University of Mosul

College of Petroleum & Mining Engineering

Department of Petroleum & Refining Engineering

Principles of Petroleum Engineering

First Year

Lecture 1

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2022 - 2023

Introduction

Petroleum engineering is a field of engineering, which is concerned with activities related to the production of hydrocarbons such as oil or natural gas. It is involved in nearly all stage of oil and gas field evaluation, development and production.

The function of petroleum engineering is to provide a basis for the design and implementation of techniques to recover commercial quantities of natural petroleum. Petroleum engineering involves several disciplines:

a- Petroleum geology:

Petroleum geology focuses on finding hydrocarbons by analysing subsurface structures with geological and geophysical methods.

b- Reservoir engineering:

Reservoir engineering aims to optimize production of oil and gas via proper well placement, production levels, and enhanced oil recovery techniques.

c- Drilling engineering:

Drilling engineering manages the technical aspects of drilling exploratory, production and injection wells.

d- Production engineering:

Production engineering manages the interface between the reservoir and the well, including downhole flow control, downhole monitoring equipment, and select surface equipment that separates the produced fluids (oil, gas, and water).

Definition of petroleum

The term petroleum includes both oil and hydrocarbon gas. Petroleum is a mixture of hydrocarbons molecules and relatively small quantities of organic molecules containing sulphur, oxygen, nitrogen, and some metals (e.g. iron, nickel, copper and vanadium). Petroleum may exist in the solid, liquid or gaseous states, depending upon the conditions of pressure and temperature to which it is subjected.

Liquid hydrocarbons are termed crude oil, to differentiate them from refined petroleum products. The hydrocarbon gases include dry gas (methane) and the wet gases (ethane, propane, etc.). Condensates are hydrocarbons that are gaseous in the subsurface, but condense to liquid when they are cooled at the surface. The plastic hydrocarbons include asphalt and related substances. Solid hydrocarbons include coal and kerogen.

Natural gas is defined as a mixture of hydrocarbons and varying quantities of nonhydrocarbons that exists either in the gaseous phase or in solution with crude oil in natural underground reservoirs.

Natural gas is classified into dissolved, associated, and nonassociated gas. Dissolved gas is in solution in crude oil in the reservoir. Associated gas, commonly known as gas cap gas, overlies and is in contact with crude oil in the reservoir. Nonassociated gas is in reservoirs that do not contain significant quantities of crude oil. Gases are classified as dry or wet according to the amount of liquid vapour that they contain.

Origin of petroleum

Two main theories have been proposed to explain the origin of petroleum:

a- Inorganic theory:

This theory assumes that oil and gas have originated in the earth's interior as a result of chemical reactions between hydrogen and carbon under conditions of high temperature and high pressure in the absence of organic matter.

b- Organic theory:

The organic theory of the origin of petroleum maintains that the hydrogen and carbon source for petroleum was organic material from decaying plants and animals forming and accumulating in oceanic sediments. The remains of animals and plants have converted to liquids and gases hydrocarbon under the effect of high temperature and pressure.

This theory is more acceptable than the inorganic theory for the following reasons:

● The inorganic theory cannot account for the necessary quantities of carbon and hydrogen needed to form large petroleum deposits.

● Many crude oil contain (prophyrins) and nearly all contain nitrogen. The presence of these materials strongly suggests organic origin as they are present in all organic matter.

● Petroleum rotates the plane of polarized light. This property is restricted to organic materials known as optical isomers.

The chemistry of petroleum

Petroleum is a mixture of hydrocarbons and other organic compounds that together dictate its chemical and physical properties. Hydrocarbons are molecules composed of hydrogen (H) and carbon (C) bonded together. Petroleum also contains lesser quantities of organic molecules that contain nitrogen (N), oxygen (O), sulphur (S), and metals (Fe, Ni, Cu, ...), (Table 1).

The proportion of hydrocarbons in the mixture is highly variable and ranges from as much as 97% by weight in the lighter oils to as little as 50 % in the heavier oils and bitumen. The proportion of chemical elements varies over narrow limits as follow:

Element	**Weight (%)**
Carbon	83 – 87
Hydrogen	10 – 14
Sulfur	0.05 – 6
Oxygen	0.05 – 2
Nitrogen	0.1 – 0.2
Metals (Fe, Ni, Cu, V, ...)	< 0.1

Table 1: Elemental composition of crude oils by weight %.

The hydrocarbons present in petroleum are classified into four general groups:

1- Paraffins or alkanes

2- Naphthenes or cycloparaffins

3- Aromatics

4- Olefins

The olefins group is formed during processing by the dehydrogenation of paraffins and naphthenes.

