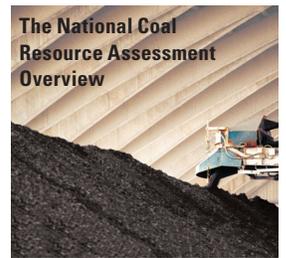


Chapter C

An Introduction to Coal Quality

By Stanley P. Schweinfurth¹



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Chapter C of

The National Coal Resource Assessment Overview

Edited by Brenda S. Pierce and Kristin O. Dennen

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An Introduction to Coal Quality

By Stanley P. Schweinfurth

Introduction

Because humans have used coal for centuries, much is known about it. The usefulness of coal as a heat source and the myriad byproducts that can be produced from coal are well understood. However, the underlying quality of coal, in terms of its mineral content, except for sulfur and iron, has not been examined carefully until relatively recently. The continued and increasingly large-scale use of coal in the United States and in many other industrialized and developing nations has resulted in increases in known hazards and has raised speculation about other possible hazards to environmental quality and human health. As a result, there is still much to be learned about the harmful and even the beneficial attributes of coal and how they may be removed, modified, avoided, or exploited to make coal use less harmful to humans and nature and (or) more useful for the general welfare.

One of the problems that accompany the mining and use of coal is acid mine drainage, which results when coal beds and surrounding strata containing medium to high amounts of sulfur, in the form of compounds known as sulfides, are disrupted by mining, thereby exposing the sulfides to air and water. Atmospheric sulfur oxides (SO_x) and subsequent acid deposition (such as acid rain) result from the burning of moderate- to high-sulfur coal. The quality of surface and groundwater may be affected adversely by the disposal of the ash and sludge that result from the burning of coal and cleaning of flue gases. These are some of the serious problems requiring either improved or new remedies. Other environmental problems are associated with emissions of carbon dioxide (CO_2) and nitrogen oxides (NO_x), two of the so-called “greenhouse gases.” These emissions are often attributed to coal use only; however, they also result from the burning of any fossil or biomass fuel, such as wood, natural gas, gasoline, and heating oil. The greenhouse gas problem requires a broader solution than just reducing the use of coal. Research currently is being conducted in the United States and several other countries into the reduction and disposal of CO_2 from coal combustion. An excellent review of the results of this research and the prospects for coal can be found in a publication of IEA Coal Research (1999).

Fluidized-bed combustion (FBC) of coal, which is a relatively new method for reducing sulfur emissions during electricity generation, is gaining wide usage. In this system, finely ground coal is mixed with finely ground limestone. Both are

fed together into a furnace in a constant stream onto a horizontally moving grate. Hot air is forced up through the grate and the entire mass is ignited at low temperatures. The forced air causes the ground coal and limestone to be mixed with the hot gases of combustion, which in turn promotes the conversion of any SO_x to gypsum as the burning mass moves along on the grate. According to the U.S. Department of Energy (2000), high-sulfur coal may be burned in this way while simultaneously capturing as much as 95 percent of the SO_x and most of the NO_x emitted.

A Federal law, the 1990 Clean Air Act, required the U.S. Environmental Protection Agency (USEPA) to conduct studies of 15 trace elements released by the burning of coal to determine if they present health hazards. These 15 elements (antimony, arsenic, beryllium, cadmium, chlorine, chromium, cobalt, lead, manganese, mercury, nickel, potassium, selenium, thorium, and uranium), along with many other potentially hazardous substances released into the air by other industries, are termed “hazardous air pollutants” (HAPs). On the basis of epidemiological studies published in 1996, the USEPA (1996) concluded that, with the possible exception of mercury, there is no compelling evidence to indicate that trace-element emissions from coal-burning powerplants cause human health problems. In December 2000, after extensive study, the USEPA announced a finding that regulation of mercury emissions from coal-fired powerplants is necessary and appropriate because coal-fired powerplants are the largest source of mercury emissions in the United States (USEPA Headquarters press release, December 14, 2000). The USEPA proposed regulations on mercury emissions in 2005. Meanwhile, arsenic is still under study, not as an emissions problem from coal combustion, but for its potential function as a toxic hazard in groundwater if it is leached from coal mining waste or from fly ash in disposal sites. Additional coal-quality research on both mercury and arsenic is being conducted at the U.S. Geological Survey (USGS) and elsewhere to help identify the sources in coals and to help resolve any remaining potential hazards issues of these two elements.

Other problems that may arise from the use of coal are not necessarily harmful to the environment or human health but affect the use and efficiency of coal-burning equipment. For example, certain constituents in coal may cause severe erosion and corrosion of, or the buildup of mineral deposits on, furnace and boiler parts. These effects greatly reduce the

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efficiency and life expectancy of a furnace or boiler, and they often require costly repairs.

Coal is abundant in the United States and other developed and developing countries, such as Russia, China, and India. Coal is relatively inexpensive and an excellent source of energy and byproduct raw materials. Because of these factors, domestic coal is the primary source of fuel for electric powerplants in the United States and will continue to be well into the 21st century. In addition, other U.S. industries continue to use coal for fuel, coke, and byproduct production, and there is a large overseas market for high-quality American coal.

Thus far, coal has been discussed as if it were a single homogeneous material, but this is done only for convenience in this report. A wide variety of coal types exist, consisting of a combination of organic and mineral components in varying proportions. For example, the sulfur content of coal may range from low (less than 1 weight percent), through medium (1 to 3 weight percent), to high (greater than 3 weight percent); ash yields may range from a low of about 3 percent to a high of 49 percent (if ash yields are 50 percent, or greater, the substance is no longer called coal). Coal may produce high or low amounts of energy when burned, or contain high or low amounts of the substances that produce organic chemicals and synthetic fuels, or contain higher or lower amounts of the elements that are considered hazardous air pollutants (HAPs). This range in properties results from coal's diverse origins, including the long and complex geologic histories of coal deposits.

The purpose of this report is to acquaint students, non-coal scientists, and the general public with some basic information on (1) the subject of coal quality and the reasons why it is complex and (2) the need for continuing studies of this complex subject. The report is written in three parts: the first part briefly describes coal use in the United States to set the stage for the importance of coal in our economy; the second part discusses the composition of coal in general; and the third part concludes the report with the reasons coal is such a complex natural resource.

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Coal Use in the United States

A discussion of coal use in the United States and of the beneficial things that come from coal is necessary in order to better understand the importance of coal quality and the need for continuing research on coal quality.

Coal use in the United States began around 2,000 years ago. Early inhabitants of this continent probably gathered coal from outcroppings, beaches, and streambeds. Coal mining by European-Americans began in Virginia, in the Richmond Basin, between 1720 and 1750. The Richmond area is known to have furnished coal during the American Revolution. Between 1750 and 1800, coal was discovered in many parts of the Northern and Southern Appalachian Basin. Then, as population moved westward after the Revolutionary War, coal deposits were discovered in the midcontinent, including Texas, the Rocky Mountain region, the Colorado Plateau, and the Northern Great Plains. For a much more detailed account of the early discovery and use of coal in the United States see "The First Century and a Quarter of American Coal Industry" by Howard N. Eavenson (1942).

After 1830, with the startup of the railroads, the real growth of the coal industry began in the United States. The railroads not only used coal, they also provided the means to transport coal, which encouraged the growth of energy-intensive industries. The growth of the railroads also encouraged the expansion of the iron and steel industry, which by the 1860s had abandoned charcoal in favor of coke for the reduction of iron ore to pig iron. Coke is a product of a certain type of coal produced by heating coal in an air-free oven, a process similar to making charcoal, until only carbon remains. Coke is much stronger than charcoal and burns with a hotter fire and is used in making steel.

