upon the deposit location and state standards. Cost effects should be predictable with a fair degree of accuracy for individual cases.

5.5 COAL

Coal is a combustible natural solid, formed from partially decomposed and subsequently metamorphosed plant remains. It is dark brown to black in color and consists primarily of carbon (more than 50% by dry weight) in the form of numerous complex organic compounds. The composition of coal varies considerably from region to region and within given fields.

Coal is generally found as a layer in sedimentary rock. These layers, called seams or beds, differ greatly in thickness, depth below the surface, and areal extent.

Because of the varieties of coals available, their widespread occurrences, and the diversity of end uses, numerous classifications of coal have been developed. Coals have been classified according to geological age, structure, recognizable coal-forming plant materials, volatile matter or fixed carbon content, and petrographic constraints.

In the U.S., coal is commonly classified as anthracite, bituminous, subbituminous and lignite. In this system, classification is by fixed carbon content and heating value calculated on a mineral-free basis. Table 5.14 is a brief summary of coal characteristics.

Anthracite, highly metamorphosed coal, is jet black in color, hard and brittle, breaks with a conchoidal fracture, and displays a high luster. Its moisture content is low and its carbon content high.

Bituminous coal is dense, compacted, banded, brittle, and displays columnar cleavage and a dark black color. It is more resistant to disintegration in air than are subbituminous and lignite coals. Its moisture content is low, volatile matter content is variable from high to medium, and its heating value is high. Several varieties of bituminous coal are recognizable.

Table 5.14: General Coal Characteristics (Ref. 16)

Class	Fixed Carbon Limits (%)	Volatile Matter Limits (%)	Heating Value Limits (%)	Agglomerating Character
Anthracite	86–96	2–14	—	Nonagglomerating
Bituminous	< 86	> 14	11,500–>14,000	Commonly Agglomerating
Subbituminous	—	—	8,300–11,500	Variable—may or may not agglomerate
Lignite	—	—	< 6,300–8,300	Nonagglomerating

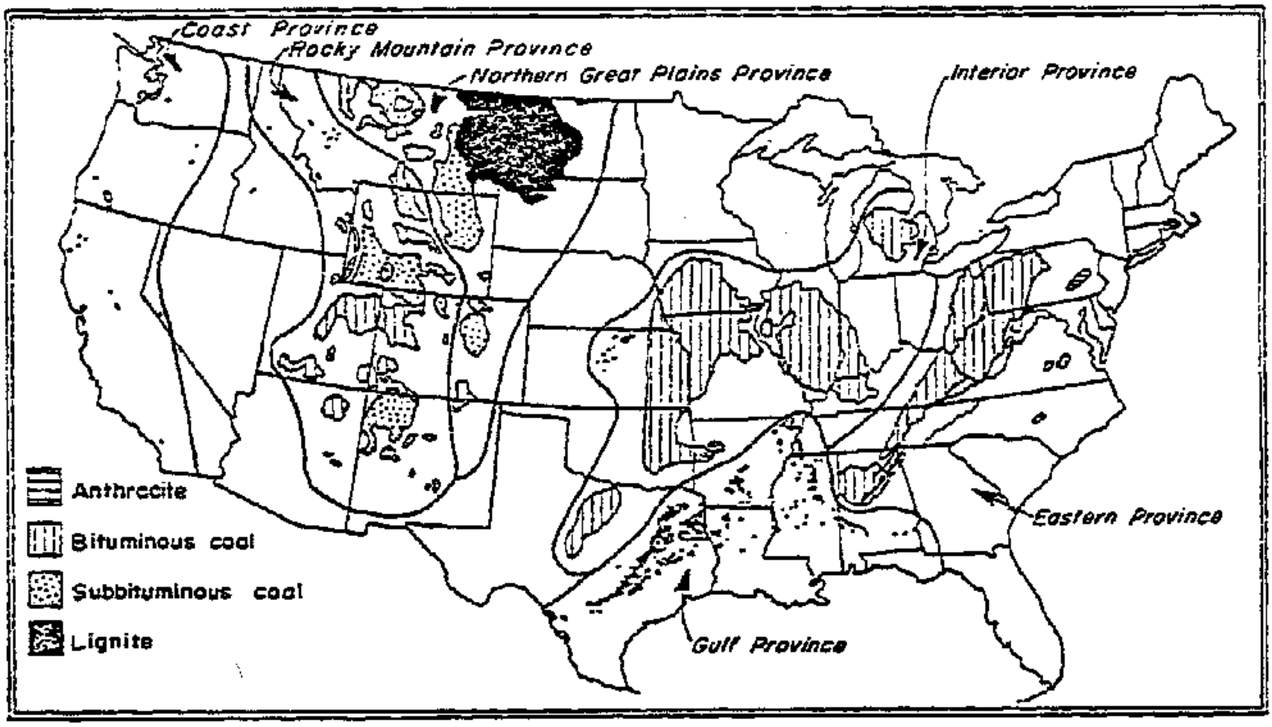
Some subbituminous coals are difficult to distinguish from bituminous. The coal is dull, black colored, shows little woody material, is banded, and has developed bedding planes. The coal usually cleaves parallel to the bedding. It has lost some moisture content, but is still of relatively low heating value.

Lignite, the lowest rank of coal, was formed from peat which was compacted and altered. Its color ranges from brown to black and it is composed of recognizable woody materials imbedded in pulverized (macerated) and partically decomposed vegetable matter. Lignite displays jointing, banding, a high moisture content, and a low heating value when compared with the higher ranks of coal.

Peat is not considered to be coal although it is a fuel. To become coal, peat must be subjected to the "coalification" process. Coalification is the progressive change in the vegetal remains as they become transformed from peat to lignite and through progressively higher ranks of coal to anthracite. The degree of coalification determines the rank of the coal. This progressive metamorphisis is the result of pressure, temperature, and time.