1- Paraffines (Alkanes):

Paraffins, also called ***alkanes***, are saturated hydrocarbons that have the general formula C_nH_{2n+2}, where n are the number of carbon atoms. Paraffins are divided into two groups of normal and isoparaffins. Normal paraffins (*n*-paraffins or *n*-alkanes) are unbranched straight-chain molecules. The simplest paraffin is methane, CH4, followed by the homologous series of ethane, propane, ect. (Fig. 1).

The smallest molecules up to the formula C4H10 (butane) are gases at standard conditions (e.g., at the Earth's surface) of temperature and pressure. Liquid compounds at room temperature range from C5H12 (pentane) to C16H34 (hexadecane). Larger molecules have an increasing number of structural variations.

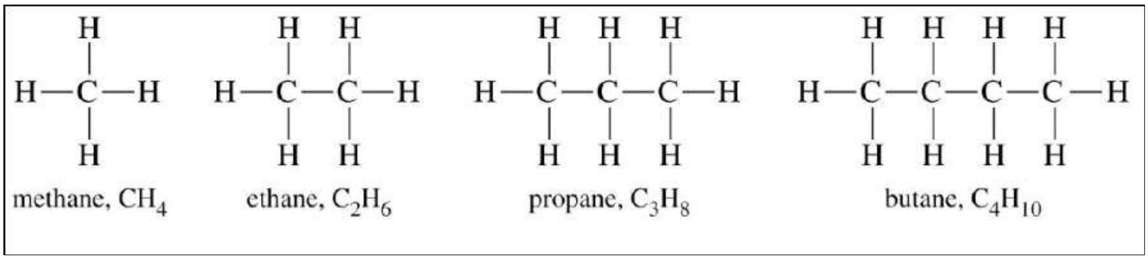

Figure 1: Examples of normal paraffins (straight chains).

The second group of paraffins is called ***isoparaffins (or isoalkanes)***; these are branched-type hydrocarbons that exhibit structural isomerisation. ***Structural isomerisation*** occurs when two molecules have the same atoms but different bonds. In other words, the molecules have the same formulas but different arrangements of atoms, known as ***isomers***. Examples of branched or isoparaffins compounds are shown below (Fig. 2).

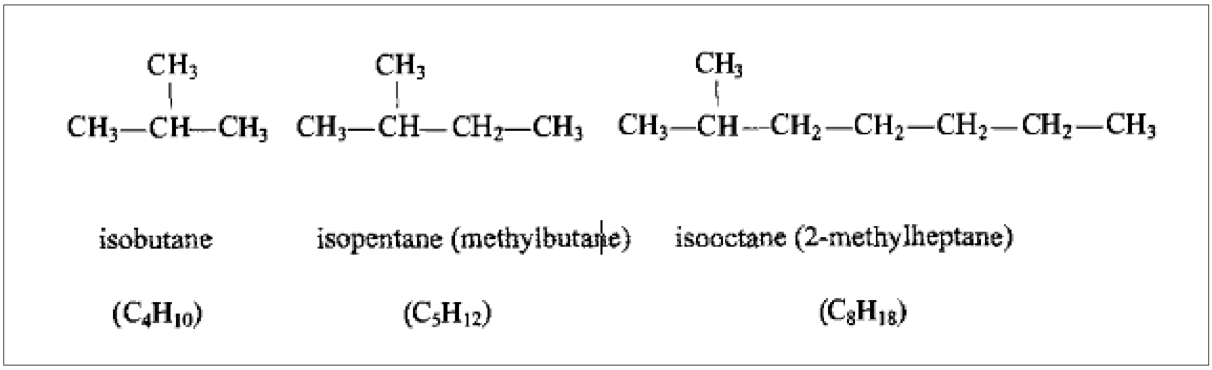

Figure 2: Examples of branched or isoparaffins compounds.

The number of isomers increases geometrically with carbon number. While there are two isomers for butane (C_4H_{10}) and three for pentane (C_5H_{12}), there are 75 isomers for decane ($C_{10}H_{22}$), (**Table 2**).

Name	Number of carbon atoms	Molecular formula	Structural formula	Number of isomers
Methane	1	CH_4	CH_4	1
Ethane	2	C_2H_6	CH_3CH_3	1
Propane	3	C_3H_8	$CH_3CH_2CH_3$	1
Butane	4	C_4H_{10}	$CH_3CH_2CH_2CH_3$	2
Pentane	5	C_5H_{12}	$CH_3(CH_2)_3CH_3$	3
Hexane	6	C_6H_{14}	$CH_3(CH_2)_4CH_3$	5
Heptane	7	C_7H_{16}	$CH_3(CH_2)_5CH_3$	9
Octane	8	C_8H_{18}	$CH_3(CH_2)_6CH_3$	18
Nonane	9	C_9H_{20}	$CH_3(CH_2)_7CH_3$	35
Decane	10	$C_{10}H_{22}$	$CH_3(CH_2)_8CH_3$	75

Table 2: Names and formulas of the first ten parrafins (alkanes).