In the 1880s, after the invention of electric turbines, coal soon became the principal energy source of steam-generated electricity. By 1918, industry in the United States depended almost entirely on coal. During World War II, demand for coal drove production to a record high, but shortly thereafter petroleum replaced coal as our chief source of energy.

Notwithstanding the widespread distribution of coal deposits in the United States, the bulk of coal mining and utilization has remained, until recently, in the eastern part of the country and mostly in the Appalachian Basin. This trend has been due to the concentration of population and industry in the East. Now, however, because of regulations based on the Clean Air Act of 1990, SO_x emissions from coal-fired powerplants, beginning in 2000, are limited. There are several ways in which coal-fired powerplants may limit their SO_x emissions—options include switching to a lower sulfur coal, instituting cleaning mechanisms (called flue-gas desulfurization [FGD] in the exhaust system), or switching to a completely different type of fuel. In any case, each of these options has costs. In general, however, powerplant managers are finding that converting from medium- and high-sulfur coal (greater than 1 weight percent) to low-sulfur coal, rather than

installing FGD systems is the least-cost option for achieving the required level of emissions (Attanasi and Pierce, 2001). Consequently, the locus of coal production is moving to the Western States because the bulk of the remaining resources of strippable, low-mining-cost, low-sulfur coal (1 weight percent sulfur or less) are located in the Northern Rocky Mountains and Great Plains region. There are reserves of low-sulfur coal remaining in the Appalachian Basin, but most of the remaining reserves occur at depth, requiring costlier underground mining methods to recover them.

After about a decade of decline following World War II, caused in large measure by the replacement of coal-burning railroad engines with diesel engines, coal production and use in the United States began to increase again due to an increasing demand for electricity by a growing Nation. The increase in coal production and consumption after World War II began slowly from a low of 420.4 million short tons (381.3 million metric tons) produced and 390.4 million tons (744.5 million metric tons) used domestically (that is, in the United States) in 1961 to a high of 1,118.7 million tons (1,014.6 million metric tons) produced in 1998 and 1,045.2 million tons (948 million metric tons) used domestically in 1999 (figs. 1 and 2) (Energy Information Administration, 2000). Data on production and consumption of coal are reported by the U.S. Department of

Energy's (DOE) Energy Information Administration (EIA), the Federal agency that monitors energy supply and demand.

The difference between the amounts of coal produced and used in the United States is accounted for mainly by exports. Coal exports earn a substantial amount of money, which helps to reduce the deficit in the balance of payments the United States makes to its foreign suppliers of consumer goods. In 1998, coal exports of 78 million tons (70.7 million metric tons) earned approximately \$2.9 billion (Energy Information Administration, 1999b).

According to the EIA (2000), approximately 1,099.1 million tons (996.9 million metric tons) of coal was produced in 1999 (slightly less than in 1998) and 1,045.2 million tons (948 million metric tons) was used domestically (slightly more than in 1998). The differences in production and consumption between 1998 and 1999 were due to a reduction in exports of 20 million tons (18 million metric tons) in 1999. Of the total coal used domestically in 1999, 90 percent (944.4 million tons; 856.6 million metric tons) was used to fuel electric powerplants, which, in turn, produced 56 percent of the electricity in the United States. The other 10 percent was used in industrial (coke and heating), residential, and commercial applications (fig. 2).

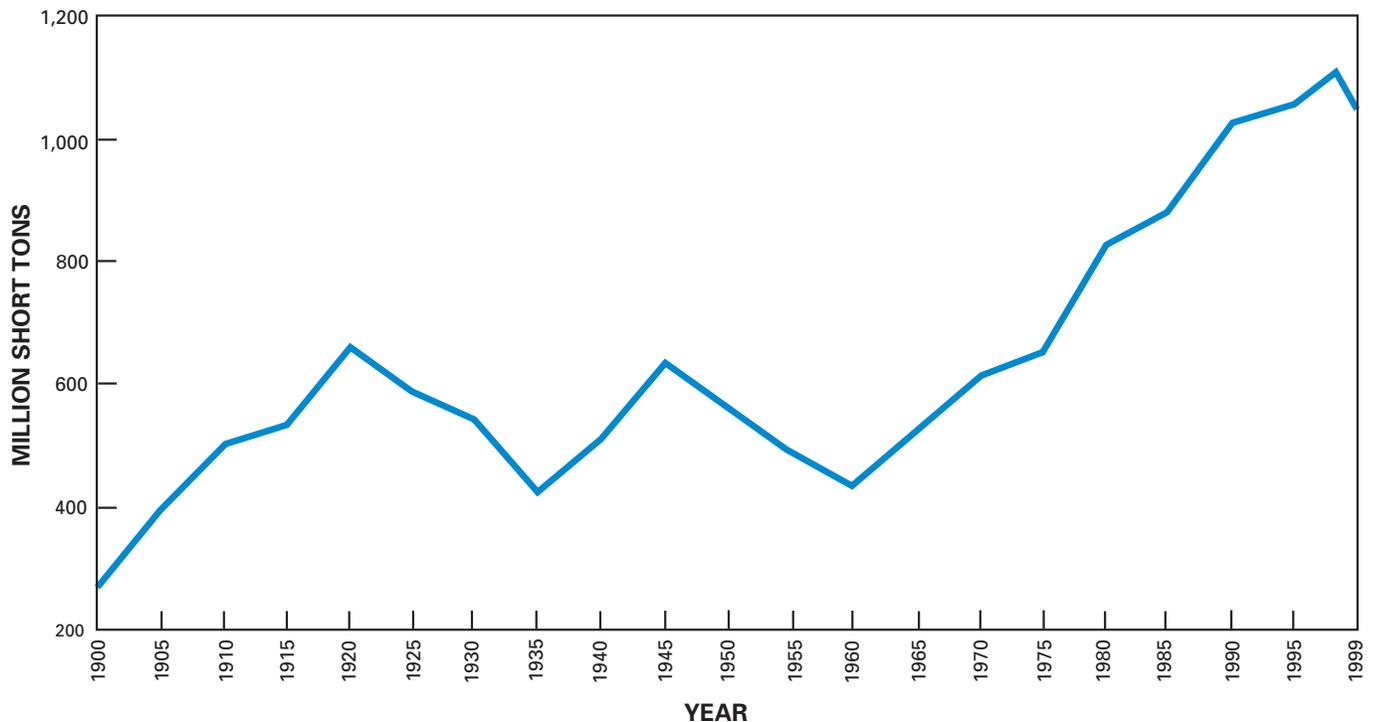


Figure 1. Graph showing trends in U.S. coal production from 1900 to 1999. The rapid growth in production after 1960 is attributed to (1) abundant reserves, (2) high productivity resulting in favorable prices for coal, and (3) the large increase in demand for electricity. The difference in production between 1998 and 1999 was due to a reduction in exports of 20 million tons in 1999. Data from Energy Information Administration (2000a). To convert short tons to metric tons multiply short tons by 0.0907185.

