and strip-mining methods to supply coal for the nearby Hayden power plant, and for power plants in the Boulder and Denver areas. Where mined, the bed is 8–10 feet thick.

RATON-WALSEN BED

The Raton-Walsen bed crops out discontinuously on the east edge of the Raton Mesa coal field from a point near Dawson, Colfax County, N. Mex., to Alamo, Huerfano County, Colo.—a linear distance of about 70 miles.

In New Mexico the bed is known as the Raton or Willow Creek bed. It crops out discontinuously near the base of the Vermejo Formation from a point near Dawson northeastward to Raton, N. Mex., a linear distance of about 20 miles. At Koehler, N. Mex., where it is known as the Raton bed, it attains a maximum thickness of 12 feet 5 inches, and is mined extensively (Wanek, 1963). At Van Houten, N. Mex., where it is known as the Willow Creek bed, it attains a maximum thickness of 13 feet and is also mined extensively (Lee, 1922). The Raton-Willow Creek bed thins rapidly from the areas of maximum thickness, and it is cut out locally by a sandstone and conglomerate zone at the base of the overlying Raton Formation. At other places in New Mexico, particularly near the Colorado State line, it has been intruded by basalt sills and the coal has been burned or altered to graphite.

As a result of the local thinning, postdepositional erosion, and destruction by sills, the Raton-Willow Creek bed contains only modest resources of a few hundred million tons, but it is one of the most important beds in New Mexico because the coal from this bed yields a high-quality metallurgical coke.

The Walsen bed of Colorado (locally known as the Lower Alamo, Cameron, Berwin, Bunker Hill, or Piedmont bed) occurs at about the same stratigraphic position in the Vermejo Formation as the Raton-Willow Creek bed and is believed to be its stratigraphic equivalent, though the two beds are not known to be stratigraphically continuous (Johnson, 1961). The Walsen bed crops out discontinuously on the northeast side of the Raton Mesa field between Morley and Alamo, Colo., a linear distance of about 50 miles. It maintains an average thickness of 3–3½ feet between these two points and is mined locally at many places. It has yielded more coal than any other bed in the Colorado part of the Raton Mesa field, largely because of its considerable areal extent and relatively uniform thickness, although it contains more ash and is less agglomerating than younger coals in the Vermejo and Raton Formations of Colorado.

WHEELER A, B, C, AND D BEDS

The Wheeler bed is the thickest and most extensive bed in the Grand Hogback–Carbondale region, Garfield County, Colo. It is recognizable as a single, continuous thick bed for a linear distance of about 20 miles, beginning at a point about 10 miles northwest of Newcastle and extending about 10 miles southeast of Newcastle. At the northwest end of the identifiable outcrop it is 30 feet thick. At Newcastle, where it was formerly mined extensively to supply coal for the Denver and Rio Grande Railroad, it attains a maximum thickness in the range of 45–48 feet. The Wheeler bed thins southeast of Newcastle, and at the point about 10 miles southeast of Newcastle it is 14–18 feet thick (Gale, 1910, p. 109–128). South of this point, the Wheeler bed apparently splits into four beds, termed from oldest to youngest the A, B, C, and D beds. The C and D beds continue southward as recognizable units for less than 10 miles. The A and B beds continue southward as recognizable units for about 25 miles into the Coal Basin area, Pitkin County, which has been described by Donnell (1962). The A, B, C, and D beds each range in thickness from about 4 to about 12 feet, and at any one place two or more of these beds are of thickness and quality suitable for mining.

The heat value and the rank of the coal in the Wheeler A, B, C, and D beds increase from north to south, and beginning roughly at the Garfield County line and extending southward into Pitkin County the coal is suitable for the manufacture of metallurgical coke. Since the mid-1950's, coal from the A and B beds in Coal Basin and the Thompson Creek area has been mined extensively for this purpose. In 1966, Pitkin County produced 718,000 tons of coal, most of which was moved by truck to the railhead at Carbondale, Colo., and then by train to steel mills near Provo, Utah (Colorado Coal Mine Inspection Div., 1967, p. 15).

The Wheeler A, B, C, and D beds dip very steeply westward into the Piceance Creek basin, and the coal is 3,000 feet below the surface only a short distance from the outcrops. As a result, the estimated accessible resources in the Wheeler A, B, C, and D beds total only about 1,000 million tons.

According to J. R. Donnell (oral commun., April 1967), stratigraphic correlations based on outcrop data and on data from wells drilled for oil and gas in the Piceance Creek basin indicate that the A bed of the Coal Basin area is stratigraphically equivalent to the Snowshoe bed of the Somerset-Paonia area and to the Cameo bed of the Grand Junction area. This equivalence suggests that there is a single bed or a group of closely related beds at the same stratigraphic horizon on the east and south sides of the Piceance Creek basin, and possibly extending at great depth under the entire 2,000-square-mile area of the Piceance Creek basin south of the Colorado River.

One of the most interesting deep occurrences of coal at the Wheeler-A–Snowshoe coal horizon is in a well drilled in sec. 13, T. 11 S., R. 92 W., in which the coal is 6,723 feet below the surface. At this point the drill penetrated 14 feet of natural coke, underlain by an estimated 12–14 feet of quartz latite, which, in turn is underlain by 12 feet of coal. This relation suggests that the quartz latite formed as a viscous igneous mass below the coal bed and, in working its way upward toward the surface, spread out laterally as a tabular intrusive into a very thick coal bed, which offered the path of least resistance. As the intrusive cooled, the rising heat formed the natural coke in the upper part of the bed, whereas the lower part was not subjected to the slow rising heat and was relatively unaffected.

ROSLYN (NO. 5) BED

The Roslyn (No. 5) bed is but one of eight mapped coal beds in the Roslyn coal field, Kittitas County, Wash. However, it has yielded more coal than any other bed in the State and is, without question, the most important coal bed in the State. As described by Beikman, Gower, and Dana (1961, p. 21–33), the Roslyn (No. 5) bed ranges in thickness from 4.5 to 7 feet and contains, on the average, about 4.4 feet of clean coal. The bed originally covered a synclinal area of about 25 square miles, but about 2 square miles has been cut out and replaced by glacial outwash material, 12 square miles has been mined out, and 10 square miles remain unmined. Past mining has, in general, removed coal to an overburden depth of 1,000 feet, and most of the remaining coal lies between 1,000 and 3,000 feet below the surface. The coal at the northwest end of the field is of high-volatile A bituminous rank and is suitable for use in coking-coal blends.

Prior to January 1, 1960, the Roslyn (No. 5) bed had yielded 57 million tons of coal, and the resources now remaining in the unmined part of the bed total 54 million tons. Very little mining has been done in other beds in the field. All mining in the Roslyn field ceased about 1964.

PRODUCTION FROM THE IMPORTANT BEDS

Although production figures are not routinely collected for individual beds, it is obvious that the 19 beds just described have yielded the bulk of past United States production. The Pittsburgh bed alone has yielded about 21 percent of total cumulative United States production, and the nine selected beds in the Appalachian basin have yielded about 50 percent of total cumulative United States production. The No. 5 and the Herrin (No. 6) beds of the Illinois basin have yielded the bulk of production from the Illinois basin. The Lower Hartshorne bed has yielded the bulk of production in Oklahoma and Arkansas. The Lower Sunnyside and Hiawatha beds have probably yielded 75 percent of total cumulative production in Utah. The Wadge, Walsen, Wheeler, and equivalent beds have yielded at least half of the total cumulative production in Colorado. This subjective analysis permits the assumption that the 19 beds described above have yielded about 75 percent of the cumulative past production of the United States.

USES OF COAL

In addition to its primary use as an economical source of heat and energy, coal is a highly versatile chemical raw material, and it is the source or main component of hundreds of chemical products.

The accompanying table shows the most important consumers of coal, and several noteworthy changes in the pattern of use over the 21-year period covered by the table. Most conspicuous is the marked increase in use of coal by the fast-growing electric utility industry. In both 1955 and 1965 this industry was the largest single user of coal, followed in order by the steel and manufacturing industries.

The growth of the utility industry is increasing at a very rapid annual rate, impelled by the growth in population, the increased use of electric appliances, particularly air conditioning, and the growth

Consumers of bituminous coal and lignite in 1945, 1955, and 1965
[In percent. Neg., negligible]

Consumer class	1945	1955	1965
Utilities	13	33	53
Steel industry:			
Coke production	17	25	21
Steel and rolling mills	2. 5	2	1. 6
Manufacturing	23. 5	23	20
Retail deliveries	21. 5	12	4
Railroads	22. 5	4	Neg.
All others	Neg.	Neg.	Neg.
Total	100	99	99. 6

Source: U.S. Bureau of Mines Minerals Yearbooks (1945, 1955, 1965).

of the aluminum and uranium industries, which use electricity in processing and refining ore.

The steel industry has always been an important and steadily growing customer for coal. Most of the annual coke production, which is recorded separately in the table, is used by the steel industry, for about 1 ton of coke is needed to produce 1 ton of steel. Most of the coke is manufactured in byproduct ovens, which also yield the basic coal chemicals—coal gas, sulfate of ammonia, light oils, and tar—from which are derived a myriad of other chemicals and products, including explosives, paints, dyes, fertilizers, plastics, nylon, and drugs.

The manufacturing industries, which constitute the third most important consumer class, use coal largely as a source of heat and power.

