This book provides readers with introductory information on oil and natural gas industry and engineering. It was written primarily for students at the university level, whose contribution will be crucial to the energy industry for continuing ability to supply the world. This book also is an essential reference for non-engineering petroleum industry technical and non-technical professionals. It addresses several petroleum and natural gas engineering issues including principals of oil and gas generation, exploration techniques, reserves estimation, field development, production optimization, reservoir management, the aspects of well drilling and completing, oil refining, oil and gas transportation, oil spill, and basic oil and gas economics. Additionally, the essential units and conversion factors were discussed in a simplified manner.

**Musaed N. J. Al-Awad**
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Musaed N. J. Al-Awad

Petroleum and Natural Gas Engg. Overview

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# Petroleum and Natural Gas Engineering Overview

## For Non-Specialists

VDM Verlag Dr. Müller

*This book is dedicated to my parents, wife and kids for their patience, understanding and encouragement which made the completion of this book possible.*

Musaed N. J. Al-Awad

# PREFACE

We can not see alternative fuels playing a substantial role in the short or medium terms, oil and natural gas will continue playing an essential part in the world's energy needs.

Oil and natural gas touch our lives in numerous ways every day. Together, they supply more than 65% of the world's energy. They fuel cars, heat homes, cook food, and generate the electricity that powers our daily lives.

Petroleum and natural gas engineering is the application of the basic sciences to the development, recovery and processing of oil and gas fields.

As its name suggests, this book provides readers with introductory information on oil and natural gas industry and engineering. It was written primarily to students at the university level, whose contribution will be crucial to the energy industry for continuing ability to supply the world.

This book also is an essential reference for non-engineering petroleum industry technical and non-technical professionals. It addresses several petroleum and natural gas engineering issues including principals of oil and gas generation, exploration techniques, reserves estimation, field development, production optimization, reservoir management, the aspects of well drilling and completing, oil refining, oil and gas transportation, oil spill, and basic oil and gas economics. Additionally, the essential units and conversion factors were discussed in a simplified manner.

It must be said that, this book has distilled many years of experience and knowledge from numerous sources worldwide as well as the long experience of the author.

Special thanks for the Research Center at College of Engineering in King Saud University, Riyadh, Saudi Arabia for the provided financial support required to initiate this work.

Thanks are extended to my professors, colleagues, and students for their valuable suggestions, comments and encouragement.

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# CHAPTER ONE
# Background and Objectives

## 1.1 Introduction

Since the discovery of the rotary drilling technique by Colonel Edwin Drake in 1859, petroleum and natural gas engineers and other industry professionals have made numerous innovations that enable the industry to find and produce the resources (oil and natural gas) that power the world economy up to date. The importance of oil and natural gas as main energy sources comes from the fact that there are no other competitive and widely available energy sources (see **Tables 1.1** and **1.2**). Petroleum is a thick natural mixture of gaseous, liquid, and solid hydrocarbons obtained from beneath the surface of the earth. Hydrogen (H) and Carbon (C) atoms form the basic of petroleum. Petroleum is the main source of energy in the world due to the following reasons:

i) Relatively cheap compared to other energy sources.
ii) Easy to use and utilize.
iii) Relatively save to human and environment.
iv) Available in large quantities and have many derivatives.
v) Produced energy by oil and natural gas is high.

Petroleum and its derivatives are used in numerous applications in various aspects of the modern life such as:

i) Fuel for internal combustion engines (automobiles and other transportation means).
ii) Feed stock for petrochemical industries.
iii) Source of energy for power plants, desalination plants, industrial factories, etc.
iv) Raw material for chemical and pharmaceutical products.
v) Manufacturing paints and coatings.
vi) Manufacturing lubricants, cleaners and solvents.

Therefore, extensive research and development efforts are required in the fields of exploration, drilling, production and treatment of crude oil and natural gas to meet the world's growing demand. Professional petroleum and natural gas engineers having the necessary engineering skills and motivation are the unique approach to accomplish these activities.

**Table 1.1 Energy sources available nowadays, 2010.**

<table>
<tr><th>Energy source</th><th colspan="4">Percentage usage</th></tr>
<tr><td>Crude oil</td><td>38%</td><td rowspan="2">61%</td><td rowspan="3">87%</td><td rowspan="6">100%</td></tr>
<tr><td>Natural gas</td><td>23%</td></tr>
<tr><td>Coal</td><td colspan="2">26%</td></tr>
<tr><td>Nuclear</td><td colspan="2">6.0%</td><td rowspan="3">13%</td></tr>
<tr><td>Hydro</td><td colspan="2">6.0%</td></tr>
<tr><td>Others</td><td colspan="2">1.0%</td></tr>
</table>

**Table 1.2 Oil types and reserves available nowadays, 2010.**

| Type of oil | Reserve, % |
|---|---|
| Unconventional oil, (Tar sand, Bitumen, and Oil shale) | 30 |
| Conventional oil (Oil produced through an oil well) | 30 |
| Heavy oil | 15 |
| Extra heavy oil | 25 |
| Total | 100 |

Petroleum and natural gas engineers are mostly responsible in the "upstream sector" of the oil and natural gas industry including drilling and completion, reservoir management, production, gathering, local transportation and primary treatment. "Downstream" activities are mostly beyond the responsibilities of petroleum and natural gas engineers. In other words, all the extensive activities preceding shipment of stabilized crude oil or sales gas are collectively known as upstream.

This book is designed to provide the students (the readers) with the fundamentals of the oil and natural gas engineering activities (upstream) in a simple and concentrated way. Petroleum engineering discipline involves petroleum geology, reservoir rock petrophysics and formation evaluation, reservoir engineering, drilling engineering, production engineering and petroleum and natural gas economics.

## 1.2 Objectives

Typical B. Sc. program curriculum in petroleum and natural gas engineering departments worldwide covers in addition to courses required by the university and the college, various specialized courses in the fields of petroleum and natural gas reservoirs including petroleum geology, oil and natural gas exploration engineering, oil and natural gas wells drilling engineering, production engineering, transportation and storage of oil and natural gas, reservoirs engineering, advanced computer applications in oil and natural gas engineering and petroleum and natural gas economics and legislations.

According to academic regulations, a textbook must be assigned for every course in the curriculum in addition to other preferred references in the same subject. The first specialized course presented for newly enrolled students of petroleum and natural gas engineering is the course titled "Introduction to Petroleum and Natural Gas Engineering". This course provides the student with an extensive knowledge covering all areas of petroleum and natural gas engineering necessary for understanding upstream activities. At the end of this course the student will have a complete image about this important engineering field.

Extensive search have shown that there is no single book covers all requirements of the introductory course mentioned above, instead, the instructors collect, simplify, and compile the required topics from too many references. Therefore, it is clear that there is a need for a book on petroleum and natural gas engineering that can be used as a textbook in introductory courses in petroleum and natural gas engineering departments. Additionally, this book is a suitable and comprehensive reference for non-specialized engineers as well.

# CHAPTER TWO
# History of Oil and Natural Gas

## 2.1 Introduction

Discovery and utilization of oil and natural gas goes back hundreds of years when oil pits near Babylon and Kirkuk in Iraq were known since 450 BC and used for flaming torches, medicine water proofing, and employed in construction of the walls and towers. In 1857 the first oil well was drilled in Bend, northeast of Bucharest, on the Romanian side of the Carpathians. In 1858, the first oil well in North America was drilled in Ontario, Canada. In 1859, Colonel Edwin Drake produced oil from 69 ft below the surface of the ground in Titusville, Pennsylvania. In 1878, the first oil well was drilled at Lake Maracaibo in Venezuela. In 1885, oil was discovered in Sumatra in Indonesia. In 1908, oil was discovered in Iran. In 1910, oil was discovered in Mexico. In 1932, oil was discovered in Bahrain. In 1938, oil was discovered in Kuwait and Saudi Arabia. In 1956, oil was discovered in Algeria and Nigeria. In 1969, oil was discovered in North Sea. Later, oil and natural gas were discovered in several parts in the Middle East.

## 2.2 The Arabian Tectonic Plate

The Earth's surface is covered by a series of continually moving crustal tectonic plates. These crustal plates are moving in different directions. Several countries in the Middle East are located in the Arabian tectonic plate (**Figure 2.1**) including Saudi Arabia, Kuwait, United Arab Emirates, Qatar, Oman, Bahrain, Yemen, Iraq, Palestine, Lebanon, Jordan, Syria, South Turkey and West Iran. The importance of this tectonic plate comes from several facts including:

i) It accumulates more than 70% and 38% of the world oil and natural gas reserves respectively.
ii) The world’s largest onshore and offshore reservoirs are located in this area (**Table 2.1**).
iii) The world’s largest gas field is located in this area.
iv) Mass oil and natural gas production come from this area.
v) Medium well depth.
vi) Excellent reservoirs rock porosity and permeability.
vii) Availability of all types of oil and natural gas.
viii) Most oil and natural gas reservoirs in this area are still in the primary recovery stage.
ix) All operations are done at minimum operating cost and maximum well productivity.
x) Excellent geographical location.
xi) Low domestic consumption (see **Table 2.2**)
xii) The area is geologically stable (no volcanoes, earthquakes, etc.).

All of the above facts have made this area a leader in providing the world with continuous, safe and relatively inexpensive oil and natural gas. Looking into other petroleum and natural gas producers around the world, it is clear that the last depleted petroleum and/or natural gas reservoirs will be from this area.

**Table 2.1 Production from World's giant oil fields.**

<table>
<tr><th>Average Productivity, bbl/day</th><th colspan="2">No. of Oil Fields</th><th colspan="2">Percentage of World Total Production</th><th>Fields Size</th></tr>
<tr><td>9,000</td><td colspan="2">4000+</td><td colspan="2">53%</td><td>Small</td></tr>
<tr><td>130,000</td><td>61</td><td rowspan="3">116</td><td>12%</td><td rowspan="3">47%</td><td rowspan="3">Giant</td></tr>
<tr><td>560,000</td><td>41</td><td>15%</td></tr>
<tr><td>993,000</td><td>14</td><td>20%</td></tr>
</table>

**Table 2.2 Total World's oil reserves and consumption, 2010.**

<table>
<tr><th>Country</th><th>Reserve percentage</th><th>Consumption percentage</th></tr>
<tr><td>Commonwealth of Independent States (CIS), and Eastern Europe</td><td>5.9</td><td>16.7</td></tr>
<tr><td>Asia and Australia</td><td>4.5</td><td>19.8</td></tr>
<tr><td>Western Europe</td><td>1.8</td><td>29.0</td></tr>
<tr><td>North America</td><td>4.2</td><td>29.0</td></tr>
<tr><td>Middle East</td><td>62.4</td><td rowspan="3">5.5</td></tr>
<tr><td>Latin America</td><td>12.5</td></tr>
<tr><td>Others</td><td>8.7</td></tr>
<tr><td>Total</td><td>100.0</td><td>100.0</td></tr>
</table>

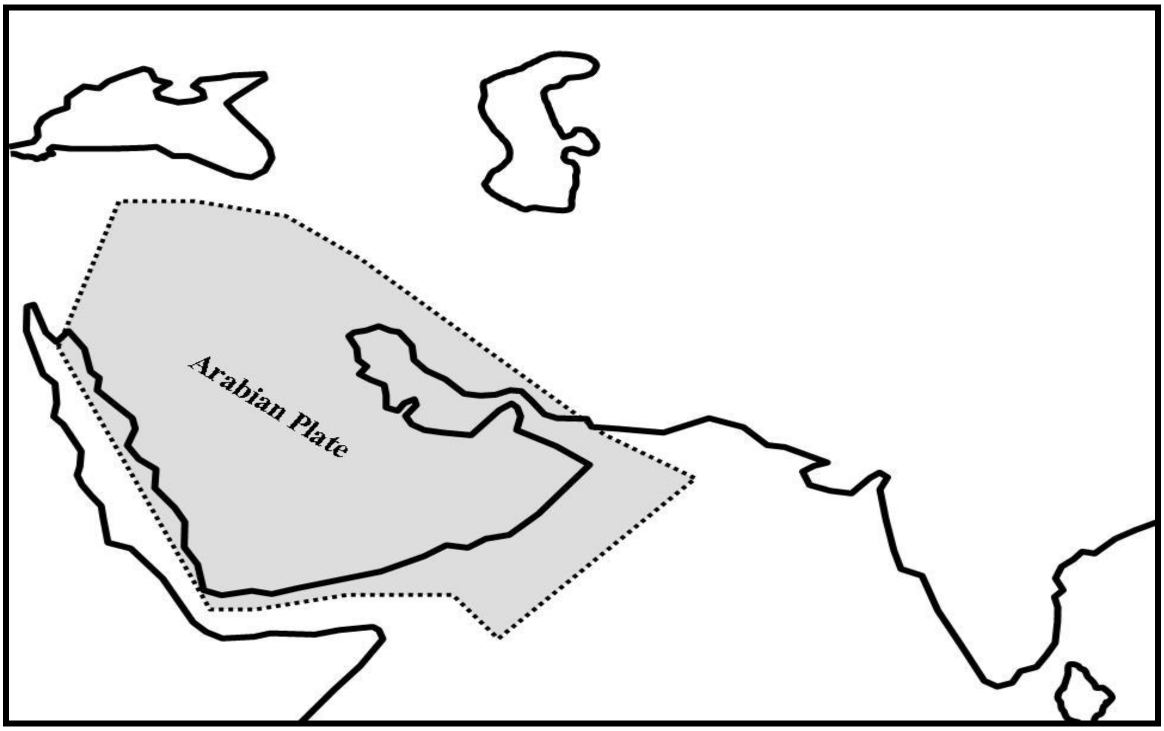



**Figure 2.1 Location of the Arabian tectonic plate.**

Therefore, petroleum and natural gas industry in this area will continue expanding, developing and recruiting too many professionals to satisfy the world’s growing demand of petroleum and natural gas. Satisfying the world’s demand must not come over the stability and safety of those reserves, i.e. oil and natural gas must be produced safely at optimum production rates to avoid any disturbance to oil-water or gas-water contacts in these reservoirs. Furthermore, the planned oil and natural gas production over long period of time and the continuous increase in oil and natural gas prices are advantages for the benefits of future generations in this area. Oil and natural gas discoveries in the Middle East area go back to the beginning of the nineteenth century as shown in **Table 2.3**. Furthermore, around 70% of the worlds oil reserves and 38% of the world natural gas reserves are located in this area. **Tables 2.4** and **2.5**, show the reserves and production capabilities of the Middle East countries compared to the other major world producers.

