

# COAL PROCESSING AND UTILIZATION

D.V. Subba Rao & T. Gouricharan



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# Dedication

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Dr. S. Krishna Murthy & Smt. Siva Nagendramma  
For their Care with Love and Affection

D.V. Subba Rao  
*Author*

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# Preface

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Coal remains the predominant source of fossil fuel and this scenario is likely to remain in the foreseeable future. The quality of coal is gradually deteriorating and affecting its utilization for all the downstream processes. Efficient utilization of the available resources requires its upgradation and coal beneficiation/washing is the most accepted method for upgradation of coal quality.

An attempt has been made to provide a book on coal processing and utilization for all the undergraduate and postgraduate students of Mineral, Mining and Metallurgical Engineering. This book gives an integrated picture of coal processing and utilization along with clean coal technology, while highlighting the presentation of all the basic principles, theory and practice in a systematic way.

This book is designed keeping in view the freshers who enter in the field of coal and its utilization. All the topics covered are dealt with in a self explanatory manner so that any new reader may find this book interesting and understand it easily. The contents of this book have been divided into three parts.

The first part of the book deals with the theories of origin and formation of coal, constituents of coal, sampling and analysis of coal, properties of coal and coking tests.

In the second part, unit operations viz., screening, size reduction, and dewatering are discussed. Prominence is given to describing the construction of washability curves by taking a hypothetical example. The beneficiation processes viz., heavy medium separation, jigging, flowing film concentration, cyclone separation, froth flotation, centrifugal separation and dry beneficiation, are dealt with in depth. The chapter “coal washing efficiency” is devoted exclusively to describing different criteria used for the evaluation of processing plant performance. Coal washing practices and recent developments in coal processing are added for the benefit of researchers. Illustrative examples and problems for practice are incorporated wherever necessary which may help the readers to use them in teaching, research and operating plants. A topic on applications of computers in coal processing plants is given in Annexure-I.

The third part, coal utilization, includes considerable details of carbonization, combustion, gasification and liquefaction.

Special emphasis is given to Indian coals by incorporating three separate chapters viz., classification of Indian coals, Indian coal resources and coal washing practice in India. Selected international and national standards used in coal and coke analysis and evaluation are given in annexure-II for the benefit of readers.

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# Foreword

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I have great pleasure to write the foreword to this book “**Coal Processing and Utilization**” authored by Mr. D.V. Subba Rao and Dr. T. Gouricharan. Mr. D.V. Subba Rao taught mineral and coal processing courses to undergraduates and guided many postgraduate students for more than 35 years. Dr. T. Gouricharan, student of D.V. Subba Rao, had more than 25 years of experience in coal preparation at Central Institute of Mining and Fuel Research (CIMFR), Dhanbad and published more than 80 papers in national and international journals.

In this book, the authors present the subject in a very simple manner and also include quite a few illustrative examples and problems for practice in order to have thorough understanding of the concepts. Keeping in view the undergraduate and post-graduate students, this book is very well articulated for ease of understanding with the broad classification of the contents into three parts.

The first part of the book deals with the geology, properties, analyses and tests of coal. The second part of the book comprises of washability characteristics, unit operations, and beneficiation processes of coal. Illustrative examples and problems for practice included will help the plant engineers, designers and researchers. The third part covers coal utilization and is of immense importance for the readers to have a good idea of carbonization, combustion, gasification and liquefaction in order to assess to what extent the coal has to be upgraded. For this, the authors are to be complimented for covering these aspects in the light of increased environmental awareness.

I am sure that the readers dealing with any aspect of coal, right from its geology to its utilization, would be benefited by this book written in the simplest possible way.

Dr. T.C. Rao  
*Formerly Director, Regional Research Laboratory, Bhopal  
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Heavy Medium Cyclone  
Figure on cover page

Table Model Sieve Shaker  
Ro-tap Sieve shaker

Bradford Breaker

Sectional view of single toothed  
roll crusher

Double toothed roll crusher

Sizer

Baum jig, Batac jig, Feldspar jig,  
ROM jig

Spiral concentrator

Falcon Concentrator

Kelsey jig

Knelson Concentrator

All-Air jig

Ramdars plant, Ardee Sort plant

High frequency vibrating screen

Rotary vacuum disc filter

Hyperbaric disc filter

CMI screen scroll centrifuge

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Part A

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Coal

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# Introduction

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**It is not use of coal,  
but how coal is used  
that must be the focus of action**

**—World Coal Institute**

Coal plays a pivotal role in sustainable development. It is the most widely used energy source for electricity generation and an essential input to most steel production. Total global coal resources are estimated at 11,000 billion tons [1], out of which extractable reserves are 909 billion tonnes, less than 10% of the total coal resources. A resource is the occurrence in the earth's crust. A reserve is a mineable part of a resource that is extractable with existing technology.

USA ranks first in coal resources with 237 billion tons. Russia, China, Australia and India come next to USA in coal resources. However, China ranks first in coal production with 3474 million tons in 2014. USA, India, Australia and Indonesia come next to China in coal production.

As estimated by the World Coal Association, coal currently fuels 41% of the world electricity and this proportion is set to remain static over the next 30 years. Poland relies on coal for over 94% of its electricity; South Africa for 92%; China for 77%; and Australia for 76%. Coal has been the world's fastest growing energy source in recent years – faster than gas, oil, nuclear, hydro and other renewable sources. Coal has played this important role for centuries – not only providing electricity, but also an essential fuel for metallurgical and cement production, and other industrial activities. About 70% of the world's steel production is based on coal.

Over the next 30 years, it is estimated that global energy demand will increase by almost 60%. Two thirds of the increase will come from developing countries – by 2030 they will account for almost half of total energy demand.

