

Chapter 7

COAL

If we as a nation are to benefit in the future from our enormous, low-cost coal reserves, a variety of efforts are necessary to (1) develop and demonstrate new “clean coal” technologies; (2) reduce uncertainty over environmental regulation and allow electric power plants (which use more than four-fifths of all the coal consumed in the United States) maximum flexibility in their actions to comply with the Clean Air Act Amendments of 1990; (3) provide regulatory incentives to offset financial risks in commercial development of new clean coal technology; (4) reduce the cost, investment risks, and environmental impacts of producing liquid fuels from coal; and (5) confront head-on the need to reduce carbon dioxide emissions associated with the use of coal.

(National Energy Strategy, Executive Summary, 1991/1992)

The Administration's policy is to help industry develop cleaner and more efficient uses for coal as part of the U.S. energy portfolio. Because the primary risks of coal use are environmental rather than economic or security-related, technology development and deployment that reduce environmental impact are critical to sustaining coal's contribution to U.S. energy needs.

(Sustainable Energy Strategy, 1995)

Coal is an organic rock (as opposed to most other rocks in the earth's crust, such as clays and sandstone, which are inorganic); it contains mostly carbon (C), but it also has hydrogen (H), oxygen (O), sulfur (S) and nitrogen (N), as well as some inorganic constituents (minerals) and water (H₂O).

Most of the world's coal exists in the northern hemisphere. The United States, former Soviet Union and China together possess more than 80% of the ultimately recoverable resources (see Figure 7-1). It is important to remember that most of the world's land mass also exists in the northern hemisphere. Furthermore, many of the nations of the southern hemisphere have not experienced industrial development to the same extent as the northern nations, and have not had the need (nor the financial resources) to mount extensive exploration programs to locate and evaluate fuel reserves.

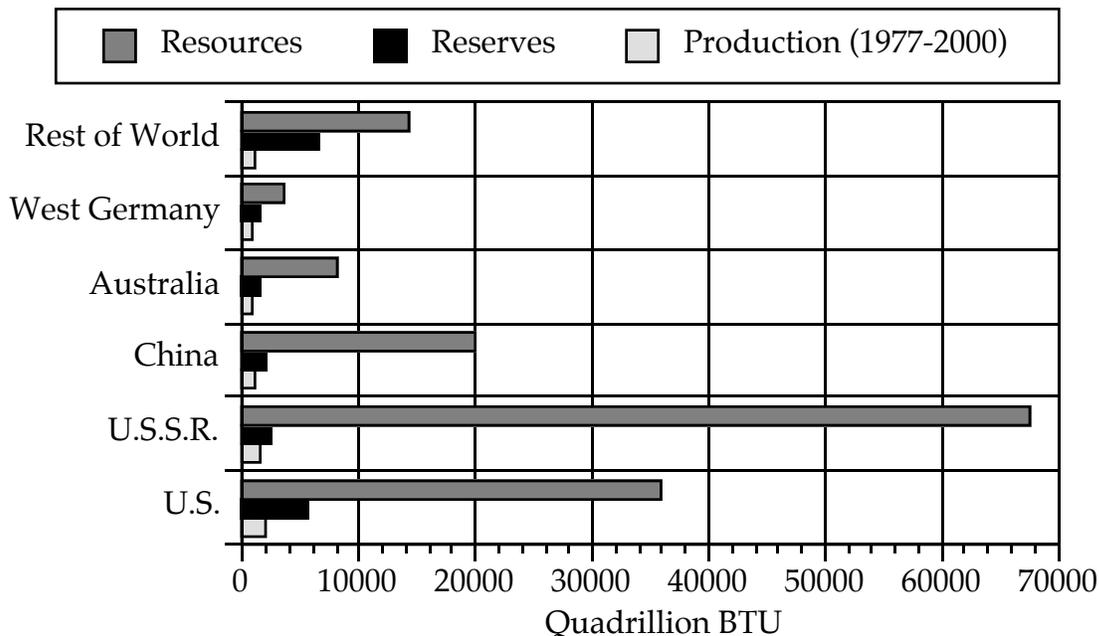


FIGURE 7-1. World distribution of coal resources and reserves.
[Source: W. Fulkerson et al., *Scientific American*, September 1990, p. 129.]

The total amount of coal in the world is so large (equivalent to about 150,000 quadrillion BTU) that the possession of even a small fraction represents a major economic benefit (see Review Question 7-2). Great Britain has as little as 1%% of the world's coal, and yet it was the world's leading coal-producing nation for over a century. Australia has less than 2% of the world's reserves, but it has been one of the leading coal-exporting nations. Both

Poland and South Africa maintain large amounts of coal exports, yet each nation does not account for even 1% of the world's coal reserves.

Of the three fossil fuels in common use – natural gas, petroleum, and coal – the United States has far more coal than gas and petroleum (compare Figures 7-1, 8-1 and 9-1). This suggests that, when supplies of gas and petroleum become scarce, it would be possible to turn to coal as our major fossil fuel energy resource.

How long could we rely on domestic supplies of coal? There are many uncertainties involved in making such an estimate. The exact quantity of coal resources is not known. We cannot predict what improvements will be made in mining technology that would allow the recovery of more of the coal than is currently achieved. We cannot evaluate with certainty what tolerance coal consumers might have for using coal of lower quality than is now typically used. Finally, it is difficult to predict the rate of coal utilization by extrapolating historical data. Annual coal consumption in the United States was virtually steady for sixty years from 1913 to 1973 (at 500 ± 100 million tons per year), except for short-term increases during the two world wars, and a short-term drop during the worst years of the Great Depression (see Figure 7-2). During the last three decades, coal use has been increasing steadily.

Any estimate of the lifetime of coal reserves must incorporate a number of assumptions. For the sake of a 'ball-park' estimate, let's assume the following: (a) no new coal reserves will be found (that is, hypothetical and speculative resources will not become reserves; see Figure 5-8); (b) no new mining technologies will be developed (conditional resources will not become reserves; see Figure 5-8); (c) all available coal will be burned regardless of quality; and (d) the annual coal consumption will increase at 5% per year (that is, it will double every 14 years). Then the lifetime of proven coal reserves would be at least 100 years (see Review Question 7-3).

The significance of this conservative lifetime estimate is that it represents an ample 'cushion' to allow the transition to new energy sources. It is likely that in the 21st century and beyond society will require non-polluting and renewable energy sources such as solar energy. In society's history, there has been a consistent pattern of at least half-a-century lag between the first discovery of an energy source and its major commercial use. For example, Michael Faraday discovered the principles of electric power generation in 1831; electricity came into widespread use in European and American homes around 1900. Edwin Drake drilled the first oil well in Titusville, Pennsylvania in 1859; automobiles became affordable when Henry Ford introduced his Model T in 1908, with a price tag of \$825. Henri Becquerel discovered the spontaneous disintegration of uranium atoms in 1896; the first commercial nuclear power plant began operating in 1954 in Shippingport, Pennsylvania. If we mark the oil price shocks of the 1970s as the birth of significant interest in solar energy and other renewable resources, it seems reasonable that massive use of solar energy may begin around 2030. There will be enough coal to carry us through to at least the year 2100. Whether coal will provide this 'bridge', as Figures 7-2 and 6-3 seem to be suggesting, will depend not on its availability, but on its continued environmental acceptance. This issue is discussed in Chapters 10 and 11.