**Table 2.3 History of oil and natural gas discovery in the Middle East, 2010.**

| Country | Oil discovery | | Country total proved reserves, Billion bbl (% of World) | Free natural gas discovery | | Country total proved reserves, Trillion ft$^3$ (% of World) |
|---|---|---|---|---|---|---|
| | Year | Location (field) | | Year | Location (field) | |
| Iran | 1908 | Masjidi-Sulaiman | 137 (13%) | 1988 | South Pars | 948 (10.1%) |
| Iraq | 1923 | Naft Khaneh | 115 (10.9%) | 2001 | Akkas | 1100 (11.8%) |
| Bahrain | 1932 | Awali | 0.125 (0.012) | 1932 | Awali | 3.2 (0.034%) |
| KSA | 1938 | Dammam | 267.7 (25%) | 1967 | Kidan | 253.2 (2.9%) |
| Kuwait | 1938 | Burqan | 101.5 (8.5%) | 2000 | Raudhatain | 101.5 (1.1%) |
| Qatar | 1939 | Dukhan | 15.2 (1.27%) | 1971 | North Dome | 910 (9.80%) |
| UAE | 1950 | Ra's Sadr | 97.8 (8.14%) | 1999 | Abu Rabah | 212.1 (2.3%) |
| Syria | 1956 | Karachuk | 3.0 (0.255%) | 1999 | NA | 8.5 (0.1%) |
| Oman | 1960 | Natih | 5.6 (0.47%) | 1998 | Habeebad-2 | 35.1 (0.37%) |
| Yemen | 1984 | Mareb/Jawf | 2.9 (0.24%) | 1984 | Mareb/Jawf | 16.9 (0.17%) |

**Table 2.4 Crude oil reserves and production in the World, 2010.**

| Country | | Reserve, $10^9$ bbl | Production, $10^6$ bbl/day | Country | | Reserve, $10^9$ bbl | Production, $10^6$ bbl/day |
|---|---|---|---|---|---|---|---|
| 1 | Saudi Arabia | 266.7 | 10.25 | 2 | Canada (total)<br>Unconventional<br>Conventional | 178.8<br>174.1<br>4.7 | 3.40 |
| 3 | Iran | 136.0 | 4.00 | 4 | Iraq | 115.0 | 2.00 |
| 5 | Kuwait | 104.0 | 2.61 | 6 | UAE | 97.8 | 2.95 |
| 7 | Venezuela | 99.4 | 2.70 | 8 | Russia | 79.0 | 9.90 |
| 9 | Kazakstan | 30.0 | 1.45 | 10 | Libya | 43.7 | 1.60 |
| 11 | Nigeria | 36.2 | 2.40 | 12 | United States | 21.4 | 8.50 |
| 13 | Rest of the World: Reserve = (181.8 x$10^9$ bbl), Production = (40.7 x $10^6$ bbl/day) | | | | | | |

**Tables 2.6** and **2.7** as well as **Figure 2.2** document the world's largest oil and natural gas fields respectively. On conclusion, the Middle East oil and natural gas reservoirs will be

the future's unique reliable supplier as most of other producers are shortly and will not satisfy their local needs as shown in **Table 2.8**.

**Table 2.5 Natural gas reserves and production in the World, 2010.**

| | Country | Reserve, $10^{12}$ $ft^3$ | Production, $10^9$ $ft^3$/day | | Country | Reserve, $10^{12}$ $ft^3$ | Production, $10^9$ $ft^3$/day |
|---|---|---|---|---|---|---|---|
| 1 | Russia | 1680.0 | 21.80 | 2 | Iran | 912.8 | 3.10 |
| 3 | Qatar | 905.0 | 15.36 | 4 | USA | 211.0 | 18.70 |
| 5 | Saudi Arabia | 253.1 | 2.45 | 6 | UAE | 215.4 | 1.65 |
| 7 | Nigeria | 184.0 | 0.77 | 8 | Algeria | 158.9 | 3.10 |
| 9 | Venezuela | 166.3 | 1.02 | 10 | Iraq | 112.0 | 0.40 |
| 11 | Kazakstan | 100.0 | 0.83 | 12 | Turkmenistan | 100.0 | 2.10 |
| 13 | Indonesia | 93.9 | 2.68 | 14 | Malaysia | 82.9 | 2.12 |
| 15 | Norway | 79.0 | 3.00 | 16 | Rest of the World | 6379.0 | 1.23 |

## 2.3 History of Oil and Natural Gas in Saudi Arabia

Exploration for oil and natural gas goes back to 1910 when the first concession was started by an Othmani Empire led by a person called "Assem" exploring the area of Farasan Islands in the Red Sea in the southern province of Saudi Arabia where some hydrocarbons seepage exist. Unfortunately this concession was ended with no discoveries. A second exploration concession was started in 1923 by "Holms" from the British investment group, the Eastern and General Syndicate searching for oil in the eastern province of Saudi Arabia (Al-Hassa). This concession was terminated at 1928 with no discoveries.

Stimulated by the discovery of oil in Bahrain in 1932, a new exploration concession was commenced in 1933 by the Standard Oil of California "SOCAL" searching for oil and natural gas in Dammam in the eastern province opposite to Bahrain Islands. After drilling several discovery wells no signs for oil or gas were found. The company decided to drill deeper in well no. 7 in Dammam dome where oil was discovered in commercial quantities at 4717 ft below sea level in 1938 (see **Table 2.9**). As the exploration and drilling continue, oil and gas reservoirs have been explored in several areas onshore and offshore (see **Table 2.10**) in several horizons of the Saudi stratigraphic column (**Figure 2.3**). These giant oil fields made Saudi Arabia as the world's most important oil producer. Given its relatively high production levels; accounting for nearly 13% of world output and 35% of total OPEC output; and more significantly, its small domestic needs; made the kingdom's dominance of international crude oil markets unchallenged.

## 2.4 Oil and Natural Gas Reserves

Energy sources are either renewable such as solar energy, water-falls (hydro-energy), winds, etc. or non-renewable such as nuclear energy, oil, natural gas, and coal. Oil reserves are classified into "conventional" and "unconventional". Conventional oil is generally defined as oil that is produced from an oil well by primary, secondary or tertiary recovery methods. Conventional oil accounts for about 95% of total oil production in the world. Unconventional oil comes from one of the following sources:

i) Extra Heavy Oil: This type of oil is refined just like conventional petroleum except that it is thicker and has more sulfur and heavy metal contamination, necessitating more extensive refining. Venezuela's Orinoco heavy oil belt is the best-known example of this kind of unconventional reserve.

ii) Tar Sand: Tar sands are oil traps that are not deep enough below the surface to allow the generation of conventional oil. Oil can be recovered from tar sand by in-situ collection or surface mining techniques. Again, this is more expensive than producing conventional oil. Canada's Athabasca tar sand is the best-known example of this kind of unconventional oil reserve.

iii) Oil Shale: Oil shales contain only kerogene and not oil. Kerogene is an intermediate product on the way from biological hydrocarbon cracking to oil formation. The oil shale layer was not hot enough to complete the oil generation. Oil production from oil shale requires extensive recovery processing and consumes large amounts of water.

iv) Synthetic Oil: This type of oil is produced from coal or any other feedstocks.

Oil and natural gas reserves are distributed among various geological eras as shown in **Table 2.11**. Most oil reservoirs are located in the Cenozoic and Mesozoic eras, while natural gas reservoirs are located in the Paleozoic eras such as Khuff formation in Saudi Arabia.

**Table 2.6 Largest oil fields in the World, 2010.**

| Field, Country | | Reserve, $10^9$ bbl | Field, Country | | Reserve, $10^9$ bbl |
|---|---|---|---|---|---|
| 1 | Ghawar, Saudi Arabia | 79 | 2 | Burgan, Kuwait | 69 |
| 3 | Cantarell, Mexico | 35 | 4 | Bolivar Coastal, Venezuela | 31 |
| 5 | Safaniya-Khafji, Saudi Arabia | 30 | 6 | Rumailia, Iraq | 20 |
| 7 | Tengiz, Kazakhstan | 20 | 8 | Ahwaz, Iran | 17 |
| 9 | Kirkuk, Iraq | 16 | 10 | Marun, Iran | 16 |
| 11 | Daqing, China | 16 | 12 | Gachsaran, Iran | 15 |
| 13 | Aghajari, Iran | 14 | 14 | Samotlor, Russia | 15 |
| 15 | Prudhoe Bay, Alaska, USA | 13 | 16 | Kashagan, Kazakhstan | 13 |
| 17 | Abqaiq, Saudi Arabia | 12 | 18 | Romashkino, Russia | 12 |
| 19 | Chicontepec, Mexico | 12 | 20 | Berri, Saudi Arabia | 12 |
| 21 | Zakum, Abu Dhabi, UAE | 12 | 22 | Manifa, Saudi Arabia | 11 |
| 23 | Marjan, Saudi Arabia/Iran | 10 | 24 | Marlim, Campos, Brazil | 10 |

## 2.5 Crude Oil Types

Crude oils vary widely in appearance and viscosity from field to field. They range in color, odor, and in the properties they contain. While all crude oils are essentially hydrocarbons, the difference in properties, especially the variations in molecular structure, mean that crude is more or less easy to produce, pipeline, and refine. The variations may even influence its suitability for certain products and the quality of those products. The petroleum industry generally classifies crude oil by the geographic location it is produced in (e.g. West Texas, Brent, or Oman), its API gravity (an oil industry measure of density), and by its sulfur content.

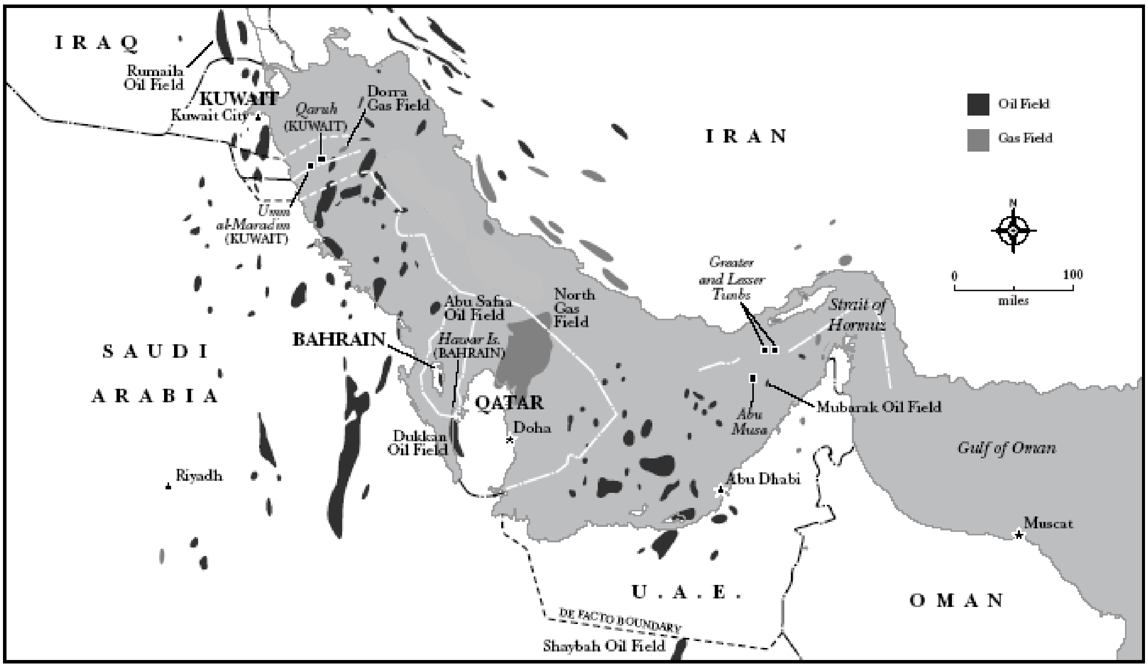



**Figure 2.2 Locations of oil and gas fields in the Arabian Gulf.**

**Table 2.7 Largest natural gas fields in the World, 2010.**

| | Field, Country | Reserve, $10^{12}$ $ft^3$ | | Field, Country | Reserve, $10^{12}$ $ft^3$ |
|---|---|---|---|---|---|
| 1 | North Dome, Qatar | 1200 | 2 | Urengoy, Russia | 275 |
| 3 | Yamburg, Russia | 200 | 4 | Orenburg, Russia | 200 |
| 5 | Shtockmanov, Russia | 200 | 6 | Umm Shaif, Abu Dhabi | 175 |
| 7 | Zapolyarnoye, Russia | 150 | 8 | Kharasevey, Russia | 150 |
| 9 | Bovanenko, Russia | 125 | 10 | Medvezh'ye, Russia | 100 |
| 11 | Hassi R'Mel, Algeria | 100 | 12 | South Pars, Iran | 100 |
| 13 | Panhandle-Hugoton, USA | 80 | 14 | Groningen, Netherlands | 66 |
| 15 | Ghawar, Saudi Arabia | 60 | 16 | North Pars, Iran | 48 |
| 17 | Dauletabad-Donmez, Turkmenistan | 47 | 18 | Karachaganak, Kazakstan | 46 |
| 19 | Shatlyk, Turkmenistan | 35 | 20 | Yashlar, Turkmenistan | 27 |
| 21 | Blanco (San Juan), USA | 23 | 22 | Gazli, Uzbekistan | 20 |

**Table 2.8 World's oil consumption, 2010.**

| | Country | Oil consumption, $10^6$ bbl/day (% of the world) | Oil production, $10^6$ bbl/day (% of the world) | Difference |
|---|---|---|---|---|
| 1 | USA, Japan and China | 30.35 (40%) | 11.39 (15%) | -18.96 |
| 2 | OPEC | 5.32 (7%) | 34.65 (45.3%) | +29.33 |
| 3 | Rest of the World | 40.33 (53%) | 30.32 (39.7) | -10.01 |

| Time | | | Properties | | | |
|---|---|---|---|---|---|---|
| Era | Age | | Formation | Lithology | Fluid type | Thickness, m |
| Cenozoic | Quarternary | | Udifferentiated | Gravel+Soil+clay | ----- | Variable |
| | | | ArRaffa'a | Gravel+Soil+clay | ----- | Variable |
| | Tertiary | Meocene | Um Assha'al | Sandstone | ----- | 28 |
| | | | Hufuf | Limestone | ----- | 95 |
| | | | Dam | Limestone+Shale | ----- | 91 |
| | | | Hadrouk | Limestone | Water | 84 |
| | | Eocene | Dammam | Limestone | Water + Oil | 33 |
| | | | Rus | Anhydrite | ----- | 56 |
| | | Paliocene | Umm Er Radhuma | Limestone | Water | 243 |
| Meozoic | | Cretaceous | Aruma | Limestone | Oil | 142 |
| | | | Wasia | Sandstone+Shale | Water | 42 |
| | | | Biyadh | Sandstone+Shale | ----- | 425 |
| | | | Buwaib | Limestone | Water | 18 |
| | | | Yamama | Limestone | Water | 46 |
| | | | Sulaiy | Limestone | ----- | 170 |
| | | Jurassic | Hith | Anhydrite | ----- | 90 |
| | | | Arab | Limestone | Oil | 124 |
| | | | Jubaila | Limestone | ----- | 118 |
| | | | Hanifa | Limestone | ----- | 113 |
| | | | Twaqiq | Limestone | ----- | 203 |
| | | | Dhruma | Limestone | ----- | 375 |
| | | | Marrat | Sand + Shale | Oil + Gas | 103 |
| | | | Manjur | Sandstone | Water | 315 |
| | | Teriassic | Jilh | Dolomite | Oil + Gas | 326 |
| | | | Sudair | Sandstone+Shale | ----- | 116 |
| Paliozoic | | Permian | Khuff | Limestone | Gas | 171 |
| | | | Unayzah | Sandstone | Gas | 33 |
| | | Carbonian | Asshajarah | Sandstone | ----- | 32 |
| | | | Jubah | Sandstone+shale | ----- | 220 |
| | | Devonian | Jauf | Limestone | Gas | 272 |
| | | | Tawil | Sandstone | ----- | 200 |
| | | Silurian | Qalibah | Sandstone | Gas | 187 |
| | | | Sarah | Sandstone | ----- | 415 |
| | | Ordovician | Qassim | Sandstone+shale | ----- | 283 |
| | | Cambrian | Saq | Sandstone | ----- | 663 |
| | | | Yatib | Sandstone | ----- | 21 |
| Primary | | Pre-Cambrian | Gabalah | SS+LS+Shale | ----- | 3000 |
| | | | Agsas | Metamorphic | ----- | Variable |
| | | | Basement | Igneous | ----- | Variable |

**Figure 2.3 Stratigraphic section of eastern part of Saudi Arabia.**

Crude oil may be considered light if it has low density or heavy if it has high density; and it may be referred to as sweet if it contains relatively little sulfur or sour if it contains substantial amounts of sulfur. The geographic location is important because it affects transportation costs to the refinery. Light crude oil is more desirable than heavy oil since it produces a higher yield of gasoline, while sweet oil commands a higher price than sour oil because it has fewer environmental problems and requires less refining to meet sulfur standards imposed on fuels in consuming countries.

