

UMR-MEC Conference on Energy

---

12 Oct 1976

## Coal Chemistry: Aspects of Analysis, Structure, Reactions, Conversion, and Byproducts

Stanley E. Manahan

Follow this and additional works at: <https://scholarsmine.mst.edu/umr-mec>

 Part of the [Chemical Engineering Commons](#), and the [Energy Policy Commons](#)

---

### Recommended Citation

Manahan, Stanley E., "Coal Chemistry: Aspects of Analysis, Structure, Reactions, Conversion, and Byproducts" (1976). *UMR-MEC Conference on Energy*. 116.  
<https://scholarsmine.mst.edu/umr-mec/116>

This Article - Conference proceedings is brought to you for free and open access by Scholars' Mine. It has been accepted for inclusion in UMR-MEC Conference on Energy by an authorized administrator of Scholars' Mine. This work is protected by U. S. Copyright Law. Unauthorized use including reproduction for redistribution requires the permission of the copyright holder. For more information, please contact [scholarsmine@mst.edu](mailto:scholarsmine@mst.edu).

COAL CHEMISTRY: ASPECTS OF ANALYSIS, STRUCTURE, REACTIONS,  
CONVERSION, AND BYPRODUCTS

Stanley E. Manahan  
Department of Chemistry  
University of Missouri - Columbia  
Columbia, Missouri 65201

Abstract

An understanding of the chemistry of coal is essential for the most efficient and environmentally acceptable utilization of this important energy resource. This is particularly true where coal conversion processes are involved. Far from being a simple carbonaceous rock, coal is a complex and variable chemical system. This paper outlines the basic principles of coal chemistry which can be helpful to geologists, engineers, chemists, and others involved with the utilization of coal.

1. INTRODUCTION

If the United States is ever again to approach any degree of self sufficiency in energy and hydrocarbons, coal must play a vastly increased role. This will involve operations of a truly huge magnitude. Consider, for example, what would be needed to replace current petroleum consumption with coal. The largest synthetic fuels industry in history was that developed in Germany during World War II. Peak output of 100,000 barrels per day was reached in 1944. This compares to current U. S. consumption of almost 20 million barrels per day. An optimistic figure of 3 barrels of synthetic crude oil per ton of coal would require about 6.7 million tons of coal per day, or 2.4 billion tons per year. This is 4 times the current rate of U. S. coal production. At least 200 conversion plants, each costing more than a billion dollars would be required.

It is obvious from the preceding figures that very large quantities of materials, tremendous investments, and substantial environmental disruption are involved in a change of the domestic energy base from petroleum to coal. In order for this to occur with minimum difficulty and maximum efficiency, it is essential for all involved to be well grounded in the fundamentals of coal science. From the standpoint of coal utilization, the chemistry of coal is perhaps the most important facet of coal science. Though studied extensively during the first half of this century, the knowledge base of coal chemistry has not kept pace with areas such as nuclear science or basic chemistry since World War II. Fortunately, this situation is now changing and our understanding of coal as a chemical system is increasing, aided particularly by recent

revolutionary advances in chemical instrumentation. As a result, future coal development, including conversion, combustion, and stack gas scrubbing, can be put upon a more logical basis.

Coal is far from being a rock made of pure carbon. It is a complex and variable chemical system. It undergoes numerous chemical reactions, and its chemical reactivity varies greatly with type of coal. The organic portion of coal contains a variety of chemical functional groups. The reactions of these groups determine a number of things, such as acid-base properties, ability to bind heavy metal ions, and amenability of coal liquids to further refining processes. The mineral portion of coal contributes to acid mine water and heavy metal pollution at the mine site, determines the characteristics of ash produced during conversion, and is a potential source of commercially valuable elements.

A thorough understanding of coal chemistry is obviously essential for chemists working with this mineral. It is also needed by geologists concerned with coal resource development, environmental engineers dealing with mine-site pollution, and individuals involved with conversion, combustion, and stack gas cleaning. With rare exceptions, the chemistry of coal has been ignored in academic chemistry departments. The study of this topic is not even widespread in departments of geology, chemical engineering, or fuel science. With the growing importance of coal, however, it is anticipated that a number of courses will be established dealing with coal chemistry.