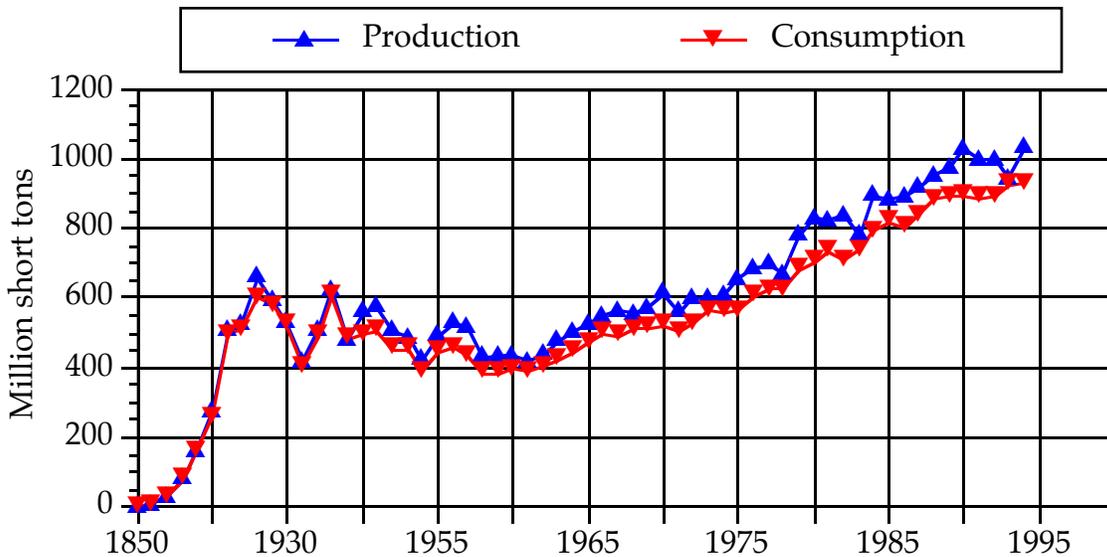


FIGURE 7-2. Coal production and consumption in the U.S. in the past 150 years. [Source: Energy Information Administration.]

Coal Formation

As described in the general discussion of the carbon cycle (Chapter 6), coal was formed from prehistoric plants, in marshy environments, some tens or hundreds of millions of years ago. The presence of water restricted the supply of oxygen and allowed thermal and bacterial decomposition of plant material to take place, instead of the completion of the carbon cycle. Under these conditions of anaerobic decay, in the so-called biochemical stage of coal formation, a carbon-rich material called *peat* was formed. In the subsequent geochemical stage, the different time-temperature histories led to the formation of coals of widely differing properties, as summarized in Table 7-1 and discussed below.

TABLE 7-1
Carbon content and age of different coals

Coal type	Approximate age (years)	Approximate carbon content, %
Lignites	60,000,000	65-72
Subbituminous coals	100,000,000	72-76
Bituminous coals	300,000,000	76-90
Anthracites	350,000,000	90-95

Properties of Coal

Although it is customary to use the word ‘coal’ in the singular, if we assembled a collection of coal specimens from around the world, we would find that this word is actually applicable to materials having a rather wide range of properties. One sample might be a wet, easily crumbled brown material looking like partially decayed wood. Another would be a very hard, glossy black, lustrous material. A third would be a soft, dull black, waxy solid. The heating values of these samples would range from about 5000 to about 15,000 BTU/lb. In a sense, there is no such thing as *coal*, if we use the word to imply a single, uniquely defined material. Rather, we might say that there are *coals*, implying a family of substances having both similarities and differences among them.

Because of wide variations in the composition and properties of coals, a classification system is needed to describe the different kinds available for use in homes and power plants. One such system, most commonly used in the United States, is summarized in Figure 7-3 and Table 7-2.

	<----- Low Rank ----->		<---- High Rank ----->	
Rank:	Lignite	Subbituminous	Bituminous	Anthracite
Age:	----- increases ----->			
% Carbon:	65-72	72-76	76-90	90-95
% Hydrogen:	~5	----- decreases -----		~2
% Nitrogen:	<----- ~1-2 ----->			
% Oxygen:	~30	----- decreases -----		~1
% Sulfur:	~0	----- increases -----		~4 --- decreases --- ~0
%Water:	70-30	30-10	10-5	~5
Heating value (BTU/lb):	~7000	~10,000	12,000–15,000	~15,000

FIGURE 7-3. Variation of selected coal properties with coal rank.

The chemical approach to characterizing coals is to determine the amounts of the principal chemical elements in them. In the jargon of the coal business, this procedure is called the *ultimate analysis* of coal. Carbon and hydrogen are the principal combustible elements in coal. On a weight basis, carbon is the predominant one. It constitutes about 60% to about 95% of the total. For most coals of 90% or less carbon, hydrogen content is generally in the range of 5%; it drops to about 2% for coals having 95% carbon. Nitrogen content of

almost all coals is in the range of 1-2%. Oxygen content is inversely related to carbon content. For example, coals of 65% carbon may contain 30% oxygen, while coals of 95% carbon may contain only 2-3% oxygen; this is significant because the more oxygen a coal contains, the easier it is to start to burn it, or to achieve its *ignition*. Sulfur content of coals is seen to be quite variable. Because of the special importance of sulfur, related to the environmental consequences of burning coals, we shall discuss the presence of sulfur in coal in some detail (see below).

Another way to characterize coals is to determine the thermal energy released when the coal is burned. We have already introduced the concept of heating value, and the range of these values for coals (see Chapter 6). We can also measure other characteristics of coals that help predict how coals will behave when handled and burned. This series of tests is called the *proximate analysis* of coal. It is important not to be confused by the name, because proximate analysis is *not* approximate; each of the tests is done under rigorously defined conditions so that any buyer or seller of coal should be able to reproduce the results in his or her own laboratory. Four characteristics are measured by the proximate analysis: moisture, volatile matter, fixed carbon, and ash.

Most coals, as they are dug from the ground, have some amount of moisture associated with them. Gentle heating of coal at a temperature slightly above the boiling point of water causes a loss of weight from the sample that is defined as *moisture*. The moisture content of coals ranges from about 5% to almost 70%. Moisture is an undesirable constituent of coals because it reduces the heating value (water does not burn!) and its weight adds to the transportation costs of coal. This is a problem for the low-sulfur subbituminous coals from Wyoming, which are currently very popular with electric power plants (see Investigations 7-2 and 7-3).

When a coal sample that has been dried to remove its moisture is heated in the absence of air - so that it doesn't burn - a further weight loss is observed. The material driven out is called *volatile matter*. The volatile matter content of coals, measured in the absence of moisture and ash, ranges from 2% to about 50%. In domestic stoves and furnaces or in small industrial appliances, coals containing large amounts of volatile matter are easy to ignite, but such coals tend to burn quickly and often burn with a long, smoky flame. As a rule, coals with higher volatile matter contents have lower heating values.

At the end of a volatile matter test, the sample remaining is usually a black solid still having a 'coal-like' appearance, suggesting that some portion of the coal substance did not vaporize. In the early days of chemistry, substances that were very difficult to change from one physical state to another were called 'fixed'. (Gases such as oxygen or nitrogen, which were extremely difficult to liquefy using the relatively primitive equipment available to early scientists, are sometimes referred to as "fixed gases.") Thus we speak of the material remaining behind after the volatile matter has been driven out as *fixed carbon*. The fixed carbon content of coals, not including the moisture and ash, ranges from 50% to about 98%. The anthracites, which contain a high proportion of fixed carbon and are a popular domestic heating fuel, may be difficult to ignite but they will often burn steadily for a long time with a short, clean flame.

Ash is the non-combustible residue formed from the inorganic or mineral components of the coal. Coals of worst quality that are burned commercially in the United States produce about 28% ash, but elsewhere in the world coals of up to 40% ash are in use. The presence of ash residue is an important distinction between the use of coal and the use of petroleum and natural gas. Burning natural gas leaves no ash, and burning even poor grades of heating oil may leave only 0.1% ash. Because natural gas and petroleum are fluids, they tend to leave behind any associated inorganic material when they are extracted from the earth. Furthermore, they have no tendency to dissolve the inorganic sediments with which they are associated in the earth's crust. Coal, on the other hand, is a solid, and it will incorporate any inorganic material from the original swamp environment or any that may have been washed or blown into the accumulating coal seam. Because coal is an immobile solid, it cannot migrate through the earth's crust to get away from these inorganic materials. As we dig coal from the earth, the mining operation may inadvertently (or inevitably) mix some rock material with the coal. The ash residue of coals follows no regular trend, but appears to depend in part on the local geology of the particular coal seam. The presence of minerals in coal is undesirable. At best these minerals are a nuisance when coal is burnt because ash must be collected and disposed of; at worst, they are environmental pollutants (see Chapter 11).