**Table 2.9 Technical data of Dammam well no.7 in Saudi Arabia.**

| Top of Arab formation = 4489 ft. | Bottom of Arab formation = 4918 ft. | | |
|---|---|---|---|
| Technical data | Reservoir section name | | |
| | Arab-A&B | Arab-C | Arab-D |
| Average net oil pay, ft. | 57 | 81 | 129.0 |
| Original pressure, psi. | 2258 | 2258 | 2258.0 |
| Depth, ft. | 4550 | 4550 | 4550.0 |
| Cumulative oil production, MMSTB. | 0 | 29 | 3.4.0 |
| Average porosity, %. | 20 | 25 | 20.0 |
| Average permeability, md. | 290 | 230 | 60.0 |
| Crud oil type. | Arab light | Arab light | Arab light |
| Stock tank gravity, $^{o}$API. | 35 | 35 | 35 |
| Sulfur content, weight %. | 1.52 | 1.52 | 1.52 |
| Original Solution GOR, SCF/STB. | 370 | 370 | 353 |
| Separator $H_2S$ content, Mole %. | 2.50 | 2.50 | 4.08 |

**Table 2.10 Oil and natural gas fields in Saudi Arabia, 2010.**

| Field | Fluid type | Discovery date | Field | Fluid type | Discovery date |
|---|---|---|---|---|---|
| Dammam | Oil | 1938 | Abu Hadriya | Oil | 1940 |
| Abqaiq | Oil | 1940 | Qatif | Oil | 1945 |
| Ghawar | Oil | 1948 | Fadhili | Oil | 1949 |
| Al-Wafrah | Oil | 1954 | Khursaniyah | Oil | 1956 |
| Manifa | Oil | 1957 | Khurais | Oil | 1957 |
| Khafji | Oil | 1960 | Khafji | Oil | 1960 |
| Hout | Oil | 1963 | Abu Sa'fah | Oil | 1963 |
| Fawaris AlJanub | Oil | 1963 | Berri | Oil | 1964 |
| Zuluf | Oil | 1965 | Janubi Um-Qdir | Oil | 1966 |
| Habari | Oil | 1966 | Jaham | Oil | 1966 |
| Al-Lulu | Oil | 1967 | Marjan | Oil | 1967 |
| Dorra | Oil | 1967 | Karan | Oil | 1967 |
| Kidan | Gas | 1967 | Jana | Oil | 1967 |
| Juraybi'at | Oil | 1968 | Jurayd | Oil | 1968 |
| Shaybah | Oil | 1968 | Marzouk | Oil | 1969 |
| Barqan | Oil | 1969 | Mazalij | Oil | 1971 |
| Harmaliyah | Oil | 1971 | Shutfah | Oil | 1972 |
| Abu Jifan | Oil | 1973 | Maharah | Oil | 1973 |
| El Haba | Oil | 1973 | Qirdi | Oil | 1973 |
| Ramlah | Oil | 1974 | Rimthan | Oil | 1974 |

| | | | | | |
|---|---|---|---|---|---|
| Kurayn | Oil | 1974 | Bakr | Oil | 1974 |
| Lawhah | Oil | 1975 | Ribyan | Oil | 1975 |
| Dibdibah | Oil | 1975 | Watban | Oil | 1975 |
| Sharar | Oil | 1976 | Suban | Oil | 1976 |
| Hasbah | Oil | 1976 | Harqus | Oil | 1978 |
| Jaladi | Oil | 1978 | Wari'ah | Oil | 1978 |
| Lughfah | Oil | 1979 | Faridah | Oil | 1979 |
| Dhib | Oil | 1979 | Hamur | Oil | 1979 |
| Jawb | Oil | 1979 | Samin | Oil | 1979 |
| Maghrib | Oil | 1982 | Tinat | Oil | 1982 |
| Jauf | Oil | 1983 | Farhah | Oil | 1983 |
| Sahba | Oil | 1984 | Dilam | Oil | 1989 |
| Hawtah | Oil | 1989 | Raghib | Oil | 1990 |
| Hilwah | Gas | 1990 | Hazmiyah | Oil | 1990 |
| Ghinah | Oil | 1990 | Nuayyim | Oil | 1990 |
| Kahf | Gas | 1991 | Midyan | Oil | 1992 |
| Umm Jurf | Oil | 1993 | Umluj | Gas | 1993 |
| Wajh South | Gas | 1993 | Nisalah | Oil | 1993 |
| Abu Markhah | Oil | 1994 | Layla | Oil | 1994 |
| Abu Rakiz | Oil | 1995 | Burmah | Oil | 1995 |
| Usaylah | Oil | 1996 | Abu Shidad | Oil | 1996 |
| Shiblah | Oil | 1996 | Mulayh | Oil | 1996 |
| Khuzama | Oil | 1997 | Waqr | Gas | 1997 |
| Sham'ah | Gas | 1998 | Hamma | Oil | 1998 |
| Sidr | Oil | 1998 | Wudayhi | Gas | 1998 |
| Kahla | Gas | 1998 | Shaden | Gas | 1999 |
| Niban | Oil | 1999 | Manjurah | Gas | 2000 |
| Ghazal | Oil | 2000 | Jufayn | Oil | 2001 |
| Tukhman | Oil | 2002 | Warid | Oil | 2002 |
| Yabrin | Oil | 2003 | Awtad | Oil | 2003 |
| Abu Sydr | Oil | 2004 | Midrikah | Oil | 2004 |
| Duayban | Oil | 2005 | Halfa | Oil | 2005 |
| Muraiqib | Oil | 2005 | Zimlah | Gas | 2006 |
| Kassab | Gas | 2006 | Nujayman | Gas | 2006 |
| Mabruk | Oil | 2007 | Dirwazah | Oil | 2007 |

**Table 2.11 World's oil and natural gas reserves over geologic periods.**

<table>
<tr><th>Era</th><th>Period</th><th>Age, millions years</th><th colspan="2">Oil and natural gas reserves, %</th></tr>
<tr><td>Cenozoic</td><td>Quaternary<br>Tertiary</td><td>1</td><td>58.0%</td><td rowspan="2">Mostly oil reservoirs containing natural gas cap</td></tr>
<tr><td>Mesozoic</td><td>Cretaceous<br>Jurassic<br>Triassic</td><td>2 - 65</td><td>26.9%</td></tr>
<tr><td>Paleozoic</td><td>Permian Devonian<br>Silurian<br>Ordovician<br>Cambrian</td><td>280 – 600</td><td>15.1%</td><td>Mostly natural gas reservoirs</td></tr>
</table>

Each crude oil has unique molecular characteristics that are understood by the use of crude oil assay analysis in petroleum laboratories. Worldwide, crude oils are classified based on API as follows:

i) Heavy Crude Oil: The API value of this oil is ranging from 6 to 10 degrees. Crude oil produced from offshore fields in Saudi Arabia such as Safaniya is a good example.

ii) Medium Crude Oil: The API value of this oil is ranging from 11 to 21 degrees. Crude oil produced from offshore fields in Saudi Arabia such as Qatif is a good example.

iii) Light Crude Oil: The API value of this oil is ranging from 22 to 30 degrees. Crude oil produced from onshore fields in Saudi Arabia such as Abu Hadriyah is a good example.

iv) Extra Light Crude Oil: The API value of this oil is ranging from 31 to 39 degrees. Crude oil produced from onshore fields in Saudi Arabia such as Abqaiq is a good example.

vi) Super Light Crude Oil: The API value of this oil is ranging from 40 to 49 degrees. Crude oil produced from onshore fields in Saudi Arabia such as Shaiba is a good example.

Generally, crude oil is classified into five main categories based on the American Petroleum Institute (API) gravity as follows:

$$°\text{API} = \frac{141.5}{\text{Specific gravity}} - 131.5 \qquad \ldots(2.1)$$

$$\text{Oil specific gravity} = \gamma_o = \frac{\text{Oil density}}{\text{Fresh water density}} \qquad \ldots(2.2)$$

Fresh water is used as a reference fluid for crude oil specific gravity calculations. Fresh water density is equal to 1.0 g/cc, 8.33 ppg or 62.4 pcf.

Crudes are also classified into three groups, according to the nature of the hydrocarbons they contain.

i) Paraffin-based Crude Oils: These contain higher molecular weight paraffins, and little or no asphaltic (bituminous) matter. They are stable at room temperature and can produce high-grade lubricating oils.

ii) Asphaltic Based Crude Oils: Contain large magnitude of asphaltic matter, and little or no paraffin. Some are predominantly naphthenes so yield lubricating oil that is more sensitive to temperature changes than the paraffin-base crudes.

iii) Mixed Base Crude Oils: Both paraffins and naphthenes are present in this type, as well as aromatic hydrocarbons. Most crudes in the world fit this category.

Desalting and dewatering of crude oil is a key process operation for the removal of undesirable components from crude oil before it reaches any of the major unit operations. The main function of the desalter is to remove salt and water from the crude oil. However, many other contaminants such as clay, silt, sand, rust, and other debris also need to be removed. These can cause corrosion and damage of downstream and upstream equipment.

Typically water content of the treated crude oil is required to be 0.3% by volume or less. Maximum sulfur content must be less than 0.5% by weight of treated crude oil. Crude oil is defined as sweet if the sulfur content is 0.5% by weight or less and sour if the sulfur content is greater than 0.5% by weight. After crude oil refining, sulfur content in all products must be less than 0.05% by weight. Another characteristic of crude oil is the total acidic number (TAN). The Tan represents a composite of acids present in the oil and is measured in milligrams (mg). A TAN number grater than 0.5 mg is considered high. To overcome high TAN, low TAN and high TAN crude oils are mixed together to get acceptable TAN number. Treatment quality and API value are the major determinants of oil price.

Barrels from an area in which the crude oil's molecular characteristics have been determined and the oil has been classified are used as pricing references throughout the world. Some of the common reference crudes are:

i) West Texas Intermediate (WTI), a very high-quality, sweet, light oil delivered at Cushing, Oklahoma for North American oil.

ii) Brent Blend, comprising 15 oils from fields in the Brent and Ninian systems in the East Shetland Basin of the North Sea. The oil is landed at Sullom Voe terminal in the Shetlands. Oil production from Europe, Africa and Middle Eastern oil flowing west tends to be priced off the price of this oil, which forms a benchmark.

iii) Dubai-Oman, used as benchmark for Middle East sour crude oil flowing to the Asia-Pacific region.

iv) The Organization of the Petroleum Exporting Countries (OPEC) Reference Basket, a weighted average of oil blends from various OPEC countries.

# CHAPTER THREE
# Origin and Geology of Petroleum Reservoirs

## 3.1 Introduction

Millions of years ago the earth was teeming with plants and animals. Much of that life was located in or adjacent to ancient rivers, lakes and seas. As plants and animals died, their remains settled to the bottom of these bodies of water. Normally, these organic materials would have simply decomposed; however, as new organic material covered older layers, the oxygen supply to the lower levels was cut off. Ancient rivers carried mud and sand that buried the organic material. Decomposition of buried organic matter was halted or slowed. As layers of organic material continued to build, their thickness reached hundreds of feet. Eventually, massive quantities of partially decomposed organic material were deposited.

During the same period the earth's crust was changing. Over millions of years other materials covered the ancient sea bottom. Rock, volcanic material, or other layers of sedimentation repeatedly buried these areas. These sedimentation layers buried the organic material hundreds or even thousands of feet deep in the earth. Folding and faulting of the earth's crust later caused the ancient seabeds to be thrust upward or downward. As the original organic material was being buried, two things began to happen: (i) the weight of material above the organic remains increased, and (ii) the organic material was compressed. This compression led to increased temperature and pressure in the organic material. Also, as the material was buried deeper and deeper, it was warmed by the high temperatures of the earth's core. The increasing pressure and temperature led to several transformations in the material. Some of the organic matter and much of the inorganic matter began to change into particles and cement-like material that eventually consolidated into rock. Since most of the organic materials originally deposited by the action of water, some water remained with the material throughout its conversion history. Also, as the layers of rock and organic matter were moved by action in the earth's crust, water could have migrated into the rock and organic matter. Water is almost always found in conjunction with petroleum. Water associated with, or part of, petroleum deposits is called "connate water". Connate water is existed in the reservoir as a thin film of water covering sand grains.

Hydrocarbons, like all other forms of matter, take various forms called “states”. The state of a hydrocarbon is primarily, just as water can be in a solid, liquid, or gaseous state depending on pressure and temperature, so can hydrocarbons occur in different states. For example, Liquefied natural gas (LNG) used by consumers is composed of methane with some ethane and butane. Liquefied petroleum gas (LPG) is principally butane or propane with some methane and ethane. Motor oil is a mixture of decane and heavier hydrocarbons. Road-paving asphalt is a mixture of the heaviest hydrocarbons, which are almost always in the solid state.

## 3.2 Origin of Petroleum

The most popular theories for petroleum origin are the organic and the inorganic theories. The organic theory is believed to be the most realistic one.

### 3.2.1 Organic Origin Theory

Organic matter from the remains of plants, animals and microorganisms were buried by rocks and volcanic materials, then was decomposed over millions of years by pressure, temperature and chemical reaction in the absence of oxygen and formed petroleum.

### 3.2.2 Inorganic Origin Theory

Hydrogen and Carbon come together under pressure and temperature below earth's surface, where chemical reactions occurred and formed oil and gas.