This paper discusses the fundamentals of coal chemistry. It is based upon a new book on that topic (1) and upon a graduate level course taught by the author. It provides a general outline for similar courses dealing with coal chemistry.

## 2. OUTLINE OF COAL CHEMISTRY

The chemistry of coal can be divided into several major categories. These begin with the biogeochemistry of coal formation and the geochemistry of coal as a mineral. The next general category to be considered is the classification of coal as a mineral and the physical and chemical analysis of coal. The third general category involves the chemical composition, nature, and structure of both the organic and inorganic coal fractions. Coal chemical reactions are considered next. The chemical aspects of coal conversion comprise another unit of study. Chemical processes involved in coal combustion and stack gas cleaning are considered. The environmental chemistry of coal utilization and conversion should be considered in any modern coal chemistry course. Finally, advanced coal technology such as magnetohydrodynamics, is discussed. A specific outline of topics covered is given below.

1. Origin, Occurrence, and Classification of Coal
  2. Physical Properties of Coal
  3. Physical and Chemical Analysis of Coal
  4. Chemical Nature of the Organic Coal Fraction
  5. Chemical Nature of the Inorganic Coal Fraction
  6. General Chemical Reactions of Coal
  7. Oxidation of Coal
  8. Reduction and Hydrogenation of Coal
  9. Coal Conversion Processes
  10. Major Coal Conversion Products
  11. Environmental and Occupational Health Considerations in Coal Conversion Processes
  12. Coal Combustion and Stack Gas Cleaning Processes
  13. Advanced Coal Technology
- ## 3. ORIGIN, OCCURRENCE, AND CLASSIFICATION OF COAL

Most important coal deposits originated with massive growths of terrestrial vegetation starting approximately 275 mil-

lion years ago during the *Carboniferous* stratigraphic period. In a sense, the formation of coal is still going on as peat deposits continue to be formed. Coal deposits were formed in vast sunken swamps called *geosynclines*. Layers of vegetable matter were covered with mineral deposits and eventually coal seams were formed. The gross physical processes affecting coal seams after deposition of the vegetable matter largely determine whether or not the coal can be mined.

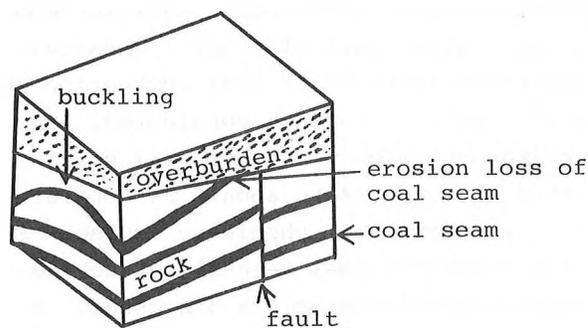


Figure 1. Coal formation showing some of the physical features affecting coal utilization.

The chemical precursors of coal are substances found in plants. Predominant among these are polysaccharides (particularly cellulose) and lignin. Other substances include protein, chlorophyll, resins, fats, and waxes. In the aggregate, these are biologically active substances with an approximate chemical formula of  $\text{CH}_2\text{O}$ . Through the coalification process they are transformed to an organic rock with an approximate formula of  $\text{CH}$ . The overall process must involve evolution of both excess oxygen, largely as  $\text{CO}_2$ , and excess hydrogen, largely as  $\text{CH}_4$ . Initially, coalification is largely a biochemical phenomenon involving fermentation and transformation of vegetable matter to humic substances. In later stages geochemical phenomena involving processes at high pressure and somewhat elevated temperatures predominate. Coal deposits exist

and are used at each stage of the coalification process. Peat with a chemical formula not far from  $\text{CH}_2\text{O}$  is used for electrical power generation in Ireland and Minnesota. Other coals in increasing order of coalification are brown coal, lignite, subbituminous, bituminous, and anthracite.