2- Naphthenes (cycloalkenes):

Nephthenes or cycloalkenes is the second major group of hydrocarbon found in crude oils. This group has a ring structure, where the carbon atoms are linked in a ring, thereby reducing the number of sites for bonding with hydrogen atoms (Fig. 3). The chemical formula for the naphthenes is CnH2n. Large naphthene molecules commonly have more than one ring. Some related compounds have a series of rings with sraight-chain branches (Fig. 3). Unlike the paraffins, all the naphthenes are liquid at normal temperatures and pressure. They make up about 40% of both light and heavy crude oil.

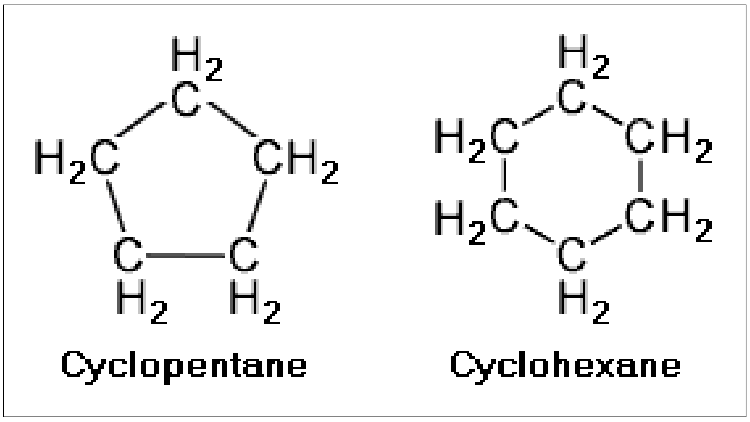

Figure 3: Naphthene, or ring, compounds have the chemical formula CnH2n.

3- Aromatics:

Aromatics are unsaturated hydrocarbon ring compounds, which their molecular structure is based on a ring of six carbon atoms. Benzene (C6H6) is the simplest compound (Fig. 4). The simplest aromatics have a chemical formula CnH2n-6, but there are many complicated compounds that combine the benzene ring with naphthene and straight-chain branches to produce a wide range of compounds. For example, toluene (C6H5CH3), in which one of the hydrogen atoms has been substituted by a methlyl (CH3) branch chain (Fig. 4), is a common constituent in aromatic crude oils.

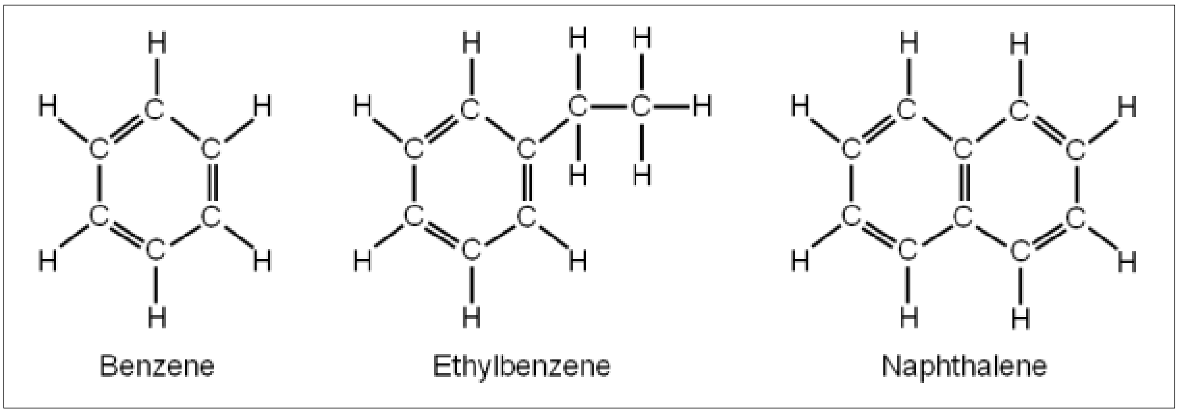

Figure 4: Aromatic compounds with chemical formula C_nH_n. The simplest compound is benzene (C6H6).

The aromatic hydrocarbons are liquid at normal temperatures and pressures. They are present in relatively minor amounts (about 10%) in light oils, but increase in quantity to more than 30% in heavy oils.