## 3.3 Geology of Petroleum Reservoirs

Geology is the science that deals with the history and structure of the earth and its life forms, especially as recorded in the rocks. Geology is so essential to the petroleum industry. Knowledge of the basic principles of this science is desirable for anyone associated with oil or natural gas. Oil and natural gas are derived from the remains of ancient life buried along with sea water in sand, clay, and lime deposits. Oil is lighter than the water, which fills voids or pore spaces in the compacted sand and lime layers. Thus, it floats and moves upward through the earth rocks until it seeps out at the surface or, more common1y, is trapped as an oil pool by some natural barrier beneath the earth's surface. Many decades of prospecting for oil have convinced the participants that there are certain basic geologic requirements for oil and gas accumulation. These pre-requisites concern the quality of the oil bearing reservoir rocks and the presence of a barrier that will trap the oil in underground pools. The reservoir is judged by its thickness (h), porosity ($\varphi$), permeability (k), pressure and type and size of the geological trap.

Rock is a natural substance composed of a mineral or group of minerals. The rocks that are of most interest to the petroleum geologist are those that contain fluids such as salt water, oil, or gas. For enough oil and gas to accumulate to form a commercially valuable deposit, there must be a reservoir of rocks with the right shape or configuration to ho1d the oil and gas and some kind of rock seal to prevent the oil and gas from leaving the reservoir. The reservoir rock is a container, and it usually holds a number of fluids in addition to the hydrocarbon (petroleum) deposit. For instance, the reservoir is almost always filled with a large amount of water as well as with the oil and gas. The fluids are usually layered with the gas on top, then the oil, and the water on the bottom. To qualify as a reservoir rock, a rock formation must be sufficiently large, porous, and thick to contain commercially profitable quantities of gas and oil. In practical, most commercial reservoir rocks are thicker than 10 feet and have porosities above 10%.

Commercial reservoir rocks also must be permeable, which means that oil and gas (if present) must be able to move or flow from one pore space to another within the rock. In oil reservoirs, the empty pore space in rocks can be filled with water alone; with water and oil; or with oil, gas, and water. Petroleum companies, of course, prefer that the rocks contain all three, because the oil and gas are profitable, and the water often assists in moving the oil and gas out of the rocks and into the well. Water and other substances force the petroleum to move by exerting pressure. Thus, commercial production ultimately depends upon the pressure, porosity, and permeability of the reservoir rock as much as on the rock's having a proper trap or a good seal to keep the petroleum in the reservoir. All of these factors are part of the petroleum geologist's concern in searching for a commercial petroleum deposit.

A petroleum reservoir is a trap containing gas, oil, and water in varying proportions. These fluids are contained in the pore spaces of rock formations among the grains of sandstones or in the cavities and fractures of carbonates. The pore spaces are interconnected so that the fluids can move through the reservoir. The porous formations have to be cut off (sealed) on all sides, above and below, in such a way that the only escape for the fluids will be through a well bore drilled into the reservoir. Sandstone ($SiO_2$) and carbonates (such as limestone $CaCO_3$ and dolomite $CaMg(CO_3)_2$ are the most common reservoir rocks. Generally, sandstone reservoirs are more porous than limestone. The least consolidated, younger sandstones are more porous than the more tightly compacted, older or more deeply buried sandstones.

The principal difference between sandstone and carbonate rocks (limestone and dolomite) is in the chemical composition of the rocks. Carbonate rocks may be dissolved easily by most acids, while sandstone rocks are virtually inert to the action of acid. Since many stimulation (acidizing) techniques depend on rock being dissolved by acid, the difference in rock types can be appreciable. Close examination of a rock with a powerful magnifying glass reveals that there are openings in the pores. A rock with pores is said to be porous or to have porosity. The porosity of a formation controls its capacity for reservoir fluids. The greater a rock's porosity, the more fluids it is able to hold. Porosity may vary from less than 5% in tightly cemented sandstone or carbonate to more than 30% for unconsolidated sands. Accurate determination of formation porosity is extremely difficult. Besides porosity, a reservoir rock must also have permeability; that is, the pores of the rock must be interconnected. These connected pores allow petroleum to move from one pore to another, thus, when a well is dril1ed into a reservoir, the petroleum has a way to move out of the pores and into the well. The rock's permeability determines how easy or hard it is for the petroleum to move or flow within the reservoir rock away to the production well. In 1856 Henry Darcy, a French engineer, devised a means of measuring the permeability of porous rocks. For this reason numerical expressions of permeability are measured in “Darcies”. Most reservoir rocks have average permabilities considerably less than one Darcy. Thus, permeability is usually measured in milli-Darcy (md) or thousandths of a Darcy. Existence, reserves and productivity of any reservoir, depend on the above properties.

## 3.4 Types of Rocks

There are three types of rocks in the earth as follows:

i) Igneous rocks are rocks that have solidified from a molten or liquid state. These rocks can be formed deep in the earth or at the surface from cooling of volcanic lava. Igneous rocks usually do not contain hydrocarbons because they have no porosity.

ii) Metamorphic rocks are formed by the metamorphosis of other existing rocks by extreme temperature and pressure. These two factors cause recrystallization of the minerals in the rocks. Metamorphic rocks normally do not contain hydrocarbons.

iii) Sedimentary rocks are formed from the deposition of particles (sediments) in seas, rivers or lakes. The accumulate sediments are cemented together to form sedimentary rocks. Sedimentary rock are those rocks where hydrocarbons are formed (source rock) and accumulated (reservoir rock). Sandstone, limestone, dolomite, shale, and evaporates are the most important sedimentary rocks for petroleum engineers.

## 3.5 Petroleum Accumulation and Segregation

As the organic remains come into sea bottom by rivers silt and mud, they buried and sealed from oxygen. As time passed, temperature, pressure and bacteria in addition to other chemical reactions caused the organic matter to change into oil and natural gas and bond sand and clay grains together to form the source rock. After the formation of oil and gas, these fluids plus saline water migrates from the source rock upward until they trapped by some kind of rock structure normally called trap. After, water, oil and gas are trapped, they start to separate according to their density and gravity. Gas will be in the top of the trap, oil will be beneath it followed by water at the lower part of the trap. Saline water will not completely separated from the oil and water, therefore portion of water will remain in both gas and oil sections as a film around sand grains in smaller pores. This water is called connate water.

### 3.6 Petroleum Accumulation Requirements

Petroleum is found in sedimentary basins in sedimentary rocks. Several geologic elements are necessary for oil and gas to accumulate in sufficient quantities to create a reservoir large enough to be worth producing. These elements include:

i) An organic-rich source rock usually high in organic matter, from which petroleum can be generated,
ii) A porous reservoir rock to store the petroleum in, and
iii) Some sort of trap to prevent the oil and gas from leaking away.
iv) A mechanism for the petroleum to move, or migrate.

#### 3.6.1 Source Rock

Most geologists agree that oil and natural gas form from the preserved soft parts of ancient organisms that were buried, and then broken down and converted into kerogens by the combined effects of heat, pressure and time. A petroleum source is any rock that contains enough kerogens to generate oil or natural gas such as shales. Short amounts of time and large amounts of heat or long amounts of time and small amounts of heat can convert kerogens to oil. Most liquid oil forms from plankton, algae, or bacteria, and most gas is associated with oil. However, some gas forms directly from "woody kerogens", such as pollen or other plant remains, or from oil that has been broken down by too much time and temperature.

#### 3.6.2 Reservoir Rock

If a rock has enough porosity and permeability to flow oil or natural gas, then it is a potential reservoir. Although it may not be very much, most rocks, in particular sandstones and conglomerates contain pore space. If enough pores are present, the pores are large enough, and they are interconnected so that fluids flow through them (i.e., the rock is permeable), then the rock is a potential petroleum reservoir. With sandstones, a porosity of 10% or more is usually needed for an economic oil reservoir, and 12% or more for a gas reservoir. Less porosity, perhaps as little as 9%, is needed if the sandstone is also fractured. Because of fracturing, carbonate (limestone and dolomite) reservoirs can have much lower porosities than sandstone reservoirs. Porosity and permeability are important, but a petroleum reservoir needs to contain hydrocarbons as well. In most rocks, the pores are filled entirely with a salty solution called formation water, but in a few some oil or natural gas are present as well.

#### 3.6.3 Geological Structures (Traps)

Traps generally exist in predictable places such as at the tops of anticlines, next to faults, in the up-dip pinch-outs of sandstone beds, or beneath unconformities. Petroleum reservoirs contain interconnected pores filled with water and hydrocarbons (oil and gas). Because most oils are lighter than water, they migrate upward through the pores, or along and faults and fractures, and make their way to the surface to discharge as oil seeps. The exception is when a seal exists, some sort of impermeable barrier that prevents the upward migration of oil. Shale, salt, and cemented sandstones are all potential seals. If the geometry is such that a seal forms a trap, such as in an anticline, then oil accumulates behind the trap to form a reservoir that, if large enough, can be commercially produced. Oil will continue to migrate into the trap until the base of the reservoir reaches a spill point, where the excess oil escapes to renew its upward migration to the surface or to another trap. Traps may also be formed by faults, pinch-outs and unconformities.

## 3.7 Types of Reservoir Traps

Traps are classified as to whether they are structural or stratigraphic. Traps formed by anticlines and faults are examples of i) structural traps, and traps formed by unconformities and pinch-outs are types of ii) stratigraphic traps. If a trap possesses both structural and stratigraphic elements, then it is a iii) combination trap. iv) Digenetic traps also exist, where phase changes from one rock type to another may create a reservoir or a seal. Diatomite reservoirs in the San Joaquin Valley in USA are an example of a digenetic trap, with Opal A and Quartz phase rocks representing reservoirs, and Opal CT phase rocks representing seals.

### 3.7.1 Structural Traps

A structural trap is formed by the folding or faulting of the rock layer that contains the hydrocarbons. Structural traps vary widely in size and shape. Some of the more common structural traps are anticline traps, fault traps, and salt dome traps. Reservoirs formed by the folding of rock layers or strata, usually have the shape of structural domes or anticlines. These anticline traps were filled with petroleum when it moved in form its source below. Fault traps are formed by breaking or shearing and offsetting of strata. The oil is confined in traps of this type because of the tilt of the rock layers and the faulting. Salt dome and plug traps are porous formations on or surrounding great plugs or masses of salt or serpentine rock that have pierced, deformed, or lifted the overlying layers.

i) Anticlines: When layers of rock are folded to create a fold, the resulting geometry is called an anticline. Because oil floats on water, the oil tries to move to the top of the anticline. If an impermeable seal, such as a shale bed, caps the dome, then a reservoir of oil may form at the crest as shown in **Figure 3.1**.

ii) Faults: If a fault moves porous reservoir rock against an impermeable seal, such as shale or salt, and the fault does not leak, then the upward migration of oil to the surface is blocked, and an oil pool accumulates against the fault as shown in **Figure 3.2**.

iii) Salt Dome: Salt dome is a large accumulation of salt which due to relatively low density and plasticity is extruded to thrust upwards into overlaying formations creating numerous structural traps as shown in **Figure 3.3**.

### 3.7.2 Stratigraphic Traps

Stratigraphic traps are caused either by a nonporous formation sealing off the top edge of a reservoir (porous) bed or by a change of porosity and permeability within the reservoir bed itself.

i) Pinch-outs, Reefs and Sand Lenses: If a porous reservoir rock is encased within an impermeable seal, such as shale or salt, then a trap may form at the up-dip pinch-out of the reservoir (i.e., where the reservoir thickness decreases to zero) as shown in **Figure 3.4**. Similarly, Reefs and sand lenses when encased with impermeable rocks can be potential traps for oil or natural gas as shown in **Figures 3.5** and **3.6**.

ii) Unconformities: An unconformity is a surface of erosion. If reservoir beds beneath an unconformity are tilted, and impermeable beds above the unconformity form a seal, then a trapping geometry results as shown in **Figures 3.7**.

### 3.7.3 Complex (Combination) Traps

When stratigraphic and structural traps are located in the same place, the whole group is named as a complex trap. In summary, the geological features necessary for accumulation of oil and natural gas in commercial reservoirs are:

i) A porous (at least $\varphi \geq 10\%$) and permeable zone of sufficient thickness (at least $h \geq 10ft$) to contain large quantities of oil and natural gas called reservoir rock.

ii) An overlaying bed of impermeable rock such as shale that is normally called cap rock.

iii) An underlying seal such as water saturated zone or a confinement by water down dip below the oil and gas in the reservoir horizon.

iv) Some type of structure feature, or discontinuity of the porous and permeable beds (i.e. stratigraphic or structural traps).

v) Sufficient pore fluid pressure (energy) to perform flow into the production wellbore.

vi) Organic rich source rock.

## 3.8 Reservoir Energy Mechanisms

A good virgin reservoir will be under sufficient pressure to initially push hydrocarbons to surface. However, as the fluids are produced, the pressure will drop and production rate will quickly decrease. In order to maintain production, some form of drive mechanism is needed.