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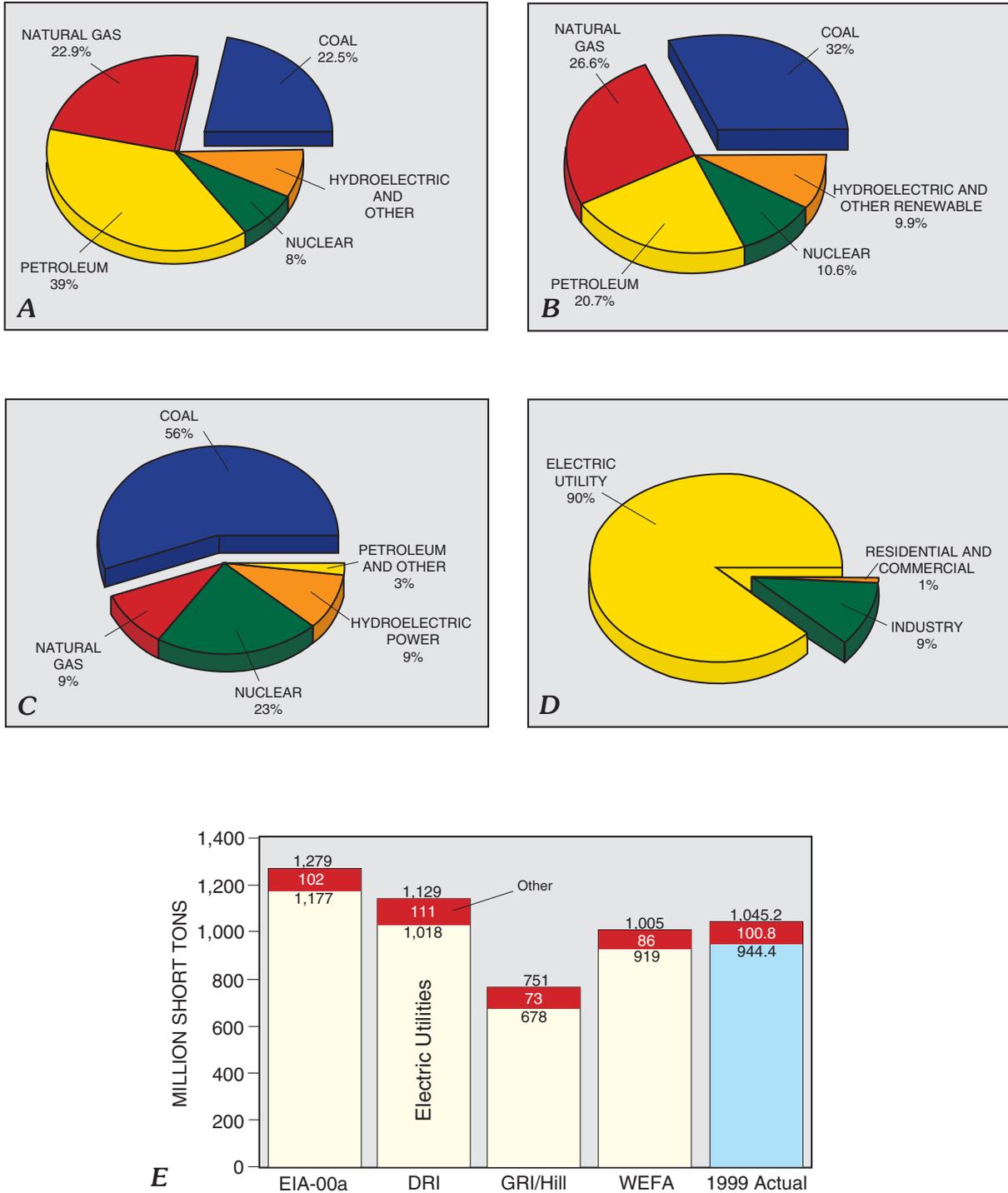


Figure 2. Diagrams showing energy consumption and production in the United States. *A*, Energy consumption in 1999. Of the various commodities consumed, approximately 54 percent of the oil and 16 percent of the natural gas are imported; coal and other commodities are almost entirely domestic; *B*, Energy production in 1999; *C*, Electricity generated in 1999, by all commodities; *D*, Coal consumption in 1999 by the economic sectors shown; and *E*, Forecasted coal consumption for 2020 by electric utilities (yellow) and other uses (red). The basis for comparison of commodities in diagrams *A*, *B*, and *C* is quadrillion Btu, or “quads.” Total quads produced and consumed in 1999 were, respectively, 72.5 and 96.6. The basis for diagram *D* is percentage of total tons, and the basis for *E* is millions of short tons. EIA, U.S. Energy Information Administration; DRI, Standard & Poor’s Data Resources, Inc.; GRI/Hill, Gas Research Institute; WEFA, The WEFA Group. Data from Energy Information Administration (1999a, 2000). To convert short tons to metric tons multiply short tons by 0.0907185.

Steady improvements in the efficiency of coal mining in the United States have kept coal prices low. In 1998, the average price of a ton of coal at the mine was \$17.67; the average price of a ton of coal delivered to electric utilities was \$25.64 (Energy Information Administration, 2000). Prices in 1986 of \$23.99 and \$33.30 per ton, produced and delivered respectively, demonstrate this trend. Furthermore, over the last decade, coal has been the least expensive of the three main fuel sources—coal, natural gas, and petroleum—in the United States. On the basis of a common unit of heat (millions of British thermal units), during the period from 1986 to 1998, coal prices averaged about 91 cents at the mine; natural gas averaged \$1.72 at the wellhead; and crude oil averaged \$2.70 at the domestic first point of purchase (Energy Information Administration, 2000). The relatively low prices for coal probably encourage continued high and (probably) increasing levels of coal use in the United States.

In 1999, the EIA (1999a) forecasted that, by the year 2020, average coal prices would decrease further to approximately \$20.01 per ton delivered to electric powerplants (in 1998 dollars). Coal production is forecast by the EIA (fig. 2) to grow to approximately 1,300 million tons (1,179 million metric tons) by 2020, of which domestic use will account for 1,279 million tons (1,160 million metric tons); of that amount, 1,177 million tons (1,067.5 million metric tons) will be used by electric powerplants. These figures indicate a rate of growth of approximately 1 percent per year for both coal production and powerplant use. Other domestic uses of coal are forecast by the EIA to remain about constant throughout that same period.

Whether or not substantially more coal is used in the future than presently, coal is abundant enough in the United States to supply anticipated requirements for much of the 21st century. The National Mining Association (NMA) (1999) reported that 30 of the largest coal companies in the United States have approximately 68 billion tons (61.7 billion metric tons) of coal in reserve. In addition, numerous small coal mining companies have reserves that are not included in the NMA's report, and there are additional coal deposits that could be mined, when and if needed.

Coal Byproducts

Coal is a very remarkable and rewarding material. In addition to providing heat to generate electricity (which is currently the primary use of coal), a myriad of other beneficial substances are derived from coal. Perhaps the best known of these substances is coke, which is used in the steel industry to separate iron from its ore. Coal is used in the production of other, perhaps unexpected, products such as pharmaceuticals, textile dyes, food and wood preservatives, and other simple or highly complex chemicals (fig. 3). These chemicals typically are produced during the production of coke by a process called destructive distillation. In this process, coal is packed into a closed, oxygen-restricted container (retort, or coke oven) and

then heated to a high temperature. This process drives off the volatile matter in the coal. The volatile matter contains the parent compounds that are used to produce the products shown in figure 3. The lack of oxygen in the retort prevents the chemicals from burning up.

In the past, large quantities of an impure gas containing methane and carbon monoxide (called town gas, or water gas) were derived from coal in the United States and elsewhere. Water gas was used for heating, cooking, and lighting but has been replaced largely by natural gas in the United States since the 1940s. In other parts of the world, notably in Germany during World War II and in South Africa today, gasoline and heating oil have been derived from coal. Currently, research is being conducted in the United States to improve the techniques and economics of producing both gas and oil (called "synfuels") from coal. This work is sponsored by the U.S. Department of Energy (DOE) (2000) and involves numerous private industrial and academic organizations.