4- Olefins:

Olefins, also known as alkenes, are unsaturated hydrocarbons containing carbon-carbon double bonds. Compounds containing carbon-carbon triple bonds are known as acetylenes, and are also known as biolefins or alkynes. The general formula of olefins and acetylenes are C_nH_{2n} and C_nH_{2n-2}, respectively.

Olefins are not naturally present in crude oils but they are formed during the conversion processes. The lightest alkenes are ethylene (C_2H_4) and propylene (C_3H_6), which are important feedstocks for the petrochemical industry.

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Lecture 2

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Petroleum system

Petroleum system:

A petroleum system encompasses of a pod of active source rock and all related oil and gas, and includes all the essential elements and processes needed for oil and gas accumulations to exist. The elements are source rocks, reservoir rocks, seal rocks and overburden, whereas the processes are generation, migration and accumulation (Fig. 1).

Elements of petroleum system:

1- Source rocks

2- Reservoir rocks

3- Seal rocks

4- Overburden rocks

Processes of petroleum system:

1- Generation of petroleum

2- Migration of petroleum

3- Accumulation and Preservation

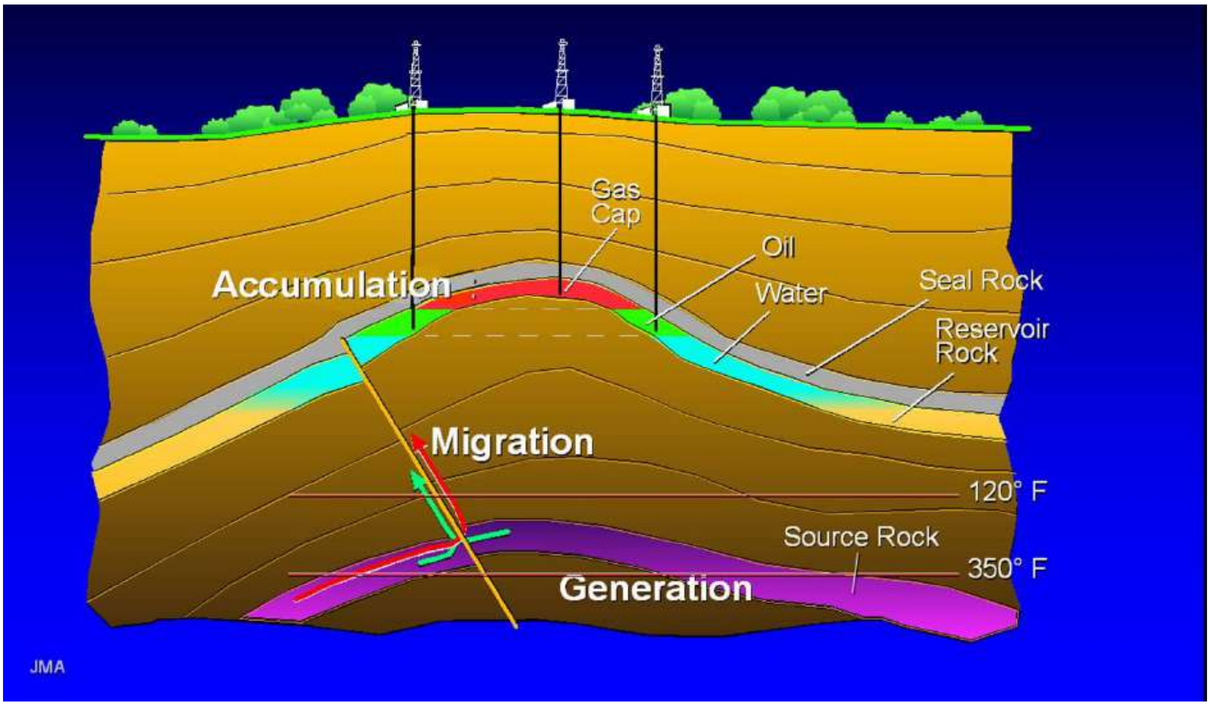

Figure 1: The elements and processes of the petroleum system.

Elements of petroleum system

1- Source rocks of hydrocarbons:

Source rocks are sedimentary rocks usually shale or limestone, in which organic matter was transformed to liquid or gaseous hydrocarbons under the influence of pressure, heat and time.

2- Reservoir rocks:

Reservoir rocks are rocks, usually sandstone or limestone, with high porosity and permeability, and have the ability to store commercial quantities of hydrocarbon. To form a commercial reservoir of hydrocarbons, any geological formation must exhibit two essential characteristics: (a) a capacity for storage (porosity), and (b) transmissibility to the fluid concerned (permeability).

3- Seal or cap rocks:

Seal rock is a less porous and permeable rock that prevents the petroleum from migrating further. Rocks like shale and salt provide excellent seals for reservoir rocks because they do not allow fluids to pass through them easily.