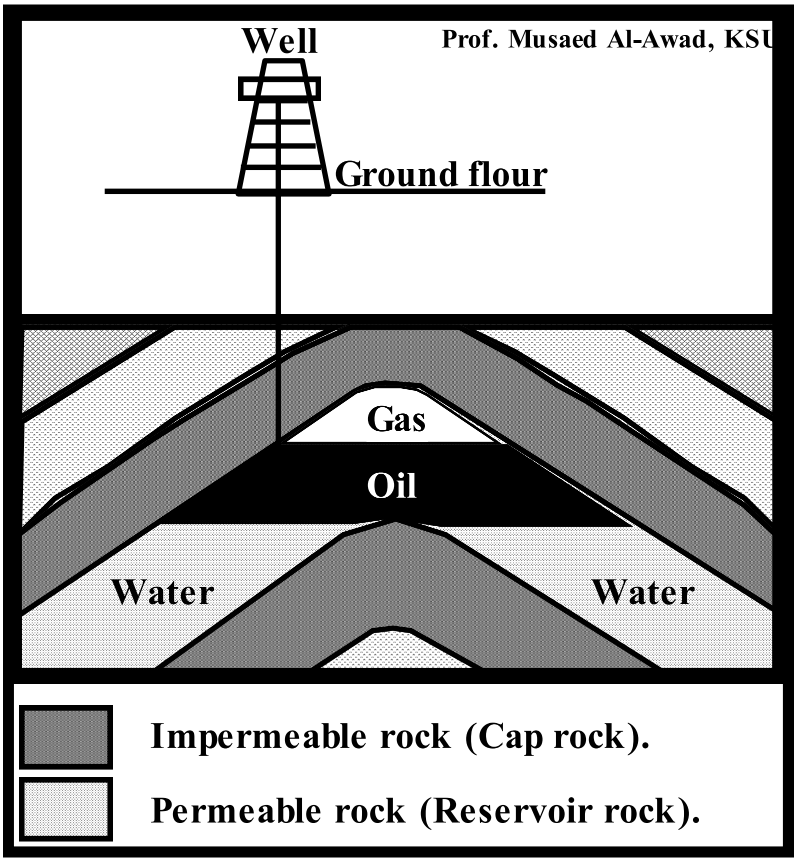



**Figure 3.1 Structural (Anticline) petroleum trap.**

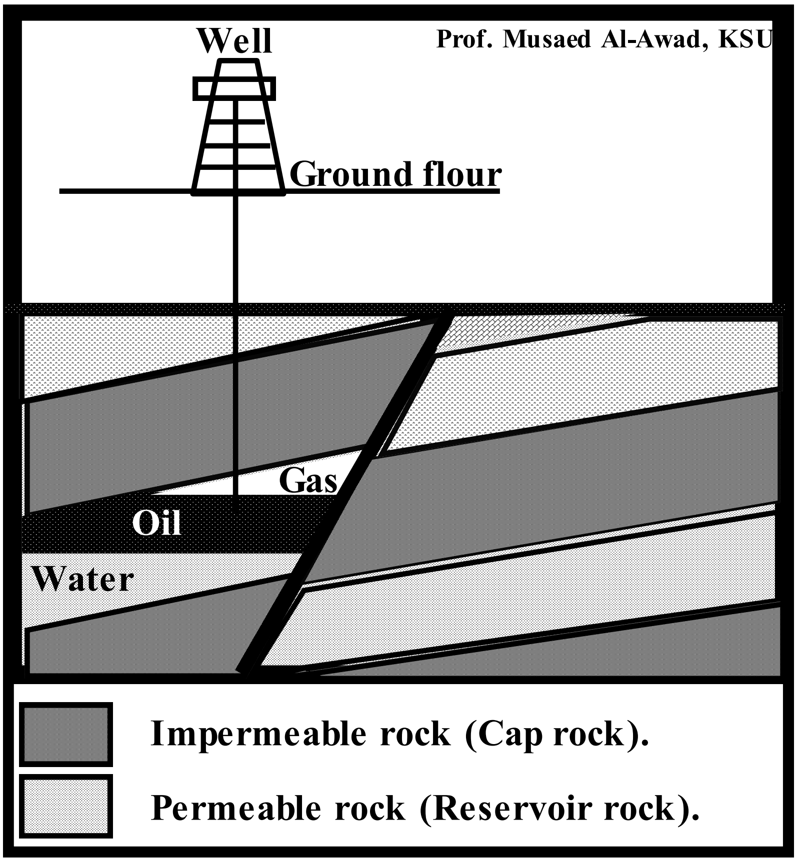



**Figure 3.2 Structural (Fault) petroleum trap.**

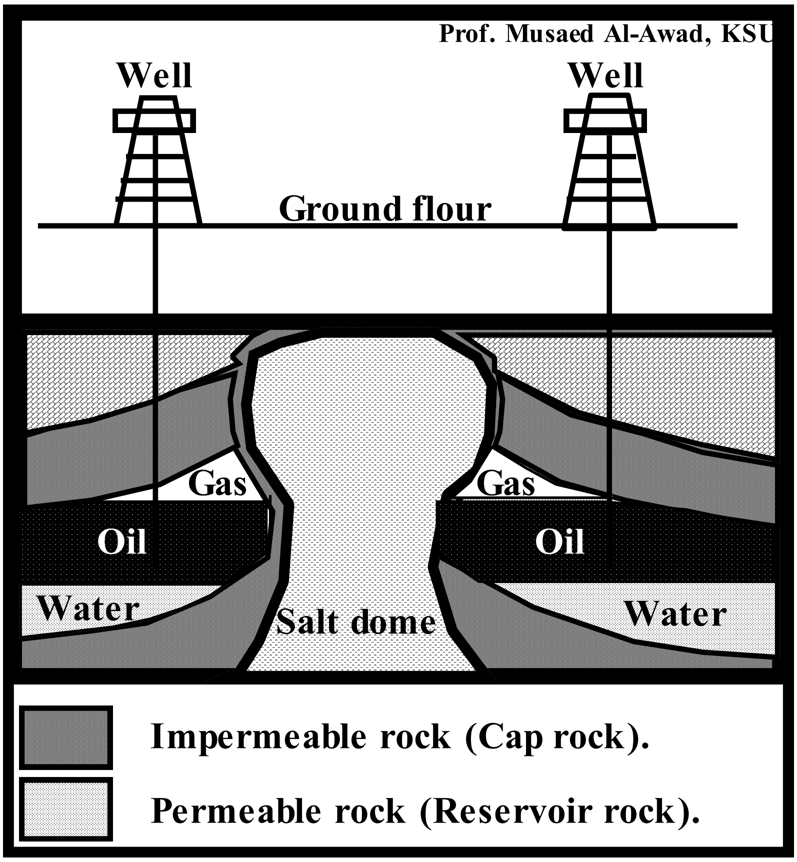



**Figure 3.3 Structural (Salt dome) petroleum trap.**

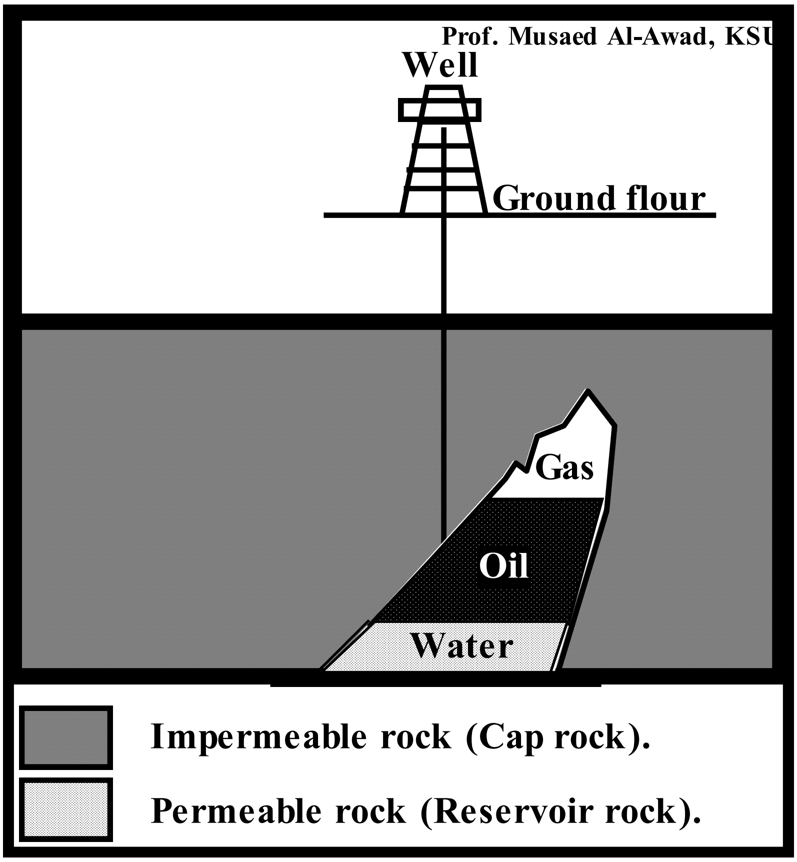



**Figure 3.4 Stratigraphic (Pinch-out) petroleum trap.**

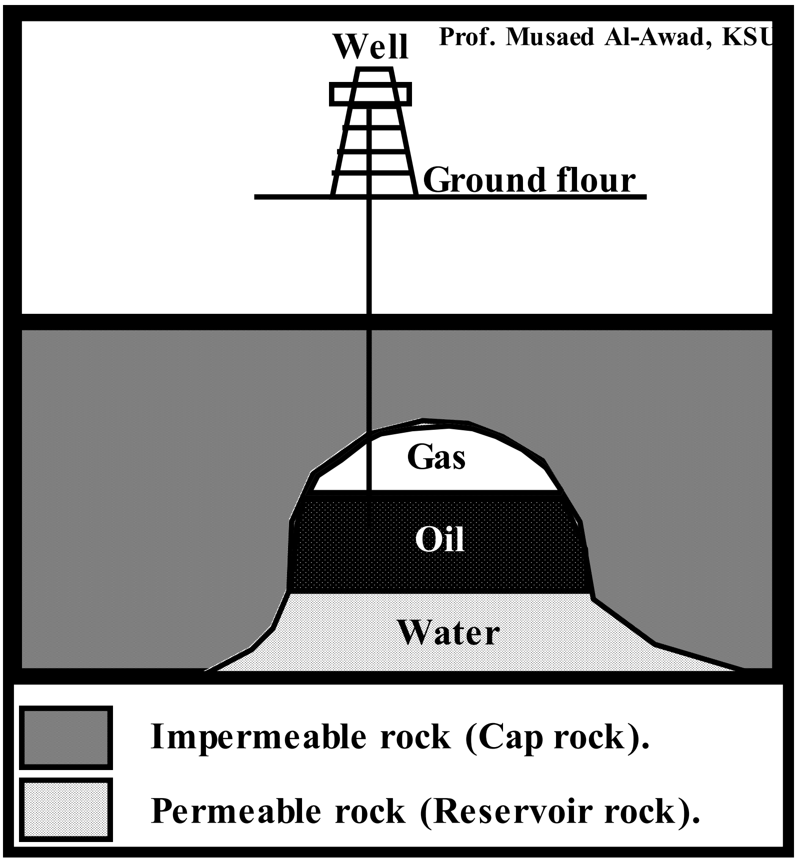



**Figure 3.5 Stratigraphic (Reef) petroleum trap.**

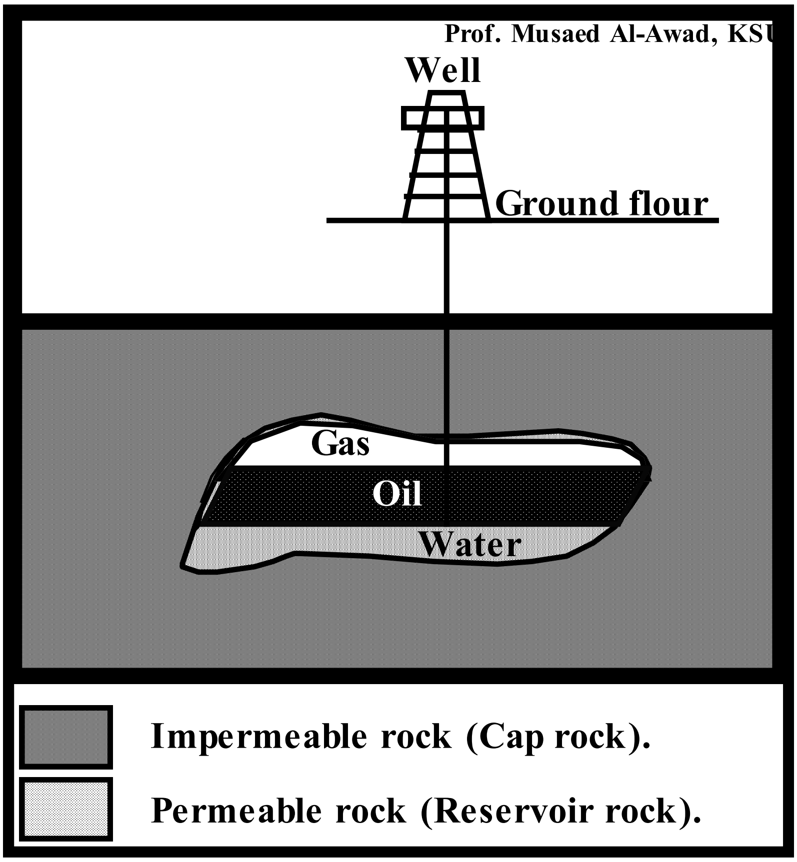



**Figure 3.6 Stratigraphic (Sand lenses) petroleum trap.**

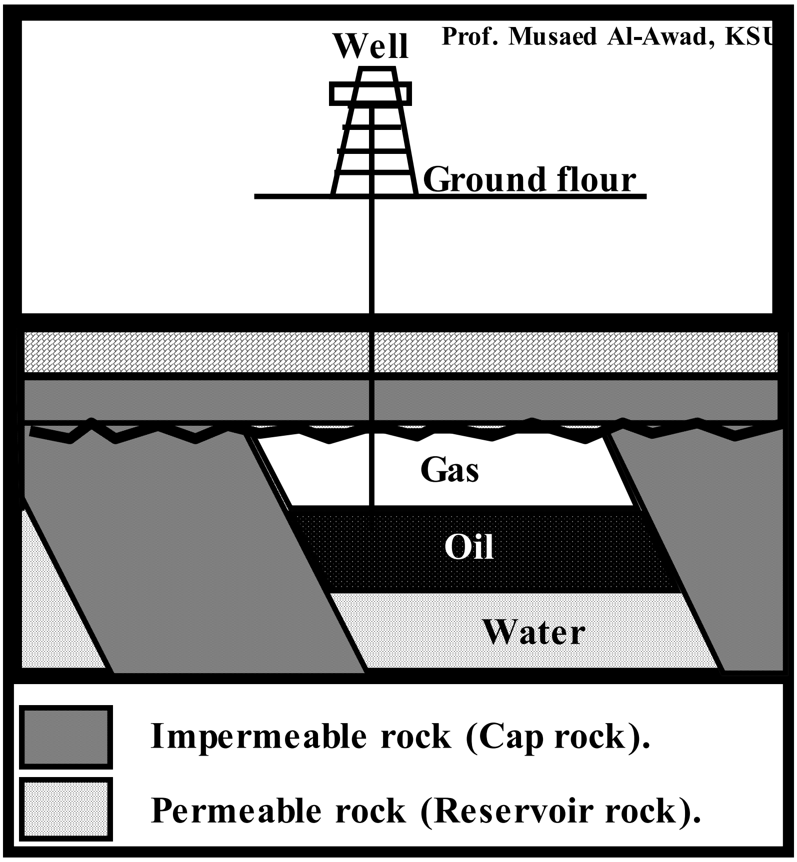



**Figure 3.7 Stratigraphic (Unconformity) petroleum trap.**

i) Gas-Cap Drive Mechanism: In reservoirs already having a gas cap (the virgin pressure is already below bubble point), the gas cap expands with the depletion of the reservoir, pushing down the liquid sections applying extra pressure.

ii) Compaction Drive Mechanism: In compaction drive, the energy for oil production is provided by the collapse of the porous medium skeleton and expansion of the pore fluids when the reservoir pressure drops. The increase in the effective stress causes pore collapse and compaction (consolidation) of the reservoir. This drive mechanism is common in highly compressible, unconsolidated reservoirs.

ii) Gravity Drainage Mechanism: In addition to the reservoir drive mechanisms mentioned previously, the force of gravity will cause oil to move downward relative to gas cap and upwards relative to water aquifer.

iv) Aquifer Drive (Water Influx) Mechanism: Below the hydrocarbons will be ground water, known as the aquifer. Water, as with all liquids, is compressible to a very small degree when under high pressure. As the hydrocarbons are depleted, the reduction in pressure on the ground water causes it to expand very slightly. Although this expansion is minute, if the aquifer is large enough, this will translate into a large increase in volume, which will push up on the hydrocarbons, maintaining pressure.

v) Solution-Gas Drive Mechanism: This mechanism (also known as depletion drive) depends on the associated gas of the oil. The virgin reservoir may be entirely liquid, but will be expected to have gaseous hydrocarbons in solution due to the pressure. As the reservoir depletes, the pressure falls below the bubble point and the gas comes out of solution to form a gas cap at the top. This gas cap pushes down on the oil phase helping to maintain pressure.