Neither peat nor graphite are coal but they represent the initial and end products of the progressive coalification process.

Coal-bearing strata underlie approximately 13% of the land area of the United States. Coal-bearing strata vary considerably, but generally are less than 3000 feet beneath the surface. However, almost 90% of all coal resources in the lower 48 states are located in four United States Geological Survey (USGS) coal provinces — Eastern, Interior, Northern Great Plains, and Mountain. Figure 5.3 depicts the provinces and major coal basins in the lower 48 states. Figure 5.4 shows the known coal deposits in Alaska.



(Ref. 15)

Figure 5.3: Distribution of Coal Resources in Lower 48 States

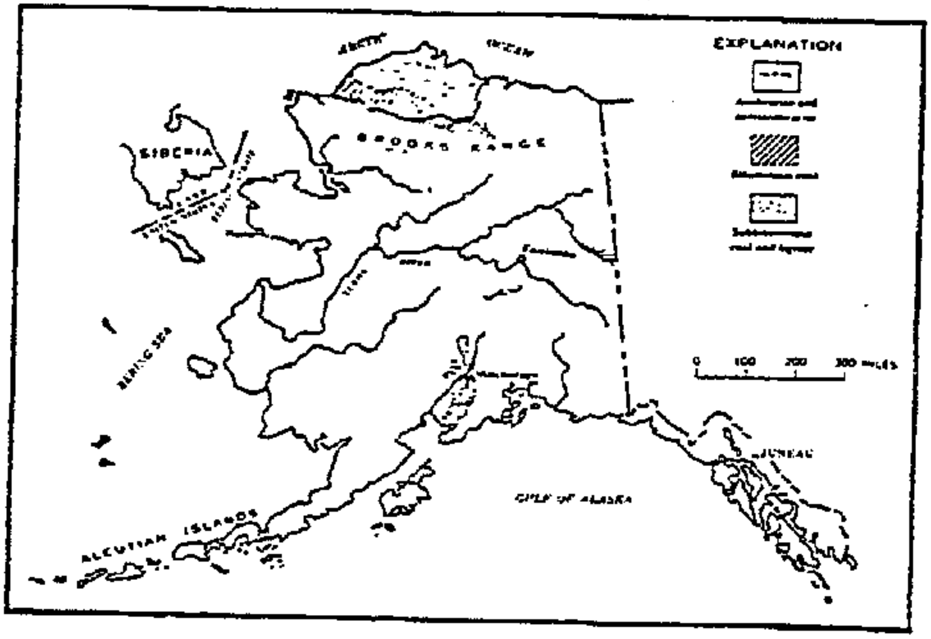


Figure 5.4: Coal Fields of Alaska (Ref. 16)

Although coal is found in 37 of the 50 states, only 26 currently have significant production. Table 5.15 shows production for the 26 states by coal class.

Table 5.15: Estimated 1979 Coal Production by States (Ref. 21)
(thousand tons)

	Anthracite		Bituminous		Subbituminous		Lignite		Total
	UG*	S**	UG	S	UG	S	UG	S	
Alaska	—	—	—	705	—	—	—	—	705
Alabama	—	—	8,125	15,695	—	8,000	—	—	23,820
Arizona	—	—	—	3,275	—	—	—	—	11,275
Arkansas	—	—	25	595	—	—	—	—	620
Colorado	—	—	5,375	12,375	—	—	—	—	17,950
Georgia	—	—	—	80	—	—	—	—	80
Illinois	—	—	32,500	26,650	—	—	—	—	59,150
Indiana	—	—	610	26,715	—	—	—	—	27,325
Iowa	—	—	225	445	—	—	—	—	670
Kansas	—	—	—	725	—	—	—	—	725
Kentucky	—	—	76,728	73,109	—	—	—	—	149,837
Maryland	—	—	888	1,829	—	—	—	—	2,717
Missouri	—	—	—	6,300	—	—	—	—	6,300
Montana	—	—	1	—	—	32,452	—	—	32,453
New Mexico	—	—	870	14,203	—	—	—	—	15,073
North Dakota	—	—	—	—	—	—	—	14,786	14,786
Ohio	—	—	13,670	29,825	—	—	—	—	43,485
Oklahoma	—	—	—	4,786	—	—	—	—	4,786
Pennsylvania	600	5,150	43,760	45,816	—	—	—	—	94,917
Tennessee	—	—	4,760	4,543	—	—	—	—	9,303
Texas	—	—	—	—	—	—	—	26,634	26,634
Utah	—	—	11,594	—	—	—	—	—	11,594
Virginia	—	—	28,543	8,495	—	—	—	—	37,038
Washington	—	—	—	—	—	5,050	—	—	5,050
West Virginia	—	—	91,240	21,141	—	—	—	—	112,381
Wyoming	—	—	730	—	—	71,093	—	—	71,823
	600	5,150	319,235	297,507	—	116,595	—	41,420	780,507

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*UG refers to underground coal mining
**S refers to surface coal mining

On an international basis, the U.S. is the third largest producer, exceeded by the U.S.S.R. and China. Table 5.16 is the estimated 1978 production rates for the five largest international producers.

Table 5.16: 1978 World Coal Production (Ref. 32)
(million tons)

Country	Anthracite	Bituminous & Subbituminous	Lignite & Peat	Total
U.S.S.R.	87	530	186	803
China	- - - - - (No details available) - - - -			680
U.S.	5	629	36	670
Poland	-	212	45	257
W. Germany	6	87	136	229
Remainder	78	604	604	1,286
Total				3,925

U.S. peat production is concentrated in Minnesota and Alaska with 1979 production being 825 thousand tons. This total quantity was used for agricultural purposes which is in sharp contrast to other countries where peat is also used as a fuel. Table 5.17 is a distribution of 1978 world production and the allocations among agricultural and fuel uses.