Average gross energy efficiency of power generation from coal-based power plants employing pulverized coal firing method is 30.5 per cent [1]. Energy efficiency can be improved during combustion stage as well as pre-combustion stage. Processing of the coal and blending the coals of different quality before the coal is combusted are the low cost solutions to increase the energy efficiency in a pre-combustion stage. Clean coal technology aims to improve the energy efficiency and to reduce the harmful emissions.

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# Clean coal technology

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The term **Clean Coal Technology** (CCT) describes a new generation of processes for the production of electricity and fuels from coal. Clean coal technology addresses atmospheric problems resulting from burning coal. The clean coal technology is of utmost importance because (i) coal is abundant and will remain a major source of energy for future years, and (ii) emission from coal based generation is a matter of serious concern. Thus, clean coal research has begun to:

- Improve the quality of non-coking coal at the pre-combustion stage for use in power generation by value addition
- Adopt new coal combustion and conversion technology for improving efficiency of coal utilization
- Reduce carbon dioxide and other pollutant emissions in the environment through Renovation and Modernization

Adoption of new and efficient technologies for improvement of coal quality at pre-combustion stage, and for combustion and conversion processes not only aims to increase in amount of energy obtained from each ton of coal used but also to reduce emission of greenhouse gases and other pollutants.

A **Greenhouse Gas** (GHG) is a gas in an atmosphere that absorbs and emits radiation within the thermal infra-red range. This process is the fundamental cause of the greenhouse effect. The **greenhouse effect** is a natural process by which thermal radiation from a planetary surface is absorbed by atmospheric **greenhouse** gases, and is re-radiated in all directions. Greenhouse gases normally trap some of the sun's heat keeping the planet warm enough for life. Burning of fossil fuels increases the greenhouse gas levels, leading to an enhanced greenhouse effect. The result is global warming and unprecedented rates of climate change.

Global warming is a significant increase in the Earth's climatic temperature over a relatively short period of time as a result of the activities of humans. In specific terms, an increase of 1 or more degrees Celsius in a period of one hundred to two hundred years would be considered global warming. Over the course of a single century, an increase of even 0.4 degrees Celsius would be significant.

The most abundant greenhouse gases in Earth's atmosphere are water vapor ( $\text{H}_2\text{O}$ ), Carbon dioxide ( $\text{CO}_2$ ), Methane ( $\text{CH}_4$ ), Nitrous oxide ( $\text{N}_2\text{O}$ ), Ozone ( $\text{O}_3$ ), and Chlorofluorocarbons (CFCs). Other greenhouse gases include sulfur hexafluoride, hydrofluorocarbons and perfluorocarbons. The atmospheric lifetime of green house

gases measures the time required to restore equilibrium following a sudden increase or decrease in its concentration in the atmosphere. Major greenhouse gases are well mixed and take many years to leave the atmosphere. The atmospheric lifetime of  $\text{CO}_2$  is estimated of the order of 30–95 years. Methane has an atmospheric lifetime of  $12 \pm 3$  years. However, the residence time of water vapor is about nine days. The Global Warming Potential (GWP) depends on both the efficiency of the molecule as a greenhouse gas and its atmospheric lifetime.

The World-watch Institute reports that carbon emissions worldwide have increased from about 1 billion tons in 1900 to about 7 billion tons in 1995. Atmospheric  $\text{CO}_2$  levels have increased by more than 40 percent since the beginning of the Industrial Revolution, from about 280 parts per million (ppm) in the 1800s to 400 ppm today [2]. Hence emission to the environment on utilizing the coal is of major concern. Therefore **Clean Coal Technology (CCT)** refers all the technologies applied to coal in order to reduce air emissions, waste product and pollutants on utilizing the coal for its process of energy conversion.

Clean coal technologies are categorized into

- 1 Coal beneficiation
- 2 Coal combustion
- 3 Coal conversion
- 4 Post-combustion

### *Coal Beneficiation Technology*

Beneficiation of coal produces higher quality coals by increasing percent carbon that can be burned more cleanly and with greater efficiency, reduces the amounts of emitted fly ash and associated hazardous air pollutants, increases calorific Value, produces required sizes of particles, minimize capital, operating and maintenance costs, reduces the need to import higher-quality coals, improves health and safety and mitigates environmental degradation.

### *Coal Combustion Technology*

Coal combustion technology aims in increasing the energy efficiency and reducing the harmful emissions while combusting the coal.

### *Coal Conversion Technology*

It comprises the technology of converting coal into gas through gasification and into oil through liquefaction. Coal conversion processes reduce pollution and increase efficiency, but adds to infrastructure needs for coal suppliers/users.

### *Post-combustion Technology*

In post-combustion technology, pollutants such as  $\text{SO}_x$ ,  $\text{NO}_x$ , and  $\text{CO}_2$  are captured and removed from the atmosphere.

# Coal – its origin and formation

---

Coal is a natural fuel, occurring in layers in the earth's crust composed mainly of plant material that has suffered partial decay and has been further altered by the agencies of heat and pressure to the varying degrees of completeness. This initial sediment formed by this process is, moist, spongy material, called peat, but this becomes compressed, dried and modified in both texture and composition due to diagenesis associated with burial and tectonic activity. The different kinds of plant material vary in their proportions in different coals, and the decay and subsequent alteration of the material proceeded to different degrees. As a result, coals show great variety in their chemical and physical properties and because of this, in their behaviour in practical use.

Coal is a stratified rock which was formed many millions of years ago from the remains of decaying trees and vegetation. Coal is unique amongst rocks because it is organic in composition. It contains the elements carbon, hydrogen and oxygen with small amounts of nitrogen and sulphur and only traces of inorganic material which are not chemically combined with the organic material forming most of coal.