Usually production is the result from some combination of all of the mechanisms mentioned previously.

## 3.9 Improved Recovery Mechanisms

The use of natural reservoir energy to produce oil and natural gas generally results in a recovery of less than 50% of the original hydrocarbon in place. If the natural drives are insufficient, as they very often are, then the pressure can be artificially maintained by applying secondary recovery methods by injecting water into the aquifer or gas into the gas cap. If the reservoir productivity is still low, then the tertiary or enhanced oil recovery techniques are applied. Tertiary recovery methods are the mechanisms of changing either the reservoir rock properties or the reservoir fluids properties by chemical recovery, thermal recovery, miscible and immiscible recovery processes. **Table 3.1** shows the percentage recovery that potentially gained at various production stages from a petroleum reservoir.

**Table 3.1 Percentage recovery at various production stages.**

| Production stage | | Percentage recovery | Oil mobility |
|---|---|---|---|
| 1 | Primary | Up to 30% | Mobile |
| 2 | Secondary | Up to 60% | |
| 3 | Tertiary | Up to 80% | Immobile |

It must be realized that conducting enhanced oil recovery research is not necessary to apply it soon, but it could be a nice tool to add more to the proved oil and natural gas reserves values.

# CHAPTER FOUR
# Petroleum Exploration Techniques

## 4.1 Introduction
Exploration methods are the techniques employed in the search for petroleum. The primary task in exploration is not directly to find oil but to provide physical evidence about the geological phenomena associated with oil accumulations that described in the preceding pages, i.e. identifying a prospective hydrocarbon region and geological structures. Geological interpretation of the data may eventually lead to drilling and the discovery of oil.

## 4.2 Exploration Techniques
In the following sections, methods employed in exploration for oil and natural gas are discussed.

### 4.2.1 Aerial Surveying
Before commencing a new exploration and before surveyors or geologists go out, it is usual to photograph the whole area from the air. An airplane fitted with a wide-angled camera flies strip wise over the area taking photographs each of which overlaps those adjoining. By stereoscopic study of these photographs a fairly accurate topographical map and a geological map showing the geological surface features observable from the air are constructed. These maps not only help in the planning of ground surveys but also enable geologists to go directly to the points of greatest interest. There is no longer any reason for surveyors or geologists to work 'blind' in the tropical rain forests or the arid deserts in which so much oil exploration has to be done. So great is the value of aerial surveys that it is usual nowadays to photograph even areas that have already been explored on the ground so that they can be reassessed. Large-scale aerial photographs are also invaluable in planning routes for roads and pipelines or sites for wells and camps.

### 4.2.2 Satellite Surveying
Growing use being made of satellites imaging techniques to detect potential subsurface deposits of hydrocarbons and other minerals. The satellite system can be equipped with a coherent infrared imaging system which scans the area of observation for detecting the hydrocarbon gas cloud which appears above an oil or natural gas reservoir.

### 4.2.3 Geological Exploration
The outcrops of the rock layers in the potential oil reservoir area are mapped as accurately as possible as a result of geological observations on the ground. Wherever possible, observations are made, in the banks of rivers, on mountain slopes and cliffs, of the inclination of the strata (the dip) and of the horizontal direction (the strike) in which they extend.

The physical characteristics (porosity and permeability) and the fossil contents of the rocks are recorded, and samples are taken, to correlate with beds exposed elsewhere, the final detailed geological map may be built up from hundreds or thousands of observations made by one or more geologists over many years. In areas of good rock exposure, field work is comparatively straight forward. However, in regions covered by superficial deposits such as river sediments or in featureless areas where surface evidence is obscure or wanting, the work is more complex. Pits or trenches may have to be dug, auger holes drilled through the weathered soil layer, or a cored section of underlying rock obtained by the use of light power driven drilling outfits. But where folds are hidden beneath sediments deposited since the deformation, they may not be revealed at all by geological and geophysical methods alone.

### 4.2.4 Geochemical Exploration

Little use has been made of geochemical exploration and its practical value is yet uncertain. One method depends on the inference that in areas overlying accumulations of oil and natural gas at high pressure, small quantities of gas may be expected to permeate to the surface and be detectable by chemical analysis. This is done by studying shallow cores and subsurface water for evidence of seepage or kerogens. The other method attempts to detect the presence of bacteria that might indicate the presence of micro-seepages of hydrocarbon gas.

### 4.2.5 Geophysical Exploration

When the geologists have concluded their subsurface investigations, they may wish to conduct geophysical programs in order to narrow down a general area of interest to a local structural prospect. They will then consider the applicability of such geophysical techniques as (i) magnetic, (ii) gravimetric and (iii) seismic methods. Each of these techniques is based upon physical forces and properties of the earth.

i) Magnetic Method: Measurement of changes in the intensity and direction of the earth's magnetic field brought about by the presence of basement magnetic rocks (organic and metamorphic rocks) can give an indication of thickness of subsurface sediments overlaying the basement rocks as shown in **Figure 4.1**.

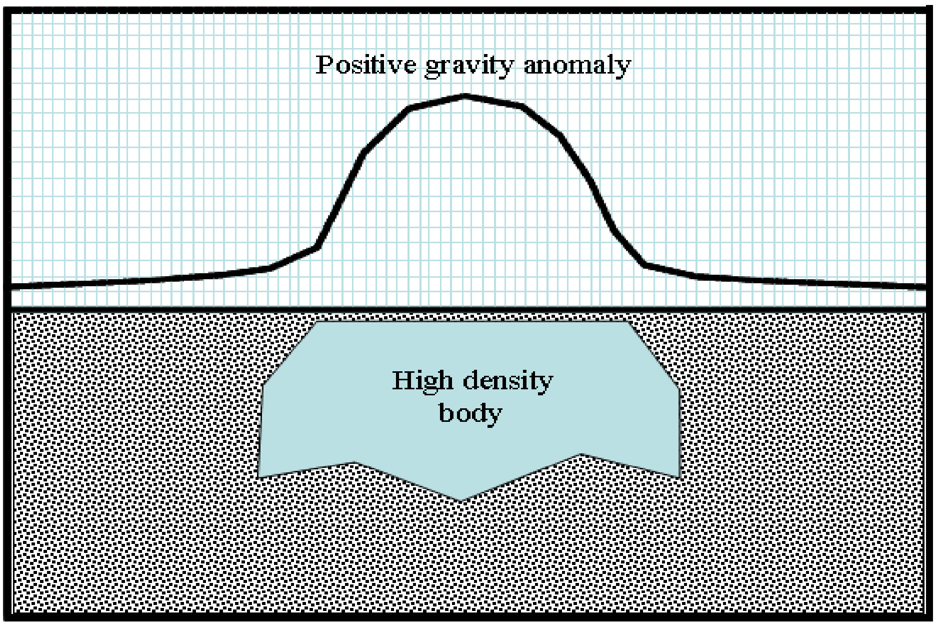



**Figure 4.1 Gravity exploration technique.**

ii) Gravimetric Method: Gravimetric method which depends on the precise measurement of slight variations in gravity, or more correctly in *"g"* the acceleration due to gravity, on the surface caused by different densities of the rocks underlying the prospecting area. As the density of the rocks varies, so does the gravitational attraction at the surface. Therefore, gravity surveys can be used to outline the structure of sedimentary basins as shown in **Figure 4.2**. This method provides information for further seismic exploration.

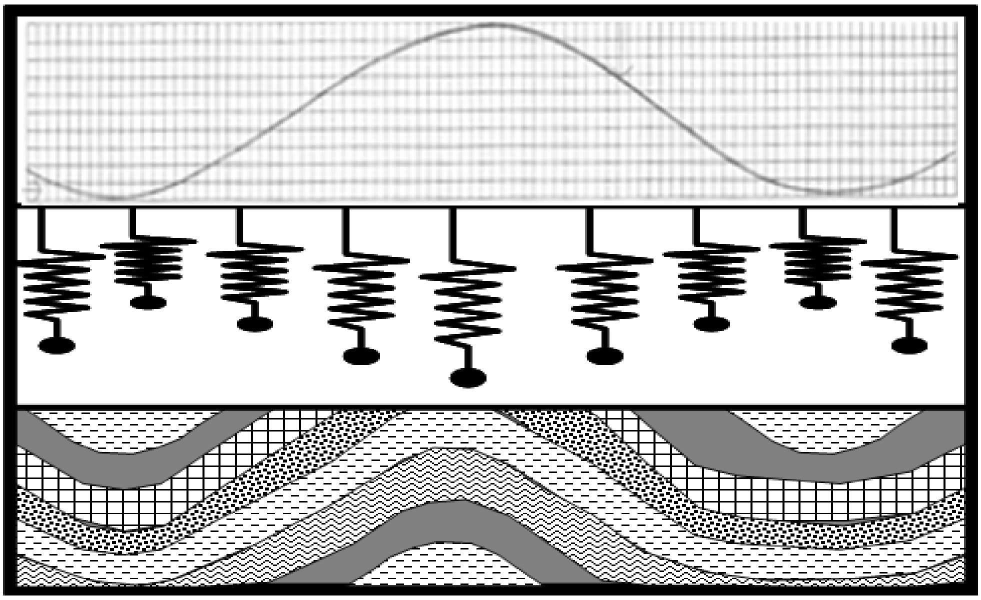


**Figure 4.2 Magnetic exploration technique.**

iii) Seismic Method: This method, which is the most effective in use at the present time for examining the earth's structure by use of geophysics, is based upon recording artificially generated shock waves that are reflected due to elastic discontinuities between different rocks. The two main methods now used are the "reflection" technique and the "refraction" technique. In both, an explosive charge or shock by means of a special truck is performed near the earth's surface. The shock waves travel down through rocks, are reflected or refracted upward, and recorded at selected points on the surface as shown in **Figure 4.3**.

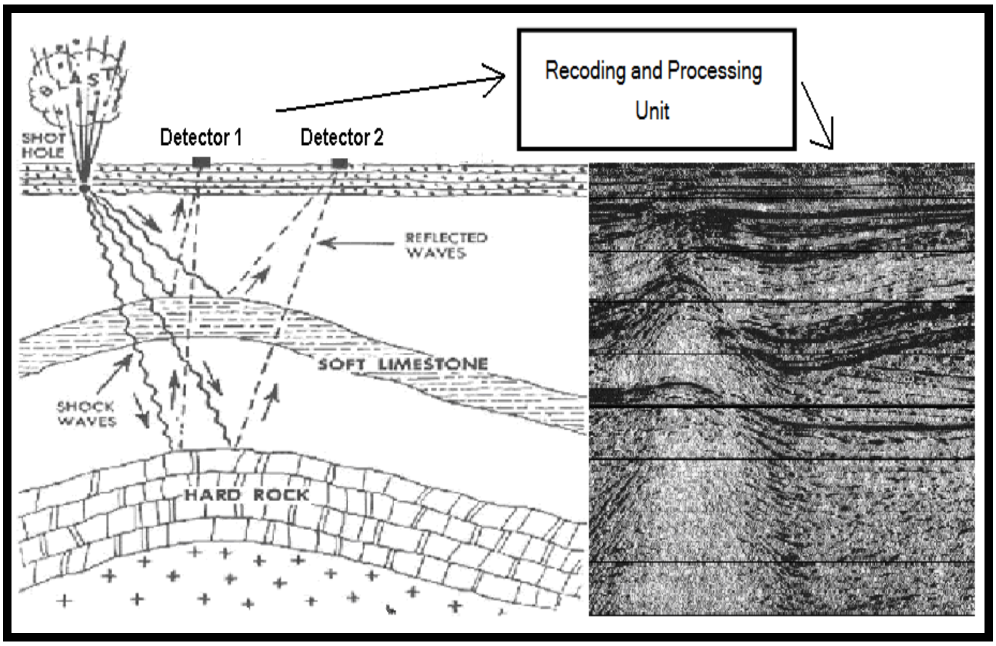



**Figure 4.3 Seismic exploration technique.**

Two definite measurements are recorded, the travel time for the waves and their velocities. From these measurements distances and depths can be calculated. In the reflection method, the explosion waves are reflected from surfaces of rocks at interfaces. The returning pulses are picked by geophones located at selected points on the surface. The geophones connected by wires to a central recorder where a high-speed detection device transfers the impulses to a chart. The refraction technique uses the principle that waves travel faster in the denser rocks than in those of lower density. Not only are the waves reflected but a portion of them is refracted along the elastic interfaces, particularly when the rock above the interface a velocity higher than the lower one. The geophones used in this method must be placed at much greater distances from the shot points than for the reflection method, and this distance may be as ten miles or more. The quantity of explosive used at the point also needs to be much larger and may be several tons in comparison with the few pounds used in the reflection technique. The main use of the refraction is for broad (large) scale exploration to define areas for more detailed examination by the more precise reflection technique.

In summary, the reflection seismograph technique in coordination with geological reasoning has been by far the most successful tool in finding oil and natural gas. The gravimeter and magnetometer methods have been more useful in explorations searching for large structural features such as salt domes. **Table 4.1** shows seismic activities worldwide.

### 4.2.6 Electrical Exploration

Electrical exploration methods depend on the great differences in resistance to the passage of electric current offered by rocks of various types, and can disclose useful information about rocks buried beneath relatively thin mantles of surface soil or alluvium. Methods based on the same principle are used much more extensively in the course of drilling wells, to identify the formations drilled through and to assess their fluid content.