Very little coal is now consumed for household heating because of the increased use of oil and natural gas for this purpose. Such coal as is used for household heating is included under "Retail deliveries," which accounted for only 4 percent of 1965 consumption.

Railroads, the largest single user of coal up to the end of World War II, turned almost completely to diesel locomotives during the 1950's, and in 1965 and 1966 accounted for less than 1 percent of coal consumption. Most of the coal consumed by railroads in 1966 was used in powerhouses and shops.

Coal is of potential future importance as a subsidiary or emergency source of pipeline gas, liquid fuels, and lubricants, all of which can be synthesized from coal by various hydrogenation processes. A considerable amount of study and experimentation is being devoted to this aspect of coal technology.

Several nonfuel uses of coal, though quantitatively unimportant, are worthy of mention. Lignite mined in Amador County, Calif., is an important source of montan wax (Jennings, 1957, p. 158), and lignite mined in Texas is used in the manufacture of activated carbon. Bituminous coal mined in Carbon County, Utah, is a source of resins.

Weathered and slacked outcrops of lignite yield a product known as leonardite, which is used to control viscosity in oil well drilling muds and to manufacture a water-soluble brown wood stain. It has been mined for these purposes in North Dakota, Texas, and Arkansas. Leonardite is high in humic acid and will absorb and retain water. Because of these properties it is in experimental use as a soil conditioner. The physical and chemical properties of leonardite have been discussed by Fowkes and Frost (1960).

Ash from utility plants is used in the manufacture of concrete and cinder blocks, and crushed coal is being studied experimentally for use in road construction.

Jet, an ornamental material in vogue in the 1890's, is a dense black variety of lignite that will take a polish. Some Pennsylvania anthracite of very uniform density will also take a polish and is used in the manufacture of jetlike ornamental objects.

Coal also contains several minor elements of great interest and potential economic importance, which are discussed next.

MINOR ELEMENTS IN COAL

Coal contains small quantities of essentially all metallic and nonmetallic elements, which were introduced into the coal bed in one or all of four different ways:

1. As inert material washed into the coal swamp at the time of plant accumulation.
2. As a chemical precipitate from the swamp water.
3. As a minor constituent of the original plant cells.
4. As a later addition, introduced after coal formation, primarily by ground water moving downward and laterally.

When coal is burned, most of these elements are concentrated in the coal ash. Analyses of coal ash show that it is composed largely of the oxides of silicon, aluminum, iron, calcium, magnesium, potassium, sodium, and sulfur, which typically make up 93–98 percent of the total weight of ash (Selvig and Gibson, 1956).

The remaining few percent of coal ash is made up of about 25 different minor elements, the concentration of which differs greatly in different areas and beds. Beginning in the 1930's and continuing to the present time, study of the minor elements in coal has increased at a slow but steady rate. The more recent reports by Zubovic, Stadnichenko, and Sheffey (1960a, b; 1961a, b; 1964; and 1966) summarize the present state of knowledge of 15 or 20 of these elements, and provide selected listings of works by other writers. Most of the minor elements occur in coal in about the same concentration as in the earth's crust; but a few, notably uranium, molybdenum, arsenic, boron, and germanium, occur locally in vastly greater concentrations; and a few others, including barium, strontium, and lead, occur in significantly greater concentrations (Francis, 1954, p. 98; Goldschmidt, 1935; Krauskopf, 1955, p. 418; Mason, 1966, p. 45). Sulfur and several noteworthy minor elements in coal are discussed in the following paragraphs.

SULFUR

Sulfur is present in all coals in amounts ranging from 0.2 to about 10 percent. Most of the sulfur, perhaps 40–80 percent, occurs as a constituent of pyrite and marcasite (FeS_2), and the remainder occurs as hydrous ferrous sulfate ($FeS_4 \cdot 7H_2O$) derived by weathering of pyrite; as gypsum ($CaSo_4 \cdot 2H_2O$); and as organic sulfur in combination with the coal-forming vegetal material. (See Walker and Hartner, 1966.)

The percentage of sulfur and of pyrific sulfur is highest in bituminous coals of Pennsylvanian age in the Appalachian and Interior coal basins. The subbituminous coal and lignite of the Rocky Mountain and Northern Great Plains regions contain relatively small amounts of sulfur, most of which is in the form of gypsum. The higher percentage of sulfur in bituminous coals east of the Mississippi River as compared with the percentage in coal in the United States as a whole is shown in the following table:

Distribution (in percent) of coal in the United States according to sulfur content

[Modified from DeCarlo, Sheridan, and Murphy (1966, p. 8)]

Coal resources determined by mapping and exploration	Low sulfur (1.0 percent or less)	Medium sulfur (1.1–3.0 percent)	High sulfur (more than 3 percent)
Total bituminous coal, subbituminous coal, and lignite	65	15	20
Bituminous coal east of the Mississippi River	20	37	43

The differences shown in the table would be more pronounced if the subbituminous coal and lignite in the Western States had been compared with bituminous coal of the Eastern States.

Sulfur is an undesirable element in coal. It lowers the quality of coke and of the resulting iron and steel products. It contributes to corrosion, to the formation of boiler deposits, and to air pollution. Its presence in spoil banks inhibits the growth of vegetation. As sulfuric acid, it is the main deleterious compound in acid mine waters, which contribute to stream pollution.

316–331—68——6

Pyrite and marcasite have a high specific gravity, and most of this material can be removed from coal by various washing and cleaning procedures. The other forms of sulfur have lower specific gravities and are more intimately mixed with the coal, and consequently are less easily removed. Nearly 65 percent of all coal mined in the United States is cleaned mechanically to remove sulfur and ash before use. However, in spite of such large-scale cleaning, the average sulfur content of coal distributed in the United States in 1964 was nearly 2 percent (Rohrman and Ludwig, 1965), and the average sulfur content of coal used by the electric utilities in 1964 was 2.3 percent (DeCarlo and others, 1966, p. 18). The utilities consume about half of all coal mined, and thus the higher percentage of sulfur in coal used by the utilities contributes substantially to the National average. The utilities prefer to use raw, unclean coal, which can be purchased at low cost on the basis of the Btu content. This coal is ground to a fine powder and burned in a cyclone furnace, in which ash and sulfur present no problem in operation. The net result is that the amount of sulfur burned and emitted to the atmosphere as SO_2, SO_3, and H_2SO_4 is much higher than is desirable from the standpoint of public health, and much research effort is being devoted to a search for economical and practical methods of reducing such emission. (See Diehl and Zawadzki, 1965.)

Although sulfur is a deleterious component of coal, it is a very important industrial chemical. The consumption of sulfur in the United States has increased rapidly in recent years, and this has resulted in a depletion of stockpiles, a steady increase in imports, and a rapid increase in price. In early 1965, for example, the sale price of pure, elemental sulfur was about $30 per ton, whereas by late 1967 the price was about $39 per ton. Sale of elemental sulfur, and possibly iron removed from coal and from flue gas, would partly offset the cost of removal. A modest amount of research is being directed toward finding economical methods for the removal of sulfur from flue gas. (See Zimmerman and Roman, 1967.)

URANIUM

Uranium occurs locally in coal as compounds or complexes intimately associated with the organic constituents. In a few localities the uranium content is high enough to suggest the possibility of mining the coal as uranium ore. As a result, a large amount of study has been directed toward such coals (Kehn, 1957; Page and others, 1956, p. 405–444, particularly the bibliographies on p. 410, 418, 430, 438, 444).

Some beds of lignite and carbonaceous shale in southwestern North Dakota and northwestern South Dakota contain an average of 0.18

percent uranium, 0.3 percent molybdenum, 0.09 percent phosphorus, and 0.01 percent vanadium. These figures apply to the full thickness of the carbonaceous beds, which contain an average of about 45 percent ash. These rocks also contain anomalously high amounts of arsenic, germanium, selenium, cobalt, and zirconium.

Carbonaceous material has a strong chemical affinity for uranium, and uranium in solution is readily absorbed or precipitated by contact with lignite or carbonaceous shale. The uranium and associated elements in the Dakota lignite deposits were probably leached by ground water from overlying tuffaceous rocks and carried downward and precipitated on and in the underlying lignite (Denson and Gill, 1956; Denson and others, 1959).

Near the common corner of North Dakota, South Dakota, and Montana, where a 13,000-square-mile area of uranium-bearing lignite has been delineated by members of the Geological Survey (see Denson and Gill, 1956; Denson and others, 1959), a small industry has recently been developed for the recovery of some of this uranium. In 1965 three recovery operations were in progress in southwestern North Dakota and one in northwestern South Dakota. The thin, impure uranium-bearing lignite beds at these localities were strip mined and concentrated by burning in open piles or by roasting in rotary kilns. Three tons of impure lignite yielded about 1 ton of ash. The ash was shipped for final concentration and recovery of the uranium to plants at Grants, N. Mex., Rifle, Colo., and Edgemont, S. Dak. (See Mitchell, 1965.) In the 3-year period 1963–65, about 150,000 tons of uraniferous lignite containing U_3O_8 valued at about $9 million was mined, concentrated, and processed. The general area contains additional comparable material with a potential mined value of about $30 million.