Of the four components determined by proximate analysis, only the volatile matter and the fixed carbon actually burn and liberate thermal energy. Since the moisture and ash contents of coals can be quite variable from one coal to another, and will further depend on whether the coal was partially dried or 'cleaned' to remove some inorganic debris, any comparison of coals on the basis of the combustible material must be corrected for the presence of moisture and ash. Similarly, the heating value is lowered by the presence of non-combustible moisture and ash. Comparing only the combustible part of coals requires that we know the heating value unaffected by moisture or ash. To make such comparisons, we correct the values of fixed carbon, volatile matter and calorific value to a *moisture- and ash-free basis*. Knowledge of properties of coals on a moisture- and ash-free basis allows us to classify (or rank) coals. This is shown in Table 7-2.

The variation of many important coal properties with rank was shown in Figure 7-3. By remembering these rule-of-thumb relationships, and the classification shown in Table 7-2, it is possible to make a fairly good guess of the composition and properties of a particular coal if we know its rank. For example, we could predict fairly confidently that a lignite will be a low-sulfur, high-moisture coal of low calorific value that ignites readily and burns quickly.

Sulfur in coal is of special interest because of potential air pollution problems (see Chapter 11). It occurs in coal in three ways. *Organic sulfur* is chemically bonded to the carbon atoms in the coal. The organic sulfur content of most coals ranges from 0.5% to about 2%. Organic sulfur may be a remnant of sulfur in proteins in the original plant material that was converted to coal, or it may have been chemically bonded to the coalifying organic matter by bacterial action. *Pyritic sulfur* occurs in coal as grains of the mineral pyrite (FeS_2). Much of the pyrite in coal was formed by reactions of iron and sulfur in

water in the coal swamp or in water washing through the coal as it accumulated. The amount of pyritic sulfur in coal is highly variable, depending on the local geologic circumstances (that is, how much iron and sulfur would get into the water).

TABLE 7-2
Classification of coals by rank

Class and group	Fixed carbon (%) ^a	Volatile matter (%) ^a	Heating value (BTU/lb) ^b
I. Anthracite			
1. Metaanthracite	>98	<2	
2. Anthracite	92-98	2-8	
3. Semianthracite	86-92	8-14	
II. Bituminous			
1. Low volatile	78-86	14-22	
2. Medium volatile	69-78	22-31	
3. High volatile A	<69	>31	>14,000
4. High volatile B			13,000-14,000
5. High volatile C			10,500-13,000
III. Subbituminous			
1. Subbituminous A			10,500-11,500 ^c
2. Subbituminous B			9500-10,500
3. Subbituminous C			8300-9500
IV. Lignite			
1. Lignite A			6300-8300
2. Lignite B			<6300

^a dry-mineral-matter-free basis; ^b mineral-matter-free, moisture-containing basis;

^c if it does not agglomerate.

Pyritic sulfur may range from about 0.5% to 7%. *Sulfate sulfur* occurs usually as iron or calcium sulfates. It is a very minor constituent of most coals. Since pyrite is held in coal simply by mechanical incorporation or physical mixing with the organic part of the coal, much of it can be removed by grinding the coal to liberate the pyrite grains, followed by relatively simple physical methods to separate the pyrite grains from the coal particles. On the other hand, organic sulfur is chemically bonded to the other atoms in coal; it can only be removed by appropriate chemical reactions that disrupt the carbon-to-sulfur bonds. As a rule, separations relying on physical processes are both simpler and much less expensive than separations based on chemical reactions. Although the development of techniques to remove organic sulfur is being investigated in laboratories around the world, so far none of these techniques has proved to be inexpensive enough to be commercially successful.

In the United States, four ranks of coal are in commercial use, as shown in Figure 7-3. Lignites, the lowest-rank coals, are found in the northern Great Plains and in Texas and the other Gulf Coast states. They have the lowest calorific values and highest moisture contents. They are used as fuel in electric power plants located in or very close to the lignite-mining areas. Subbituminous coals occur mainly in the Rocky Mountain states. They too are used exclusively for electric power generation. Bituminous coals are the coals of greatest commercial use in the United States. Two major deposits of bituminous coal exist, one in the Appalachian mountain states - eastern Kentucky, western Virginia, Ohio, West Virginia, and Pennsylvania - and a second in the central part of the United States, in western Kentucky, Indiana, and Illinois. Bituminous coals are used for electric power generation, and some special bituminous coals are converted to coke for use in the metallurgical industry (see below). Anthracites are the highest-rank coals and contain the largest amounts of both carbon and fixed carbon. Commercially useful deposits of anthracite occur in a relatively small region in northeastern Pennsylvania. As mentioned previously, anthracite is a premium coal for domestic use. If properly cleaned before being sold, it is a low-ash, low-moisture, and low-sulfur coal. Although it is very difficult to ignite in household furnaces, it burns with a short, hot and clean flame for a long time.

Illustration 7-1. Calculate the carbon-to-hydrogen atomic ratio of an Illinois (bituminous) coal that has the following ultimate analysis (elemental composition): 81.3% C; 5.3% H; 9.8% O; 1.7% N; 1.9% S.

Solution.

$$\frac{\text{C}}{\text{H}} = \frac{81.3 \text{ g C}}{5.3 \text{ g H}} = \left(\frac{81.3 \text{ g C}}{5.3 \text{ g H}} \right) \left(\frac{1 \text{ g H}}{1 \text{ mol H}} \right) \left(\frac{1 \text{ mol C}}{12 \text{ g C}} \right) = 1.3 \frac{\text{mol C}}{\text{mol H}}$$

This result is to be compared to the analogous calculations for petroleum and natural gas; see Illustrations 8-1 and 9-1.

Coal Utilization

There are three major pathways for coal utilization. These are illustrated in Figure 7-4. The principal process by which coal is used is *combustion*, as shown in Figure 7-5. Combustion involves burning the coal in air to liberate thermal energy (heat). The heat is used as such for comfort or to carry out many industrial processes that require high temperatures; it is also used to generate steam for use in electric power plants. *Carbonization* is the heating of coal to high temperatures in the absence of air; it is used in manufacturing coke for the metallurgical industry. Figure 7-5 shows that this is a small

market but it is still a very important one: its development in the 18th century ushered in the Industrial Revolution. *Conversion* uses various chemical processes to transform coal into gaseous or liquid fuels, called synthetic fuels (see Chapter 10); currently only one commercial synfuels plant exists in the United States. Common to all these processes is prior mining of the coal, its preparation (processing) and its transportation to the consumers.