One of the most common classifications of coal is by rank. Increasing coal rank generally accompanies increasing coalification. As rank increases, the percentage of fixed carbon (that not present in volatile carbon compounds) increases, and the percentage of volatile matter decreases (though reaching a maximum for high-volatile bituminous coal of intermediate rank). Moisture decreases markedly with increasing rank. The heat content goes up with increasing rank. A list of coal types in order of increasing rank with approximate heating values (Btu/lb) in parentheses is: peat (very low), brown coal (5,500-8,000), subbituminous (8,000-12,000), bituminous (11,000-15,000), and anthracite (13,000-16,000). Bituminous coal is furthermore divided into classifications of high-, medium-, and low-volatile bituminous coal.

Discrete fragments of organic coal are classified by *maceral type*. These are distinguished by appearance, opacity, reflection of light, color, and other characteristics. Typical maceral types include fusinite, vitrinite, resinite, and exinite. In some cases maceral type may be related to the origin of the coal. For example, alginite comes from fossil algal bodies making up boghead coal.

Classification of coal by rank, maceral type, and other commonly used systems is not entirely satisfactory from the viewpoint of coal chemistry. Other systems are needed to describe coal as a chemical system, particularly its reactivity. This is especially needed for coal conversion studies.

#### 4. PHYSICAL PROPERTIES OF COAL

The physical properties of coal and coal ash have a strong bearing upon the ways in which it is used and upon its chemical reactions. Among these, the electrical properties of dielectric constant and electrical conductivity are useful in classifying coal and understanding its structure. The magnetic property of diamagnetic susceptibility has been used to determine the aromatic nature of coal molecular structure. In recent years paramagnetic resonance has been widely used to elucidate coal chemical structure. From a practical standpoint in both conversion and combustion, the mechanical properties of elasticity, grindability, hardness, and plastic deformation must be considered. Of particular importance are the physical changes which occur when coal is heated. These include swelling, caking, "melting," loss of gases, and carbonization. Of course these are strongly tied in with chemical phenomena.

#### 5. PHYSICAL AND CHEMICAL ANALYSIS OF COAL

Standard methods exist for the determination of various important physical properties of coal. Chemical analysis can be divided into the general categories of (1) proximate analysis, (2) ultimate analysis, and (3) trace analysis. Proximate analysis is basically the determination of water, volatile matter, fixed carbon, and ash. This is accomplished by progressive heating and burning accompanied by measurement of weight changes. The water and ash contents are particularly important in determining the quality of the coal.

Ultimate analysis consists of the chemical determination of carbon, hydrogen, nitrogen, sulfur, and oxygen. Carbon and hydrogen are determined simultaneously by collecting and weighing carbon

dioxide and water evolved when the coal sample is burned. Nitrogen remains a difficult element to determine. Although a variety of methods are available, the standard method remains the Kjeldahl procedure in which the organic matrix is broken down in boiling sulfuric acid liberating amino nitrogen in the form of ammonium ion,  $\text{NH}_4^+$ . This is liberated from basic solution as  $\text{NH}_3$  gas which is collected and titrated. The American Society for Testing and Materials (ASTM) recognizes three methods for the analysis of sulfur in coal. The first of these is the Eschka method in which coal is ashed in a mixture of sodium carbonate and magnesium oxide (Eschka mixture). A second approach utilizes sodium peroxide fusion and a third consists of the analysis of the residue left from the determination of coal heat content in an oxygen-bomb calorimeter. In all three cases sulfate is measured. Oxygen remains the most difficult element to determine. It is usually calculated by subtracting from 100 the sums of the percentages of hydrogen, carbon, nitrogen, and ash.

The determination of minor elements in coal has gained in importance as the role of these elements in health and as environmental pollutants has been recognized. Among the important classes of minor, or "trace" elements are halogens, boron, phosphorus, the metalloids, and the heavy metals. Relatively new techniques of chemical analysis such as atomic absorption spectrometry, neutron activation analysis, and, most recently, inductively coupled plasma optical emission spectrometry have greatly facilitated the analysis of these elements.

The bottom line for the usefulness of coal in most applications is of course the heat content. This is readily determined by oxygen-bomb calorimetry.

## 6. CHEMICAL NATURE OF THE ORGANIC COAL FRACTION

The organic chemistry of coal is highly complex and variable. Because of its complexity and the lack of attention given to it by well qualified chemists during the last two decades, much of the organic chemical nature of coal remains a mystery. Fortunately, a number of well qualified researchers supported with sophisticated chemical instruments are now hard at work on the problem, and substantial advances are anticipated.