Table 5.17: 1978 World Peat Production (Ref. 22)
(thousand tons)

Country	Agricultural Use	Fuel Use	Total
U.S.S.R.	145,000	66,000	211,000
Ireland	91	5,167	5,258
West Germany	2,257	251	2,508
Finland	224	2,061	2,285
U.S.	822	—	822
Canada	480	—	480
Other	1,591	36	1,627
	150,465	73,515	223,980

The U.S. coal resource position is excellent. As of January 1, 1976, a total of 438 billion tons was identified as an in-place resource considered potentially mineable. Table 5.18 provides details of the distribution of this resource among the states.

Table 5.18: 1976 U.S. Coal Reserve Base (Ref. 23)
(millions of tons)

State	Anthracite	Bituminous	Subbituminous	Lignite	Total
Alabama	—	2,009	—	1,083	3,092
Alaska	—	698	5,446	14	6,158
Arizona	—	325	—	—	325
Arkansas	96	270	—	26	392
Colorado	26	9,144	4,121	2,966	16,256
Georgia	—	1	—	—	1
Idaho	—	4	—	—	4
Illinois	—	67,969	—	—	67,969
Indiana	—	10,714	—	—	10,714
Iowa	—	2,202	—	—	2,202
Kansas	—	998	—	—	998
Kentucky	—	26,001	—	—	26,001
Louisiana	—	—	—	*	*
Maryland	—	1,048	—	—	1,048
Michigan	—	127	—	—	127
Missouri	—	5,014	—	—	5,014
Montana	—	1,385	103,418	15,767	120,569
New Mexico	2	1,860	2,736	—	4,598
North Carolina	—	32	—	—	32
North Dakota	—	—	—	10,145	10,145
Ohio	—	19,230	—	—	19,230
Oklahoma	—	1,618	—	—	1,618
Oregon	—	*	17	—	17
Pennsylvania	7,109	23,728	—	—	30,837
South Dakota	—	—	—	426	426
Tennessee	—	965	—	—	965
Texas	—	—	—	3,182	3,182
Utah	—	6,552	1	—	6,553
Virginia	138	4,166	—	—	4,303
Washington	—	255	1,317	8	1,580
West Virginia	—	38,607	—	—	38,607
Wyoming	—	4,003	51,369	—	55,372
Total	7,371	228,925	168,425	33,617	438,337

It is estimated that of the portion which can be mined underground, approximately 297 billion tons, 50% is recoverable under current technological and economic conditions, resulting in a proven reserve figure of 149 billion tons. The surface mined portion of the 438 billion tons, approximately 141 billion tons, is estimated to be 85% recoverable, yielding a proven reserve of 120 billion tons. The total proven reserves of 269 billion tons is about 350 years supply at present production rates.

As an indication of the order of magnitude of this resource, the 269 billion ton proven reserve of coal has a heating value of approximately 6000 quad while the 28 billion barrel proven reserve of U.S. crude oil contains 160 quad.

These reserve estimates are based on surface mining to a depth of 150 feet and underground mining to a depth of 1,000 feet. Below 1,000 feet, a substantial quantity of coal is present; however, under current mining conditions, recovery of this coal is marginally economical. Currently, the best estimate of the total coal resource — identified and hypothetical — remaining in the ground is 4 trillion tons.(24)

Total world coal resources and proven reserves as of 1976 are estimated at 12.7 trillion tons and 786 million tons, respectively.(24) The U.S. share, 31% of the total resource and 34% of the proven reserves, is the largest of any country.

Estimates of U.S. peat resources vary widely. Figures of approximately 14,(25) 24,(26) and 120(27) billion tons on an air dried basis have been reported. One estimate of world resources reports 324 billion tons, of which the U.S.S.R. share is 49%, Canada 30%, and the U.S. 6%.(28)

The analysis of coal is complicated by the heterogeneous nature of the material. Two standard analytical procedures are available depending upon how much and what type of information is desired — proximate and ultimate analyses. Covered in these tests are moisture content, volatile matter, ash, and chemical constituents such as carbon, hydrogen, sulfur, nitrogen and oxygen. Some of the most significant properties which must be determined for coal feedstocks used in synfuel plants are:

- Carbon and hydrogen content — the percentages are crucial in the design of the plants since they are key constituents of the synthetic fuels.

- Volatile matter — the products driven out of coal when heated (excluding water). This analysis is an important design consideration for coal pyrolysis units.

- moisture — the moisture content of the coal.
- Ash — the non-combustible residue that remains after coal is burned. Bottom streams from gasifiers contain large amounts of ash. Direct liquefaction plants also have streams containing large quantities of ash.
- Free swelling index (FSI) — a measure of the increase in volume of coal when it is heated without restriction. This characteristic is of great importance for moving or fixed bed gasifiers which may plug up.
- Sulfur — an element occurring in coal in organic, pyritic and sulfate sulfur forms. Air emission regulations dictate the extent and complexity of equipment required to reduce the three sulfur forms to tolerable levels.
- Ash fusion temperature — a range of temperatures where, essentially, the ash content of coal begins to soften and eventually becomes fluid. Knowledge of this characteristic is critical in gasifier design.
- Heating value — a direct indication of the energy value of coal expressed in British thermal units (Btu's) per pound.

Table 5.19 illustrates the variability of some typical U.S. coals.