Coal combustion products (CCPs), consisting of fly ash, bottom ash, boiler slag, and flue-gas-desulfurization material, also have become important in the economy. As coal burns, it emits sulfur in the form of sulfur oxide. FGD is the process by which a chemical, such as limestone (CaCO_3), is injected into the flue-gas stream to trap the sulfur by combining with it to produce gypsum (CaSO_4). Gypsum is heavy and falls to the bottom of the FGD unit as sludge in a wet process, or as a powder in a dry process.

According to the U.S. Geological Survey (Kalyoncu, 1999), approximately 57.2 million tons (51.9 million metric tons) of fly ash, 15.2 million tons (13.8 million metric tons) of bottom ash, 2.7 million tons (2.4 million metric tons) of boiler slag, and 22.7 million tons (20.6 million metric tons) of FGD material were produced in the United States in 1998. The amounts of each CCP that were used in 1998 were (in percent) 33.6, 31.3, 80.1, and 10, respectively; the rest was disposed of in landfills, settling ponds, and the like.

Coal fly ash is used mainly as an additive in concrete; fly ash may also be used as structural fill or as road-base material and may also be used in waste stabilization and mining applications. Bottom ash is used mainly as road-base and structural-fill material as well as in concrete and as grit for snow and ice control. Of the boiler slag that is used, most is used as blasting grit and roofing granules. FGD gypsum is used mainly in wallboard, with small amounts being used in concrete and agricultural applications.

There are other, perhaps less well known, products that can be derived from coal that are not now produced, or, if they are, it is only in very small quantities. For example, sulfur oxides can be captured from flue gas and used to make sulfuric acid, which is an important industrial raw material. Other valuable elements, such as mercury and chlorine (also industrial raw materials) may be recovered from flue gas (Finkelman and Brown, 1991).

What is Coal?

Composition

Coal begins as peat, which forms in mires. A mire is a swampy environment that contains the conditions necessary to allow peat to form and collect into more or less thick beds. Peat is converted to coal through a long and complicated process, which will be described in a later section.

Coal is composed of complex mixtures of organic and inorganic compounds. The organic compounds, inherited from the plants that live and die in the mires, number in the millions. The more than 100 inorganic compounds in coal either were introduced into the mire from water-borne or wind-borne sediment or were derived from elements in the original vegetation; for instance, inorganic compounds containing such elements as iron and zinc are needed by plants for healthy growth. After the plants decompose, the inorganic compounds remain in the resulting peat. Some of those elements combine to form discrete minerals, such as pyrite. Other sources of inorganic compounds used by the plants may be the mud that

coats the bottom of the mire, sediments introduced by drainage runoff, dissolved elements in the mire water, and wind-borne sand, dust, or ash.

Coals may contain as many as 76 of the 90 naturally occurring elements of the periodic table (fig. 4); however, most of those elements usually are present in only trace amounts (on the order of parts per million). Occasionally, some trace elements may be concentrated in a specific coal bed, which may make that bed a valuable resource for those elements (such as silver, zinc, or germanium) (Finkelman and Brown, 1991). Some elements, however, have the potential to be hazardous (for example, cadmium or selenium), particularly if they are concentrated in more than trace amounts. Although as many as 120 different minerals have been identified in coal, only about 33 of them commonly are found in coal, and, of these, only about eight are abundant enough to be considered major constituents (table 1).

The organic compounds in coal are composed of the elements carbon, hydrogen, oxygen, nitrogen, sulfur, and trace amounts of a variety of other elements. Although only a few elements compose the organic compounds found in coal, these compounds are extremely complex and, as a result, they are

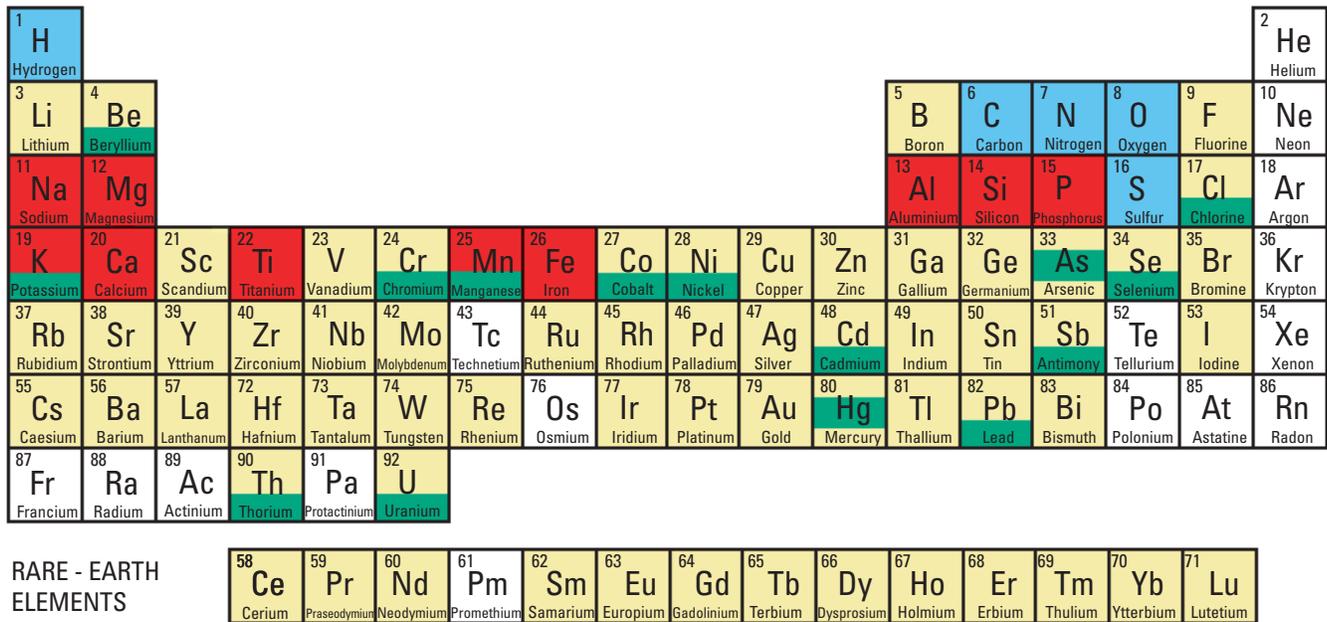


Figure 4. Periodic table of the elements showing all known naturally occurring elements on Earth. The 76 elements found in coal are highlighted by colors with regard to their general abundance in coal, as follows: blue, major elements (generally greater than 1.0 percent in abundance); red, minor elements (generally greater than or equal to 0.01 percent); and yellow, trace elements (generally less than 0.001 percent). Pursuant to the Clean Air Act of 1990, the U.S. Environmental Protection Agency (USEPA) studied 15 of these elements as potentially hazardous air pollutants (HAPs); green bars in their boxes indicate those 15 elements. Thirteen of the original 15 were cleared when the USEPA found that there was no compelling evidence that they cause human health problems; a green bar across the bottom of the box indicates those elements. Two elements from the original 15, mercury (Hg) and arsenic (As), indicated by a green bar across the centers of their boxes, are still under study—Hg as a HAP and As as a potential pollutant in groundwater that flows through fly-ash and coal-mine spoil piles. Furthermore, the USEPA has proposed that mercury emissions from powerplants be regulated as the largest source of such emissions in the United States. Modified from Sargent-Welch (1979).