4- Overburden rocks:

Overburden rock, an essential element of the petroleum system, is that series of mostly sedimentary rock that overlies the source rock, seal rock, and reservoir rock. Generation of hydrocarbons from thermal degradation of organic matter in the source rock is determined by thickness of the overburden rock in conjunction with the physical properties and processes that determine temperature in sedimentary basins.

Processes of petroleum system

1- The generation of hydrocarbons:

The most important factor in the generation of hydrocarbons (crude oil and natural gas) from organic matter in sedimentary rocks is temperature. A minimum temperature of about 150^{o}F is necessary for oil generation under typical sedimentary basin conditions (Fig. 2). This temperature is obtained by burying the organic-rich source rocks.

At relatively shallow depths, the temperature is not sufficient to generate oil. Therefore, just a few feet below the surface, bacterial action on the organic matter forms large volumes of biogenic or microbial gas. It is generated very fast and is almost pure methane gas.

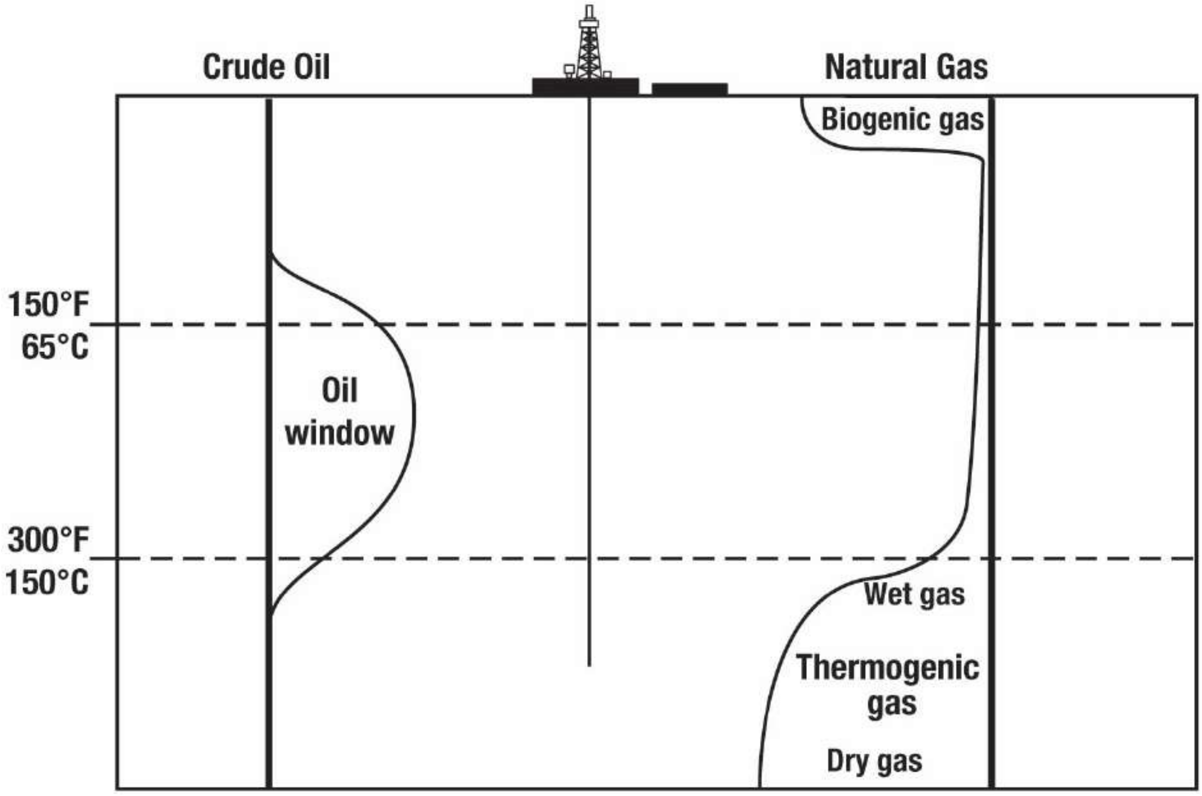

Figure 2: Generation of crude oil and natural gas.

In a typical sedimentary basin, oil generation starts at about 150^{o}F and ends at 300^{o}F. If the source rock is buried deeper, where temperatures are above 300^{o}F, ***thermogenic gas*** is generated. The zone in the earth's crust where the oil is generated is called the ***oil window***. It occurs from about 2 to 5km. Crude oil generated in the oil window is originally good oil with ^{o}API gravity between 30 to 40. The heavy oil is formed later when bacteria, along with chemical and physical processes, degrade the good oil to form heavy oil. Below the oil window, thermogenic gas is generated from thermal cracking of crude oil and organic matter left in the source rocks.