It is beyond the scope of this work to go into organic chemical coal structure in detail. Some feeling for the topic can be gained however from consideration of an approximate chemical formula and hypothetical "molecule" of coal. The chemical formula of Illinois No. 6 coal is rather close to  $C_{100}H_{85}S_2N_2O_{10}$ . A hypothetical molecule of coal with approximately this formula is shown in Figure 2.

predominant feature. This is necessary to accommodate the low atomic ratio of hydrogen to carbon. It also gives rise to polycyclic aromatic hydrocarbons in the liquid hydrocarbon products from coal pyrolysis (coal tars) and direct hydrogenation of coal. Most models of coal structure show only minimal straight chain alkane components, although this is subject to some debate. The presence of phenolic -OH groups leads to the production of phenols in coal pyrolysis and hydrogenation products. Similarly, organically bound nitrogen leads to production of nitrogen bases. Organic sulfur compounds also persist in conversion products. Compounds of oxygen, nitrogen, and sulfur all interfere with refining processes and must be removed from coal liquids by hydrocracking prior to further refining. Unlike pyrite, organic sulfur groups cannot be removed from coal prior to combustion and lead to the formation of pollutant  $SO_2$ . Organically bound nitrogen

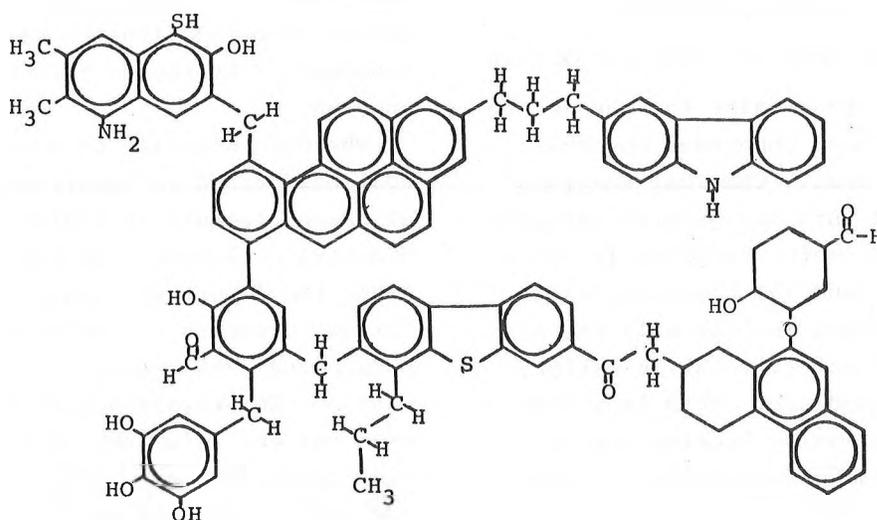


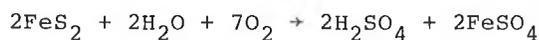
Figure 2. A hypothetical "molecule" of coal with the approximate formula,  $C_{100}H_{85}S_2N_2O_{10}$ . This figure shows some of the predominant structural and functional characteristics of coal.

As shown in Figure 2, coal consists largely of aromatic ring structures connected by alkane, ether, and other linkages. The aromatic ring structure is the

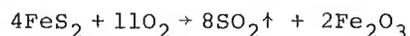
is the primary contributor to nitrogen oxides emissions from coal combustion. Other functional groups bind trace elements to coal.

## 7. CHEMICAL NATURE OF THE INORGANIC COAL FRACTION

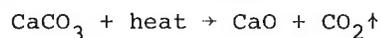
Mineral matter typically constitutes approximately 10 percent of coal used at a power plant, though in some cases it is as much as 30 percent. The nature and composition of this mineral matter varies with the source of coal. In general, clays make up approximately half of coal mineral matter. These are predominantly kaolinite  $[(OH)_8Si_4Al_4O_{10}]$  and illite  $[(OH)_4K_2(Si_6 \cdot Al_2)Al_4O_{20}]$ . When heated during combustion or conversion these lose water and form fused ashes of aluminum and silicon oxides. Sulfides and, to a limited extent, sulfates constitute a second major mineral fraction. The most significant of these is iron pyrite,  $FeS_2$ . It is responsible for acid mine water production by the bacterially mediated oxidation of pyrite,



and much of the sulfur dioxide produced in coal combustion:



Carbonate minerals of calcium, magnesium, iron(II), and manganese(II) make up a third major class of coal mineral matter. The oxides formed by heating of calcium and magnesium carbonates,



are responsible for the basic character of some fly ashes. These are potential sources of base for stack gas scrubbing. The fourth major mineral fraction is silica,  $SiO_2$ . Fused silica makes up much of the glassy material in bottom ash and fly ash.

The inorganic portion of coal contains a large number of trace elements. The distribution of trace elements between the organic and inorganic fractions of coal varies with the particular element. This important area has not been investi-

gated as much as it should be. Among the most environmentally significant trace elements commonly occurring at levels greater than 1 part per million are chlorine, arsenic, beryllium, bromine, cadmium, cobalt, chromium, fluorine, molybdenum, nickel, lead, selenium, and antimony. Mercury typically is found at levels of around 20 parts per billion, which is still significant considering its toxicity and volatility. Zinc may be present at levels as high as several parts per thousand and is of commercial interest in some coals.

## 8. GENERAL CHEMICAL REACTIONS OF COAL

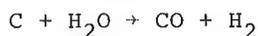
As a complex organic system, coal is capable of undergoing a large number of organic chemical reactions. The simplest of these is dissolution in either "non-reactive" solvents or in conjunction with hydrogen addition. Pyrolysis is the breaking down of coal to volatile components and char by heating. Oxidation and reduction will be discussed in subsequent sections. Coal is readily halogenated. This has found little practical use, but may be a troublesome side reaction in coal conversion processes. Functional groups containing oxygen, sulfur, and nitrogen undergo various chemical reactions used to remove and characterize these groups. The reactions of minerals and trace elements, particularly during conversion processes are quite important, but have not been investigated extensively.

## 9. OXIDATION OF COAL

The oxidation of coal to produce heat is of course the primary use of this mineral. Because of the presence of elements other than carbon and hydrogen, combustion of coal can be a complicated process which produces troublesome byproducts. Sulfur in coal goes to sulfur dioxide, the single most troublesome pollutant. Fly ash is responsible for particulate matter emis-

sions, and the character of bottom ash must be known to enable its safe disposal. Nitrogen in coal produces nitrogen oxide pollutants. Mercury, selenium, and some other trace elements are volatilized.

Partial oxidation of coal with oxygen and water to produce synthesis gas is a prime source of hydrogen and is the first step in a number of conversion processes, including several which are now in commercial operation. Heat for the process is generated by the reaction of coal with oxygen to produce carbon dioxide and water, and the hot coal (char) reacts with added steam,



Partial oxidation of coal in the presence of water and base results in the addition of oxygen-containing functional groups, particularly carboxylic acid groups, to the coal accompanied by various degrees of breakdown in the coal structure. Humic acids, fulvic acids, and ultimately substituted benzene carboxylic acids, are produced. Partial oxidation has been explored as a route to the manufacture of synthetic organic chemicals.

#### 10. REDUCTION AND HYDROGENATION OF COAL

For the most part, chemical reduction of coal consists of the addition of hydrogen. This is a very significant process for both coal structure determinations and coal conversion processes. Direct hydrogenation of coal can be accomplished with, or without an added catalyst. In the latter case, coal mineral matter is thought to have a self-catalytic effect. Commonly coal is ground and placed in a slurry with an organic solvent prior to hydrogenation. The solvent may be a hydrogen donor solvent which bonds to  $H_2$  and then donates hydrogen to the coal. Normally more solvent is produced as a product of coal hydrogenation.

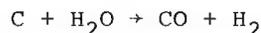
The primary products of hydrogenation

are hydrocarbons ranging from methane,  $CH_4$ , to coal tars. The production of lighter hydrocarbons requires a higher input of hydrogen. Because of coal's aromatic nature, the liquid hydrocarbons are predominantly aromatic hydrocarbons and polycyclic aromatic hydrocarbons.