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Table 1. Common minerals found in coal and their elemental compositions. Although more than 120 different minerals have been identified in coal samples, only about 33 of these occur in most coal samples; of these, only about eight generally are abundant enough to be considered as major constituents.

[Data from R.B. Finkelman, written commun. (2000)]

Mineral name	Chemical composition	Remarks
Major mineral constituents (In general order of abundance)		
Quartz	SiO ₂	
Clay minerals:		
Kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄	
Illite	KAl ₄ (AlSi ₇ O ₂₀)(OH) ₄	
Montmorillonite	(½Ca,Na) _{0.7} (Al,Mg,Fe) ₄ [(Si,Al) ₄ O ₁₀] ₂ (OH) ₄ •nH ₂ O	
Chlorite	(Mg,Al,Fe) ₁₂ [(Si,Al) ₈ O ₂₀](OH) ₁₆	May have Mn. (Clays may also contain Be, Cr, Ni, and other trace elements.)
Pyrite	FeS ₂	May contain As, Cd, Co, Hg, Ni, Sb, and Se.
Calcite	CaCO ₃	
Siderite	FeCO ₃	May contain Mn.
Minor mineral constituents		
Analcime	NaAlSi ₂ O ₆ •H ₂ O	
Apatite	Ca ₅ (PO ₄) ₃ (OH,F,Cl)	
Barite	BaSO ₄	
Chalcopyrite	CuFeS ₂	
Clausthalite	PbSe	
Crandallite group:		
Crandallite	CaAl ₃ (PO ₄) ₂ (OH) ₅ •H ₂ O	
Florencite	CeAl ₃ (PO ₄) ₂ (OH) ₆	
Gorceixite	BaAl ₃ (PO ₄) ₂ (OH) ₅ •H ₂ O	
Goyazite	SrAl ₃ (PO ₄) ₂ (OH) ₅ •H ₂ O	
Dolomite	CaMg(CO ₃) ₂	
Feldspars	(Ca,K,Na)AlSi ₃ O ₈	
Galena	PbS	
Marcasite	FeS ₂	May contain same elements as pyrite.
Monazite	(Ce,La,Y,Th,Nd)PO ₄	
Rutile/anatase	TiO ₂	
Sphalerite	ZnS.....	May contain Cd.
Xenotime	YPO ₄	
Zircon	Zr(SiO ₄)	
Trace mineral constituents		
Chromite	FeCr ₂ O ₄	
Gibbsite	Al(OH) ₃	
Gold	Au	
Gypsum	CaSO ₄ •2H ₂ O	
Halite	NaCl	
Magnetite	Fe ₃ O ₄	
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(OH) ₂	

not well understood; however, research is being conducted into understanding organic structures in coal. The organic compounds in coal produce heat when coal is burned; they also may be converted to synthetic fuels or may be used to produce the organic chemicals shown in figure 3.

The affinities of trace elements for either the organic compounds or the minerals in coal affect the quality of the coal. If trace elements are organically bound, then it is difficult to remove them from the coal by cleaning processes such as crushing and washing, which remove mineral matter from coal before it is burned. Organically bound trace elements may be released only by burning, or by deep chemical leaching, which is both very difficult and uneconomical. In contrast, trace elements associated with clays or pyrite may be removed largely from the coal by cleaning processes. The trace elements then may be disposed of in an environmentally safe manner or recovered and put to some other use. To date, however, the recovered mineral matter from coal has not been used for very many purposes, with a few major exceptions, such as gypsum, the various forms of ash, and a small amount of germanium (used in semiconductors). Two tables are included in this report to provide information about coal composition. Table 1 provides a general list of the minerals in coal. Table 2 provides a list of the contents of a specific coal sample and the procedures used to obtain those results.

Minerals in Coal

The most common minerals in coal (for example illite clay, pyrite, quartz, and calcite) are made up of the most common elements (in rough order of abundance): oxygen, aluminum, silicon, iron, sulfur, and calcium. These minerals and other less common minerals usually contain the bulk of the trace elements present in coal (table 1). Minerals in coal commonly occur as single crystals or clusters of crystals that are intermixed with organic matter or that fill void spaces in the coal; sizes of mineral grains range from submicroscopic to a few inches. Some clusters of mineral grains, however, such as coal balls or vein fillings, may reach sizes of as much as several feet across.

Although much is known about the minerals in coal, much remains to be learned about their occurrence, abundance, origin, and composition. For example, the type of clay mineral in a coal, whether montmorillonite or illite, determines how a coal will react when burned. Montmorillonite (table 1) may or may not break down (dissociate) into its constituent parts when coal is burned; if it does dissociate, then, upon cooling, it may recombine with other elements or minerals to form mineral deposits on the inside surfaces of furnaces and boilers. This process (called “slagging” or “fouling”) produces barriers to heat exchange in the affected equipment, which can substantially reduce its efficiency and require costly repairs. Illite (table 1), however, with its simpler composition, does not cause such problems under normal furnace operating conditions. Where these two clay minerals and others occur,

their relative abundances, relationships to other minerals, and exact compositions are subjects for continued research in coal quality.

When coal is burned, most of the mineral matter and trace elements generally form ash; however, some minerals break down into gaseous compounds, which go out the furnace’s flue. Pyrite, for example, breaks down into the individual elements iron and sulfur. Each element then combines with oxygen to become, respectively, iron oxide and an oxide of sulfur, commonly referred to as SO_x . Iron oxide, a heavy solid, becomes part of the ash, and SO_x , a gas, is emitted as part of the flue gas. Some trace elements also dissociate from their organic or mineral hosts when coal is burned and follow separate paths. Most become part of the ash, but a few of the more volatile elements, such as mercury and selenium, may be emitted in the flue gas.

The mineral content of coal determines what kind of ash will be produced when it is burned (table 2). The fusion temperature (melting point) of the ash (table 2) dictates the design of furnaces and boilers. In general, if the fusion temperature is relatively low, then the molten ash is collected at the bottom of the furnace as bottom ash, requiring one design; however, if the fusion temperature is relatively high, then the part of the ash that does not melt easily, called “fly ash,” is blown through the furnace or boiler with the flue gas and is collected in giant filter bags, or electrostatic precipitators, at the bottom of the flue stack, requiring a different design. Coals that are relatively rich in iron-bearing minerals (such as pyrite or siderite) have low fusion temperatures, whereas coals relatively rich in aluminum-bearing minerals (such as kaolinite or illite) tend to have high fusion temperatures. If an electricity-generating or heating plant is designed to burn one type of coal, then it must continue to be supplied with a similar coal or undergo an extensive and costly redesign in order to adapt to a different type of coal. Similarly, furnaces designed to use coal that produces high amounts of heat will suffer severe losses in efficiency if they must accept coal that burns with substantially less heat.

Macerals

The particles of organic matter in coal, inherited from the remains of plant parts, are called “macerals.” Many different types of macerals occur in coal. The identification of the original plants and their parts (such as bark, roots, spores, or seeds) that produced individual coal macerals is helpful in determining coal quality. However, these connections usually are difficult to make because the original plant material has been compressed or altered beyond recognition. Coal balls result when mineral matter (such as calcite, pyrite, or siderite) infuses and mineralizes (petrifies) a small volume of peat before it is compressed. Coal balls often contain coalified plant materials that have maintained their original structures because the mineral matter has prevented compression and degradation of the plants. Coal balls, therefore, can be used as

Table 2. Results of standard American Society for Testing and Materials (ASTM) analyses (top of table) and U.S. Geological Survey (USGS) research analyses (below the ASTM analyses) of a sample (USGS 212277) of Pennsylvanian bituminous coal from the Mary Lee coal bed, Walker County, Alabama.