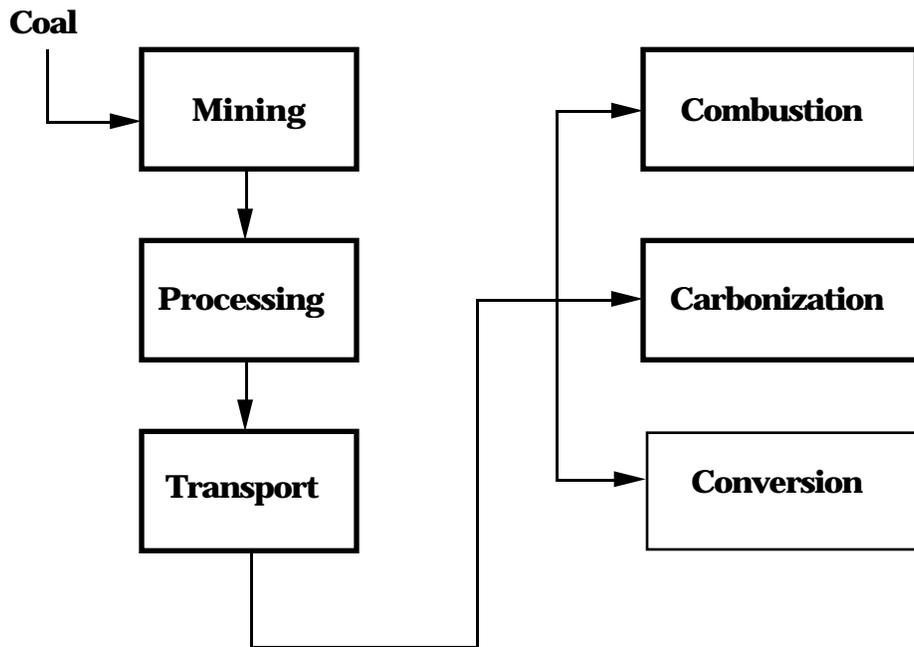


FIGURE 7-4
Pathways to coal utilization.

Coal Mining. Coal must be mined to get it from the ground to the factories or electrical power plants where it will be used. Two broad categories of mining techniques are used.

Surface mining, also called *strip mining*, is a highly efficient process, in that it can recover virtually all of the coal in a given seam. Strip mining is also highly productive, in that thirty to forty tons of coal can be produced per worker per day. About 60% of all coal mined in the United States comes from strip mines; practically 100% of the lignite and subbituminous coal production is obtained from strip mines. However, strip mining is a controversial activity, primarily because of its impact on the environment. In strip mining the fertile top soil must be removed to expose the coal. If the top soil is not properly stored during mining, and then replaced and re-seeded after mining, nothing can grow in the

mined area. The strip-mined lands will resemble a lunar landscape. This environmental tragedy is especially evident in the Appalachians and in the anthracite region of Pennsylvania, where uncaring or unscrupulous mine operators abandoned the mined lands after the coal was recovered. With appropriate care, however, the top soil can be replaced, and with drainage, fertilizing, watering, and seeding of new plants, the mined land can be restored to provide an attractive and productive plant community. Even with mined land reclamation, some disruption of the landscape is inevitable while mining is actually in progress.

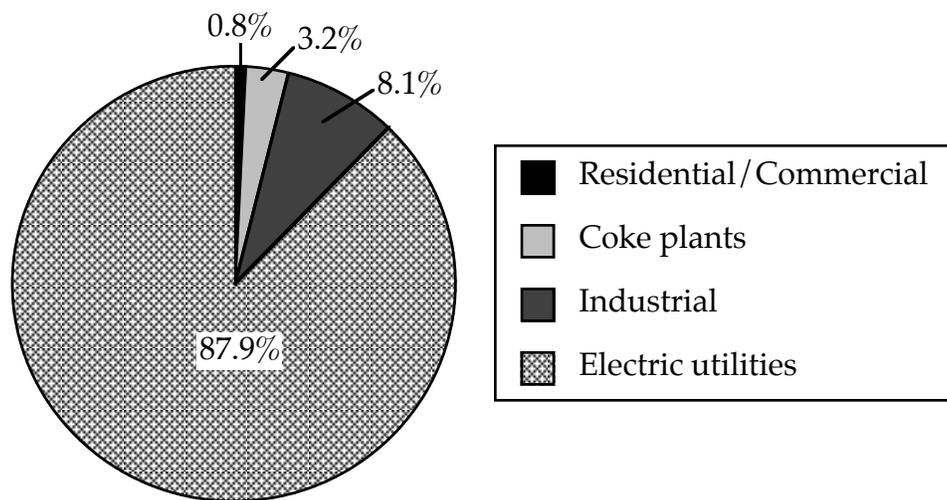


FIGURE 7-5. Distribution of coal utilization pathways in the United States. [Source: Energy Information Administration.]

Underground mining is generally performed by one of two methods. The *room and-pillar method* cuts ‘rooms’ into the coal seam, and leaves large pillars of unmined coal standing to help support the ‘roof’. Leaving these pillars of coal means that only about 60% of the coal in a seam is actually extracted. In the *longwall method* mechanized mining equipment is used to gouge the coal away from the seam face. The mining equipment is designed to allow the roof to collapse as the coal is removed. Longwall mining is more efficient than room-and-pillar mining in that it allows the recovery of almost all the coal, but its use is restricted to mining situations that can physically accommodate the large machinery used. Underground mining is much less productive than strip mining. It is highly mechanized today; nevertheless, it remains an unpleasant and dangerous occupation.

Numerous technical problems are associated with underground mining. Air in the mine must be kept safe. Both methane and carbon dioxide are released as by-products during the formation of coal. These gases can be trapped in the coal and accumulate in the mine as the

coal is removed. Accumulation of carbon dioxide can cause asphyxiation. Methane can cause explosions or fires. Electronic detectors and alarms are used to safeguard miners, but mines still require good ventilation. In addition, mining creates a lot of coal dust. The amount of dust in the air must be controlled. A mixture of fine coal dust and air is easily ignited; it is a powerful explosive, which can cause devastating, and often fatal, mine explosions. Long-term exposure of miners to coal dust leads to the debilitating *black lung disease*. Some very deep mines may extend below the natural water table, requiring huge pumps to keep the mines from flooding. The water in coal mines is usually very acidic (because slow oxidation of the pyrite in coal produces sulfuric acid). If acid mine water drains into rivers or lakes it can kill the aquatic life; if it finds its way to the top soil, it can dissolve away minerals and nutrients needed by plants.

Table 7-3 and Figure 7-6 summarize the information on the principal U.S. mines of coals of different rank. Much of the coal, generally of low rank and low sulfur content, is now mined west of the Mississippi river, principally in Wyoming, but also in Texas, Montana, North Dakota, Colorado and New Mexico. Its transportation to the high-volume consumers in the Northeast, the Midwest and elsewhere will increasingly be necessary, particularly because of its low sulfur content. Continued use of high-sulfur coals from Kentucky, West Virginia and Pennsylvania will be difficult because of the strict provisions of the Clean Air Act regarding sulfur oxide emissions (see Chapters 11 and 21).

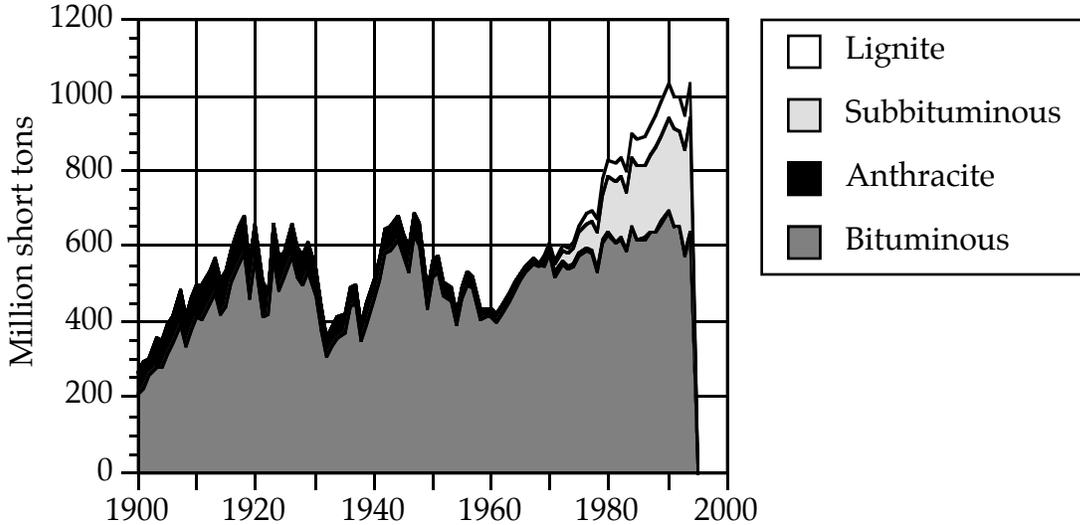


FIGURE 7-6. Production of coal in the United States by rank.
[Source: Energy Information Administration.]