Coal is a stratified rock, since geologists regard as rocks all natural, solid substances, organic or inorganic, that compose the earth's crust. From petrological point of view, coal may be considered as a mildly metamorphosed sedimentary rock, with properties depending on both the nature of the original parent material or maceral assemblage and the degree of diagenesis or metamorphism to which it has been subjected. Being an unusual rock type, coal is also a highly significant part of the stratigraphic succession in many sedimentary accumulations. Coal beds are widely used as markers for stratigraphic correlation, and as indicators of specific depositional environments in basin analysis. From a more pragmatic viewpoint, coal may be regarded simply as a special kind of economic mineral deposit. All of the above considerations are important in some way to the economic coal geologist, along with aspects such as the most appropriate means of evaluating and developing individual deposits for use. The economical value of coal deposit, and physical, legal and sociological constraints on their extraction and use are likewise of great concern to mining and processing engineers, mineral economists, environmental scientists and host of other technical specialists involved in the various operations of the coal industry.

In trade, industry, and legal affairs coal is considered as a mineral and it is sometimes spoken of as mineral coal. In restricted technical sense, it is not a mineral, because a mineral according to Dana [3] is an inorganic homogeneous substance with a definite chemical composition and internal atomic structure, all of which requirements coal lacks. A block of coal of appreciable size is not homogeneous and though



the composition of certain constituents comprising it may be expressed by a chemical formula, the composition of coal as a whole varies markedly from point to point.

Coal is a primary source of heat and power. It has long been the backbone of industrial life. The popular definition of coal is that of Miss. Stopes and Wheeler [4] according to whom, "Ordinary coal is a compact stratified mass of mummified plants (which have in part suffered arrested decay to varying degrees of completeness)." But the scientific definition of coal is given by E.A.N. Arber [5] who defines, "Coal is a solid stratified rock, composed mainly of hydrocarbons and capable of being used as a fuel to supply heat or light or both."

### 3.1 ORIGIN OF COAL

Chemical and geological studies have conclusively shown that coal is formed from vegetable material such as trees, vesicular plants, spores etc. The longer remains like tree trunks, bark, leaves and some plant residues can be seen with naked eye. Small structures such as wood cells, spores and algae are identified with the help of a microscope. The various ranks of coal represent different degrees in the conversion of the original plant material. The method of accumulation of the vegetable matter has also influenced the nature and properties of coal.

It is considered that coal was formed from decaying vegetation and mineral matter, compressed beneath many layers of fallen trees, leaves and soils. About 250 million years ago, much of the area now occupied by Great Britain was covered by large shallow lake or swamp surrounded by low lying land, which, here and there, extended into the lake and subdivided it into several parts. The climate at that time is considered to have been warm and humid, with a heavy rainfall, so that conditions were favourable to the growth of luxuriant vegetation. Large trees, many resembling giant ferns, grew in dense forests on the low lying land or in the shallow waters of the lake and succeeding generations of trees as they died and accumulated on the floor of the lake, forming a vegetable sludge.

Two theories, *in situ* and *drift*, have been put forward as to the modes of origin of coal seams. The first, *in situ* (the growth-in-place) theory says that coal seams occupy more or less the site on which the original plants grew and where their remains accumulated. The coal formed under this theory is not polluted much with the extraneous dirt, and the seams thus formed are not very thick.

In the case of drift theory, the formation is of a quite different in nature. Plants formed to coal seams were drifted from one place, where it actually grew and die, by flood or river transportation and accumulated in a lake or estuary. Under some earth quake or other geological sequence, everything had gone under ground and covered up with earth strata.

From time to time sinking of the floor of the lake or swamp drowned the forests, and sediments (sand and mud) carried by rivers were deposited in layers above the vegetable sludge. Eventually, with a halt in the sinking, the water became shallow again, trees re-established themselves, and the whole cycle was repeated. This occurred many times over, so that there accumulated twenty or thirty or even more layers of vegetable sludge separated by layers of sand and mud. The last two materials, with little more change than hardening, eventually formed sandstone and shale,

but the conversion of the plant material into coal involved a considerable change in composition.

Each layer of vegetable sludge which forms further as coal bed is called **Coal Seam**. Coal generally occurs as layered sedimentary rock/bed as part of earth crust and this layer is called the coal seam. In a sequence, wherever a coal seam occurs, irrespective of its geological age, the seam is usually a minor constituent of the rock to which it belongs. Sandstone, shale or carbonaceous shales generally overly the coal seams. Formations of series of coal seams separated by layers of sand and mud (sedimentary rock) are known as **Coal Measure**.

The coal formed under drift theory is naturally contaminated by extraneous dirt with the formation of shale and sandstone bands. Collected evidences indicate that the majority of coal seams in the world are of in situ origin whereas Indian coals are of drift origin. That is why percentage of ash is much higher than the coals under in situ formation. One advantage in this coal is that, the seams are thick due to prolonged accumulation of drifted vegetation in lakes. China has got a seam of over 600 ft, the thickest one in the world. In India, the Jheengurdah seam of Singrauli coalfield in Sidhi district in U.P border is about 152 meters (500 ft) thick, stands in the second position in the world. One may visualize how much drifted plant was accumulated to form such a thick seam which can be worked out simply by open cast system by removing over burden.

## 3.2 FORMATION OF COAL

Coal is formed from vegetation by coalification. Coalification is the process of the chemical transformation from vegetation into coal. There were two important stages in the formation of coal from vegetable matter. The first one is **Peat stage** or **Biochemical stage** and the second one is **Metamorphic** or **Geochemical** or **Dynamochemical stage**.