**Table 4.1 Worldwide seismic exploration teams activities, 2009.**

| Location | September 2005 | September 2006 | September 2009 |
|---|---|---|---|
| Africa | 28 | 47 | 74 |
| Canada | 8 | 12 | 15 |
| Former USSR Countries | 27 | 44 | 47 |
| Europe | 18 | 24 | 36 |
| Middle East | 14 | 14 | 35 |
| Far East | 47 | 43 | 73 |
| Latin America | 21 | 21 | 36 |
| USA | 36 | 63 | 75 |
| World total | 219 | 268 | 391 |

### 4.2.7 Drilling Exploration

In view of the great cost of a deep exploration well, exploration surveys by one or more of the previously mentioned methods, though costly, will save much money. After the geologists and geophysicists have found what appears to be a favorable location for drilling, the prospect is sometimes further checked by drilling a number of small diameter holes, several hundred feet deep, with a light portable drilling rig. When all data have been assembled and a prognosis has been made of the layers to be expected at depth, a location is selected for an exploration well and deep drilling is started. There are many potential sources of important information my be obtained while drilling a well. Some of these information sources may provide data not otherwise available from other sources, or confirm data obtained from one or more of the potential sources of information. These include rock cuttings, reservoir fluid samples, mud logs, cores, well logs and Drill Stem Tests.

i) Rock Cuttings: During the drilling operation, rock removed from the subsurface formations by the drill bit, are being returned to the surface on a continuous basis. These samples are analyzed in order to describe the subsurface geology and for indications of hydrocarbon presence within the cuttings. A cuttings analysis with well depth is used to complete a stratigraphic column as a summary of subsurface geology.

ii) Core Samples: When a formation of interest is encountered while drilling, one of the most important sources of downhole information is the core of the reservoir rock. A typical core is a rock cylinder, normally 4" to 6" in diameter, of the reservoir rock retrieved from the wellbore to the surface in a core barrel. The core is sent to the laboratory for analysis. Potential information obtained includes rock type, rock characteristics, source of the sediments, depositional environments, porosity, permeability, radioactive properties and estimates of fluid saturations in the rock. Sidewall cores, which are less than 1" in diameter and less than 3" in length, can be taken instead of the full hole cores which can be 30 – 60 feet in length.

iii) Reservoir Fluid Samples: Reservoir fluid samples are collected from any reservoir rocks that are of potential interest. These fluid samples are sent to the laboratory for a PVT analysis. This provides important reservoir fluid data such as chemical composition, fluid formation volume factors, bubble point pressure, solution gas oil ratio, viscosity and density.

iv) Mud Logs: The drilling fluid, pumped through the inside of the drill string and exiting the drill bit while drilling, carries rock samples back to the surface in the drilling mud. When drilling into a rock formation containing hydrocarbons, traces of reservoir fluids encountered will be returned to the surface in the drilling mud. Surface samples of the mud are collected and analyzed for hydrocarbon presence. This is known as a mud log. The mid log contains description of the rock type based on inspection under a microscope, plot of penetration rate, gas composition based on gas chromatography, oil cut based on washing the cuttings in toluene and ultraviolet fluorescence to determine presence of oil.

v) Well Logs: A log of a well is a determination of downhole properties relative to depth. Many types of logs are run in a borehole, depending upon the information desired and equipment available. Typical logs run are electric logs, magnetic logs, sonic logs, radioactive logs and physical logs of various types. Properties measured by these logs may include pressure, temperature, rock density, porosity, permeability, fluid saturations, magnetic properties, radioactive properties and sonic velocity. In most instances more than one log are run simultaneously during a logging run.

The first well may reveal a commercial reservoir, but usually more than one well will be necessary, the first wells giving only geological information or sufficient shows of oil or gas to justify further drilling before a final judgment is passed on the value of the area (see **Figure 4.4**). All wells drilled to discover accumulations of oil are “exploration wells”, commonly known, especially by the drillers, as 'wildcats' a designation emphasizing the hazards and the speculative nature of drilling in a new area.

A successful wildcat is called a “discovery well”, an unsuccessful one is called a “dry hole”. After oil has been discovered, the next three wells; normally called “outstep appraisal" wells; are drilled to confirm the size and quality of the discovered field. All subsequent wells being "exploitation" wells or "development" wells. If the discovery well "prove" an oilfield, data from this well and appraisal wells are used in drawing up temporary plans for the development of the discovered oil or natural gas field. The development plans are revised when further information are obtained. At this stage, a new field will then have been added to the world's oil and natural gas map.

## 4.3 Contour Maps

Contour maps are one of the most effective means of displaying exploration data for a specific area. A contour line connects points of equal value. If a contour line represents an elevation on the surface of the earth ground, it is called a topographical contour. A map showing topographical contours for an area is called topographical map. If such a contour line represents an elevation of a rock layer below ground surface, then it is called structural contour as shown in **Figure 4.5**. A map showing structural contours for an area is called structural map. Structural maps are very important way for identification of geological structures (traps) below earth surface.

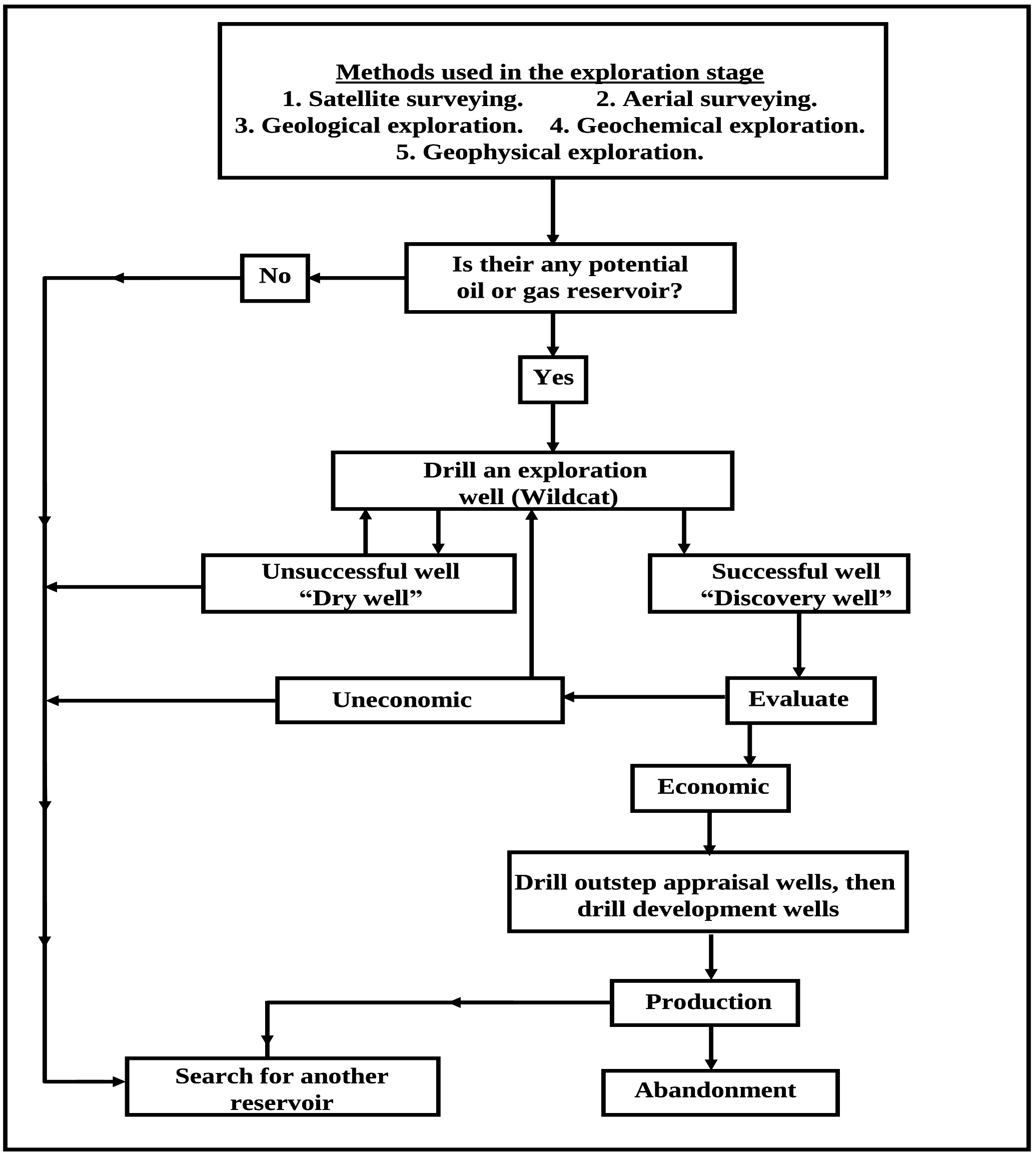



**Figure 4.4 Oil and natural gas exploration and development process.**

## 4.4 Basis of Petroleum Field Development

The development of petroleum fields from initial exploration through evaluation and into subsequent development can vary in length depending upon the size of the field, its complexity, and the environment in which the field is located. The various phases of the development of an oil or natural gas field are as follows:

i) Exploration: In this stage, several exploration techniques are conducted searching for potential geological structures (traps). Surface and subsurface structural maps are produced at this stage.

ii) Discovery, Evaluation and Development: After completing the exploration stage of an oil or gas field, exploration, discovery and appraisal wells are drilled. Reserve, lithology, petrophysical properties (porosity, permeability, etc.), saturations, productivity, etc. are estimated at this stage by the utilization of data obtained from core testing, logging and well testing. If the reservoir is found commercially feasible, numerous other wells are drilled for production, injection and monitoring. The total number of these wells depends on the size and geology of the field. After sometime, infill wells are drilled to enhance recovery from this field if necessary.

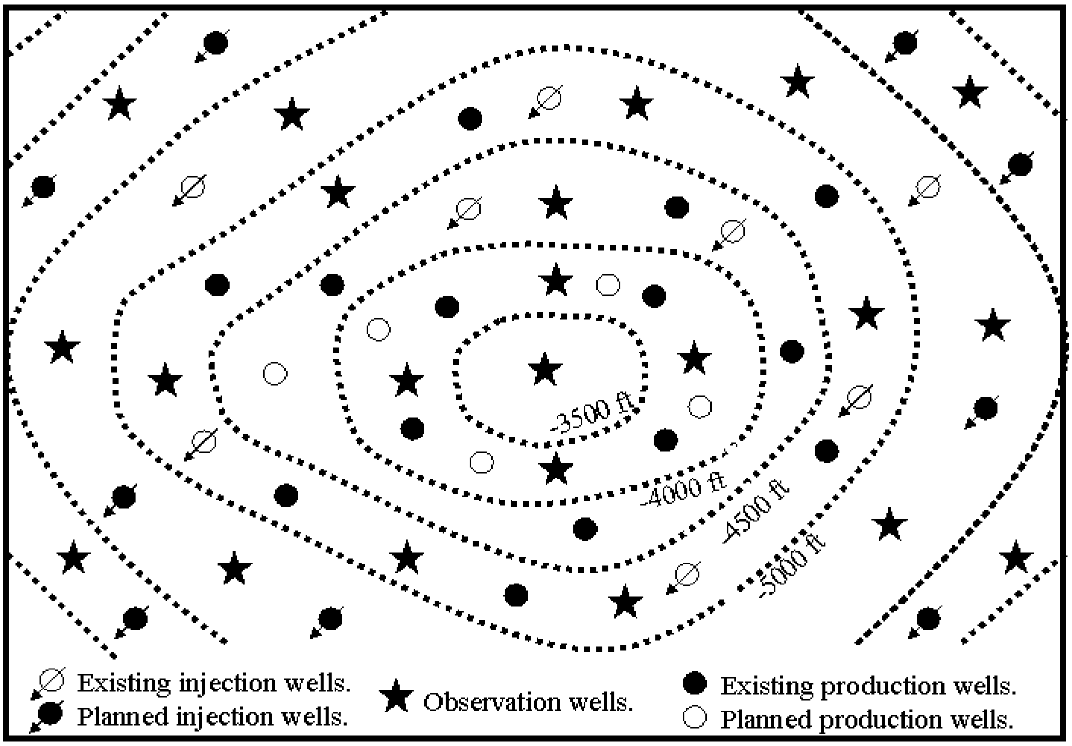



**Figure 4.5 Typical development scheme of petroleum reservoirs.**

iii) Production and Utilization: The main goal in this stage is to achieve maximum rate for maximum period possible at maximum safety for personnel, reservoir, and the environment. After the drilling program is completed, the gathering pipelines network is constructed and production is directed to the gas-oil separation plant (GOSP) to remove water, gas, salts, and solids from the produced hydrocarbons.

iv) Abandonment: Development and workover processes continue if the economic limit is not reached. The reservoir abandonment process starts by closing wells that can no longer produce oil or gas economically, i.e., the cost of well maintenance and its production will exceed the revenue coming from hydrocarbon production. When the last well in the field is closed, the field is known as “depleted field”.

# CHAPTER FIVE
# Chemistry of Petroleum

## 5.1 Introduction

The word "petroleum" came from Latin "Petro" means rock and "Oleum" means oil. It is gaseous, liquid or solid mixture of many hydrocarbons and hydrocarbon compounds occurring naturally in rocks. Crude oil is composed of a mixture of many substances, from which various refined petroleum products (such as gasoline, kerosene, fuel oil, and lubricating oil) are obtained. These substances are mainly composed of carbon (C) and hydrogen (H), and are therefore called hydrocarbons. Other elements, such as oxygen (O), sulfur (S), and nitrogen (N), may also be present in relatively smaller quantities, together with traces of phosphorus (P) and heavy metals like vanadium (V) and nickel (Ni). Despite wide variations in the chemical composition of crude oil and natural gas, their elemental compositions are shown in **Tables 5.1** and **5.2**.

**Table 5.1 Typical elemental composition of crude oil.**

| Element | Composition, % |
|---|---|
| Carbon | 84-87 |
| Hydrogen | 11-14 |
| Sulfur | 0-3 |
| Nitrogen | 0-1 |
| Oxygen | 0-2 |

**Table 5.2 Typical composition of typical natural gases.**

| Hydrocarbons | | |
|---|---|---|
| Name and symbol | | Volume % |
| Methane | $CH_4$ | 70 – 98 |
| Ethane | $C_2H_6$ | 1 – 10 |
| Propane | $C_3H_8$ | Trace – 5 |
| Butane | $C_4H_{10}$ | Trace – 2 |
| Pentane | $C_5H_{12}$ | Trace – 1 |
| Hexane | $C_6H_{14}$ | Trace – 0.5 |
| Non-Hydrocarbons | | |
| Name and symbol | | Volume % |
| Nitrogen | $N_2$ | Trace – 15 |
| Carbon dioxide | $CO_2$ | Trace – 1 |
| Hydrogen Sulfide | $H_2S$ | Trace |

Under normal surface conditions of pressure and temperature all gases will be separated from the crude oil and therefore it is called dead oil. The principal compounds in petroleum are paraffins, naphthenes, and aromatic hydrocarbons, with subordinate amounts of asphaltic-type materials. A typical example of crude oil composition is shown in **Table 5.3**.

**Table 5.3 Typical composition of crude oil.**

| Hydrocarbons | Composition, weight % |
|---|---|
| Paraffins | 28 |
| Naphthenes | 45 |
| Aromatics | 18 |
| Asphaltenes | 9 |

Natural gas is a gaseous mixture under both reservoir and normal surface conditions of pressure and temperature (see chapter two). Breaking down of long-chain hydrocarbons to shorter-chain hydrocarbons with release of free carbon is called thermal degradation (cracking). In the other hand, recombining hydrocarbon chains in different ways to produce various petrochemicals is called reforming. Burning of hydrocarbons in the presence of oxygen resulting in generation of energy, carbon dioxide, and water is called oxidation.