TABLE 7-3
Location and capacity of principal coal mines in the United States

State	1995 production*	1995 average quality**	1995 average % sulfur**	Low S reserves†	Total reserves†
Alabama	24,640	11,861	1.20	2,824	3,018
Alaska	1,698	—	—	2,548	2,548
Arizona	11,947	10,274	0.53	121	121
Colorado	25,710	9,895	0.39	10,000	10,096
Illinois	48,180	9,970	1.14	1,925	33,969
Indiana	26,007	10,338	1.57	1,171	4,329
Kansas	285	8,730	0.43	0	683
Kentucky	153,739	11,625	2.42	9,195	16,258
Missouri	548	9,216	0.57	0	3,851
Montana	39,451	8,520	0.68	71,996	75,389
New Mexico	26,813	9,033	0.80	8,215	8,215
N. Dakota	30,112	6,585	0.74	5,998	7,224
Ohio	26,118	12,122	1.89	1,635	11,718
Oklahoma	1,876	8,557	0.36	521	816
Pennsylvania	61,576	12,315	2.12	6,851	12,520
Texas	52,684	7,346	0.77	6,272	10,057
Utah	25,167	11,550	0.47	2,475	3,001
Virginia	34,099	12,743	1.03	1,362	1,362
Washington	4,868	8,267	0.69	729	729
W. Virginia	162,997	12,418	1.98	13,922	19,649
Wyoming	263,822	8,738	0.50	41,994	45,403
Total	1,032,974	—	—	187,479	273,913
Surface				90,907	122,925
Underground				96,572	150,988

*thousand short tons; **received at electric power plants ('quality' is given in BTU/lb).

†in million short tons (low S coal has less than 1.68 %S/10⁶ BTU).

[Source: Energy Information Administration.]

Coal Preparation (Processing). Once the coal has been mined, it is usually processed to separate the inorganic, ash-forming components and to produce appropriately sized particles. The various operations involved in this processing are collectively known as *coal preparation* or *coal beneficiation*. The degree of preparation depends on the intended use of the coal. For residential or commercial heating – a very small market for coal nowadays – lumps about 1 inch in size are desired, along with as small an amount of inorganic constituents as practicable (to leave little ash after burning). Coal to be used for the

production of coke for the iron and steel industry has the most stringent requirements. It must have low ash (typically less than 5%), low sulfur, and must be of bituminous rank. As mentioned above, this is a small but very important market for coal. Coal for use in electric power plants – by far the largest market for coal – has the least stringent requirements. Substantial amounts of ash can be tolerated. The coal need not be pulverized before transportation, but for firing in modern power plants it will be reduced in size to about 0.1 mm before being burned.

Coal Transportation. After the coal has been prepared, it will be transported to the point of use. It may then be stored at the plant site for some time before being consumed. Transportation of coal is efficient (see Figure 4-14) but very expensive. It can double the cost of coal. For example, a lignite that costs \$10 per ton if purchased at the mine site in western North Dakota can cost \$20 per ton delivered by train to a power plant in eastern South Dakota. For long-distance transportation, trains or ships and barges are used. *Unit trains* are an efficient approach to transportation. They may contain 100 or more coal cars – only coal cars – and these shuttle continuously between the mine and the consumer. Because the unit trains do not have to be broken down and reshuffled in rail yards, over the course of a year a given coal car used in a unit train will actually transport six or seven times more coal than a similar car that is a component of ordinary freight trains.

A possible alternative to present transportation strategies is shipment of coal by *slurry pipelines*. Coal is pulverized to a size of 1-10 mm, mixed with roughly an equal weight of water, and the resulting slurry is pumped through pipelines from the mine to the point of use. Such pipelines may find increasing use in the United States. However, with current combustion technology, it is necessary to separate the coal from the water at the “receiving end” of the pipeline, leaving an impure water that must be treated before being returned to the environment. Slurry pipelines have been controversial in the arid regions of the western United States, because the agricultural industry perceives that precious water is being pumped out of the region. Furthermore, slurry pipelines are vigorously opposed by the established transportation industry.

Most large-scale users of coal will provide for storage of coal supplies on site. This can involve a short-term storage for a few days, to guard against brief interruptions of supply, as might be caused by a railroad accident, or long-term storage, of one to two months' supply, as protection against severe disruptions such as labor strikes. If proper procedures for stockpiling the coal are not used, heat can be generated in the pile until, in extreme cases, the coal will actually catch fire. A very slow reaction of the coal with oxygen in the air liberates heat. If the heat is not dispersed, not only will the temperature of the coal pile increase, but the rate of the chemical reaction between oxygen and coal will also increase. This effect establishes a "vicious cycle" of greater and greater heat build-up with faster and faster reaction until the coal ignites in a phenomenon known as *spontaneous combustion*.

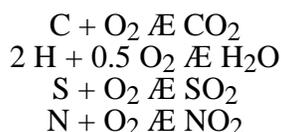
Coal Combustion. Coal combustion for domestic heating has been practiced since antiquity. Today the use of coal for domestic heat is a very minor market for coal in the

United States (see Figure 7-5). Less than 1% of the coal sold is used for domestic heating and cooking, and only a very small percentage of households use coal as a primary source of energy.

There are several reasons for the limited residential use of coal. Electricity, natural gas and fuel oil heating systems, with thermostats connected to automatic control mechanisms, are much more convenient for homeowners to use than is coal. Coal is a dirty fuel. Depending on the kind of coal used, coal dust and ash dust can get all through the house, requiring frequent and thorough housecleaning. Furthermore, the ashes must be collected and taken outdoors for refuse collection and proper disposal. Shortly after World War II, the interstate natural gas and oil pipelines expanded rapidly, making these two fuels more available throughout the United States. At about the same time, several very long and bitter labor strikes in the coal industry caused short-term disruptions in the available coal supply. Some consumers perceived that oil and natural gas were more 'secure' (that is, less susceptible to disruption by labor action) than coal. This confluence of two trends – the greater availability of oil and gas, and the disruption of coal supplies – led to a shift to greater use of oil and gas in domestic applications.

Despite the relatively small current domestic use of coal, we shall discuss briefly the small-scale combustion of coal for two reasons: to illustrate some general principles of combustion, and because coal-fired stoves or heaters are making a modest come-back as auxiliary sources of household heat.

Coal has been used as a source of domestic heat in China at least since 500 B.C. Romans used coal during their occupation of Gaul and Britain. In 1295, Marco Polo returned to his native Italy from a lengthy expedition to China and reported on the use of coal as an energy source. For about the last 3000 years, the standard way of burning coal on a small scale is using various versions of the *updraft combustor* (see Figure 7-7). The hottest part of the fire is on the grate. Here *complete combustion* of the elements in coal occurs. Although the components of coal are chemically bonded in a complex structure, for illustrative purposes we can write the reactions as if they were simply individual elements. Thus we have the following simple chemical equations:



Higher in the bed of coal, there will be less oxygen available for combustion, because some of the oxygen in the air sweeping through the bed has already been used up. In an atmosphere which has a deficiency of oxygen, *incomplete combustion* occurs:



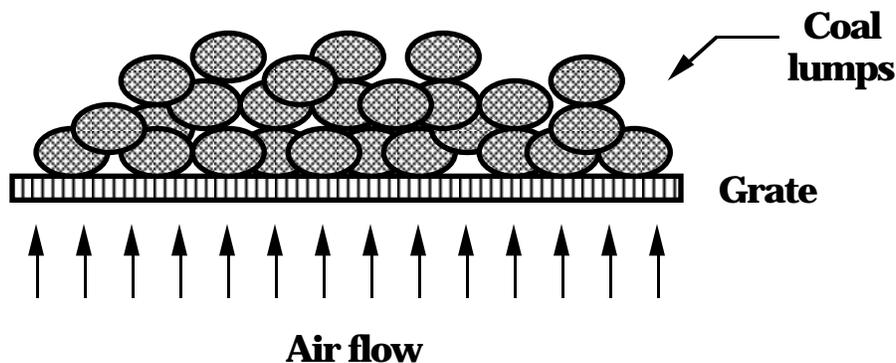


FIGURE 7-7. Coal burning on a grate in an updraft combustor.