GERMANIUM

In the United States, germanium is produced primarily as a by-product of zinc smelting. The expanded use of germanium as a semiconductor in crystal diodes, transistors, and rectifiers in the period following World War II greatly stimulated interest in coal as a secondary source of this element. (See Stadnichenko and others, 1953; Headlee and Hunter, 1951; Schleicher, 1959.) Where germanium is present in a coal bed it is concentrated locally in the top and bottom layers, or just above a thick parting, and is much more abundant in the bright bands (vitrain) than in the dull bands.

The highest concentration of germanium discovered to date in the United States has been in coalified logs and pieces of woody coal in rocks of Cretaceous age in the Atlantic Coastal Plain. Some of these logs contain as much as 7.5 percent germanium in the ash. The commercial coal richest in germanium is the Lower Kittanning bed in eastern Ohio. The germanium is concentrated in the lowermost layer of this bed. Samples of this layer contain a maximum of 0.2 percent germanium in the ash, and the ash ranges from 3.54 to 6.86 percent (Stadnichenko and others, 1953, p. 1, 9).

A 2-inch layer of Nodaway coal from Greenwood County, Kans., contains 0.99 percent germanium in the ash, and the ash constitutes 10.98 percent of the coal (Schleicher, 1959, p. 174).

Following the period of intensive study in the late 1950's, interest in germanium in coal slackened because of increasing competition of silicon as a semiconductor, and because of increased efficiency in use of germanium. Since the late 1950's, byproduct and imported germanium have supplied the commercial demand.

BARIUM AND STRONTIUM

Barium and strontium both show significant, but not large, concentrations in the ash of some coals. Analyses of the ash of 35 samples of coal, as reported by Deul and Annell (1956, p. 163), showed averages of 0.54 percent SrO and 0.31 percent BaO.

The barium and strontium seem to be, in large part, remaining constituents of the original plant cells and, in small part, the result of enrichment by circulating ground water.

BORON

The concentration of boron in certain coals is also much higher than the apparent concentration of boron in the earth's crust. Analyses of the ash of 319 samples of low-rank coal from Texas, Colorado, North Dakota, and South Dakota showed an average of about 0.1 percent boron, and individual beds elsewhere have been reported to contain as much as 2 percent boron in the ash (Duel and Annell, 1956, p. 163–164).

Boron is a minor constituent of living plants and is concentrated in the surface and near-surface soils supporting the growth of such plants (Robinson, 1964). Much of the boron in coal certainly was derived from the original plant constituents.

GOLD

Gold is likely to occur, at least in small quantities, in any coal bed that formed near a contemporaneous eroding source of supply. The gold is probably introduced at the time of plant accumulation in any one or all of three different ways.

1. A peat-forming swamp is obviously an area of decreasing stream velocity, and may, therefore, receive a certain amount of mechanically

transported finely divided gold. Sand-filled channels that cut through coal beds could contain fossil placers locally.

2. Clarke (1924, p. 660–662) has cited very good geologic and chemical evidence that gold may be carried in solution. Emmons (1917, p. 305–308) and Krauskopf (1951, p. 869) have pointed out that acid chloride solutions in the presence of a strong oxidizing agent yield conditions favorable for the solution of gold. Cloke and Kelly (1964) have provided a quantitative analysis of this reaction. The role of humic acid has been discussed by Freise (1931), Fetzer (1934, 1946), Steelink (1963), and Zvyagintsev (1941). The role of potassium silicate, ferric salts, halogens, nitric and hydrochloric acids, and manganese dioxide has been discussed by Clarke (1924, p. 660–662). Regardless of the means of solution, gold is easily precipitated by carbon, ferrous salts, other metals, and many sulfides. Thus, the reducing properties of coal make it a good chemical trap for gold.

3. Lungwitz (1900) and Goldschmidt (1935, p. 1101) have presented evidence that gold may be picked up by growing plants and ultimately concentrated in the plant humus. Lungwitz found $0.10 to $1.17 gold (at $20.67 per ounce) per ton of ash of trees growing on a gold placer deposit. The maximum gold content was in the branches. He did not check the roots. He suggested that plants contribute to the solution of gold. Of several gold-bearing coal beds in Europe analyzed by Goldschmidt, the average content of gold in the ash of the richer coals was 0.0002 percent. He concluded that the enrichment of gold in coal is 20–100 times the average concentration of gold in the earth's crust.

According to Stone (1912, p. 63–64), both gold and silver occur in the coal and overlying sandstone of the Cambria coal field, Crook and Weston Counties, Wyo. According to Jenney (1903, p. 461) gold occurs in coal in the Kremmerer field, Lincoln County, Wyo., and in the Wales field, Sanpete County, Utah.

The tantalizing amount of information available on the occurrence of gold in coal suggests that a modest program of sampling and analyzing the ash of commercial coals would prove interesting, and that particular attention should be devoted to coals that may have formed near eroding areas of Precambrian rocks, or near eroding areas of sulfide mineralization.

INDUSTRIAL ROCKS AND MINERALS ASSOCIATED WITH COAL

In parts of all coal-field areas, shale, sandstone, and limestone are closely associated with coal and may be of considerable local industrial importance, particularly if they can be extracted with the coal at relatively low cost.

The clay zone (or seat earth) that commonly underlies coal is mined locally for use in making refractory brick. Where this material is of suitable composition and thickness it may be of more economic value than the overlying coal. Sandstone may be useful as a building and construction material; limestone may be useful as road metal and as an ingredient in cement; and clay and shale may be useful for the manufacture of brick, or as ingredients in cement.

The possibilities of recovering industrial rocks and minerals associated with coal have been summarized in a comprehensive report prepared by the U.S. Office of Coal Research (1965).

OWNERSHIP OF COAL LANDS

The coal lands of the United States are held by several broad classes of owners, including the Federal and State Governments, mining and manufacturing corporations, railroads, Indian tribes, and private individuals. Information about the ownership of the surface, coal, and mineral rights for any individual tract of land can be ascertained fairly readily from the records of appropriate county, State, or Federal agencies. However, no study of the overall distribution of ownership has been made to date because of the size and complexity of the task, and because of day-to-day changes in ownership.

Most of the coal lands in the East and in the Mississippi Valley region are privately owned. In the Appalachian basin, many large tracts of coal land are held by mining, manufacturing, or landholding corporations. In this area also, the three or four main eastern coal-hauling railroads own some coal lands along their rights-of-way. In areas remote from transportation facilities, some coal acreage is owned by individual counties, having been acquired during the depression of the 1930's through failure of the owners to keep up real estate tax payments. A few small tracts in State parks and forests and elsewhere in the East are held by the Federal Government, but, in general, such federally owned coal lands constitute only a very small part of the total in the East.

Most of the coal lands in the Rocky Mountain and northern Great Plains regions are owned by the U.S. Government. In disposing of lands in the public domain according to public land laws before 1920, the Federal Government appraised each tract of land for its coal value and fixed the sales price accordingly. Following passage of the Mineral Leasing Act of 1920, the Federal Government reserved coal rights on all lands classified as valuable for coal when such lands were sold. Although thousands of acres of coal lands, including coal rights, were sold before 1920, the Federal Government is still the largest single owner of coal lands, or coal rights, in the Rocky Mountain and northern Great Plains regions. Township plats of most areas in the Rocky Mountain and northern Great Plains regions prepared in recent years by the U.S. Bureau of Land Management show the past disposal of Government lands. The Government-owned coal in these regions and elsewhere can be leased in return for a modest royalty. Regulations pertaining to such leases are contained in a circular distributed by the U.S. Bureau of Land Management (1964).

In the early days of construction of the transcontinental railroads, the railroad companies received as a form of subsidy considerable areas of land, including coal rights, adjoining the rights-of-way. The Union Pacific Railroad, for example, received alternate sections in a checkerboard pattern for a distance of 20 miles on both sides of the right-of-way. The Northern Pacific Railroad received alternate sections for a distance of 40 miles on both sides of the right-of-way. Although much of this land was sold to settlers, the western railroads as a group probably hold the second largest acreage of coal land in the West.

In Oklahoma, New Mexico, and Arizona, fairly large acreages of coal land are owned by various Indian tribes. This land is leased and administered by the U.S. Bureau of Indian Affairs.

In Washington and Oregon the percentage of coal land owned privately is somewhat higher than it is in the Rocky Mountain region, but even in these States the Federal Government owns large areas of coal land.

WORLD COAL RESOURCES

As here estimated, the original coal resources of the world as determined by mapping and exploration total 9,500 billion tons; the additional resources in unmapped and unexplored areas total 7,330 billion tons; and the amount potentially present in the full extent and thickness of known areas of coal-bearing rocks totals 16,830 billion tons. (See table 8.)

These figures, which are at best only gross approximations, were obtained by analysis and extrapolation of estimates from about 50 countries, most of which are not strictly comparable. The estimates differ primarily because of differences in the point of view of the estimators, and secondarily because of differences in the minimum thickness of coal included, the maximum thickness of overburden considered, and the amount of geologic and exploratory information available.