[Data from Bragg and others (1998). Btu, British thermal unit]

ASTM standard analyses					
(1) Proximate analysis (in percent)			(2) Ultimate analysis (in percent)		
Moisture	2.6		Hydrogen	5.0	
Volatile matter	32.2		Carbon	67.6	
Fixed carbon	50.1		Nitrogen	1.5	
Ash	15.1 ¹		Oxygen	9.6	
			Sulfur	1.2	
			Calorific value		
			Btu/lb	12,060	
			Air-dried loss (%)	0.3	
			Forms of sulfur (percent)		
			Sulfate	0.01	
			Pyritic	0.66	
			Organic	0.55	
(3) Free swelling index = 2.5			(4) Ash fusion temperature (°F)		
			Initial	2,300	
			Softening	2,430	
			Fluid	2,520	
(5) Hardgrove grindability index = 0.0			(6) Equilibrium moisture (%) = 0.0		
USGS research analyses					
Oxides (in weight percent of ash)					
USGS ash	16.0 ¹				
SiO ₂	50.0	Al ₂ O ₃	26.0	CaO	3.4
MgO	0.28	MnO	0.02	Na ₂ O	0.38
K ₂ O	2.5	Fe ₂ O ₃	7.0	TiO ₂	1.2
P ₂ O ₅	1.3	SO ₃	2.3		
Minor elements reported on a whole-coal basis (in ppm)					
Si	37,000	Al	22,000	Ca	38,000
Mg	270	Na	450	K	3,400
Fe	7,800	Ti	1,100	S	1,500
Trace elements reported on a whole-coal basis (in ppm)					
Ag	0.011	As	7.6	Au	1.1
B	66.0	Ba	150.0	Be	0.99
Bi	1.1	Br	11.0	Cd	0.058
Ce	24.0	Cl	540.0	Co	3.9
Cr	22.0	Cs	2.3	Cu	12.0
Dy	2.5	Er	1.1	Eu	0.47
F	140.0	Ga	5.3	Gd	1.7
Ge	0.98	Hf	1.0	Hg	0.22
Ho	0.76	In	0.76	Ir	1.7

¹USGS ash slightly different than ASTM ash because of different temperatures used in ashing furnaces.

Table 2. Results of standard American Society for Testing and Materials (ASTM) analyses (top of table) and U.S. Geological Survey (USGS) research analyses (below the ASTM analyses) of a sample (USGS 212277) of Pennsylvanian bituminous coal from the Mary Lee coal bed, Walker County, Alabama—*Continued*.

USGS research analyses—<i>Continued</i>					
Trace elements reported on a whole-coal basis (in ppm)— <i>Continued</i>					
La	13.0	Li	40.0	Lu	0.15
Mn	35.0	Mo	0.19	Nb	2.1
Nd	8.5	Ni	9.4	Os	2.5
P	900.0	Pb	4.8	Pd	0.11
Pr	7.6	Pt	0.52	Rb	32.0
Re	1.1	Rh	0.25	Ru	0.25
Sb	0.7	Sc	5.1	Se	1.5
Sm	1.9	Sn	0.34	Sr	340.0
Ta	0.36	Tb	0.33	Th	3.9
Tl	0.52	Tm	0.52	U	1.0
V	24.0	W	0.6	Y	5.9
Yb	1.1	Zn	11.0	Zr	24.0

an aid in connecting the degraded, compressed plant matter of a coal bed to the original plants.

Macerals are grouped into three main subdivisions: (1) vitrinite, (2) liptinite, and (3) inertinite. These subdivisions are recognized by the American Society for Testing and Materials (ASTM) (1999), and each subdivision contains additional maceral subtypes, except vitrinite, which is a single maceral subdivision. In this report, just the principal maceral types will be discussed, with brief referral to some of the subtypes for illustrative purposes.

Vitrinite, which is the most common maceral, results from the coalification of amorphous humic (decayed) plant material. Vitrinite, sometimes called pure coal, is sensitive to heat, becoming denser, tougher, and more vitreous (glassy) as it is subjected to higher heat levels with depth in the Earth or proximity to an external heat source such as a volcano or an igneous intrusion. Coal scientists use an index of the intensity of vitrinite reflectance to determine the level of heat, or maturity, to which coals and other organic matter, such as petroleum, have been subjected.

Liptinite develops from waxy or oily plant parts such as spores, algae, and resin; the liptinite group contains several subgroups based on these original plant parts—sporinite, alginite, and resinite, respectively. Liptinite macerals are more enriched in hydrogen than either vitrinite or fusinite; consequently, liptinite-rich coals produce larger amounts and higher grades of liquid fuel when subjected to destructive distillation than either vitrinite- or fusinite-rich coals. Some coals, called “bog-head” or “cannel” coals, consist almost entirely of oil-rich algal and plant-spore material. These coals tend to yield large amounts of coal oil (kerosene) when subjected to destructive distillation because the macerals are rich in

oily material. However, both cannel and bog-head coals are relatively rare.

Inertinite incorporates a group of common macerals that form from partially oxidized or burned plant cell walls. Fusinite, or mineral charcoal, is a prominent representative of this group. Mineral charcoal is produced when, occasionally and sometimes seasonally, the surface layers of a peat mire dry out and some surface peat either slowly oxidizes or catches fire, or some growing plants are partially charred. (The common and naturally occurring fires of the Florida Everglades are modern examples of this process.)

Coals can range in maceral composition from mostly vitrinite to mostly fusinite, depending on the original plant matter and the degree of preservation. Vitrinite-rich coals are shiny, black, clean, and are subject to conchoidal fracture like glass because of their even texture; they often exhibit iridescence (called “peacock coal”) on fresh surfaces. Fusinite-rich coals, in contrast, are, similar to charcoal—dull, black, friable, and dusty.

Coal Rank

A major factor in determining coal quality is coal rank. Rank refers to steps in a slow, natural process called “coalification,” during which buried plant matter changes into an ever denser, drier, more carbon rich, and harder material. The major coal ranks, from lowest to highest, are lignite (also called “brown coal” in some parts of the world), subbituminous coal, bituminous coal, and anthracite. Each rank may be further subdivided, as shown in figure 5. The rank of coal is determined by the percentage of fixed carbon, moisture (inherent water), volatile matter, and calorific value in British