This reaction is undesirable for two reasons. First, less heat is liberated when carbon is burned to form carbon monoxide than when carbon is converted to carbon dioxide. Much more important, however, is the fact that *carbon monoxide is a deadly poison*. It forms very strong chemical bonds with the iron atoms in the hemoglobin in blood. Ordinarily, these iron atoms form bonds to oxygen molecules, and transport oxygen to all the cells of the body. As carbon monoxide bonds to the iron, its presence prevents the iron from 'carrying' an oxygen molecule through the bloodstream. If a large number of hemoglobin molecules are 'saturated' with carbon monoxide, the inability to transport oxygen throughout the body can lead to death. Sometimes, especially at night, it might seem convenient to heap a lot of coal onto the fire so that the fire will burn through the night without someone having to get up to replenish the coal. However, the potential exists that with too much coal there may be an inadvertent production of carbon monoxide, leading to poisoning and possibly even death (see Chapter 11).

An additional problem associated with the combustion of coal in small units is the production of smoke and soot. In the complete absence of oxygen, carbon and carbon compounds will not burn. If the fire is starved of oxygen, particles of carbon from the coal may not burn, but rather be liberated from the coal as soot particles. In addition, smoke is formed when the top-most layers of coal on the grate become hot enough to evolve volatiles (as in the volatile matter test in the proximate analysis of coal). These volatiles may undergo partial combustion or carbonization to form tars and soot. The first complaints about such air pollution from coal smoke were made in London in 1275! (And some people think that pollution is a new problem...) There is a British slang term, "the big smoke," which originally was a reference to London (much as Americans call New York "the big apple") but which sometimes is used to refer to any large city. Even today, cities like Scotland's Edinburgh have these black deposits on many of their buildings. In the early years of this century, Pittsburgh was exposed to 1000 tons of soot being deposited per square mile each year. This coal smoke reduced the amount of sunlight reaching the ground by 40%. In addition to the aesthetic problems of soot depositing on clothes and

other belongings, coal smoke can also contribute to health problems. In the atmosphere, the sulfur oxides from the burning of sulfur in coal can be converted to sulfuric acid. The sulfuric acid mist can condense onto tar or soot particles. Inhaling these particles can in turn lead to serious health problems in the respiratory tract. In addition, soot particles coated with sulfuric acid can absorb moisture, forming thick, noxious fogs. These issues are covered in more detail in Chapter 11.

In spite of these problems, coal is one of the cheapest and most reliable fuels for use in electric power plants. The fluctuations in its price are summarized in Figure 7-8. More than 85% of the coal mined in the United States is burned for electric power generation (Figure 7-5), and about half of our electricity is produced in coal-fired power plants (see Chapter 18). Half of world's coal is also burned in power plants (see Figure 5-13). As discussed in Chapter 4, the coal is burned to liberate heat. The chemical energy liberated from the combustion of the coal is captured by water, which evaporates to form steam. The kinetic energy of the steam is used to turn a turbine, which is a device that captures the kinetic energy of a moving fluid and converts it to kinetic energy in a rotating piece of machinery. In a power plant, the turbine is connected to an electrical generator, which converts the mechanical (kinetic) energy of the rotating turbine shaft into electric energy.

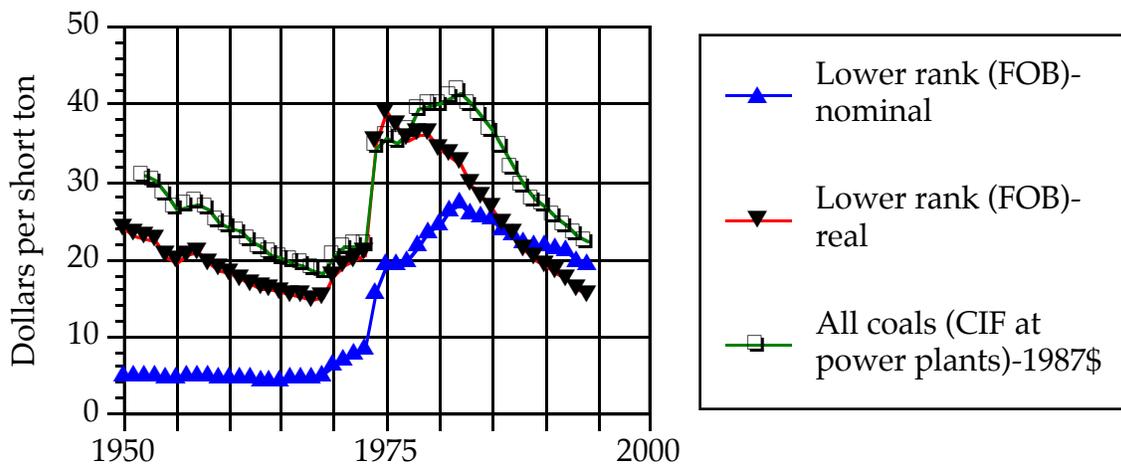


FIGURE 7-8. Historical trends in the price of coal in the U.S. [Source: Energy Information Administration.]

Since the price of electricity to the consumers depends in part on the costs the electric utility must pay for fuel, it is important to generate the maximum amount of steam (and hence the maximum amount of electricity) from a given amount of coal. As the coal burns, we want to insure that as much heat as possible will be liberated by the combustion process; in other words, we want to insure that complete combustion takes place. We have seen that problems of incomplete combustion in domestic furnaces come from oxygen starvation and

from poor penetration of air inside the porous lumps of burning coal. In most power plant boilers, two approaches are used to avoid these problems. First, the coal is ground to a very fine particle size (pulverized) before it is burned. Second, an air stream is used to blow the pulverized coal into the furnace. Further steps include using multiple burners mounted on the walls of the furnace so that as they fire coal and air into the furnace, they create a very turbulent (that is, well mixed) flame, insuring intimate contact of the burning coal particles with air. Additional streams of air are also injected into the furnace to insure an ample supply of oxygen.

With all these steps taken to insure rapid and complete burning of the coal particles in a very turbulent flame, very high temperatures – around 1500 °C – are generated in the hottest region of the furnace. Two techniques are used to capture this heat and produce high-pressure and high-temperature steam. The walls of the boiler can be constructed of pipes through which water is passed. Additional heat can be captured from the hot combustion gases by installing tubes in the flue, in somewhat analogous fashion to improving the heat recovery from a domestic stove by installing a water heater in the flue. The steam generated in the boiler of an electric power plant can have temperatures as high as 550 °C and pressures of 280 atmospheres. The steam drives the turbine, which is connected to the electric generator. The First Law efficiency of the turbine itself is typically about 45%. However, not all of the heat liberated by burning coal is captured in the steam. Some heat is lost from the steam en route to the turbine. Other minor inefficiencies, such as friction in rotating shafts, also exist. As a result, only about 35% of the chemical energy in the coal (measured as its calorific value) leaves the other end of the plant as electric energy on its way to the consumers (see Table 4-2).