Table 5.19: Typical Coal Analyses

	Anthracite	Bituminous			Sub-bituminous	Lignite	
Analysis	Pennsylvania[a] Anthracite	Pennsylvania[b] Upper Kittanning	East[c] Kentucky Fire Clay	West[c] Kentucky #9	Montana[c] Decker	East[c] Texas****	North[c] Dakota***
Moisture, %	3.9	2.5	3.6–7.3	5.0	—	31.8	37.9
Volatile matter, %	4.38	32.5	33.8–37.2	39.8	—	30.9	26.7
Fixed carbon, %	83.04	—	51.2–57.5	49.7	—	27.6	29.2
Ash, %	8.68	—	5.0–8.1	10.5	4.0**	9.7	6.2
Sulfur, %	0.59	1.16	0.6–1.3	3.2	0.4**	0.9	0.6
Heating value, Btu/#*	13,462	—	12,580– 13,480	12,940	9,652**	7,226	6,783**
FSI	non agglomerating	5½	—	—	—	—	—
Ash fusion, °F Initial	2800+	2800+	—	—	—	—	—

* Dry, ash free basis

** As received

*** Average of 23 analyses

**** Average of 70 analyses

a Ref. 5.23
b Ref. 5.27
c Ref. 5.19

Figure 5.5 is a general comparison of the average values of key characteristics of coal by class and subclass from Reference 16. The data shown previously in Table 5.19 fit well within this general comparison. For reference, peat properties lie to the left of the first column.

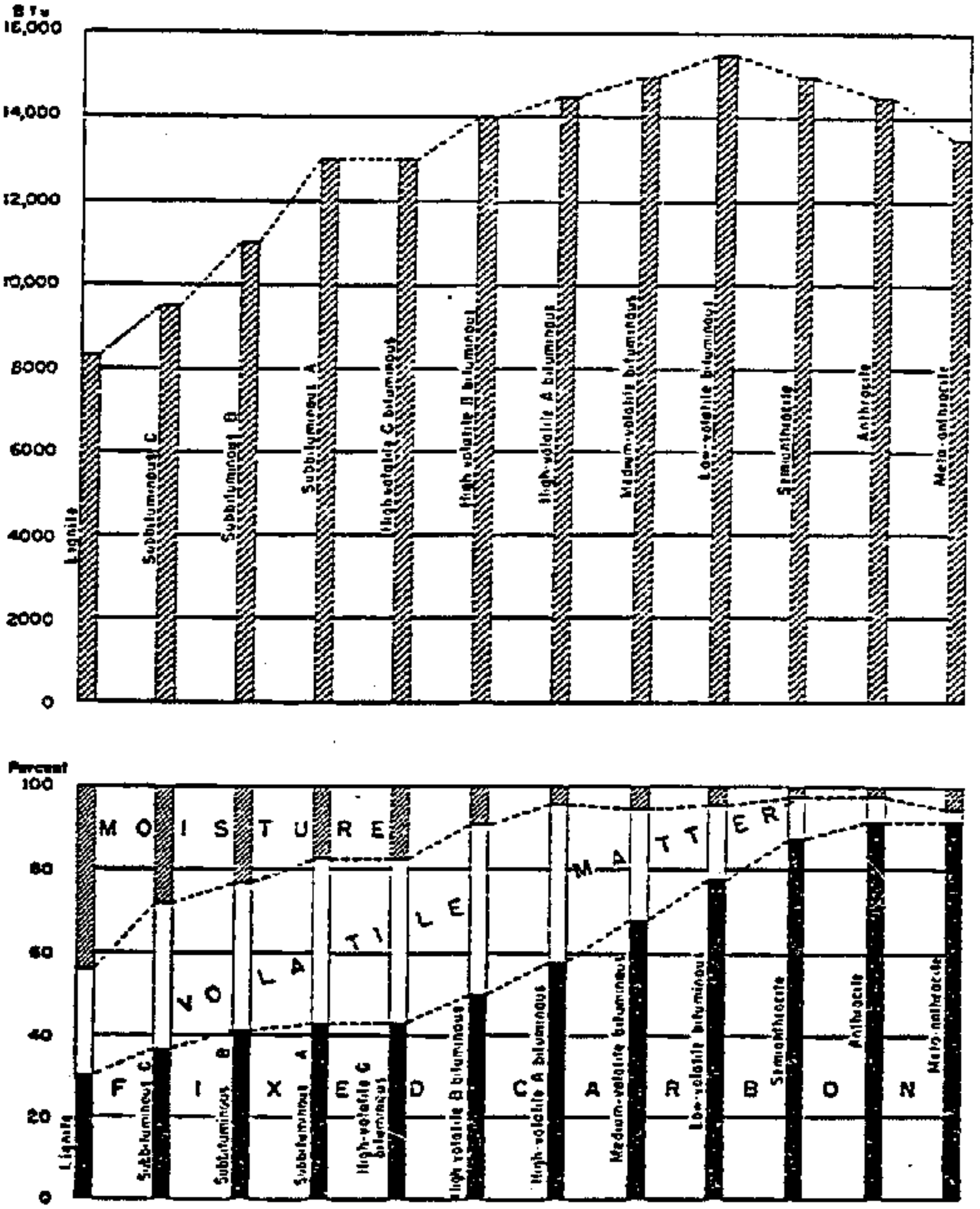

Figure 5.5: General Comparison of Key Characteristics of Coals (Ref. 16)

The principal coal mining methods are underground and surface. A third type, auger mining, is occasionally identified as a distinct method. Until 1920, virtually no coal was surface mined. However, by the early 70's, over 50% was mined by this method in the U.S.

The choice of mining method depends upon a number of considerations, including seam depth and thickness, deposit size, and local geology. Of these considerations, seam depth is often the most important because of its association with the lower cost and relatively greater safety of surface mining. As a rough rule of thumb, an overburden to seam ratio of 10(15) was considered economically satisfactory in 1965 for surface mining. By the mid 70's this ratio increased to about 30/1 as a result of technological improvements. Currently the ratio stands at approximately 15(30) as a result of stringent reclamation regulations.