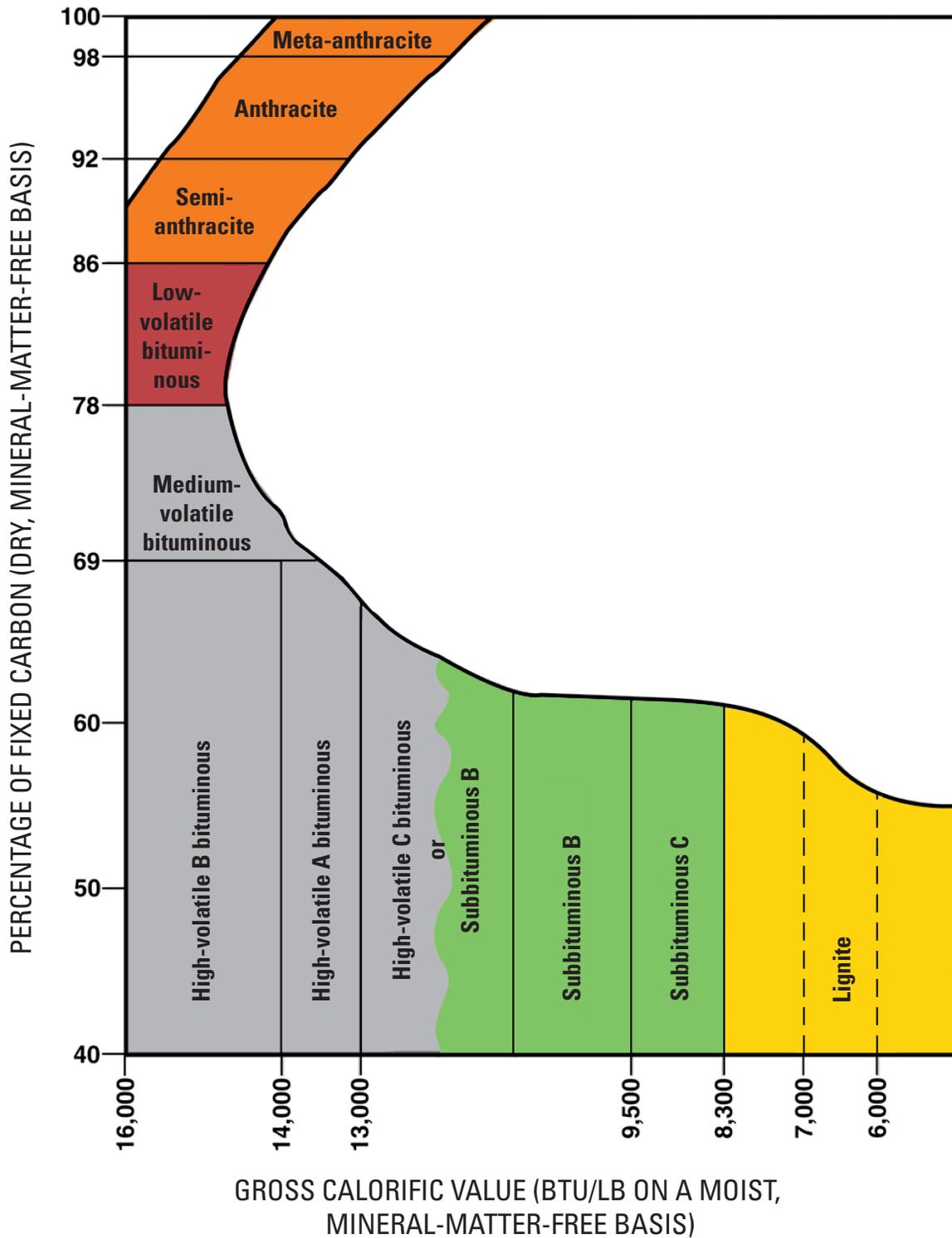


Figure 5. Diagram showing classification of coals by rank in the United States. Rank is a measure of the progressive alteration in the series from lignite to anthracite. Higher rank coals are generally harder, contain less moisture and volatile matter, and have higher calorific values. Modified from Trumbull (1960). For a more detailed explanation of coal-rank determination, see American Society for Testing and Materials (1999).

thermal units per pound (Btu/lb) after the content of mineral matter and sulfur have been subtracted from the total. Fixed carbon is solid, combustible matter left in coal after the lighter, volatile, hydrogen-rich compounds are driven off during coalification. Volatile matter is slowly removed from coal during coalification but may be rapidly removed during destructive distillation. The volatile matter contains the raw materials from which the organic chemicals are obtained. In the United States, the tests to determine the amounts of the above-mentioned substances and the rank of the coal are performed using standards published by the American Society for Testing and Materials (1999).

In general, the higher the rank of a coal, the more deeply it was buried, and, therefore, the higher the temperature it was subjected to during and after burial. Older coals tend to be of higher rank because they are more likely to have been buried more deeply for longer periods of time than younger coals. To give a sense of the effects of increasing rank, the following example may be used: lignite is soft, dusty, and can ignite spontaneously under the appropriate conditions, whereas anthracite is quite hard, clean to the touch, and must reach a temperature of about 925°F (496°C) before it will ignite. Furthermore, anthracite contains about twice the calorific value of lignite (about 15,000 Btu/lb, 3,780 cal/g and 7,000 Btu/lb, 1,764 cal/g, respectively) because lignite contains more moisture and oxygen and less fixed carbon than anthracite. Sub-bituminous and high-volatile bituminous C coals have oxygen and moisture contents and calorific values that range between those of lignite and anthracite. Bituminous coals of higher rank than high-volatile A (fig. 5) have calorific values that may exceed those of anthracite.

Why is Coal So Complex?

Coal is complex because of the wide variety of factors that determine the quality of coal. These factors include (1) the plants, plant remains, and other organisms (such as bacteria) in the peat mire, (2) biological and chemical processes and the degree of preservation of the plant matter, (3) the geometry and location of the mire, (4) the mineral matter that accumulated with the plant material or that was introduced at some later stage, and (5) coalification. Geologic age and history will be a recurring theme throughout this discussion.

The Plants

Coal begins as peat, which forms in mires having favorable conditions for peat preservation. These mires, which are generally filled with standing or slowly moving water, are ideal places for prolific plant growth. When plants fall into the mire, water covers them and slows or prevents rapid decomposition. Slow decomposition and a quiet environment allow plant matter to accumulate and form peat. The organic matter composing the peat may accumulate in place or, less

commonly, may be carried by flowing water to accumulate elsewhere, but generally nearby. Most coal beds were formed from plant material that accumulated in place.

Plant communities (flora) in peat mires may consist of many plant types, or of only a few. Mire flora have changed substantially through geologic time because of plant evolution. For instance, lycopsids and tree ferns are found in older coal beds; more modern plant forms (such as rushes, water lilies, mangrove, and bald cypress trees) may be found in younger coal beds. Flora of the Cretaceous Period (145.5 to 65.5 million years ago) included abundant species that contained relatively more resinous substances than those of the much earlier Pennsylvanian Period (318 to 299 million years ago). Tertiary plants (65.5 to 1.8 million years ago) generally were woodier than those of either the Pennsylvanian and (or) the Cretaceous Periods. In addition, floral communities varied from location to location even within the same time period. These changes in plant species resulted in small changes in nutrient requirements. The result is that geologically younger coals may have different mineral matter compositions than older coals.

Biological and Geochemical Processes

Once plant debris has been deposited in a peat mire, it is subjected to degradation and decomposition by microbial action, oxidation, and biogeochemical processes. These processes are pervasive and, to a large extent, determine the character of any resultant coal. The processes operate on microbiological and microchemical levels and are constantly changing and, therefore, are difficult to characterize. What is known is that (1) the degradation processes are carried out by oxygen from the atmosphere and various microorganisms, such as bacteria and fungi, and (2) the processes are moderated by the acidity or alkalinity of the available water. When the oxygen in the peat has been depleted, anaerobic bacteria (such as those responsible for fermentation) continue the process of degradation. Although pervasive, the process of plant decomposition is also selective in that different plant parts degrade at different rates. The most resistant plant parts, such as bark, cuticle, spores, lignin-rich wood, and charcoal (fusinized peat), are the parts most often retained in coal as macerals.

When standing water covers fallen plant matter, atmospheric oxidation is halted and, soon thereafter, biochemical change slows to a virtual halt. Once plant matter is converted to peat and is buried, further substantial changes depend more on increases in temperature and pressure than on oxidation and biochemical processes. The acidity or alkalinity of peat mire water may also control the rate and amount of change that takes place. Usually, the more acidic the water, the more plant matter is preserved because bacterial activity is reduced. If their work is carried to completion, bacteria and fungi reduce the peat to CO₂, water, and ash—the same effect as burning, although much slower.