Three potential pollutants (see Chapter 11) are formed when coal is burned in a power plant boiler: sulfur oxides, nitrogen oxides and fly ash. Sulfur in the coal is converted to sulfur dioxide, SO₂, and sulfur trioxide, SO₃. It is usually convenient to refer to these oxides of sulfur collectively as SO_x (pronounced ‘socks’). Some combustion systems operate at such high temperatures that they convert nitrogen to a mixture of nitrogen oxides, collectively represented as NO_x (pronounced ‘knocks’). There are two sources of NO_x. Nitrogen chemically bonded to the carbon in the coal burns to form *fuel NO_x*. The air used in the combustion process contains 79% nitrogen. At extreme temperatures some of this nitrogen can be converted, by the intense heat of the combustion reactions, to *thermal NO_x*. The ash, produced from burning the inorganic constituents in the coal, should drop to the bottom of the boiler, where it can be collected and removed. However, the turbulent flame and the rapidly moving stream of combustion gases sweep some of the very fine particles of ash up through the boiler and out of the flue. These ash particles are known as *fly ash*.

Coal Carbonization (Coking). The second largest use of coal is the manufacture of coke for the metallurgical industry. Iron and its alloys (particularly the various kinds of steel) are perhaps the most versatile metallic construction materials known to humankind. Unfortunately, iron occurs in nature not as metallic iron but rather in ores containing iron compounds such as oxides or carbonates. The production of metallic iron requires a

chemical reaction to remove the oxygen from the iron compounds and liberate the iron as the metal. The conversion of a metal oxide to metal is an example of a general type of chemical reaction known as reduction (as opposed to the inverse process called oxidation). Substances that we add to the reaction to cause the reduction to take place are termed *reducing agents*. Among the most powerful types of reducing agents, and among the least expensive, are various forms of carbon or substances rich in carbon.

Beginning in about the 16th century, the population of Europe began to expand rapidly, and as the population increased, so did the market for new items, such as household goods and farm implements. At the same time, industrial progress was also being made. Both of these factors resulted in an increasing demand for iron, for manufacturing consumer items, farm tools and machinery.

In the 1600s, the preferred reducing agent for liberating metallic iron from its ores was charcoal. Charcoal is made by heating wood in the absence of air, driving out the moisture and a variety of other products and leaving behind the carbon-rich porous solid. As the demand for iron increased, so too did the demand for the necessary reducing agent, charcoal. The greatly increased consumption of wood to make the charcoal led to such extensive cutting of the forests in England that the English Parliament enacted legislation restricting the establishment of new iron foundries. This situation provides a 300-year old example of how limitations of energy supplies (in this case, wood to produce charcoal) led to limitations on industrial development and, by extension, to impacts on people's standards of living (by limiting the availability of articles made of iron).

As early as 1609, attempts were made to substitute coal for charcoal in iron-making. We have seen that, as coal is heated, some volatile compounds are released from it. When using coals containing appreciable amounts of volatile matter, the escaped volatiles could react with, or dissolve in, the iron metal as it is being formed. The impurities in the iron were very undesirable, because they weakened the metal and made it difficult to shape useful objects from the iron. A similar problem had been encountered in the brewing industry, where charcoal had been used to dry the malt used in the brewing process. Substituting coal for charcoal led to horrible tastes in the beer or ale, because the volatiles escaping from the coal were absorbed by the malt and ruined its flavor. The brewers discovered that if coal is heated in an inert atmosphere to drive off the volatiles, the remaining residue (which is largely the fixed carbon, called char or coke) is still very useful as a fuel.

When many kinds of bituminous coals are heated in an inert atmosphere, they soften and swell to form a plastic mass. The escaping volatiles pass through this plastic material, which then resolidifies to a carbon-rich solid upon further heating. Coals that pass through a plastic stage on heating are called *caking coals*. Some caking coals resolidify on heating to form a hard, very strong, carbon-rich porous mass suitable for use as a reducing agent in the metallurgical industry. This material is called *coke*, and the special class of caking coals that yield a satisfactory coke are known as *coking coals*. (It is unfortunate that the words caking and coking are so similar, because they are not synonymous. All coking coals are necessarily caking coals, but not all caking coals are coking coals.)

To be useful in the metallurgical industry, the coke needs to meet five criteria. To be a useful reducing agent, the coke must have a very high carbon content. To keep the iron reasonably pure, the coke must have low contents of sulfur and ash. To provide ample heat, the coke must have a high content of fixed carbon and have a high calorific value. To let air pass through the fuel bed, but yet keep the fuel bed from being collapsed by the weight of iron ore, the coke must be quite porous and very strong. Finally, to help keep the cost of the iron low, the coke must be cheap.

Coke is a strong reducing agent, it is relatively cheap, and it adds little or no impurities to the iron. However, because coke is essentially all fixed carbon, it was very difficult to ignite and burn in the primitive iron-making furnaces of the century. The first iron made by using coke as a reducing agent was very brittle, because poor combustion of the coke was not getting the iron hot enough during the iron-making process. This problem was solved in 1735 with the invention of the blast furnace. The blast furnace is charged with successive layers of coke (the fuel and reducing agent), iron ore, and limestone (which collects any impurities from the ore into a molten slag). Air is blown through the furnace at high pressure, burning the carbon in the coke to carbon monoxide. Carbon and carbon monoxide react with iron oxides to form iron metal, which can be drained from the furnace as a liquid. The impurities in the ore and any coke ash are collected into a liquid slag, which can also be removed from the furnace.

The invention of the blast furnace led to the large-scale manufacture of inexpensive iron articles. The availability of cheap items for household use and for farm equipment improved people's standards of living. The availability of inexpensive industrial machinery made from iron or steel revolutionized manufacturing and transportation. This change indirectly affected people's lives because, for the first time in human history, machinery could be substituted on a wide scale for human or animal muscle power. Using big machines allowed work to be centralized into factories, rather than being done in households or on farms. Centralizing work into factories meant that people who worked in the factories would cluster into urban areas around the factories. The increasing urbanization of the population brought with it all of the benefits - and all of the problems - associated with city life.

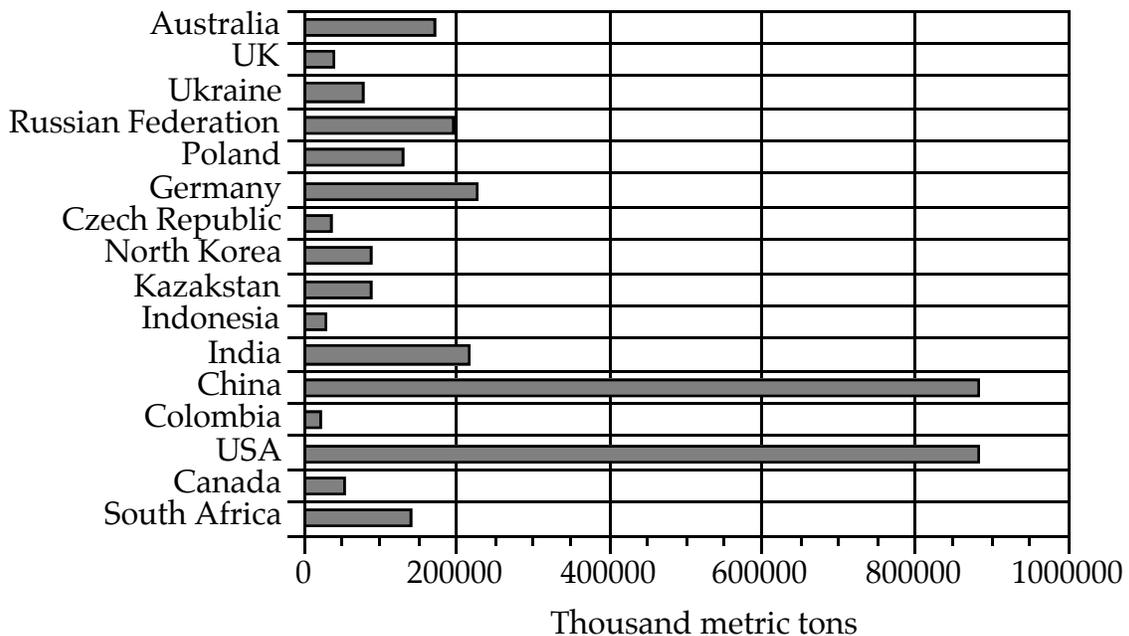
For a nation to sustain a vigorous iron and steel industry, it needs plentiful supplies of coking coal, iron ore, and limestone. The nations that possessed all three of these raw materials have been dominant in world affairs – nations such as Great Britain, the United States, Russia and Germany. A major military objective during the German invasion of the Soviet Union in 1941 was the Donets Basin, a rich deposit of good-quality coking coal. This coal was thought to be so important that as the tide of battle turned later in the war, Hitler refused to allow the Donets region to be given up. Ultimately, the Soviet armies encircled and totally destroyed the German forces in the region; had the German armies withdrawn instead, they could have been used elsewhere (against the Anglo-American invasion of Normandy, for example) and could possibly have affected the outcome of the war.