There are two major methods of surface mining, contour and area. Contour mining is generally used in hilly or mountainous terrain. With this mining method, the overburden is removed from the slope to create a flat excavation, or bench, which is flanked by a vertical highwall on one side and a downslope pile of spoils on the other. The exposed surface layer of coal is then mined. Coal exposed in the highwall may also be mined by large drills or augers which pull the coal horizontally from the seam.

Area mining, used in flat terrain, is accomplished by excavating a trench to expose the coal deposit. As succeeding cuts are made to expose the coal, the overburden is piled into the trench from which the coal has already been mined.

There are also two major methods used in underground mining, room and pillar, and longwall. In both methods, the coal deposit is reached by digging or boring a vertical shaft or a tunnel — horizontal or slanting. Thereafter, in room and pillar mining, a passageway is excavated through the coal seam. From the passageway, rooms are formed by mining the coal using combinations of hand and machine cutting and loading, and leaving portions in place to act as support pillars for the strata overlying the rooms. In typical U.S. underground mines (which are mostly in the East), coal and surrounding material strengths are low, and coal seams range from two to six feet thick. As a consequence, the rooms are long and narrow, typically 10 to 20 feet wide and several hundred feet long.

Longwall mining is the other underground mining method which, up to now, has not found wide usage in the U.S., although it is used extensively in Europe. In this method, a shearing drum or plow moves back and forth across the working face of the seam between two access passageways or galleries. The cut coal drops onto a conveyor which moves it to the transportation system being used to remove the coal from the mine. The roof in the area immediately behind the mining operation advances. As the jacks are moved, the roof in the area from which the coal has been mined is allowed to collapse. The major advantage offered by longwall mining is recovery of a higher percentage of the coal in place than is possible with the room and pillar method.

Surface and underground mining techniques produce significant physical impacts, although the areal disturbances of surface mining are generally more visible. Both methods disturb the surface, produce wastes that require disposal, can affect water resources, and expose materials that produce acids when dissolved in water.

Four major types of residuals are of importance to surface mining methods:

- Water — The principal water pollutants in surface mining are suspended solids which are a product of runoff from solid waste piles. The water may also be acidic.
- Air — Pollutants occur from diesel-fueled equipment and wind erosin. Regional variations in pollution generation rates occur for a variety of reasons. Wind erosion has been found the greatest in Northwest and Southwest regions due to the prevailing climatic conditions. On the other hand, diesel emissions are the least in these same regions due to the local prevelance of electrically powered equipment.

- Solids — Wastes production varies substantially as a function of the mining technique. Water pollutants are converted to solid wastes in the mines' water treatment facility. In area mining, solid wastes are produced only during the initial cut to open the mine. In some contour mines, solid wastes and overburden are continually dumped downslope except for the necessary material above the surface of the coal which is used to backfill the bench.
- Land — Land use residuals arise from two factors. One is an incremental residual arising from the land actually stripped. The other involves the fixed land required for the life of the mine. Included in this latter factor is the land required to store the initial cut refuse and the land required for the water treatment plant and settling pond.

Underground mining is also concerned with four major types of residuals:

- Water — The principal water pollutants are acid drainage from the mines and suspended solids in the runoff water from solid waste piles. The acid drainage problem is most prevalent in Appalachia since many mines are located above drainage levels and the overburden may not be alkaline.
- Air — Electrically powered equipment is generally used underground. As a consequence, air emissions cause no undue problems although the mine dust and any methane can be hazardous to the miners' health.
- Solids — The principal residual is produced during the treating of the acid mine water with an alkali. The quantity of solids produced progressively decreases from Northern Appalachia through Central Appalachia to the Central region.
- Land — The greatest land use impacts are associated with subsidence, refuse storage sites and the site for a water treatment facility, if present. Greater subsidence results from the longwall mining technique than from the room and pillar because the roof is allowed to collapse as the mining progresses. The decision to treat acid mine and runoff waters with alkali converts the water pollutants to solid wastes which require land for settling ponds and treatment facilities.

5.6 OTHER

A substantial number of other energy sources exist in the U.S. Some, like nuclear and geothermal, are non-renewable. Others, such as photovoltaic, hydro, wind, ocean thermal energy conversion (OTEC), direct radiation, and biomass, are dependant upon solar activity and are considered renewable.

These non-fossil energy sources are either in commercial use, under active development, or at various stages of research and development. As discussed in Chapter 4, nuclear and hydro made a contribution to the overall 1978 U.S. energy supply of 3.9% and 1.6%, respectively. At the same time, all the other forms contributed 1.4% of the total, with the difference of 93.1% being supplied by non-renewable fossil energy.

5.6.1 Nuclear

Since the first commercial fission electric power generating plant went into operation at Shippingsport, Pennsylvania, in 1957, a total of 71 plants have been commissioned with a generating capacity of 54 thousand MW gross.(30) The future growth of the industry is uncertain. The resources and proven reserves of uranium oxide at the beginning of 1980 are estimated at 2,625,000 and 645,000 tons, respectively.(31) The proven reserve figure is sufficient to fuel approximately 125 thousand megawatt fission units for their estimated life of 40 years.

5.6.2 Hydroelectricity

Although hydroelectric energy production continues to increase, its relative position in the overall energy supply has decreased since its peak in 1940. Limited availability of environmentally acceptable dam sites will limit future growth. Although hydro power has been attractive as a renewable energy source, most dam construction projects have sparked environmental controversy. Assuming average rainfall, the hydro potential of the U.S. is estimated at 390 thousand MW.(15)

5.6.3 GEOTHERMAL

Geothermal energy emanates from the hot mass of molten rock that forms the earth's core. Most of the heat is too deep within the earth to be extracted for practical use; however, it can be used when geologic conditions concentrate the energy into hot spots, i.e., thermal reservoirs. Three categories of thermal reservoirs are hydrothermal, geopressured resources, and dry rock. It should be noted that the methane component contained within the geopressured resource has been discussed briefly as unconventional natural gas, previously in this chapter. A total of 742 MW of electricity was generated in the U.S. from all geothermal sources in 1979.(32) Estimates of proven reserves of the geothermal resource vary widely with values of 400,000 and 148,000 MWe for 50 years being reported.(15) Proven reserves range from 1,000 MWe to 60,000 MWe for 50 years.