### 3.2.1 Peat stage or biochemical stage

On dry ground, fallen trees and plants are attacked by oxygen from the surrounding air. Cellulose, which is their principal constituent, is slowly converted to carbon dioxide and water and the tree and tree rots, leaving little trace of the trees and vegetation are water logged, however, air cannot penetrate to the cellulose and decay takes place anaerobically (i.e. in absence of air) by the action of bacteria. In this case, decay takes place slowly and is gradually halted as the products of decomposition accumulate and bacteria can no longer survive. During the period of bacterial decay, the trees and vegetation are covered by fresh debris by vegetation, soil and rocks deposited by movements of the earth's crust. Because the bacterial degradation of cellulose is a slow process, the products of decomposition have been buried to a considerable depth by the time the bacterial action ceases. The resulting product thus formed is called as **PEAT**. In a peat, the bacterial processes are only partially completed, because some of the products which accumulate in the deposit are aseptic and prevent the complete break down of the plant tissues. Resins and waxy plant skins resist bacterial decay more strongly than wood, so these compounds tend to accumulate in the deposit.

The principal chemical components of wood from which peat formed are:

Cellulose $n(C_6H_{10}O_5)$	45–65%
Lignin	25–35%
Water and proteins in solution	10–15%
Waxes and resins	0.5–15%

The following is the analysis of wood:

<i>Dry, ash-free material</i>	<i>percent</i>
Carbon	50.0
Hydrogen	6.2
Oxygen	43.8

When wood is subjected to bacterial processes, the cellulose, lignin and protein are partially decomposed and their residuals combine to form products of varying composition that resemble humus, called humic acid. Humic acid occasionally occurs as a thick jelly, also called dopplerite, after its discoverer, Doppler [6].

A typical analysis shows that peat contains 70–90% humic acid and 5–30% resins and waxes. The following is the analysis of peat:

<i>Dry, ash-free material</i>	<i>percent</i>
Carbon	55-65
Hydrogen	5.5
Oxygen	32

The amount of water present in peat varies greatly and may be as high as 90%. Near the surface, peat is light in colour, but at lower depths it becomes darker and finally black.

### 3.2.2 Metamorphic or geochemical or dynamochemical stage

Soon after burial under an impervious cover, all bacterial action ceases and subsequent chemical changes are taking place in the deposit during metamorphic stage. During this stage, the progressive changes that occur within coals are an increase in the carbon content and a decrease in the hydrogen and oxygen content, resulting in a loss of volatiles. This together with continued water loss and compaction results in the reduction of the coal volume. Products of such coalification are methane, carbon dioxide and water, and are caused by temperature, pressure and time.

**a Temperature:** Temperature changes can be achieved in the two following ways.

- 1 The direct contact of the coal with igneous material, either as minor intrusions or as deep-seated major intrusions. The coals exhibit loss of volatiles, oxygen, methane and water, and the surrounding sediments will show evidence of contact metamorphism, for example, the local development of high rank coal in

the Gondwana coals of South Africa and India, and in the Paleogene–Neogene coals of Sumatra, Indonesia.

- 2 The rise in temperature associated with the depth of burial. Increasing depth of burial results in a decrease in the oxygen content of the coals, and the increase in the ratio of fixed carbon to volatile matter. In normal coals, exceeding 300°C, temperature increases with increasing depth. For the temperature effect on coal seams, **Carl Hilt** (1873) shows that the rate of chemical change doubles for a rise of 5°C to 10°C so that coals in the lower seams of coal measures are generally more mature (i.e., of higher rank) than those of higher seams, because of the temperature gradient of the earth's crust. This variation of rank with depth is known as Hilt' law [7].

- b **Pressure:** The influence of pressure is at its greatest during compaction and is most evident from the peat to sub-bituminous coal stages. With increasing chemical coalification, pressure has less influence. Pressure changes from a few pounds to many hundred pounds per square inch. Pressure is important mainly in its effect on temperature, particularly dynamic pressure due to resistance to earth movements.
- c **Time:** Temperature and pressure operates for enormous lengths of time. The effect of the time factor is that in various parts of the world, the coal seams in younger geological formations find on the whole to be less mature or less coalified than those in older formations.

Degree of coalification is less where sediments have subsided rapidly and time only has a real effect when the temperature is sufficiently high to allow chemical reaction to occur. Where very low temperatures occur over a very long period, little coalification takes place, for example, the Lower Carboniferous lignites in the Moscow Basin. The influence of time therefore is all the greater when the temperature is higher.

While the main course of coalification was probably decided by the heat and pressure resulting from burial of the coal swamps, in the regions of intense earth movements, pressure accompanied by heat increase the degree of coalification.

Variations in the conditions of temperature and pressure to which the seam was exposed have led to variations in the transformation of the decaying wood as follows:

- 1 Conditions which were not truly anaerobic led to the formation of peat.
- 2 Low alkalinity (absorbing carbon dioxide) in the surrounding clay led to the formation of lignites.
- 3 High alkalinity in the surrounding clay led to the formation of bituminous coals.