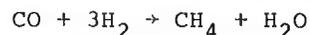
#### 11. COAL CONVERSION PROCESSES

The objective of coal conversion is to produce (1) gaseous fuels, (2) hydrocarbon liquids, or (3) solid solvent refined coal which is low in sulfur and ash and which has a high Btu content. Coal may be converted to other products by a large variety of processes. These range from the very simple to the highly sophisticated. Some are as old as the processes used to manufacture "water gas" during the 1800's, whereas others use sophisticated technology and have not yet reached the pilot plant stage.

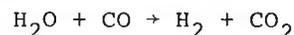
There are two basic processes for obtaining gas from coal. The first of these consists of reacting hot coal or coal char with water,



to produce synthesis gas consisting of a mixture of CO and  $H_2$ . There are many variations on this basic process. If the coal is heated by partial combustion in air, the product contains a high percentage of nitrogen and is a low heat content gas suitable only for burning on site. If a nitrogen barrier is employed, such as using pure oxygen to burn the coal, a medium Btu gas is produced which is primarily a mixture of CO and  $H_2$ . This gas may be upgraded to high Btu methane by methanation over a nickel catalyst:



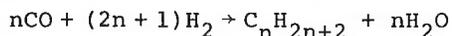
This reaction is preceded by a water-gas shift reaction,



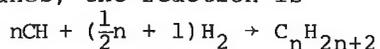
to obtain the needed 3/1 ratio of hydrogen

to carbon monoxide.

Hydrocarbon liquids can be obtained from synthesis gas by the Fischer-Tropsch hydrogenation of carbon monoxide:



This process is employed in the largest commercial coal liquids plant now operational, which is located in Sasol, South Africa. Direct hydrogenation of coal is also used to produce coal liquids. If carried as far as the production of alkanes, the reaction is



Normally the hydrogenation is carried only far enough to produce primarily aromatic compounds, which requires much less expensive hydrogen. Modern processes call for the production of appreciable quantities of valuable methane by rapid, high temperature hydrogenation of coal, thus avoiding the inefficient, troublesome methanation of carbon monoxide.

The mildest form of coal conversion is the manufacture of solvent refined coal. Coal is slurried with a solvent generated in the solvent refining process. The addition of hydrogen at elevated temperature and pressure results in the dissolution of most of the organic coal and the generation of more solvent. Some hydrogen sulfide is also produced. The product is filtered or centrifuged to remove char and mineral matter. The solvent is then stripped off for recycling leaving a solid with a low mineral and water content, appreciably lower sulfur content, and considerably higher heat content than the original coal. This process is essentially a way of making a premium coal fuel from low grade coal.

At this writing the future of coal conversion remains in doubt, largely because of steeply escalating costs. In applications where the desired product is heat to fire a boiler, or even for space heat-

ing, it does not appear that coal conversion can compete with direct combustion, even in cases where much-maligned stack gas scrubbing is required by high sulfur coals. The capital costs of a coal conversion industry of sufficient magnitude to provide a large fraction of domestic energy needs runs into hundreds of billions of dollars. Before making that investment, alternatives should be considered. For example, an upgraded, electrified national railway network, powered largely by coal fired electrical plants could provide the bulk of domestic freight transportation needs and an appreciable fraction of passenger transport. In addition it would enable low cost transport of coal to most areas of the country having the greatest need for energy. Centralized coal-fired power plants generating electricity and piping heat to large apartment and industrial complexes could substitute for much of the petroleum and natural gas now used by industry and for home heating.

## 12. MAJOR COAL CONVERSION PRODUCTS

The major products of coal conversion depend of course upon the process used as explained above. Liquefaction of coal by direct hydrogenation yields by far the greatest variety of chemical products numbering in the hundreds of compounds. The hydrocarbon products of coal hydrogenation may be classified into the categories of (1) a light oil stream boiling up to 260°C, (2) a middle oil stream boiling from 260 to 320°C, (3) a heavy oil stream boiling above 320°C, and (4) a pitch residue solidifying around 200°C. The light oil stream may be refined directly for sale. The middle oil may be refined or recycled through the process for additional hydrogenation. The heavy oil stream is used as a slurry vehicle for the feed coal. The pitch is burned to raise process steam or recycled for further hydrogenation.