5.6.4 SOLAR

Solar energy warms the earth's surface and atmosphere, drives the winds and ocean currents, and produces, through photosynthesis, all the food on which life depends. There are four potential applications of solar energy in addition to hydropower — direct radiation, wind, organic fuels, and ocean thermal gradients.

Direct solar radiation, falling on a surface perpendicular to the sun's rays at the outer limits of the earth's atmosphere, has an intensity of 442 Btu per hour per square foot. This quantity, known as the solar constant, is reduced by an average of 54% in the earth's atmosphere, and eventually reaches the earth's surface at a rate of 2.4 million quad per year. At any given point on the earth, the amount and intensity of solar radiation varies with season, latitude and atmospheric transparency.

The annual average solar radiation density for all locations is 1,450 Btu/ft^2/day. Various temperature range solar collectors and photovoltiac cells are the technologies predicated upon direct solar radiation.

Wind energy accounts for about 2% of all solar radiation to the earth. Thereof, only about 30% is generated in the lowest 3,300 feet of the atmosphere, with a substantially smaller percentage being available in the lower 500 feet, which is the level most useful to man.

Organic fuels (biomass) eventually may be attractive from many standpoints. A year-round average for solar production efficiency of just over 1% is typical for most high-yield crops. As a result, the land required for a given energy output is very high. Based on yields of 10 to 30 tons of biomass per acre per year, the land required for a 100-MWe organic-fired powerplant, for example, would be somewhere between 25 and 50 square miles.

Ocean thermal gradients arise because the surface temperature of the oceans between the Tropic of Cancer and the Tropic of Capricorn stay remarkably constant at about 25°C while the water temperature is 5°C at depths as shallow as 3,300 feet. The technology to recover energy from the approximate 20°C temperature difference depends upon large, thin-walled heat exchangers operating in a corrosive seawater environment. No commercial demonstration has been made yet for OTEC.

Although the amount of solar energy reaching the earth is immense compared with the world's commercial energy system, the problems of collecting, storing and using this energy in the commercial system in an economic manner are extensive.

6.0 CONVERSION TECHNOLOGIES

This chapter briefly reviews the technologies by which abundant U.S. sources of fossil energy, primarily oil shale and coal, can be converted to liquid and gaseous fuels. Fundamental concepts inherent in all anticipated synfuels plants are discussed first. Next, the basic techniques for producing synfuels are qualitatively described — pyrolysis, gasification, direct liquefaction, and indirect liquefaction. Within the discussion of each technique, processes and their status are given.

Herein, the emphasis is on those synfuels as defined by the Energy Security Act of 1980.

6.1 FUNDAMENTALS FOR SYNFUEL PLANTS

Although there are a number of possible techniques for converting coal, oil shale, tar sands, and heavy oil into more desirable liquid and gaseous products — i.e., synfuels — there are some important fundamental concepts inherent in all anticipated synfuels plants. Regardless of the conversion technology, there are important similarities in size, complexity, cost, and conversion efficiency. A schematic diagram showing the various coal conversion processes is shown in Fig. 6.1.

6.1.1 Physical Size of Synfuel Plants

High capacity synfuel plants are required to minimize production costs. Synfuel plant size will not be limited by the potential market for products, but by constraints of engineering design; local feedstock availability; environmental, health, and safety requirements; and financial risk. A synfuel plant, capable of the equivalent of 50,000 barrels per day of oil, is still a major engineering and financial challenge since it will require an investment of some $2 to $4 billion and about five years to construct. A synthetic natural gas (SNG) plant of equivalent output would produce about 250 million cubic feet