The differences in point of view result from the fact that coal is an abundant bulk commodity in most parts of the world, and annual pro-

TABLE 8.—*Estimated total original coal resources of the world, by continents*[1]

[In billions of short tons]

Continent	Resources determined by mapping and exploration (1)	Probable additional resources in mapped and unexplored areas (2)	Estimated total resources (3)
Asia [2]	[3] 7,000	4,000	[4] 11,000
North America	1,720	2,880	4,600
Europe	620	210	830
Africa	80	160	240
Oceania	60	70	130
South and Central America	20	10	30
Total	[3] 9,500	7,330	[4] 16,830

[1] Original resources in the ground in beds 12 in. or more thick and generally less than 4,000 ft below the surface, but includes small amounts between 4,000 and 6,000 ft.
[2] Includes European U.S.S.R.
[3] Includes about 6,500 billion short tons in the U.S.S.R.
[4] Includes about 9,500 billion short tons in the U.S.S.R. (Hodgkins, 1961, p. 6).

duction is typically only a very small part of the total potentially available in the ground. Economic interest is thus centered only on the thicker and more accessible beds, whereas long-range national planning and good resource management require consideration of thinner and less accessible beds that may be needed in the future. For some countries, particularly the highly industralized countries that make extensive use of coal, estimates are available for resources in several categories according to thickness of coal and overburden, and according to several points of view. For most countries, however, only one estimate is available.

In table 8 most of the estimates used to obtain the continent totals in column 1 are of resources determined by mapping and exploration, and in column 3 the estimates are of total resources. Figures in column 2 were obtained by subtracting the figures in column 1 from those in column 3. The figures for each continent are rounded totals of figures for the countries represented. Where only one type of estimate was available for a country, the second desired type was obtained by analysis and extrapolation of the existing type. Therefore, the continent totals show only the general order of magnitude of resources.

Most of the figures in column 1 and many in column 3 were taken from Statistical Yearbooks of the World Power Conference (Brown, 1948, 1950, 1952, 1954, 1956, 1958; Parker, 1962), which specify that the tonnages of hard coal shall be in beds "containing not less than 30 cm. (12 in.) of merchantable coal and situated not more than 1,200 meters (3,937 ft) below the surface * * *"; and that tonnages of lignite and brown coal shall be in beds "containing not less than 30 cm. of merchantable lignite or brown coal and situated not more than 500 meters (1,640 ft) below the surface * * *." However, many of the individual estimates making up the totals in column 1 are based on more conservative assumptions. The estimates for the United States, for example, are based on a minimum thickness of 14 inches for anthracite and bituminous coal, and 30 inches for subbituminous coal and lignite; and a maximum overburden of 6,000 feet. The estimates for India are based on a minimum thickness of 4 feet and a maximum overburden of 2,000 feet for all coal.

The bulk of the tonnage shown in column 1 lies between 0 and 2,000 feet below the surface, and only a small amount lies between 2,000 and 4,000 feet. The bulk of that listed in column 3 also lies between 0 and 2,000 feet, but larger amounts are present between 2,000 and 4,000 feet, and a small additional amount lies between 4,000 and 6,000 feet. Because most of the coal in the world occurs in shallow structural basins, the amount potentially present decreases with each thousand-foot increase in depth, and the amount potentially present below 3,000 or 4,000 feet is small as compared with the larger amounts at shallow depth.

Some of the figures used in obtaining the continent totals in column 1 are for remaining resources in the ground as of various dates in the past; others are for original resources. Most of the figures used to obtain the continent totals in column 3 are for original resources. The bulk of the tonnage in table 8, and particularly the totals, is properly classified as original resources.

The total figures for the United States as shown in table 2 are included in the figures for North America in table 8. On the basis of data obtained from mapping and exploration, the United States contains remaining resources of 1,560 billion tons, or about one-sixth of the total world resources of 9,500 billion tons. On the basis of the amount potentially present in the full extent and thickness of coal-bearing rocks to a depth of 6,000 feet, the United States contains remaining resources of 3,210 billion tons, or about one-fifth of the total potential world resources of 16,830 billion tons.

Table 8 shows clearly that Asia contains most of the world's potential coal resources. This tonnage is concentrated in Russia and China, each of which is an important coal-producing country. The table also shows that the coal resources of Europe have been well established by mapping and exploration, and that estimates will not be greatly increased by future work. Finally, table 8 shows that Africa, Oceania, and South America contain small resources as compared with the rest of the world, but that the quantities assumed to be available are sufficient to justify continued exploration and development.

These revised estimates differ markedly from those presented in the report of the Twelfth International Geological Congress (Internat.

Geol. Cong. 12th, 1913), but where more recent information is not available this older report contains much useful information on the geology and occurrence of coal in various countries.

WORLD COAL PRODUCTION

In 1966, world coal production totaled 3,121 million tons, of which the U.S.S.R. contributed 21 percent, Western Europe, 18 percent, the United States, 18 percent, and the People's Republic of China, 12 percent. The remaining 31 percent was produced in many smaller countries and regions (U.S. Bur. Mines, 1966, p. 703–704).

Coal production in the U.S.S.R. and China has increased markedly in recent years as shown in figure 9. These increases provide supporting evidence of the strong industrial growth in the two countries that has been an announced objective for many years.

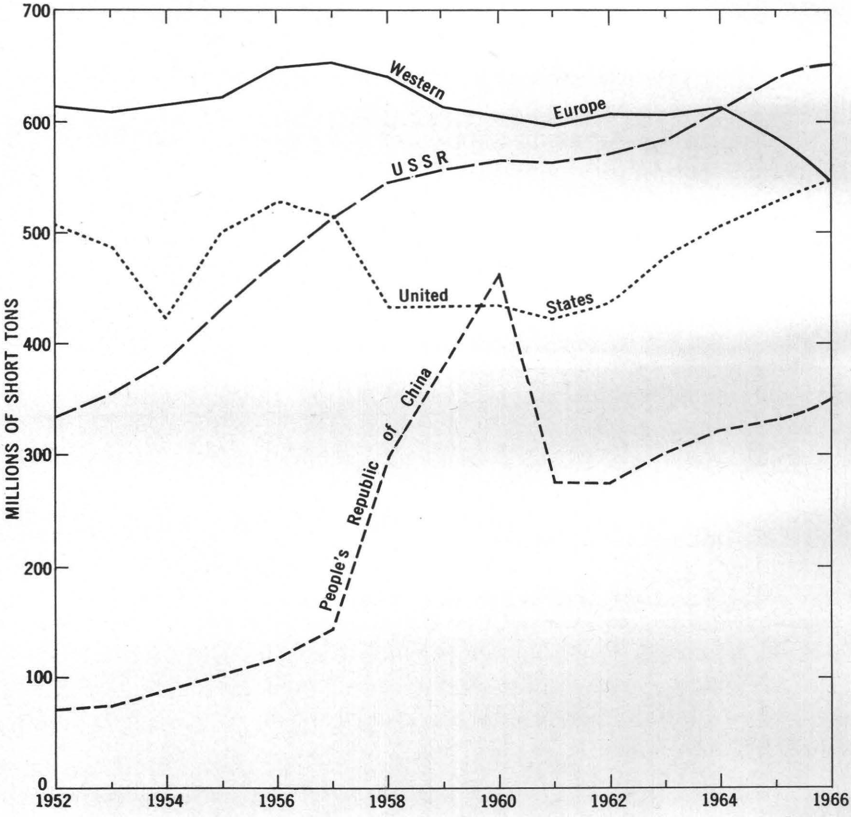

FIGURE 9.—Coal production in the U.S.S.R., Western Europe, the United States, and the People's Republic of China, 1952–66. (Source: U.S. Bur. Mines, 1952–66.)

Certain features of the four curves in figure 9 are worthy of comment. The level line for Western Europe prior to 1964 and the decline beginning in 1964 reflect difficulty in maintaining past levels of coal production because of gradual depletion of the thicker and more accessible coal beds. In the summer of 1966, Great Britain was engaged in exploration for new supplies of coal under the shallow waters of the Firth of Forth. The normal increase in total use of energy in Western Europe has been met by gradual increased use of atomic energy, particularly in Great Britain, by imports of coal from the United States, and by greatly increased use of petroleum products obtained from North Africa and the Middle East.

The pronounced increase in coal production in the U.S.S.R. between 1952 and 1958 represents a period of strong industrial growth based on use of coal. The leveling and more gradual increase since 1958 reflect increased use of water power and of petroleum products. As a result of recent discoveries of petroleum, the U.S.S.R. is now a net exporter of petroleum and petroleum products.

The upward trend in the production curve for the United States beginning in 1962 represents vastly increased use of coal by the electric utilities, which has been brought about by lower cost strip-mined coal, lower transportation costs, and improvements in methods of burning coal.

The very pronounced increase in coal production in the People's Republic of China during 1957–60 reflects a planned program—The Great Leap Forward—made possible in part by technical assistance from the U.S.S.R. The sharp decline after 1960 is the result of closing uneconomical mines opened hastily during the Great Leap Forward and the withdrawal of technical assistance by the U.S.S.R. The more normal growth rate between 1961 and 1966 represents normal improvement with regard to economic feasibility and without outside assistance. Wang (1964, p. 1293) has suggested that the figures for 1959 and 1960 are probably exaggerated about 20 percent because of unrealistic claims and the inclusion of impure coal. If this is so, the actual 1960 coal production in China may have been on the order of 350 million tons.