2- The migration of hydrocarbons:

After gas and oil are generated in shale source rocks, some is expelled from the impermeable shale. The generation of a liquid (crude oil) or gas (natural gas) from a solid (organic matter) causes a large increase in volume. This stresses the source rocks and fractures the shale. The hydrocarbons escape through the fracture.

Because gas and oil are light in density compared to the water that also occurs in the pores of the subsurface rocks, petroleum rises (Fig. 3). Oil and gas can flow upward along faults and fractures. It can also flow laterally and upward along unconformities and through carrier beds. ***Carrier beds*** are rock layers that are very permeable and transmit fluids. The vertical and lateral flow of the petroleum from the source rocks is called ***migration.*** If there is no trap on the migration route, the gas and oil will flow out onto the surface as a gas or oil seep (Fig. 3). If there is a trap along the migration route, the gas and oil can accumulate in the trap.

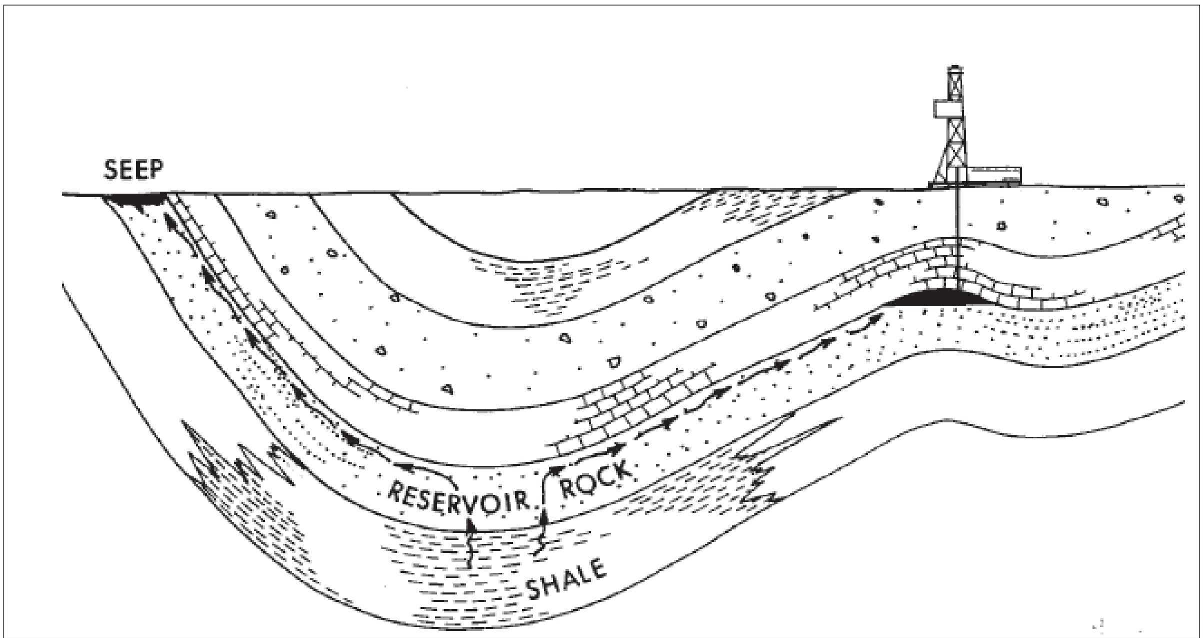

Figure 3: Migration of gas and oil in a sedimentary rock basin.

3- Accumulation of hydrocarbons:

The trap must be in position before the gas and oil migrate through the area. If the trap forms after the migration, no gas or oil will occur in the trap. Once the gas and oil migrate into the trap, they separate according to density. The gas, being lightest, goes to the top of the trap to form the free gas cap, where the pores of the reservoir rock are occupied by gas. The oil goes to the middle of the trap, the *oil reservoir*. Saltwater, the heaviest, goes to the bottom.

The boundary in the reservoir between the free gas cap and the oil is the ***gas-oil contact*** (Fig. 4). The boundary between the oil and the water reservoir is the ***oil-water contact***. The gas-oil and oil-water contacts are either relatively sharp or gradational and are usually level.