The precise nature of the changes that took place in the gradual conversion of plant material into coal is not known. Some scientists suggested the following overall reactions for formation of coal from wood:

- 1 According to **Regnault** (1900) [8]  
 $(C_6H_{10}O_5)_4 \rightarrow C_6H_6O + 7 CH_4 + 3 H_2O + 8 CO_2$   
 Cellulose                      Bituminous
  
- 2 According to **Parr** (1910) [9]  
 $(C_6H_{10}O_5)_5 \rightarrow C_{20}H_{22}O_4 + 3 CH_4 + 8 H_2O + 6 CO_2 + CO$   
 Cellulose                      Lignite
  
 $(C_6H_{10}O_5)_6 \rightarrow C_{22}H_{20}O_3 + 5 CH_4 + 10 H_2O + 8 CO_2 + CO$   
 Cellulose                      Bituminous
  
- 3 According to **Mott** (1942) [10] the following changes occur in the series wood to anthracite

Stage	Products evolved
Wood to low rank lignite	$64 H_2O + 8 CH_4 + CO_2$
Low rank lignite to low rank bituminous coal	$CO_2$
Low rank bituminous coal to semi-anthracite	1st stage $1.42 H_2O + 0.43 CH_4 + CO_2$ 2nd stage $5 H_2O + 3 CH_4 + CO_2$ 3rd stage $1.45 H_2O + 5.8 CH_4 + CO_2$
Semi-anthracite to anthracite	$36 CH_4 + H_2O$

From the reactions suggested by Mott, it can be observed that the rate of methane evolved increases rapidly from bituminous coal to semi-anthracite, and from semi-anthracite to anthracite. This results in a fall of the hydrogen content of coal. These reactions account for large quantities of methane associated with coal mines containing carbonaceous coals and anthracites.

# Constituents of coal

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Since coal is derived chiefly from vegetal matter, it consists mainly of the elements that go to compose plants, but it differs from plants in composition in as much as certain proportions changed during the fermentation and metamorphic processes that have caused the formation of coal. As the plants accumulated under water, some silt also settled along with them. Thus at a later stage, some mineral matter got mixed with the coal as it formed. In addition to the plant and mineral matter, an appreciable amount of animal matter may have been imprisoned in the coal and this may have caused a variation from normal composition, especially in nitrogen and phosphorous content.

Hence the coal as obtained from the earth's crust is not strictly a coal but consist of **coal** (or coal substance), **mineral matter** and **moisture**.

## 4.1 COAL SUBSTANCE

Coal substance (or simply coal) is that part of the plant's organic material (or cellulose) which has been later converted during the coalification reactions to form coal beds.

The principal elements from which coals are composed are some ones which make up wood and other vegetal matter: carbon, hydrogen and other elements characteristic of the inorganic matter. Carbon, hydrogen, oxygen, nitrogen and a portion of the sulphur are combined in very complex molecules with high molecular weights, which were produced from the original vegetal substances by the coalification reactions. The exact course of these reactions is not known, but all the evidence points to a gradual loss of carbon, hydrogen and oxygen, most probably by the elimination of water, carbon dioxide and methane. Thus the whole substance suffered wastage but as the hydrogen and oxygen were lost at proportionately higher rates than the carbon, the net result was that the percent carbon of the maturing coal increased with the degree of coalification.

The extent of these changes is shown by the following analysis of wood, representing the starting material, and anthracite which is the most mature form of coal:

	<i>Wood</i>	<i>Anthracite</i>
Carbon %	50.0	96.0
Hydrogen %	6.2	3.0
Oxygen %	43.8	1.0

As a result of the changes in the relative proportions of carbon, hydrogen and oxygen, other characteristics also change. Two elements nitrogen and sulphur amount to about 1 or 1.5% and show no marked variation with the degree of coalification. The part they play in the chemistry of coal is not fully understood, but compared with carbon, hydrogen and oxygen, they are relatively unimportant.

## 4.2 MOISTURE

The moisture in coal can be considered to occur in two parts, though the dividing line between them is not absolutely definite. One part, called the **free moisture**, occurs on the surface of the coal and in its cracks and joints. It is easily lost by evaporation, and except during unusually wet and cold weather, the amount of free moisture in sized grades of coal is generally small when it reaches the consumer, but washed smalls, which sometimes drain badly, may retain considerable quantities. Large amounts of free moisture are clearly undesirable in the coal as purchased, since they have to be paid for the same price as coal. On the other hand, a limited amount of free moisture is always present in the coal as eventually used, and water is often added to dry smalls to assist combustion.

The other part, called **inherent moisture**, is the amount of moisture in the following forms:

- 1 **Hygroscopic moisture:** This is the water held inside the capillaries of the coal substance.
- 2 **Decomposition moisture:** This is the water incorporated in some of the coal's organic compounds.
- 3 **Mineral moisture:** This is the water which forms part of the crystal structure of clays and other minerals present in the coal.

This inherent moisture is more or less constant for coals of a given rank. Much of it, especially the moisture in the pores of the coal, is driven off by heating to 100°C but some of the mineral and decomposition moisture may not be liberated until temperatures exceed 500°C.

The inherent moisture is also called air-dried moisture because, under normal atmospheric conditions, it is not removed by evaporation. The percent of air-dried moisture can be used as a broad indication of the rank of the coal. It is some extent affected by the atmospheric conditions existing at the time of air drying. For this reason, the conditions under which coal is air-dried in preparation for laboratory examination are carefully specified.

The moisture in the coal reduces the calorific value of coal, increases the consumption of coal for heating purposes and lengthens the time of heating. If coal is exposed to an atmosphere of increasing humidity at a fixed temperature, it absorbs more and more moisture. The quantity of moisture the coal has at saturated atmosphere (96–99% relative humidity) is called **near saturation moisture** or **bed moisture** and is a better measure than the air dried moisture for determination of rank of high volatile bituminous, sub-bituminous and lignitic coals and serves as parameter in some coal classification systems.