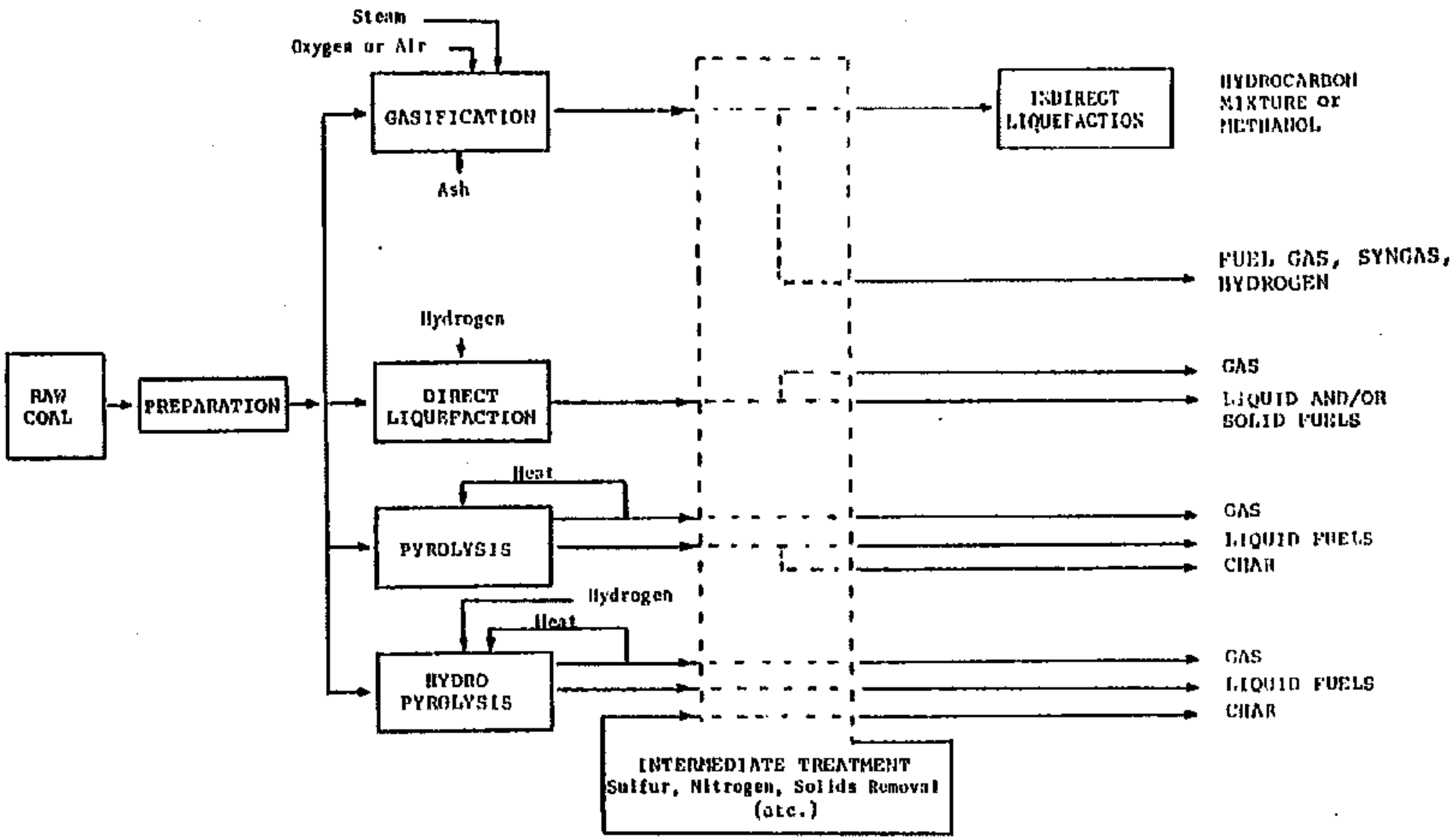

Figure 6.1: Coal Conversion Processes

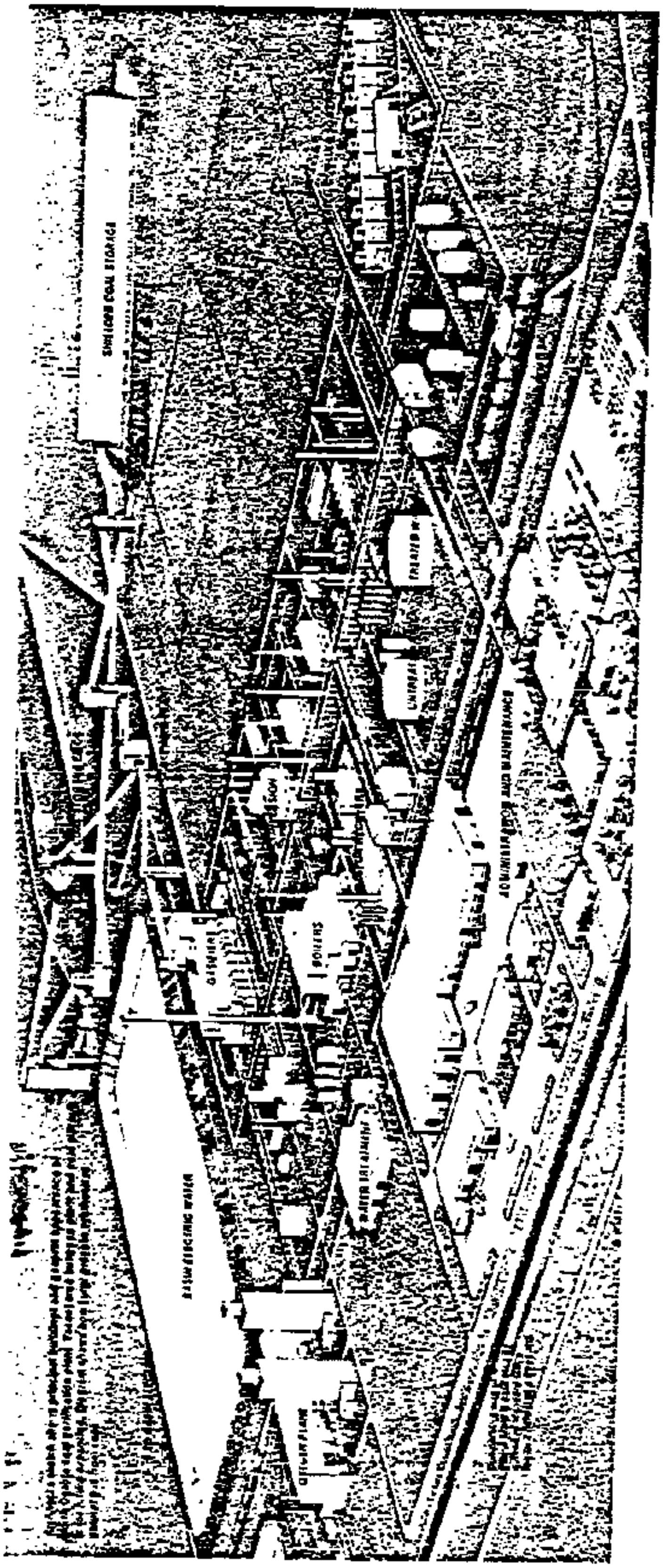

Figure 6.2: Great Plains Gasification Plant

of gas per day (CFD).