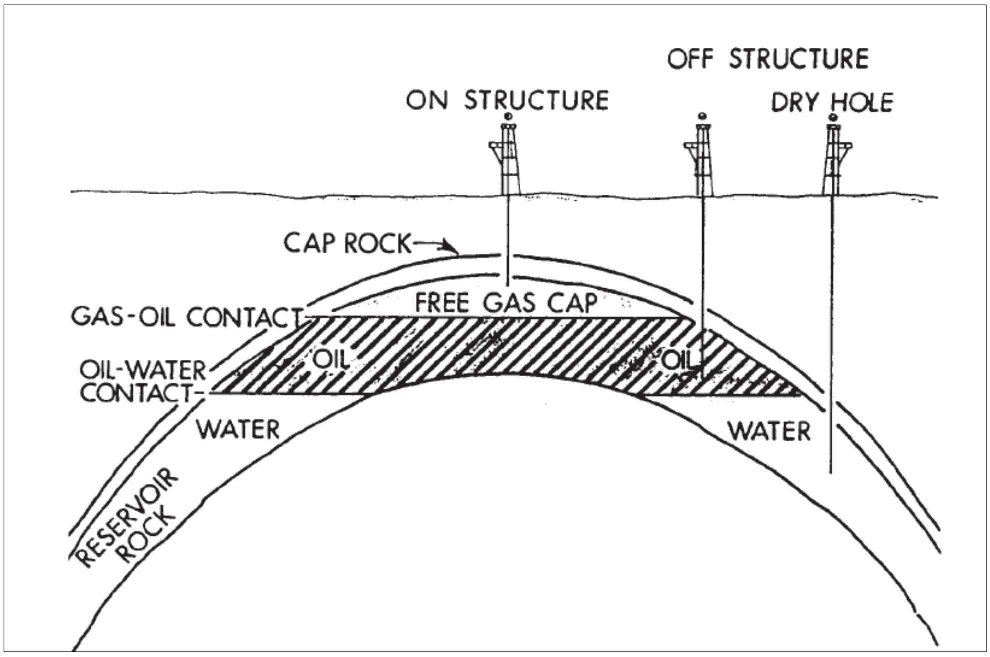

Figure 4: A reservoir with a free gas cap shows the gas-oil contact and oil-water contact.

In a trap, the reservoir rock must be overlain by a cap rock or seal (Fig. 4), an impermeable rock layer that does not allow fluids to flow through it. Two common cap rocks are shales and salt layers.

Lecture 3

Properties of reservoir rocks

Petroleum reservoir:

The petroleum reservoir consists of porous and permeable rocks, usually sedimentary rocks, of which the pores and fissures are filled with water and oil, water and gas, or rarely water, oil and gas, (Fig. 1).

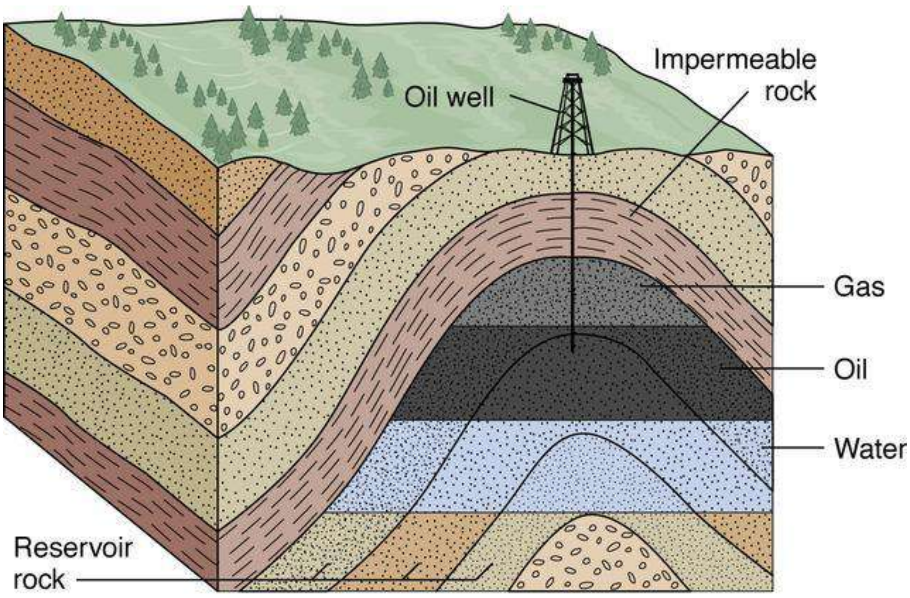

Figure 1: Petroleum reservoir consists of porous and permeable rocks and filled with water, oil and gas.

Discovering a petroleum reservoir does not necessarily mean that petroleum can be produced (recovered) economically from it. This depends on two key factors:

1- The quantity of petroleum within the reservoir.

2- The rate at which it can be produced.

If the two parameters justify the cost of production then the reservoir is considered a petroleum reservoir or trap. The quantity of recoverable petroleum in a reservoir or trap and the rate it can be produced depend primarily on the properties of the reservoir rock and the fluids it contains.