### 4.3 MINERAL MATTER

No coal consists entirely of organic compounds. Inorganic material is also present in the coal as impurities. Mineral matter refers to such impurities as they exist in the coal. The mineral matter is non-combustible. The residue from this mineral matter after coal has been burned is called ash. The average ash content of the entire thickness of a coal seam is at least 2 or 3%, even for very pure bituminous coals, and 10% or more for most commercial mines. Material that is too high in ash for ordinary use is called bone coal, carbonaceous shale, or black slate.

Mineral matter present in coal may be classified broadly into those that form ash and those that contribute sulphur. Ash forming mineral matter is of two types namely **inherent mineral matter** and **extraneous or adventitious mineral matter**. The inherent mineral matter represents inorganic elements present in plants giving rise to coal beds. It is very small in amount, about 2% or less of the total ash, different in composition and not possible to separate by usual beneficiation methods. A new process developed at Central Institute of Mining and Fuel Research (CIMFR) Dhanbad (formerly Central Fuel Research Institute CFRI), called oil agglomeration technique which consists mainly of leaching of coal impurities by petroleum oil, can to some extent remove inherent mineral matter. The inherent mineral matter is a useful classification when applied to the practical problems of coal cleaning. Generally speaking, it defines the lower limit to which coal can be separated physically from its mineral impurities. This is true because theoretically all extraneous mineral matter can be removed.

The extraneous mineral matter is due to the substances which got associated with the decaying vegetable material during its conversion into coal, and also due to the rocks and dirt getting mixed up during mining and handling of coal. The former of extraneous mineral matter is in a fine state and intimately associated with the organic mass of coal. Hence difficulties are experienced in removing this from coal by mechanical methods. The second type of extraneous mineral matter is more amenable to coal cleaning methods. The major portion of mineral matter of commercial coal is extraneous. In Indian coals, the mineral matter content is not only high but is of intimately associated due to the drift origin.

The bulk of the mineral matter of coal is due to clay or shale consisting of aluminosilicates of different composition. Other constituents identified are carbonates, sulphides, oxides, chlorides and sulphates. Table 4.3 shows coal minerals and their frequency of occurrence.

When coal burns, shale and other hydrated minerals lose water of hydration while sulphides, sulphates and carbonates usually decompose, resulting in loss of weight, hence the ash of coal is always less than the mineral matter content.

Sulphur occurs in coal in three forms. It is present in organic combination as part of the coal substance, as pyrites or marcasite, and as sulfates. The amount of organic sulphur normally is not over 3%, but in exceptional cases may be as much as 11%. The sulphates, mainly calcium and iron, rarely exceed a few hundredths percent except in highly weathered or oxidized samples. Pyrites and marcasite constitute the principal form of sulphur found in coals. Because of the difficulty in distinguishing one from the other, they usually are designated simply as pyrite. Pyrite occurs in coal in veins, lenses, nodules or balls and pyritized plant tissue. Microscopic pyrite also



Table 4.3 Minerals identified in coal (compiled from various sources).

Group	Minerals	Occurrence*
Clay	Illite	dominant – abundant
	Kaolinite	common – very common
	Montmorillonite	rare – common
	Chlorite	rare
	Biotite	very rare
Carbonates	Siderite	common – very common
	Ankerite	common – very common
	Calcite	common – very common
	Dolomite	rare – common
Sulphides	Pyrite	rare – common
	Marcasite	rare
	Sphalerite	rare
Oxides	Quartz	rare – common
	Hematite	rare
	Magnetite	very rare
	Rutile	very rare
Chlorides	Sylvine	very rare – common
	Halite	very rare – common
Sulphates	Gypsum	rare
	Baryte	rare

\*Occurance – Dominant: > 60%  
 Abundant: 30 – 60%  
 Very common: 10 – 30%  
 Common: 5 – 10%  
 Rare: 5 – 1%  
 Very rare: < 1%  
 } of the total mineral matter content in the coal

occurs as small globules, fine veinlets, euhedral crystals finely disseminated throughout the coal, cell fillings, and replacement of plant material. Elemental sulphur has been reported to occur in amounts of as much as 0.15% in some coals.

Depending on the nature of the coal, the mineral matter present may be derived from a number of different sources. Nature of mineral matter or impurities present in coal are of the following types:

- residual inorganic matter of coal forming plants
- mineral matter washed or blown into the coal forming mass during the period of its formation
- pyrites formed by the reaction of iron sulphate with coal forming matter
- sedimentary deposits during the coal forming periods
- deposits formed through deposition of bedding planes
- saline deposits
- slate, shale, clay etc. from the underlying and overlying strata

The minerals present in coal are of great significance in aspects of coal classification, testing and use, as well as in problems such as seam correlation and the development of depositional models. The mineral matter can have an effect on the coal's behaviour at low temperature, at medium temperature such as in carbonization, and at the high temperatures of the combustion process.

#### 4.4 PETROGRAPHIC CONSTITUENTS OF COAL

Close examination of coal in hand specimen generally shows it to be composed of different layers. Under the microscope, these layers in turn are seen to be composed of mixtures of discrete entities. Coal petrology is the study of the origin, composition and technological behaviour of these different materials, while the systematic quantification of their proportions and characteristics under the microscope is sometimes known as coal petrography.

The petrology of coal may be studied at either a megascopic or a microscopic scale. From a megascopic point of view, coal may be classified into two broad groups, the banded or humic coals and the non-banded (massive) or sapropelic coals. The humic coals are visibly stratified, consisting of layers or bands of organic material of varying appearance. Such coals are derived from a heterogeneous mixture of a wide range of plant debris. The sapropelic coals are homogeneous, tough materials and made up of spores or algae material.