RELATION OF COAL IN THE UNITED STATES TO OTHER FORMS OF ENERGY

The industrial machine of the United States annually consumes prodigious quantities of energy. The mineral fuels and waterpower produced in 1966, for example, contained the heat equivalent of 12 horsepower of mechanical energy per person operating continuously, 24 hours per day and 365 days per year. Furthermore, the production and use of energy are increasing annually at a very rapid rate. As shown in figure 10, the overall use of energy in the United States has tripled in the last 50 years and has doubled in the last 25 years. And the curve is still headed sharply upward. This upward surge in the use of energy is impelled in part by our rapidly growing population, which has doubled in the last 50 years, and in part by our increased reliance on machines and manufactured products. Considering the potential future increase in use of energy that will be made possible by technologic improvements in production, transportation, and use, and by new and expanded consumer demands, the curve is likely

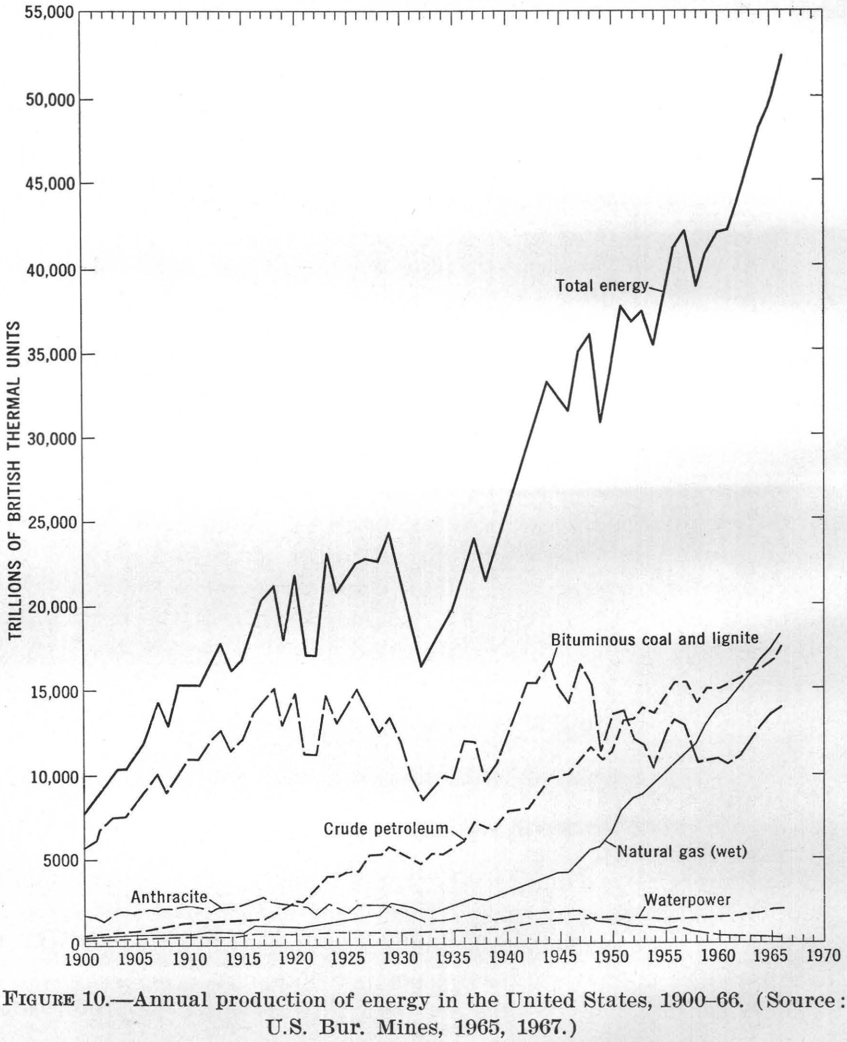

Figure 10.—Annual production of energy in the United States, 1900–66. (Source: U.S. Bur. Mines, 1965, 1967.)

to rise steeply and more or less continuously throughout the forseeable future. With consumption of energy in progress on such an enormous and ever increasing scale, it is interesting and instructive to review the position of coal in the total energy pattern.

During 1966, a record year in the production and use of fuel in the United States, coal supplied only 27 percent of the total energy produced from all sources, whereas petroleum and natural gas supplied 69 percent. The remaining 4 percent was supplied primarily by waterpower (U.S. Bur. Mines, 1967, p. 21). As shown in figure 11, the percentage of total energy supplied by coal, including bituminous and subbituminous coal, lignite, and anthracite, has decreased steadily from about 90 percent in 1900 to the present record low of 27 percent.

The percentage decrease in use of coal through the years has been accompanied by a corresponding percentage increase in the use of petroleum and natural gas, which have had greater consumer appeal because of their convenience, and which have filled a number of new uses not competitive with coal. Included in the percentage figures for petroleum and natural gas, for example, are gasoline and diesel oils used in automobiles and trucks, heavy oils used in road construction and maintenance, natural gas consumed in the manufacture of carbon black, and lubricants.

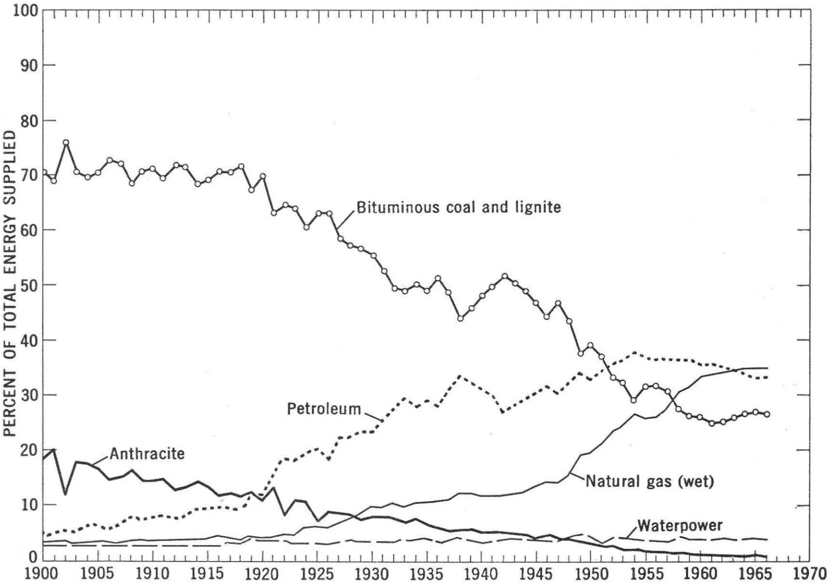

FIGURE 11.—Percentage of total energy supplied by mineral fuels and waterpower in the United States, 1900–66. (Source: U.S. Bur. Mines, 1965, 1967.)

The decrease in the percentage contribution of coal to the total production of energy in the United States has not been accompanied by a comparable decrease in the actual production of coal. (See fig. 10.) More accurately, the production of coal leveled off at the end of World War I, and for most subsequent years has varied between 400 and 600 million tons. The lowest recorded production was in 1932, when only 360 million tons was mined, and the highest was in 1947, when 688 million tons was mined (U.S. Bur. Mines, 1964, p. 49, 187). The position of coal in the industrial economy is bolstered by its increased use in the production of electricity and in the manufacture of steel. (See p. 73.)

PROBLEMS OF COMPARING ESTIMATES OF FOSSIL FUELS RESOURCES

Estimates of resources of coal, oil shale, and bituminous sandstone cannot be compared readily with estimates of petroleum and natural gas because the two kinds of fuel occur in different environments and are calculated in different ways.

Coal, oil shale, and bituminous sandstone occur in stratified deposits that are near the surface and are readily visible in outcrops in most parts of the United States. The gross distribution of rocks containing these deposits has been known for many years.

Because coal occurs in lens-shaped bodies of fairly uniform breadth and thickness, estimates of the total quantity in the ground can be made with reasonable accuracy through use of detailed information on the thickness, number, and continuity of coal beds at the outcrops, and through general knowledge of the thickness, areal distribution, and structure of the coal-bearing rocks.

The total resources of bituminous sandstone and oil shale can be estimated with similar accuracy because these substances also occur in lens-shaped or tabular bodies that can be studied at the surface, and because the thickness, areal distribution, and structure of the enclosing rocks are also well known.

Petroleum and natural gas, on the other hand, are highly mobile substances. Originally present as widely disseminated minute globules in sedimentary rocks, they move underground through pore spaces in the rocks and accumulate only where traps or barriers prevent further migration. Because a great variety of subsurface structural and stratigraphic relations create such traps, the total number existing in the widespread, thick sequences of sedimentary rock in the United States cannot be predicted accurately, nor can the amount of ultimately recoverable petroleum and natural gas contained in these traps be ascertained. In many respects, the ultimately recoverable petroleum and natural gas in the United States is being determined by an ever improving technology in methods of exploration, drilling, and recovery. In 1967, for example, wells 30,000 feet deep were entirely practicable, whereas only 30 years ago the limit was about 12,000 feet. Comparable improvements have been made in primary, secondary, and even tertiary recovery practices.

Because petroleum and natural gas deposits are hidden deep below the surface, only minimum proved reserves in developed areas can be estimated with acceptable accuracy. For the same reason, past estimates of total resources of petroleum and natural gas have been little more than conservative statements of opinion based on current estimates of proved reserves and on the existing technology. Consequently, the past estimates for total recoverable resources of petroleum and natural gas tended to be conservative, and they had to be increased frequently to accord with new discoveries and with improved methods of drilling and recovery.

In recent years, the amount of subsurface geologic information has increased progressively through intensive drilling and interpretation, and recent estimates of total resources of petroleum and natural gas have been based on a more sophisticated analysis of the total volume of favorable rock, trends of deposition, number and position of unconformities in the stratigraphic succession, and other factors that tend to improve the accuracy of the estimates.