### 13. ENVIRONMENTAL AND OCCUPATIONAL HEALTH CONSIDERATIONS IN COAL CONVERSION PROCESSES

The gross environmental effects of a major coal conversion industry involve those associated with mining, water use, waste heat, and solid waste byproducts. Not the least of these is the waste heat problem, because even the best processes will lose approximately 35 percent of the original Btu input as waste heat. Despite their large magnitude, the overall environmental effects of coal conversion are largely predictable and can be handled with existing technology.

However, coal conversion results in the formation of appreciable quantities of toxic and "exotic" compounds. The nature, quantities, and effects of these have not been investigated in detail, and they constitute a major problem. The design of a major coal conversion industry must entail careful consideration of environmental chemistry (2) to avoid the creation of unforeseen problems which will endanger health, cause delays in production, and be very expensive to remedy.

Considering all coal conversion processes, the undesirable byproducts to be considered are carcinogenic polycyclic aromatic hydrocarbons (known to be produced in large quantities, toxic phenols, carcinogenic aromatic amines, odorous and toxic sulfur compounds, metal carbonyls and arene carbonyls, herbicidal and toxic halogenated hydrocarbons, organometallic compounds, hydrides, organohydrides, and miscellaneous "exotic" compounds formed by reactions of the 50 or more trace elements commonly occurring in coal. In addition to knowing what kinds of undesirable byproducts may be produced, means for eliminating and preventing their transmittal to products or the environment must be developed. Worker health must have a particularly high priority.

### 14. COAL COMBUSTION AND STACK GAS CLEANING PROCESSES

Chemical processes are quite important in the combustion of coal and scrubbing of stack gas effluents. Utilization of high sulfur coals - the major U. S. coal resource east of the Mississippi river - requires either conversion to cleaner fuels or sulfur removal at the time of combustion. Progress is being made on various processes, using primarily fluidized bed furnaces, for the removal of sulfur dioxide during combustion. Additional research remains to be done on the high temperature combustion phenomena and inorganic chemistry involved.

Stack gas scrubbing processes have suffered from political considerations stemming from two differing schools of thought. On one side agencies charged with environmental protection have maintained that adequate technology exists for effective and economical stack gas scrubbing. However, the leading candidate, wet limestone scrubbing is plagued with operation problems, produces stupendous amounts of sludge, and contributes to water pollution from sludge leachate. Some power interests have tried to discredit all scrubbing processes as ineffective, prohibitively expensive, and damaging to the environment. As a consequence of their positions, neither side has pushed for the chemical and engineering research needed to develop scrubbing processes, particularly those based upon entirely new concepts. This situation is unfortunate in view of the fact that despite its problems, scrubbing is much more simple and efficient than coal conversion and offers the single best hope for the utilization of vast domestic high sulfur coal resources.

A high priority should be given, therefore, to research upon, and development of new, effective scrubbing processes.

## 15. ADVANCED COAL TECHNOLOGY

A study of coal chemistry in this age should consider advanced and emerging technology. An example of this is magnetohydrodynamics, which promises to almost double the conversion of coal chemical energy to electricity. Chemically MHD involves a very complicated high temperature system including volatile alkali metal "seed" compounds. Coal-fired fuel cells might even be envisioned. As research progresses, other advanced concepts will emerge.

## 16. CONCLUSIONS

Because of vast domestic reserves, coal remains the best prospect for U. S. energy self-sufficiency. The most effective utilization of this resource requires the application of modern technologies for coal combustion, coal conversion, and advanced coal technology. These technologies require that persons involved have a knowledge of the chemistry of coal. This paper has outlined the basic topics which constitute a broad coverage of modern coal chemistry.

## ACKNOWLEDGEMENT

Some aspects of the research upon which parts of this paper are based were supported by the United States Department of the Interior Office of Water Research and Technology Matching Grant B-115-MO.

## REFERENCES

1. Stanley E. Manahan, *Coal Chemistry*, publication scheduled for 1977.
2. Stanley E. Manahan, *Environmental Chemistry*, 2nd ed., Willard Grant Press, Boston, Mass. 1975.