##### 4.4.1 Lithotypes in banded coals

After careful examination of the different layers in a number of coal seams, Dr. M.C. Stopes [11], a palaeobotanist, in 1910 concluded that there were four distinct types of coal layers or **Banded constituents**, which she defined according to their appearance as seen by the unaided eye, and named as **Vitrain**, **Clarain**, **Durain** and **Fusain**. In current usage, these constituents are regarded as **Lithotypes**.

**Vitrain** is the black, glossy, vitreous material that is probably the most striking component of bituminous coals. Vitrain tends to be more brittle and often breaking with a conchoidal fracture. It is assumed that Vitrain was originated from barks of special type of plants which had first undergone into the chemical and physical changes for coalification than other parts of debris. This will not make hand dirty, if touched. It is coking in nature and is responsible for lustrous black band of bituminous coal. In humic coals, vitrain is widely distributed.

**Clarain** resembles nearly the same like Vitrain but it is less glossy and can be identified with experience. It has a silky luster and on a vertical face it is seen to be finely laminated. It breaks usually with a splintery fracture. It makes the hand slightly dirty. It includes relatively large plant fragments, particularly in the vitrain bands, and it seems reasonable to assume that the bright coal or clarain was formed from material that was not transported into the swamp but come directly from the trees growing there. Clarain is the most common macroscopic constituent of humic coals.

**Durain** occurs as grey to black bands with a dull to slightly greasy luster. The material is relatively hard and tends to break into large, blocky fragments. Fracture

surfaces of durain are rough. Durain may sometimes be confused with impure coal or carbonaceous shale, which are also often dull and hard, but it can be distinguished by its lower density. Durain was formed possible from trunks and main woody matters.

**Fusain** is a soft friable material that closely resembles wood charcoal. It is of silky luster, black and frequently somewhat fibrous. Fusain usually occurs as thin lenses between the bands of other types and is only a very minor constituent of most bituminous coal seams on a volumetric basis. It is only 3 to 5% in coal. Fusain is non-coking in nature and soils the hand when touched.

The terms **duroclarain** and **clarodurain** have been added to this list to extend the number of terms available for megascopic coal description. They represent material that is intermediate in character between clarain and durain.

Microscopic studies of the four different bands of ordinary coal revealed that two of them, namely the vitrain and fusain, are homogeneous, showing the same kind of material throughout. The clarain and durain bands, on the other hand, are heterogeneous, consisting of different kinds of easily determinable microscopic features.

The distinction between bright components (Vitrain and Clarain) and dull components (Durain and Fusain) is most apparent in bituminous coals, in some lignites, to a less extent in anthracite coals.

#### 4.4.2 Lithotypes in sapropelic coals

Sapropelic coals represent accumulations of algae or spore remains. Sapropelic coals are characteristically fine grained, faintly bedded to homogeneous, massive materials. They are generally dark in colour with a dull to greasy luster and typically display a marked conchoidal fracture. Sapropelic coals may occur as layers or plies within seams of banded or humic coal, often at the roof.

The two major types of sapropelic coal are **cannel coal** composed largely of spores or fine organoclastic detritus, and **boghead coal** composed largely of algae. Cannel coals are black and dull, sometimes with a rather greasy luster. They are homogeneous and compact fine grained coals and breaks with a conchoidal fracture. The most characteristic feature of all cannel coals is the almost uniform size of the constituent particles. The ash content of cannel coal is usually high. Cannel coals occur in most coalfields all over the world. Cannel coals contain little (about 5%) or no algae, whereas boghead coals contain more than 5% algae. Boghead coals, also known as torbanites, are similar to cannels in appearance, except that they tend to be browner in colour.

#### 4.4.3 Coal maceral groups

The constituents of coal were classified microscopically by Thiessen [12] in 1920 as **anthroxylon**, **attritus** (translucent and opaque) and **fusain** (which corresponds to macroscopic classification of Stopes: vitrain, clarain, durain, and fusain). This classification was based on visual characteristics of the coal constituents in thin sections under transmitted light. The use of thin section was later replaced by measuring the reflectance on a polished surface because of the experimental convenience of the latter technique.

The transmitted-light technique is advantageous for morphological investigations, whereas reflected light is suitable for quantitative measurements. For example, reflectance measurements frequently can be used effectively to:

- 1 Determine yields of coal carbonization products, such as coke, tar, gas, and light oils.
- 2 Obtain heating values and specific gravity properties of gases produced in coal carbonization processes.
- 3 Determine the free-swelling index and heating values of coals.
- 4 Categorize coals for certain combustion uses.
- 5 Predict the oxidation tendencies of coals.

The differences between the two techniques led to two different nomenclatures in coal petrology. All of Thiessen's coal constituents – anthraxylon, attritus, and fusain – are present in ordinary coals, regardless of rank. According to the presence or absence of anthraxylon, coals are classified into two major groups:

- 1 Banded coals – composed of both anthraxylon and attritus.
- 2 Non-banded coals – composed entirely or almost entirely of attritus.

The banded coals were subdivided into (1) Bright coals contain predominately vitrain and clarain, (2) Semisplint coals contain predominately clarain with some vitrain and durain, (3) splint coals contain predominately durain with some vitrain and clarain. The non-banded coals were divided into cannel and boghead coals contains predominately durain with lesser amounts of vitrain than splint coal.

European workers usually define the micro-constituents of coal as macerals, deriving from maceration of plant matter. These macerals are grouped into **vitrinite**, **exinite** (liptinite), and **inertinite**. In U.S. nomenclature, vitrinite and exinite are equivalent to anthraxylon and translucent attritus; Inertinite is frequently divided into **micrinite** and **fusinite** and are equivalent to opaque attritus and fusain. Of the four lithotypes, vitrain and fusain are each composed primarily of a single maceral or maceral group. Vitrain is essentially all vitrinite and fusain is essentially all inertinite. Clarain contains predominantly vitrinite while durain contains predominantly micrinite. The macerals and maceral groups of lithotypes are given in Table 4.4.1.