Despite the recognized difficulty of comparing resource estimates of the several fossil fuels, it is possible to show the approximate relative magnitude of these resources as currently estimated by converting estimates to their total heat-value equivalents, and by making minor adjustments to allow for differences in parameters, methods, or points of view used in making calculations.

Estimates of the resources of the various fossil fuels are thus presented in table 9, which shows the estimated recoverable resources of coal and other fossil fuels as of January 1, 1967, in standard units of measure, in quadrillions of Btu, and as a percent of the total. The table gives the resources of the individual fossil fuels under two headings, termed "Measured or proved resources" and "Total resources" as discussed in the table and in subsequent paragraphs.

MEASURED OR PROVED RESOURCES

"Measured or proved resources," as presented in columns 1, 2, and 3 of table 9, includes material of the same thickness, quality, reliability, or accessibility as that being recovered under present economic conditions. The sources of the figures used, and their conservative nature, are explained in accompanying footnotes.

TABLE 9.—*Comparison between remaining recoverable resources of coal and other fossil fuels in the United States as of Jan. 1, 1967*

[Neg., negligible]

Mineral fuel	Measured or proved resources			Total resources [1]			Production 1966 (quadrillions of Btu) [3]
	Standard units of measure [2]	Quadrillions of Btu [3]	Percent according to Btu content	Standard units of measure [2]	Quadrillions of Btu [3]	Percent according to Btu content	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Coal	[4] 54	1,080	51	[5] 1,436	28,810	73	14
Petroleum and natural-gas liquids	[6] 46	252	12	[7] 373	[8] 2,030	5	19
Natural gas (dry)	[9] 289	299	14	[10] 1,692	1,751	4	18
Bitumen from bituminous sandstone	[11] 1	6	Neg.	[12] 2	11	Neg.	Neg.
Oil from oil shale	[13] 80	464	22	[14] 1,140	6,612	17	Neg.
Total		2,101	99		39,214	99	51

[1] Total coal resources in all categories of thickness, reliability, and overburden to a maximum depth of 3,000 feet; ultimate resources of petroleum, natural gas, and other fossil fuels, reduced to allow for past production and losses to Jan. 1, 1967. Includes data in columns 1, 2, and 3.

[2] Coal in billions of tons; petroleum, natural-gas liquids, bitumen from bituminous sandstone, and oil from oil shale in billions of barrels; and natural gas in trillions of cubic feet.

[3] Resource and production figures converted to Btu according to the following heat values: anthracite, 12,700 Btu per pound; bituminous coal, 13,100 Btu per pound; subbituminous coal, 9,500 Btu per pound; lignite, 6,700 Btu per pound; petroleum, oil from oil shale, and bitumen from bituminous sandstone, 5,800,000 Btu per barrel; natural-gas liquids, 4,011,000 Btu per barrel; and natural gas, 1,035 Btu per cubic foot.

[4] Remaining resources of 1,560 billion tons as determined by mapping and exploration from table 1, reduced by 50 percent to 780 billion tons to allow for future losses in mining, and this in turn, multiplied by 7 percent to yield 54 billion tons. The 7 percent factor represents coal 28 inches or more thick, and 1,000 feet or less below the surface, as determined by an analysis of data for 21 States in which the resources have been classified in detail. It is presumably roughly applicable to the United States as a whole. (See fig. 6.)

[5] Total estimated remaining resources of 2,873 billion tons to a maximum overburden depth of 3,000 feet from table 2, reduced by 50 percent to 1,436 billion tons to allow for future losses in mining. Small additional tonnage in overburden range of 3,000 to 6,000 feet not included. (See table 2.)

[6] Proved reserves of 31 billion barrels, plus indicated additional reserves of 7 billion barrels of petroleum; plus 8 billion barrels of natural gas liquids. Estimate by American Petroleum Institute as reported in the Oil and Gas Journal (1967a, p. 128–129).

[7] Original economical recoverable resources of 400 billion barrels of petroleum, plus 60 billion barrels of natural-gas liquids, for a total of 460 billion barrels; minus cumulative past production to Jan. 1, 1967, of 78 billion barrels of petroleum and about 9 billion barrels of natural-gas liquids, for a total past production of 87 billion barrels, leaving a remainder of 373 billion barrels. Estimate by Hendricks (1965, p. 12).

[8] Btu content calculated on the assumption that 20 percent of the total recoverable resources will be natural-gas liquids.

[9] Proved reserves, Jan. 1, 1967. Estimate by the American Gas Association as reported in the Oil and Gas Journal (1967a, p. 130–131).

[10] Original economical recoverable natural-gas resources of 2,000 trillion cubic feet, minus cumulative past production to Jan. 1, 1967, of about 308 trillion cubic feet, for a remainder of 1,692 trillion cubic feet. Estimate by Hendricks (1965, p. 12).

[11] 50 percent of estimated resources of bitumen in bituminous sandstone deposits near Vernal and Sunnyside, Utah; Casamlia, Santa Cruz, Edna, Sisquoc, Sulphur Mountain, and San Ardo, Calif.; and Uvalde, Tex. Deposits are classed as measured, indicated, and inferred, and are generally 1½ miles or less from the outcrops. The bitumen content averages generally more than 20 gallons per ton.

[12] 50 percent of estimated resources of bitumen in sandstone deposits listed in footnote 11 and elsewhere, containing 10 gallons or more of bitumen per ton, and averaging about 15 gallons. Estimate by K. G. Bell (written commun., 1965).

[13] 50 percent of oil in known resources of oil shale considered to be minable and amenable to processing under present economic conditions. Grade ranges from 30 to 35 gallons per ton in units more than 25 feet thick and lying less than 1,000 feet below the surface. Estimate by Duncan and Swanson (1965, p. 13).

[14] 50 percent of oil in known resources of oil shale, including material of marginal grade as low as 10 gallons per ton. About 30 percent of the total ranges in grade between 25 and 100 gallons per ton, and probably averages about 30 gallons per ton. About 70 percent ranges in grade between 10 and 25 gallons per ton, and probably averages about 15 gallons per ton. Estimate by Duncan and Swanson (1965, p. 9). Duncan and Swanson (p. 9) recorded large potential additional tonnages of oil shale, but these resources are less well documented, or are of lower grade than that accepted for use in this table.

TOTAL RESOURCES

"Total resources," as presented in columns 4, 5, and 6 of table 9, includes not only all the material in columns 1, 2, and 3 but also much larger quantities of material of marginal or submarginal grade or accessibility that is estimated to be available for future use as needed. The larger amount of marginal or less accessible material may be obtained in the future at higher costs, expressed in man-hours and materials, than at present, or what is more likely, it will be obtained at very nearly the same costs by a future improved technology. The sources and nature of these estimates are also explained in accompanying footnotes.

In order that the figures in columns 4, 5, and 6 would be as nearly comparable as possible, some deeply buried coal, and some low-grade oil shale were omitted from consideration (footnotes 5 and 14). It is unlikely that this omitted material will be needed in the foreseeable future.

The figures for petroleum and natural gas resources used in columns 4, 5, and 6 of table 9 are those of Hendricks (1965, p. 12). These figures are for the conterminous States and Alaska, and the adjoining continental shelves of both areas, and include an allowance for a future improved extractive and secondary recovery technology, as well as allowance for future increased prices for both products.

New drilling techniques based on use of a flexible nonrotating continuous drill pipe and on high-pressure hydraulic erosive action offer much promise of reducing the cost of drilling. In drilling on the continental shelves and in shallow inland seas and lakes, the depth of water presents fewer problems with each succeeding year. An increase of only a few hundred feet in feasible water depth would add significantly to the ultimately recoverable resources of petroleum and natural gas.

Estimates of total potential petroleum resources prepared by Weeks (1963) and by Hubbert (1967, p. 2227), and of total potential natural gas resources prepared by the Potential Gas Committee (1967, p. 5), are smaller, more stringent, and less inclusive than the Hendricks estimates, and this is one reason why they were not used in columns 4, 5, and 6 of table 9. Another reason, equally impelling, is the fact that the figures for coal in table 9 include some coal in thin and relatively inaccessible beds, and the larger Hendricks estimates for petroleum and natural gas permit a more reasonable percentage balance between resources of the several diverse kinds of fossil fuel. However, the estimates by Weeks, Hubbert, and the Potential Gas Committee were made by technically sound procedures, and they are, and will continue to be, of great interest and value to students of fuels resources.

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The preponderance of coal in the total fossil fuel resource picture as currently estimated is clearly shown in columns 3 and 6 of table 9. In column 6, which is the more significant, coal represents 73 percent of the total resources of fossil fuel in the United States, whereas petroleum, natural-gas liquids, and natural gas together represent only 9 percent.

Based as they are on estimates by different individuals working on different commodities from slightly different points of view, the calculated percentage figures obviously express a qualitative rather than an exact quantitative relation between the several kinds of fossil fuel. This should not detract from their interest and value.

In view of the relatively large resources of coal and the relatively small resources of petroleum and natural gas, it is instructive to consider the rates at which these fuels are currently being produced and consumed. In column 7 of table 9, the production of each fuel for the year 1966 has been converted to quadrillions of Btu. On this uniform basis it will be noted that the production of petroleum, natural-gas liquids, and natural gas combined is more than twice the production of coal. Thus, petroleum, natural-gas liquids, and natural gas, which represent 9 percent of the total fossil fuel supply, are being used more than twice as fast as coal, which represents 73 percent of the fuel supply. These disproportionate ratios point to the day when we shall be forced to place greater reliance on coal and oil shale, and on atomic, solar, and tidal energy.