Figure 6.2 is an artist's rendering of the Great Plains Gasification Plant which will initially produce 125 million CFD. This is 50% of the presently expected norm for plant size.

The Great Plains plant will be located on approximately 2 square miles of land. When operated at a capacity of 125 million CFD it will consume 14,000 tons of lignite per day, that is one railroad car of lignite every eight minutes around the clock, seven days a week.

For the full capacity plant, the lignite would be gasified in 24 Lurgi gasifiers with 4 spare gasifiers. Installed Lurgi gasifiers have a total height equivalent to an 8-story building. As seen in Figure 6.2 the gasifiers are only a small portion of the entire synfuel plant.

Oil shale processes must handle even larger amounts of material than coal plants. A 50,000 barrel per day oil shale plant would require 70,000 tons per day of oil shale. This represents mining, transporting, crushing, retorting, and disposing of about 1.5 million cubic feet per day of broken oil shale, the equivalent of one railroad car every 90 seconds.

6.1.2 Complexity of Synfuel Plants

Most synfuel technologies are inherently complex, with many individual steps required. Most of the processing steps involve established commercial practice. Typical steps are grinding, drying, mixing, preheating, reacting, ash separation, flashing, hydrotreating, and distillation. In addition to these steps in the main processing sequence, there are auxiliary operations such as hydrogen generation, removal of sulphur and nitrogen compounds, wastewater processing, and electric power generation.

Many processing steps are familiar to experienced engineers and can be designed with confidence. In most new synfuel processes, however, there are one or more processing steps which do not have established technology. The steps having technological uncertainty dominate RD&D activities for each synfuel technology. Even if a particular step in the synfuel process were completely eliminated, most of the remaining steps would still be required so the total cost would not be greatly decreased. Frequently, when a given process eliminates a technologically difficult step, it requires additional steps in another stage of the process.

The size of synfuel plant components is determined by the natural constraints which govern. These involve principles of physics and chemistry. The physical size of individual components for a commercial-scale synfuel plant may be set by fabrication or transportation facilities. High capacity plants may require parallel process trains, e.g., the 28 gasifiers in the Great Plains plant discussed above. Solutions to some of the metallurgical and instrumentation/control problems involve innovative engineering and equipment.

6.1.3 Cost Estimates for Synfuel Plants

Large sizes of synfuel plants do not cost proportionally more than small sizes. For example, increasing the capacity of a synfuel plant 5 times may only increase its cost 2.6 times. For this reason, one of the most effective means to minimize the cost of synfuels is to take advantage of the economies of scale and use large plants. Beyond certain large sizes, however, diseconomies of scale set in because of management complexities and resource constraints.

The advantages of large-scale processing plants have been empirically quantified by the "exponential rule." The relation between capital cost and plant size is given by the equation:

$$\text{Capital Cost} = kS^x$$

where: k is a constant
S is a plant production rate

The exponent, x, is generally between 0.4 and 0.9, although more usually between 0.6 and 0.8. The "exponential rule" only applies for process plants which are similar in all respects except size. It is generally not applicable for situations where sizes differ by more than a factor of ten.

The proverb "practice makes perfect" has been quantified in terms of learning curves. For manual assembly operations, it has been generally shown that when the quantity of units produced is doubled, the assembly time required per unit is reduced about 20%. For manufacturing operations the validity of learning curves has been demonstrated many times, and the cost reductions anticipated due to learning curve experience are a common part of industrial management.

Application of learning curve experience to process industries is less well defined than for manufacturing industries. Cost reductions due to learning are observed in the process industries, such as petroleum refining and petrochemicals, and can confidently be expected for synfuel plants.(33) Stating these expectations in a quantitative way, however, is difficult. Learning experience is the anticipated factor when the costs of synfuel plants are quoted as being for the "nth plant."

The undemonstrated nature of many synfuel processes is a major source of uncertainty regarding cost estimates. With significant commercial experience, more accurate process cost estimates can be made for a specific location. In the early commercial stage, there are frequently better process designs developed which usually give lower product and capital cost. Conversely, new technologies are subject to a number of factors that contribute to cost estimating inaccuracies. However, detailed design studies can be performed to give reasonably accurate estimates. Such studies require thousands of hours by experienced engineers.

Lack of information frequently contributes to low initial cost estimates. Peculiarities of a chemical reaction or a novel enviromental hazard cannot be predicted for a proposed new process, even after a moderate amount of experimental investigation. Lack of engineering experience on the part of some research personnel results in oversimpliification of the process and hence, low cost estimates.(34) In addition, it is human nature not to be as critical of "good news" as of "bad news." For this reason laboratory data tend to have optimistic biases, even when there is considerable effort to obtain objective information.

Within a large company having experienced personnel doing all steps of research, development, engineering design, construction, and plant operation, the uncertainties and potentials for an optimistic bias can be reasonably identified and specific contingencies allowed for them. Careful specification of estimating procedures and working with the same group of engineers and managers for many years enables an experienced company to effectively cope with new technologies. When many different companies and governmental entities are involved with the same technology, this level of confidence is exceedingly difficult to attain. The proprietary nature of some information further compounds the uncertainty about cost estimates.

Projecting construction costs into the future is made difficult by inflation and changes in the rate of inflation, especially because construction costs have been increasing at rates well above inflation rates. But there are additional factors which contribute to the problem. More rigorous environmental controls, complex instrumentation and controls, and special materials and metals can significantly increase plant investment costs. If a considerable number of synfuel plants are built at the same time, shortages, or even near shortages, of equipment, material or labor will cause additional price increases. Delays in completion of construction, whether due to technology or regulatory problems, can significantly increase the final construction cost.

6.1.4 Efficiency of Synfuel Technologies

Efficient technologies for the conversion of abundant resources into synfuels are desired both to reduce product costs and to conserve natural resources.

When economic ground rules are established, the optimum process