The development of modern, industrialized urban life as we know it, and the outcome of major world events, hinges on the fact that some bituminous coals soften, swell, and turn to coke. Both in its use to produce coke and as a fuel, coal has been the principal ‘motor’ of industrial development in the last two centuries. Whether its importance will decline in the next century, and at what rate, is a major policy question facing society today.

REVIEW QUESTIONS

7-1. The productivity in U.S. coal mines has doubled in the last decade (see NYT of 6/8/93, “Striking Coal Miners Fight To Protect Shrinking Power”), from 2 to 4 tons per miner per hour. At the same time the number of miners employed in bituminous coal mines has dropped to around 120,000. Using this information, estimate the annual production of bituminous coal in the U.S. Compare it with the information provided in Figure 7-6.

7-2. The “1994 Energy Statistics Yearbook” of the United Nations reports that the world coal production was 3.33 billion metric tons. (a) What percentage of this production is accounted for by the following 16 countries?



- (b) What percentage of world production is in the U.S. and China?
- (c) Compare the information in this graph with that provided in Figure 7-6. Is the agreement good?
- (d) Compare the information in this graph with that provided in Figure 6-4. What average heating value for coal do you have to assume to get good agreement? Is this value reasonable?

7-3. Check the statement made on p. 115 that, at 5% growth rate, the U.S. coal reserves would last for at least 100 years.

7-4. Indicate whether the following statements are true or false:

- (a) In general, the sulfur content of bituminous coals is lower than that of any other rank.
- (b) As the rank of coal decreases, so does the carbon content of coal.
- (c) As the rank of coal decreases, so does the moisture content of coal.
- (d) Most of the low-rank coal in the U.S. is mined east of the Mississippi river.
- (e) Coal conversion is the main method of coal utilization in the U.S. today.

7-5. A subbituminous coal from Wyoming has the following elemental composition: 75% C, 4% H, 19% O, 1.5% N and 0.5% S. Calculate its atomic hydrogen-to-carbon ratio.

7-6. Compare the quantities of CO₂ produced by burning the bituminous coal of Illustration 7-1 and the subbituminous coal of Review Question 7-5. Which coal produces more CO₂ per pound? Which one produces more CO₂ per 10⁶ BTU of heat produced. Assume that the heating values are 13,000 for the bituminous coal and 10,000 BTU/lb for the subbituminous coal. (Hint: Remember that for every 12 tons of carbon in any fuel, 44 tons of CO₂ are produced.)

INVESTIGATIONS

7-1. Asia is poised for rapid economic development in the 21st century. Do Asian nations have enough coal? Prepare a graph that compares their production and consumption of coal. See the *Economist* of 8/15/92 (“Asian energy: Quenching the tigers' thirst”). For the particularly important case of China (see Investigation 21-40), see NYT of 11/29/95 (“China's Inevitable Dilemma: Coal Equals Growth”).

7-2. We have seen in Table 7-3 that Wyoming has a lot of coal. What is perhaps even more important, Wyoming has a lot of low-sulfur coal. Find out more about “Wyoming's Rich Vein of Clean-Burning Coal” (NYT of 12/28/90). Compare this information with that provided in Table 7-3. See also *National Geographic* of 1/93, p. 55 (“Wide Open Wyoming”).

7-3. One problem with using the low-rank Wyoming coal is the expense of transporting all that water that it contains (see Figure 7-3). Find out about a way to get around this problem. See NYT of 9/30/92 (“Making Coal More Useful By Cooking Out the Water”).

7-4. In an article entitled “The Curse of Coal,” Ted Gup of *Time* magazine (11/4/91) recounts some of the hazards of coal mining and problems in the coal industry. Summarize his main points. See also NYT of 3/17/91 (“Coal Miners Contend Their Plight Is Worsening”), the *Economist* of 2/13/93 (“American coal mining: Seam of trouble”) and NYT of 9/19/95 (“Saving Money or Saving Lives”).

7-5. The dramatic decline, and perhaps demise, of British coal (which once made possible the Industrial Revolution) has been well documented in the media. Summarize the reasons for these events. See *Time* of 10/26/92 (“An Era Is History as King Coal Nears Death”), *Newsweek* of 10/26/92 (“How Green Is Their Valley? Closing the coal pits threatens miners—and Major”), WSJ of 10/14/92 (“British Coal Plans Mine Closings, To End 30,000 Jobs”), NYT of 10/14/92 (“Britain to Shut Most of Its Coal Mines”) and 10/22/92 (“Britain Now Seeks Market for Coal”), and the *Economist* of 10/17/92 (“A deep seam of trouble”), 10/24/92 (“The Economics of Coal: The case for phasing in the coal closures more gently is strong. The case for saving the threatened mines is not.”) and 3/27/93 (“A disappearing world”).

7-6. Coal mines are declining in Russia as well. Why? See NYT of 2/29/96 (“Woes of Modern Russia Mirrored In the Decline of Its Coal Mines”) and the *Economist* of 12/4/93 (“Russian coal: Rouble down pit”).

7-7. What does it mean to “carry coal to Newcastle?” See the *Economist* of 10/17/92 (“Coal from Newcastle”).

7-8. A more balanced account of coal's prospects can be found in the *Economist* of 4/2/94, in an article entitled “Coal: Joys from the black stuff,” PI of 10/3/94 (“Coal makes a comeback as fuel for power plants”) and NYT of 3/3/96 (“Coal Tries for a Comeback”). Summarize the reasons for such (guarded) optimism.

7-9. Coke from coal played a key role in the Industrial Revolution sparked by the steel industry. Today's steel industry is as important as ever, but not without its problems. Find out about the use of coal and coke in modern steelworks. See NYT of 11/30/94 (“Steelmakers Big and Small Join in a Quest for Better and Cheaper Methods”).

7-10. Access to energy resources in environmentally protected areas is not such a hot issue for coal as it is for oil (see Investigation 21-1). Why not? Yet there are some controversies, as discussed in NYT of 9/28/92 (“U.S. Set to Open Public Land for Mining”). For the most recent one, in the aftermath of President Clinton's declaration of a new national monument in Utah, see the relevant NYT editorial of 9/18/96, as well as a response to it in

NYT of 10/13/96 (“Mining the Coal in Utah”). See also *USA Today* of 12/26/96 (“Set-aside of Utah coal reserve questioned: Some see connection to Indonesian concern”).

7-11. Colombia is a country plagued with political problems but richly endowed with energy resources (see Investigation 8-5). Find out why a U.S. company is “bullish” on Colombian coal, in NYT of 7/27/95 (“U.S. Venture Bets on Colombian Coal”).