LIFE EXPECTANCY OF UNITED STATES FOSSIL FUEL RESOURCES

The many imponderable factors to be taken into consideration make it impossible to estimate the life expectancy of United States fossil fuel resources with any degree of accuracy. Even such basic factors as the magnitude of proved and total resources, just discussed, are only approximations based on data currently available, and to a certain extent on present needs and technology.

Other factors, such as the continuing increase in population and use of energy, increase in recoverability and improvement in use of energy, imports of petroleum and petroleum products, new sources of energy, and interchangeability of fuels, are so highly variable and so closely related as to defy precise analysis. These factors are summarized briefly in the following paragraphs to emphasize the uncertainty attending statements about the life expectancy of fuel resources.

INCREASE IN USE OF ENERGY

Any consideration of the life expectancy of fossil fuel resources must make generous allowance for the probable future increase in use of fuel. The only yardstick available for this purpose is the experience of the past 50 years. During this period an unprecedented fourfold increase in the use of energy has taken place (fig. 10). This increase is due in part to an increase in population and in part to an increase in the per capita use of energy. It is difficult to project such a steeply rising trend far enough into the future to be meaningful, but any projection will yield results of very large magnitude. The U.S. Bureau of Mines (1965, p. 17) has estimated that the total energy use in 1980 will be 88,073 trillion Btu, which is a 56-percent increase over the record 56,542 trillion Btu consumed in 1966. Most students of trends in the use of energy agree that use will double in about 20 years. To support such an increase, all fuels will be needed in ever increasing quantities.

RECOVERABILITY

In the production of petroleum, recoverability has increased steadily throughout the years, and this is one reason why proved reserves of petroleum have increased in recent years despite greatly increased consumption and decreased drilling. The improvement in recoverability of petroleum and natural gas has been brought about in many ways—by unitization, by scientific spacing of drilling, and by injection of gas, water, steam, and fire in partially depleted fields. Secondary recovery practices are now commonplace, and tertiary recovery has been accomplished in some of the older fields where the primary or secondary recovery procedures were inefficient.

Similarly, many methods have been devised to improve recoverability in coal mining. In this report the recoverable resources of coal are assumed to be only 50 percent of the total in the ground. This factor accords with past experience in underground mining in many large districts where careful studies have been made. The recoverability of a steadily increasing number of individual underground mines is, however, much higher than 50 percent, and the recoverability from strip mining is 80 or 90 percent. Overall recoverability in coal mining could, therefore, be increased considerably, perhaps to 65 percent. Any increase in recoverability of fossil fuels can be expressed directly as an increase in total resources and in life expectancy.

IMPROVEMENT IN USE OF FUELS

Improvement in the use of petroleum is illustrated by the advances in refining and hydrogenation techniques by which a barrel of petroleum is made to yield more than a barrel of refined products of the desired composition.

Improvement in use of coal is illustrated by the marked economies introduced in the production of electricity at electric utility plants in the United States. In 1920, for example, an average of 3 pounds of coal was required to produce 1 kilowatt-hour of electricity, whereas in 1961 and subsequent years only 0.86 pound was required (U.S. Bur. Mines, 1965, p. 137). This improvement has been made possible largely through increased steam pressures, increased heat of operation, and use of the cyclone furnace, in which finely powdered coal is burned in a stream of compressed air.

The modern concept of long-distance transmission of electricity by extra-high-voltage direct current favors the development of very large central generating stations fired by low-cost coal from nearby strip mines or by atomic energy. These large generating plants produce electricity in large volume at very low unit cost. When they are interconnected in vast regional networks that distribute peak loads, low-cost electricity will become available to everyone. The production of electricity is the fastest-growing segment of the fuel economy, and it is having and will continue to have a profound effect on the use of fuel in the United States.

IMPORTS OF PETROLEUM AND PETROLEUM PRODUCTS

The large resources of petroleum in the Middle East, northern Africa, Venezuela, Mexico, Canada, and elsewhere are needed only in small quantities at the points of origin. This petroleum is finding increased markets in the United States, which is at present the world's largest consumer of petroleum products, and in western Europe, which is a growing and potentially very large market. The United States has been a net importer of foreign petroleum and petroleum products since 1948. The amount of such imports has increased steadily throughout subsequent years, and in 1966 reached a maximum of 939 million barrels, or about 22 percent of total domestic demand (U.S. Bur. Mines, 1966, p. 809). The amount and percentage of imported petroleum and petroleum products is controlled by a mandatory oil import control program initiated in 1959, which is intended to ration and distribute imports between companies and regions in such a way as to maintain a healthy domestic petroleum-producing industry, and at the same time to allow domestic consumers to benefit by the lower cost of imported petroleum and petroleum products. The life expectancy of domestic petroleum resources will be lengthened commensurate with the amount of imported petroleum and petroleum products.

NEW SOURCES OF ENERGY

The life expectancy of petroleum and natural gas and other fossil fuels will also be lengthened to the extent that other energy sources such as atomic energy, solar energy, earth heat, wind, and tides can be utilized. (See United Nations, 1962.)

Atomic energy is in use for the production of electricity on an ever increasing scale. At the end of 1966 about 15 such plants were in operation, and they produced 0.1 percent of the total United States energy supply. At the beginning of 1967 about 22 additional nuclear-fired plants, representing about half of total new electric generating capacity, were in the planning and construction stage. The Atomic Energy Commission (Faulkner, 1966) has estimated that by 1980 about 25 percent of total United States electric power will be generated in nuclear-fired plants. These plants will not directly replace any existing generating plants because of the projected marked increase in future use of electricity. However, antiquated plants, particularly those fired by petroleum and natural gas, will gradually be abandoned, and the percentage and actual use of petroleum and natural gas for the generation of electricity will certainly decrease.

Solar energy is likewise in use on a very small scale in special applications such as powering radios in satellites and telephones in remote areas. Ayers and Scarlott (1952, p. 272–283) believe that solar energy as a benign large-scale constant energy source deserves greater attention as a source of commercial electricity and process heat than it has yet received.

INTERCHANGEABILITY OF FUELS

Appraisal of the life expectancy of any individual fuel is further complicated by the fact that most fuels can be used interchangeably, and at most installations the choice of fuel is determined largely by cost. The preferred position of petroleum and natural gas in the fuel economy is due to their present abundance, comparative economy, and convenience and will, therefore, continue as long as adequate quantities of petroleum and natural gas can be produced in the United States, and as long as imported petroleum is available in domestic markets.

On the other hand, as petroleum and natural gas become more expensive, many users of these fuels, particularly the electric utilities, will convert to more economical sources of energy. Thus, long before petroleum and natural gas resources in the United States approach exhaustion, we may expect increasing reliance to be placed on other energy sources, a trend in which coal, oil shale, and atomic energy will contribute substantially. This period of transition may be greatly lengthened by utilization of imported supplies of petroleum, or shortened by a prolonged period of international tension and war, and it will be obscured by fluctuations in the economic cycle and by irregularities in the rate of discovery of new petroleum and natural-gas fields. Because of these many variables, a realistic estimate of the life expectancy of any fuel is not possible.

RATIOS BETWEEN RESOURCES AND PRODUCTION

Although it is manifestily impossible to predict the life expectancy of any individual fuel, the ratios between estimated resources and annual production provide figures that are more meaningful for comparative purposes than the resource figures alone. In this discussion, only figures for total resources in columns 4, 5, and 6 of table 9 will be considered or compared The figures for proved or measured resources in columns 1, 2, and 3 of table 9 represent merely a working inventory—or the choice, or most accessible, or best known part of the total resource—and the quantities can certainly be increased by future exploration or technologic development which, in effect, would constitute a withdrawal from the larger stockpile of material tabulated in columns 4, 5, and 6.

Table 10 gives the ratios for January 1, 1967, and January 1, 1981. Column 1 in table 10 is taken directly from table 9, column 4. Column 2 is 1966 annual production in the same units of measure. Column 3 is obtained by dividing the figures in column 1 by those in column 2. The resulting quotients do not, of course, represent life expectancy, because of anticipated future increases in use of fuels and other factors discussed previously. They do, however, emphasize the vast difference in quantity between coal and oil shale on one hand, and petroleum and natural gas on the other.

Column 4 is a projection to January 1, 1981, in which use of coal, petroleum, natural-gas liquids, and natural gas is assumed to increase at a modest rate of 3.1 percent compounded annually. Column 5 is the

TABLE 10.—*Ratios of total remaining recoverable resources of fossil fuels to production as of January 1, 1967, and as estimated for January 1, 1981*

[Neg., negligible]

Fossil fuel [1]	Jan. 1, 1967			Jan. 1, 1981		
	Estimated recoverable resources [2]	Domestic production 1966 [3]	Ratio of resources to production	Estimated recoverable resources [4]	Estimated domestic production 1980 [5]	Ratio of resources to production
	(1)	(2)	(3)	(4)	(5)	(6)
Coal	1,436	0.545	2,620	1,426	0.800	1,800
Petroleum and natural-gas liquids	373	3.4	110	313	5.2	60
Natural gas (dry)	1,692	16.0	106	1,404	25.0	56
Bitumen from bituminous sandstone	2	Neg.	∞	?	?	?
Oil from oil shale	1,140	Neg.	∞	?	?	?