Mire Location, Climate, and Hydrology

The geographic location, climate, and hydrology of the original peat mire also affect coal quality. At present, mires are located in tropical, temperate, and cool climates, near coastlines and inland, beside rivers and within river deltas, and in upland areas (Cameron and others, 1989). This wide variety of geographic locations and climates in which mires develop was most likely the case at least as far back as the Devonian Period (416 to 359 million years ago).

Peat mires located close to rivers or within river deltas have the possibility of periodic flooding and the introduction of large amounts of mineral matter. Mires along coastlines, while not as easily subjected to river flooding, may be affected by offshore or coastal storms that wash sediment over offshore bars and beaches into the mires located behind them. The added mineral matter may be disseminated in the peat, may occur as layers in the peat, or may cause peat formation to stop. Discrete laterally continuous layers of mineral matter in coal beds are called “partings.”

Climate and hydrology, which to some extent depend on geography, affect the growing season and the amount of rainfall that a mire receives and, therefore, help determine the kind of plants that will grow in the peat mire. Thick, extensive coal beds generally are thought to have originated as large peat mires in warm, humid, and tropical to subtropical regions. Thin and discontinuous coal beds may also form in those regions but are also known to have formed in cooler, less humid regions—areas where thick and extensive coal beds are less likely to have formed.

Mineral Matter

The living plants in a peat mire absorb mineral matter from (1) the soil they grow in, (2) the water of the mire, and (3) introduced mineral matter, such as water-borne or wind-borne sediment, or volcanic ash. Some of the dust and ash may be dissolved in the mire water and serve to support plant growth. Volcanic ash and some types of dust are rich in the nutrients required for vigorous plant growth. Wind-borne dust and volcanic-ash falls affect all types of mires. The dust or ash can occur as disseminated grains in the peat or as discrete partings. Partings may be paper thin or they may be several feet thick.

Throughout geologic time, the peat mires that were not destroyed by erosion or oxidation were buried by sediments, which, depending on their source, affected the mineral-matter content of the resultant coal in different ways. In general, river-borne sediments tend to be richer in some elements, such as iron, whereas ocean-borne sediments tend to be richer in other elements, such as sulfur.

In many coals, some of the mineral matter was introduced by epigenetic (low temperature) mineralization after the bed was formed. In this process, ions in moving water were introduced into fractures (called “cleat,” see the following section,

“Coalification”) and along bedding planes in the coal bed, and minerals were deposited when the water lost its ability to maintain these mineral-forming ions in solution. This could occur when the ion-bearing water entered a different temperature and (or) chemical environment.

Epigenetic minerals commonly include pyrite, calcite, siderite, and kaolinite, and, in rare cases, sphalerite and galena (see table 1 for compositions of these minerals). Epigenetic mineralization, estimated to have been introduced into coal beds of Pennsylvanian age during the Permian Period, is particularly notable in coals of the midcontinent region of the United States (Brannon and others, 1997; Cobb, 1979).

Coalification

From the time peat is buried, it goes through a series of chemical and physical changes called “coalification,” which is the process that produces coals of increasing rank (fig. 5). Coalification is a continuing process involving increases in both temperature and pressure resulting from burial in the Earth. Burial is a process that may happen very slowly or relatively rapidly depending on the speed and magnitude of the geologic forces operating on the region. Of the two—increasing temperature and increasing pressure—increasing temperature is considered more important in promoting coalification. Higher temperatures eliminate moisture and volatile elements and, therefore, help produce coals of higher rank and higher heat (calorific) value. Higher temperatures are generally associated with deeper burial in the Earth, although proximity to an unusual source of heat, such as a volcano, could produce similar effects.

When increases in depth of burial and (or) temperature no longer occur, coalification slows and then ceases (unless another source of higher heat affects the coal). Thereafter, the coal will remain at the same rank if it is raised up again (either by tectonic uplift or erosion of overlying sediments, or both) into a region of much lower temperature or pressure. However, once the coal is exposed to weathering (oxidation), it is slowly reduced to the equivalent of ash.

Coalification affects both the organic matter and the mineral matter in coal. As coalification proceeds, organic matter, which is relatively rich in water, oxygen, and hydrogen, gradually loses those constituents and becomes relatively enriched in fixed carbon. Some of the hydrogen and carbon are converted to methane gas (CH₄) in the process. Changes that occur to the mineral matter during coalification are less well understood. During coalification, clay minerals may become more refractory (that is, less affected by heat and chemicals), and the elements in other minerals may become rearranged, making them more crystalline. As a result, coalification processes produce complications for the study of coal quality.

Although deeper burial (and, therefore, higher temperatures) imply older age, coals of approximately the same geologic age may exhibit a wide range in rank depending on their geologic histories. For example, Pennsylvanian coals

in the Eastern United States range in rank from anthracite in easternmost Pennsylvania to high-volatile C bituminous coal in western Illinois and Iowa. The Pennsylvanian coal beds in what is now eastern Pennsylvania were subjected to strong mountain-building forces during the late Paleozoic, when the Appalachian Mountains were formed. During this time, the coal beds were forced deep into the Earth into zones of high heat and then were compressed into tight folds. In contrast, the Pennsylvanian coal beds to the west, in what is now western Pennsylvania, Ohio, Indiana, Illinois, and Iowa, were subjected to lesser depths of burial and relatively little or no mountain-building forces.

During the process of coalification, sets of roughly parallel, closely spaced (fractions of an inch to several inches) fractures (cleat) form in the coal. Cleat tends to form in two sets at right angles to one another; one set, the face cleat, is dominant, while the other set, the butt cleat, may be only poorly developed. Cleat is generally well developed in bituminous coals, whereas lignites and subbituminous coals, both less well coalified, generally exhibit only incipient cleat. Anthracite in eastern Pennsylvania generally does not exhibit cleat because strong mountain-building forces, in effect, welded the coal into massive, solid beds. (For a thorough discussion of coalification see Damberger, 1991.)

Conclusions

Although much is known about coal quality, much also remains to be learned. To this end, research on coal quality is being conducted in both the public and private sectors. Current studies encompass all aspects of the origin, burial history, and composition of coal in order to understand the various factors involved in determining coal quality, such as how and where to find the most appropriate coal for a specific use and how to clean coal to make its use more environmentally and industrially acceptable.

In the past, the only consideration given to coal quality was whether coal lumps held together during shipping, burned easily to produce a hot fire, and did not produce too much ash. Today, however, concerns about human health, the environment, energy demands, and the supply of certain raw materials have broadened our concept of coal quality and have increased our need to know much more about the origins, nature, and effects of coal quality. Fortunately, recent advances in analytical capabilities have made the task of understanding the intricacies of coal quality much easier to achieve.

An extensive evaluation of coal quality must be central to coal use. Whatever coal is used for—whether for the direct production of energy, chemicals, synthetic fuels, or the recovery of useful minerals—and whatever problems and solutions accompany that use depend on the quality of the coal. Additional, sophisticated, multidisciplinary research on coal quality is required for the future. The results will help make it possible for society to continue to benefit from the good qualities of

coal and to make progress in avoiding the undesirable effects of coal use.

In the near-term, the most immediate advancements related to coal-quality research appear to be improvements in the efficiency of coal use (including more efficient production of synthetic fuels) and the development of methods to best understand, and thus control, the less desirable components in coal that have the potential to contribute to environmental degradation and adverse health effects. In the longer term, the recovery of useful substances from coal (such as iron, silver, sulfur, and zinc, as well as organic chemicals, gypsum, and ash) should be an exciting area for research related to coal quality.

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