The maceral groups serve as a basis of coal petrography. They are not only physically distinct but also have very different chemical characteristics.

The petrographic composition of the coal influences the ease of winning the coal, since the macerals making up the lithotypes have a definite relationship to the power required to mine the coal. McCabe L.C [14] has stated that fusain require the least power for breakage, vitrain require twice, clarain three times and durain 7.5 times as much. A study found that the amount of power required to mine the tough durain coal was as much as 40% greater than that required for the friable clarain coal. The difference in power consumption in a seam depends upon the physical character of the coal, including petrographic composition, cleat, and fracture, and can be influenced by such other factors as type of miner used and type of mining operation.

Mining method adopted in coal mine influences the distribution of macerals. In the various size fractions of coal from the continuous miner operation, the proportions

Table 4.4.1 Macerals and Maceral groups of Lithotypes [13].

<i>Macroscopic lithotypes</i>	<i>Microscopic</i>	
	<i>Maceral groups</i>	<i>Macerals</i>
VITRAIN	Vitrinite	Collinite and telinite
CLARAIN	Vitrinite dominant Exinite and Inertinite less prominent	Collinite and telinite Sporinite, cutinite, alginite, resinites, and waxes Fusinite, micrinite, sclerotinite, and semifusinite
DURAIN	Inertinite dominant Vitrinite and Exinite less prominent	Fusinite, micrinite, sclerotinite, and semifusinite Collinite and telinite Sporinite, cutinite, alginite, resinites, and waxes
FUSAIN	Inertinite	Fusinite

of group macerals are more consistent than in the coal mined in the ordinary manner. The breaking action of the miner no doubt minimized the influence of the natural breakage characteristics of the coal.

Another problem in coal mining is the size consist. The size consist of the run-of-mine coal is influenced by (1) the macropetrographic structure of the seam and the cleat system, (2) the types of mining machines used, and (3) the location of the mine. The most reliable way to evaluate the overall effect of these parameters is the size analysis of a sample representing a working face, normally a fixed number of mine cars.

The effect of petrographic composition on coal breakage is evident in the preparation plant as well as in the mine. Two methods of breaking coal are used in plants – impact and compression. Natural characteristics of coal components are important factors in impact breakage, and screening the coal results in selective concentration of certain macerals, group macerals, and lithotypes.

In a finely stratified coal seam that does not include any thick layers of dull or bright coal the size consist of micro-lithotypes of macerals of lumps, nuts, and fines is practically the same. By contrast, if a seam includes one or more layers of durain thicker than about 3/8 inch, the hard durain, especially in low rank coals, tend to concentrate in the nuts or, if the durain layers are extremely thick, in the lumps. When a seam contains thick layers of bright coal, the soft and mostly brittle vitrain concentrates in the – 3/8 inch coal; a high content of soft fusain, in the form of layers or lenses, will lead to concentration of this friable lithotype in the fines.

#### 4.4.4 Vitrinite reflectance as a measure of rank

The rank of a coal is characteristic of the stage reached by it in the course of transformation process which began with decayed vegetal debris and the final stage of which is represented by graphite. Hoffman & Jenkner (1932) [15] were first to observe the fact that the reflectance of vitrinite increases progressively with increasing rank. Following on their fundamental findings, the quantitative determination of the rank of coal by making reflectance measurements has become more and more an acceptable parameter of coalification, because it is independent of further genetic peculiarities in the coal mass.

#### 4.4.5 Micropetrographic characteristics of gondwana coals

The petrographic properties of Gondwana coals reveal regional and stratigraphic variations amongst the seams of different coalfields and within the same coalfield respectively. Several authors extensively studied the petrographic compositions of Gondwana coals of different parts of the world. Their work firmly established that the flora and climate resulted in major petrographic differences between these coals and those from Carboniferous periods. In the later case vitrinite is predominant maceral while in the Gondwana coals the inertinite content may reach as high as 70%.

The main petrographic differences are caused by the bio-chemical processes during the first stage of coalification. Petrographic composition explains significant differences in coal chemistry and has a direct effect on utilisation. On account of their low vitrinite content, Gondwana coals are comparatively low in hydrogen and high in nitrogen (1.6–2.6% d.a.f). The substantial proportions of fusinite and semifusinite, with their relatively greater porosity, allow higher in-situ moisture retention and result in lower heating values than those of Carboniferous coals of the same maturity. Volatile matter is also affected. According to Kroger (1968) [16], the increase in volatile matter yield corresponds to a rise in the wax-resin component of vitrinite.

The mineral matter in the Gondwana coals occur mainly in two forms e.g. finely divided state dispersed throughout the coal as well as micro-banding, which is very common and is very difficult to be removed by conventional beneficiation methods, and second one as macroscopically visible bands and lenses. The Gondwana coals have been affected by igneous intrusions in the form of dykes and sills and as a result the mineral matter content of the affected coal seam is further increased, especially with respect to carbonate.

Petrography is a very eminent tool, which enables very quick and reliable information regarding (1) Coal genesis, seam correlation and stratigraphic studies (2) Constitution (both organic and inorganic components), Determination of Rank and reactivities (3) Association of maceral-maceral and maceral-mineral matter (i.e. microlithotype study) (4) Coal beneficiation/washability studies for steel & power industries and establishing different blend proportions based on rank and reactive components (5) The char morphology has gained paramount status in deciphering the burnout behaviour of coal in different thermal power plants.