Properties of reservoir rocks:

The physical properties of reservoir rocks are essential for reservoir engineering calculations as they directly affect both the quantity and the distribution of hydrocarbons. Also, when these properties combined with fluid properties, control the flow of the existing phases (gas, oil, and water) within the reservoir.

The properties of the reservoir rocks can be estimated from well logs or core samples. The most important rock properties are porosity, permeability and saturation.

1- Porosity:

The porosity is defined as a measure of the storage capacity (pore volume) that is capable of holding fluids. Quantitatively, the porosity is the ratio of the pore volume to the total volume (bulk volume). This property is determined mathematically by the following relationship:

$$\text{Porosity} = \frac{\text{Pore volume}}{\text{bulk volume}}$$

$$\phi = \frac{V_p}{V_b}$$

$$\phi = \frac{V_b - V_g}{V_b}$$

Where ϕ : porosity

V_p : pore volume

V_b : bulk (total) volume

Vg : grain volume

The porosity can be expressed either as a fraction or as a percentage. The porosity of the commercial reservoirs may range from about 5% to about 30% of bulk volume.

The sedimentary rock consists of grains and pore spaces (void spaces). Some of the pore spaces are isolated from the other pore spaces by cementation, whereas in many states, the pore spaces are interconnected (Figure 2). This leads to two distinct types of porosity:

a- Absolute porosity

b- Effective porosity

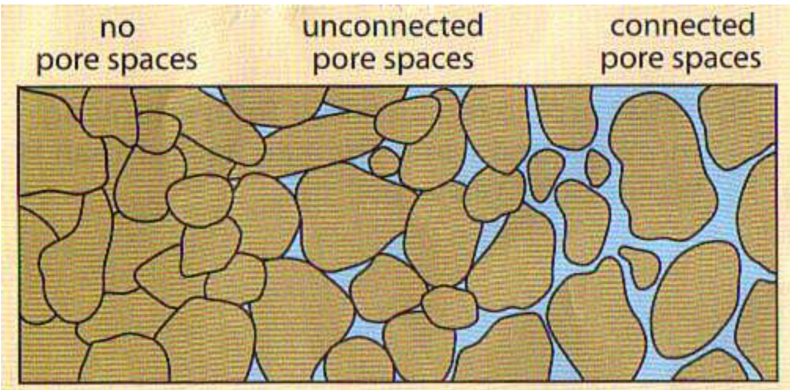

Figure 2: Types of pore space in a rock, connected and unconnected (isolated).

Absolute (total) porosity:

The absolute porosity is defined as the ratio of the volume of all pores in the rock to the total volume (bulk volume) of the rock. The absolute porosity is expressed mathematically by the following relationship:

$$\text{Absolute porosity} = \frac{\text{total pore volume}}{\text{bulk volume}}$$

or

$$\text{Absolute porosity} = \frac{\text{Bulk volume} - \text{grain volume}}{\text{bulk volume}}$$

Effective porosity:

The effective porosity is defined as the ratio of the interconnected pore volume to the total or bulk volume. The value of the effective porosity is used in all reservoir engineering calculations because it represents the interconnected pore space that contains the recoverable hydrocarbon fluids. One important application of the effective porosity is its use in determining the original hydrocarbon volume in place.

$$\text{Effective porosity} = \frac{\text{interconnected pore volume}}{\text{bulk volume}}$$

Porosity can be classified according to the mode of origin into primary and secondary.

Primary porosity:

The primary porosity is that developed in the deposition of the rock. The clastic sedimentary rocks are the typically rocks that exhibit primary porosity. Typical clastic rocks which are common reservoir rocks are sandstone rocks.

Secondary porosity:

The secondary porosity is that developed after the deposition of the rock by some geological processes. The secondary porosity is classified into three classes based on the mechanisms of formation:

1- Solution porosity: This porosity formed by the solution of the more soluble portions of the rock.

2- Fractures and joints porosity: This type is common in many sedimentary rocks, and it is created by structural failure of the reservoir rocks under tension caused by tectonic activities such as folding and faulting.

3- Dolomitization porosity: This type of porosity is formed when limestone (CaCo3) is transformed into dolomite CaMg(Co3)2 according to the following chemical reaction:

$$\underset{\text{Limeston}}{2CaCo3 + Mg^{2+}} \longrightarrow \underset{\text{Dolomite}}{CaMg(Co3)2 + Ca^{2+}}$$

The volume of dolomite is less than that of calcite, so the replacement of calcite by dolomite in a rock increases the pore space in the rock by 13% and forms an important reservoir rock.