[1] Coal in billions of short tons; petroleum, natural-gas liquids, bitumen from bituminous sandstone, and oil from oil shale in billions of barrels; and natural gas in trillions of cubic feet.

[2] From table 9, column 4.

[3] Coal from U.S. Bureau of Mines (1967, p. 10); petroleum, natural gas liquids and natural gas from Oil and Gas Journal (1967a, p. 128–129).

[4] Reduced from figures in column 1 by cumulative production 1967 through 1980, assuming 3.1 percent compound annual increase over 1966 domestic production.

[5] Assuming 3.1 compound annual increase in domestic production rounded. Does not include imported petroleum and petroleum products, which are assumed to remain at about 20 percent of total annual consumption.

estimated production of each fuel in 1980 based on this projected increased. Column 6 is obtained by dividing the figures in column 4 by those in column 5.

The figures in column 6 do not represent life expectancy as of January 1, 1981, for the same reasons cited for the figures in column 3, but they do show the tremendous potential drawndown on the resources of petroleum and natural gas that could result from a modest assumed increase in use extended over a relatively short period of time.

FUTURE TRENDS IN USE OF FUELS

To support the projected future increase in demand for energy, all fuels will be needed in increasing quantities, and the need for economy and efficiency will require that each fuel be put to the use for which it is best suited. This second fact alone will result in certain pronounced changes in use.

In the generation of electricity, which is the fastest growing segment of the fuel economy, use of natural gas and petroleum will be gradually decreased and finally abandoned as the remaining resources of natural gas and natural-gas liquids are diverted to household heating, and the remaining resources of petroleum are diverted to the manufacture of liquid fuels and lubricants. To replace these fuels in the generation of electricity, use of coal will increase, at least over the near term, and use of atomic energy will greatly increase. Over a longer period of time, atomic energy will probably replace all but the lowest cost, strip-mined coal as fuel for the generation of electricity. This is an inevitable and desirable trend, for natural gas is more valuable and desirable as a household fuel, and petroleum is more valuable and desirable as a source of liquid fuels and lubricants, whereas coal and atomic energy are more suitable for the generation of electricity in large central stations.

In household heating, use of petroleum will decline, and use of natural gas will increase. Over a longer period of time, most household heating will probably be accomplished by a high-Btu gas made artificially from coal or by electricity generated in large central stations powered by coal or atomic energy.

In the manufacture of liquid fuels and lubricants for use primarily in mobile internal combustion engines, most domestically produced petroleum will gradually be diverted to these purposes alone, and domestic deposits of coal, oil shale, and bituminous sandstone will gradually become increasingly important as subsidiary sources of synthetic liquid fuels and lubricants.

These changes in pattern of use of fuels will greatly extend the life expectancy of domestic petroleum and natural-gas resources by transferring more of the future energy-supply burden to coal, oil shale, and bituminous sandstone, which, in total, are much more abundant than petroleum and natural gas.

These trends could, of course, be greatly delayed by increased imports of petroleum from foreign sources, but imports on the required scale could take place only in a peaceful well-ordered world. It is more likely that the trends will be accelerated by a period of international tension in which international trade in petroleum is curtailed.

CHANGES IN TREND ALREADY IN PROGRESS

The anticipated changes in the pattern of use of fuel are, in fact, already underway on a small scale that is obscured by the much larger increase in total energy consumption. For example, the use of coal by the electric utilities and the use of natural gas for household heating have increased annually for many years, and continued increase is in prospect for both trends. The use of natural gas by the electric utilities, which has also increased annually for many years, reached an apparent peak in 1964. As previously (p. 95), mentioned, 15 nuclear-fired electric generating plants have been constructed in the United States, and 22 additional nuclear plants were in the planning and construction stage in 1967. Since about 1964, the major oil-producing companies of the United States have formed corporate alliances with coal-producing companies or have acquired options or titles to large blocks of coal land. The oil companies of the United States have also acquired interests in oil-shale lands, and are seeking to increase those interests. Extraction of oil from the Athabaska tar sands, Alberta, Canada, began on a commercial scale in the fall of 1967 (Oil and Gas Jour., 1967d).

In mid-1967 a pilot plant intended to convert coal to gasoline went into a 3-year period of experimental operation at Cresap, W. Va. The plant was designed by the Consolidation Coal Co. and Standard Oil Co. of Ohio, and was financed by the Office of Coal Research, U.S. Department of the Interior. The plant is intended to consume about 25 tons of bituminous coal per day, and to produce 60–75 barrels of synthetic crude oil per day. At an assumed coal cost of $4.50 per ton, the synthetic crude is expected to cost about $1.50 per barrel, and gasoline made from the crude is expected to cost 10.5–13 cents a gallon (Oil and Gas Jour., 1967c).

In late 1967, plans were being drawn for the construction near Rapid City, S. Dak., of a large pilot plant intended to produce high-Btu synthetic gas from lignite. The plant is expected to produce gas with a heat content of at least 900 Btu per thousand cubic feet that will sell in the price range of 40 to 50 cents per million Btu (Oil and Gas Jour., 1966).

A second coal-to-synthetic gas plant using a hydrogenation process different from that to be employed in the Rapid City plant is scheduled for construction in 1967 or 1968 in southwestern Pennsylvania or nearby West Virginia (Oil and Gas Jour., 1967b).

By 1969 an experimental plant intended to remove ash and sulfur from coal is scheduled to be in operation at Tacoma, Wash. The plant will yield a high-Btu soluble product suitable both as a clean-burning fuel and as a basic hydrocarbon compound that can be converted to any desired form. The plant will be operated by the Pittsburgh and Midway Coal Co. under contract with the Office of Coal Research.

FUTURE OF THE COAL INDUSTRY

In the changing patterns of use of fuel, coal has an assured position throughout the foreseeable future because of its abundance, widespread distribution, and chemical versatility. For the near and intermediate terms the prospects are very favorable; for the more distant future, the prospects are even more favorable in terms of both volume of production and variety of use.

The past history of the coal industry (p. 85–88) was characterized by intense competition with petroleum and natural gas, in which these fuels captured the railroad and household markets almost completely and made great inroads into the utility, cement, and manufacturing markets. Nevertheless, coal production remained remarkably constant, generally ranging from 400 to 600 million tons annually. Since 1961, when an interim low of 420 million tons was recorded, coal production has increased steadily, and it is quite unlikely that this low will ever again be witnessed. The large and now steadily increasing tonnage of coal is used in the generation of electricity, in the manufacture of coke and byproduct chemicals, and in the manufacturing industries.

As a major source of fuel in the generation of electricity, coal is indirectly recapturing part of the household market lost years ago to petroleum and natural gas. Use of electricity in the homes is increasing, owing to increased use of electric light, electrically operated motors and appliances, radios, and television sets. In the growing electric era, homes in vastly increasing number are being cooled and air-conditioned by electricity, and many are being heated by electricity.

As the future unfolds, it is certain that the amount of coal used in the manufacture of coke and byproduct chemicals will increase at a rate commensurate with growth in the gross national product, and that coal used in the generation of electricity will increase at least to the year 2000, by which time nuclear energy probably will furnish about half of the total electric generating capacity of the United States (Coal Age, 1966). By the year 2000 it seems certain that coal will be largely responsible for the remaining half of generating capacity in coal-fired plants already constructed and planned for construction in the future.

Beyond the year 2000 the future of coal in the generation of electricity becomes cloudy, but much coal will still be used in older highly efficient coal-burning plants in and near coal fields, and in small plants serving small communities. The future of coal in the generation of electricity hinges primarily on the success of research to perfect breeder and fusion reactors that would contribute permanently to reducing the cost of nuclear power, and on the success in constructing and maintaining a power-distribution network of continental scope. The rapid pace of technologic improvement in the atomic energy field suggests that beyond the year 2000 coal will be gradually phased out of the electric utility market by atomic energy.

While this transition is taking place, coal, as a remarkably versatile high-Btu chemical compound, is likely to become a source of synthetic gas, liquid fuels, lubricants, as well as thousands of hydrocarbon chemicals used by the manufacturing industries. (See Linden, 1966.) If and when coal takes over any part of this market, now served by petroleum and natural gas, the demand for coal will be enormous, and will more than compensate for the diminution of the utility market. In comparison with oil shale, which also has an excellent potential future as a source of synthetic liquid fuels and lubricants, coal has about 5 times the Btu content and only about one-eighth the amount of ash, and it occurs in abundance in the central and eastern parts of the United States where population and industry are concentrated, as well as in the central Rocky Mountain States where the richest oil shale is concentrated.

CONCLUSIONS

The past familiar pattern in the use of fuel in the United States is at the threshold of a period of massive change that will continue and intensify for many generations. The main features of the changing pattern are (1) greatly increased total use of energy, (2) greatly increased use of atomic energy, coal, oil shale, and bituminous sandstone, and (3) use of each fuel to the fullest extent possible for the purpose or purposes for which it is best suited. The increased reliance on these new or previously subordinate sources of energy will broaden the base of supply, increase the amount of energy available, increase the amount of hydrocarbon chemicals potentially available, and thereby ensure that the energy needs of our growing economy can be met for many generations to come.

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