## 5.2 Types of Chemical Compounds in Petroleum

Since the bulk of the chemical compounds found in petroleum are hydrocarbons, it is necessary to know the chemistry of these compounds. As the name implies, a hydrocarbon is a compound consisting of carbon and hydrogen only. Even though only two elements are present, the number of compounds of this type is very large. This is due to the fact that the carbon atom has the ability to combine with itself and form long chains. The hydrocarbons may be classed according to structure of the molecule. The classes of hydrocarbon are:

### 5.2.1 The Chain Aliphatic Hydrocarbons Series

#### 5.2.1.1 The Paraffin Saturated Hydrocarbons

They are very important class of hydrocarbons that are found in petroleum. These series are characterized by:

i) The fact that the carbon atoms are arranged in open chains (i.e. not closed rings).
ii) Have single bonds. That is, one valence of each carbon is used to form the chemical bond between adjacent carbon atoms in the chain. These hydrocarbons are said to be saturated since they contain all the hydrogen atoms possible.
iii) They are characterized by their chemical inertness.
iv) The first four members of these series are gases under standard conditions of temperature and pressure (60 $^oF$ and 14.7 psi). Those from $C_5H_{12}$ to $C_{17}H_{36}$ are liquids. From $C_{18}H_{35}$ upwards these hydrocarbons are colorless, wax like solids.
v) The general formula of these series is $C_nH_{2n+2}$.
vi) The name of these series are ending with -ane, the simplest member of these series is the methane of a structural formula as follows:
vii) Due to the branching of the carbon chains after propane (n=4) the isomerism phenomena occurs in this group of hydrocarbons.

Hydrocarbons compounds that have the same molecular formula but have different structures and consequently different physical and chemical properties are called isomers.

#### 5.2.1.2 The Unsaturated Hydrocarbons

They are very reactive. Because of their high reactivity, these hydrocarbons are not found in crude oil to any great extent. This series is characterized by:

i) The bonds between the carbons are double or even triple bonds, so these compounds will add more hydrogen under appropriate conditions and they are said to be unsaturated.

ii) They are very reactive.

According to the number of bonds this group can be divided to:

A) The Olefin Series: This group is characterized by:
i) It has one double bond.

ii) Isomerism occurs not only due to the branching but the position of the double bond in the molecule is also a source of isomerism.

iii) The general formula for this series is $C_nH_{2n}$.

iv) The name of this series has the suffix -ene, in the case of the isomers the position of the double bond is indicated by number located after the name. For example,

v) $CH_2 = CH - CH_2 - CH_3$ named butene-l, and
vi) $CH_3 – CH = CH - CH_3$ named butene-2,

vii) The simplest member of this series is ethylene whose structure is: $CH_2 = CH_2$

B) The Diolefin Series: This group is characterized by:
i) They have two double bonds in the molecule.

ii) The general formula for this series is $C_nH_{2n-2}$.

iii) Their name have the suffix -adiene, the positions of the two double bonds are indicated by two numbers placed after the name.

For example,

$CH_2 = CH – CH = CH_2$ is named as butadiene-l,3

C) The Acetylene Series: This group is characterized by:
i) It has triple bond.

ii) The name has the suffix –ine.

iii) The general formula for this series is $C_nH_{2n-2}$.

iv) The first member of this series commonly named acetylene has the structure shown below:

$CH \equiv CH$ is known as Acetylene $C_2H_2$

### 5.2.2 The Naphthene Cyclic Hydrocarbon Series

The Naphthene hydrocarbons are also called cyclo-paraffins not including benzene ring. They are characterized by:

i) They are saturated in which the carbon chains form closed rings.

ii) The general formula for this series is $C_nH_{2n}$.

iii) They are named by placing the prefix cyclo- before the name of the corresponding paraffine hydrocarbon.

These compounds, being saturated, are very stable and are important constituents of crude oil.

### 5.2.3 The Aromatic Cyclic Hydrocarbon Series

These hydrocarbons are also cyclic and may be considered to be derivatives of benzene ($C_6H_6$). It consists of a six-metered ring with alternate single and double bonds. **Table 5.4** summarizes the main hydrocarbon.

## 5.3 Naming of Hydrocarbons

Generally, every organic substance should have a completely descriptive and systematic name representative to its structure. In additional to rules shown in Table 5.3, naming of hydrocarbons is shown in **Figure 5.1**. The structural formulas of some hydrocarbons are shown in **Figure 5.2**.

**Table 5.4 Summary of main hydrocarbon types and structure.**

| Properties | | | Molecular formula | Suffix or Prefix |
|---|---|---|---|---|
| Aliphatic type | Chain | The Paraffinic saturated hydrocarbons (Single bond) | $C_nH_{2n+2}$ | -ane |
| | Chain | The Olefinic unsaturated hydrocarbons (One double bond) | $C_nH_{2n}$ | -ene |
| | Chain | The Diolefinic unsaturated hydrocarbons (Two double bonds) | $C_nH_{2n-2}$ | -adiene |
| | Chain | The Acetylene unsaturated hydrocarbons (One triple bonds) | $C_nH_{2n-2}$ | -ine |
| | Cyclic ring | The Naphthenic saturated cyclic Hydrocarbons | $C_nH_{2n}$ | Cyclo- |
| Arenes type | Cyclic ring | The Aromatic unsaturated cyclic Hydrocarbons | $C_nH_{2n-6}$ | Cyclo- |

## 5.4 The Importance of Hydrocarbons and Its Derivatives

The most important application for hydrocarbons and its derivatives are:

i) For use in internal combustion engines,

ii) Heat and electricity generation, and

iii) Manufacturing of lubricants, asphalts, solvents, waxes and hundreds of other petrochemical products.

## 5.5 Petrochemical Industries

The main objective of the petrochemical industry is to add-value to the abundant hydrocarbon resources. The petrochemical industry, which produces chemicals using oil and natural gas as major raw materials, occupies an important position in worldwide manufacturing and consuming sectors. Oil and natural gas are composed primarily of hydrocarbons. Most petrochemicals contain hydrogen or carbon or both. Petrochemicals can be converted into thousands of industrial and consumer products, including plastics, paints, rubber, fertilizers, detergents, dyes, textiles and solvents.

The industry consists of two major divisions:

i) The primary petrochemical industry produces basic chemicals, such as ethylene from oil or gas, and

ii) ii) The secondary industries convert the basic petrochemicals into materials that may be directly used by other industries.

In Saudi Arabia, the establishment of Saudi Basic Industries Corporation (SABIC) in 1976 is a milestone in the Kingdom's development of viable basic and downstream petrochemical and supporting industries, which utilizes local resources of hydrocarbons and minerals, as raw materials.

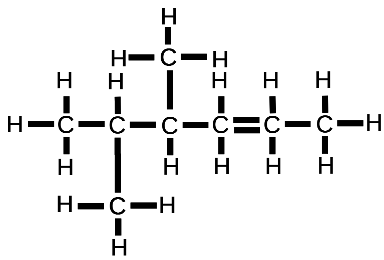
| Example: 2,3- DiMethyl-Hexene-4 | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2,3 | - | Di = 2 | Methyl | - | Hexene | - | 4 |
| Places of Attachments | - | Number of Attachments | Names of Attachments | - | Name of Hydrocarbon | - | Places of Double Bonds |
| Molecular formula: $C_nH_{2n}$ or $C_8H_{16}$<br>Group: Olefinic<br>Structural formula: | | | | |  | | |

**Figure 5.1 Method of hydrocarbons naming.**

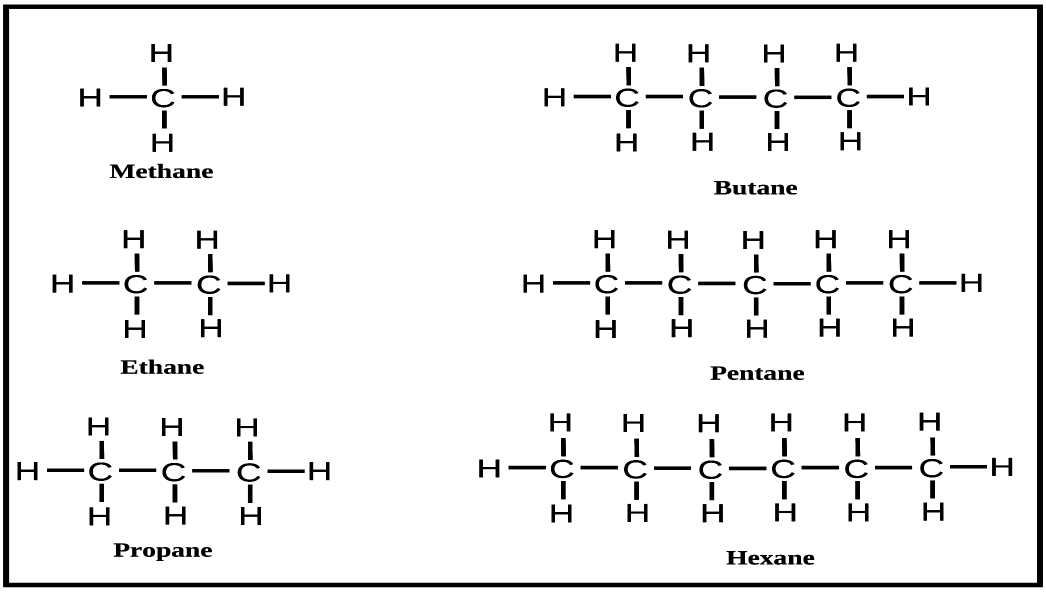



**Figure 5.2 Structural formulas of some hydrocarbons.**

# CHAPTER SIX
# Petroleum Well Drilling Engineering

## 6.1 Introduction

The History of oil well drilling technology is studied with the familiar names of Colonel E. Derrick. The emergence of commercial use for petroleum in the mid-1880s accelerated the development of equipment and techniques used to drill for oil. The earliest oil wells were drilled percussively by hammering a “cable tool” into the earth. Soon after, cable tools were replaced with “rotary drilling”, which could drill boreholes to much greater depths and in less time. Modern wells drilled using rotary drilling can achieve lengths of over 25,000 feet.

Until the 1970s, most oil wells were “vertical” (although different lithology and mechanical imperfections cause most wells to deviate at least slightly from true vertical). However, modern directional drilling technologies allow for strongly “deviated or directional” wells which can, given sufficient depth and with the proper tools, actually become “horizontal” (see **Figure 6.1**). This is of great value as the reservoir rocks which contain hydrocarbons are usually horizontal, or sub-horizontal; a horizontal wellbore placed in a production zone has more surface area in the production zone than a vertical well, resulting in a higher production rate. The use of deviated and horizontal drilling has also made it possible to reach reservoirs several kilometers or miles away from the drilling location (extended reach drilling), allowing for the production of hydrocarbons located below locations that are either difficult to place a drilling rig on, environmentally sensitive, or populated.

Drilling for hydrocarbons is undertaken practically any where that potential reservoir rock exists. Surface environments of oil well drilling locations can be categorized as either “onshore” (land) or “offshore” (marine). Although in certain parts the difference is rather difficult, e.g. onshore environments in some places are vary drastically from desert to mountain. Below the surface, conditions are a little less variable but far from pleasant. In general, drilling difficulty increases with increased depth. Most of the sediments in the sedimentary basins in which drilling is conducted were deposited along with, or later invaded by, water. Consequently, the porous rocks of the petroleum reservoir and the formations above it are full of water.

In many cases the oil and natural gas accumulations make up little of the total volume of the fluids saturating the reservoirs and their associated aquifers. It is the column resulting from all this water, reaching up towards the surface that causes the pressure encountered in the fluid filled pore space of the reservoir rock. The pressure at different depths increases according to the density of the water, the rate of pressure increase, or gradient, will increase with salinity.

An oil well is a term for any hole through the Earth's surface designed to find and produce both oil and natural gas hydrocarbons. The establishment and life of an oil or natural gas well is divided into five stages: planning, drilling, completion, production and abandonment.

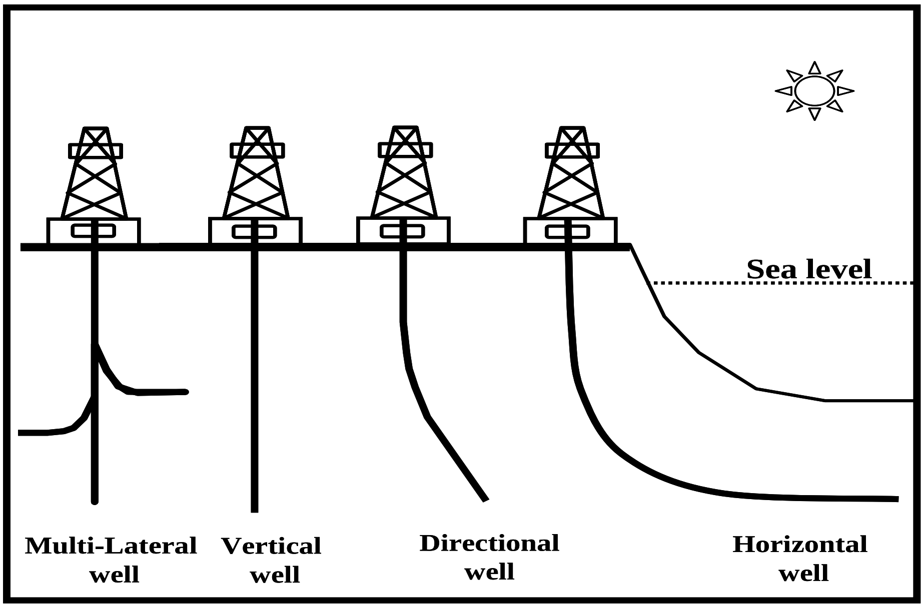



**Figure 6.1 Types of oil and natural gas wells.**

## 6.2 Drilling Technology

Cable tool or percussion drilling is recognized by many as the first drilling method employed to dig wells into the earth for the purpose of reaching petroleum deposits or water. This method is still in use in some of the shallow wells, although rotary drilling has taken over the bulk of modern drilling activities. Due to huge demand for oil and natural gas, exploration and drilling activities are growing rapidly worldwide as shown in **Table 6.1**.

**Table 6.1 Worldwide drilling rig activities, 2009.**

| Location | August 2005 | | August 2006 | | August 2009 | |
|---|---|---|---|---|---|---|
| | Onshore | Offshore | Onshore | Offshore | Onshore | Offshore |
| Canada | 541 | 5 | 479 | 3 | 379 | 2 |
| Europe | 25 | 46 | 21 | 56 | 49 | 49 |
| Middle East | 173 | 31 | 225 | 31 | 247 | 34 |
| Africa | 78 | 20 | 98 | 25 | 50 | 15 |
| Latin America | 242 | 66 | 265 | 61 | 307 | 79 |
| Asia-Pacific | 134 | 112 | 135 | 113 | 134 | 119 |
| USA | 1338 | 102 | 1643 | 100 | 1813 | 65 |
| World total | 2531 | 382 | 2688 | 389 | 2979 | 363 |

### 6.2.1 Cable Tool Drilling Method

Cable percussion (cable tool) drilling is the oldest, simplest, and most reliable technology available for borehole drilling (see **Figure 6.2**).

It will drill any formation and is completely self contained and requires no mud, bits, pumps, chemicals, etc. The basic concept for cable tool drilling consists of repeatedly dropping a heavy metal bit into the ground, eventually breaking through rock and punching a hole through to the desired depth. The bit, usually a blunt, chisel shaped instrument, can vary with the type of rock that is being drilled.

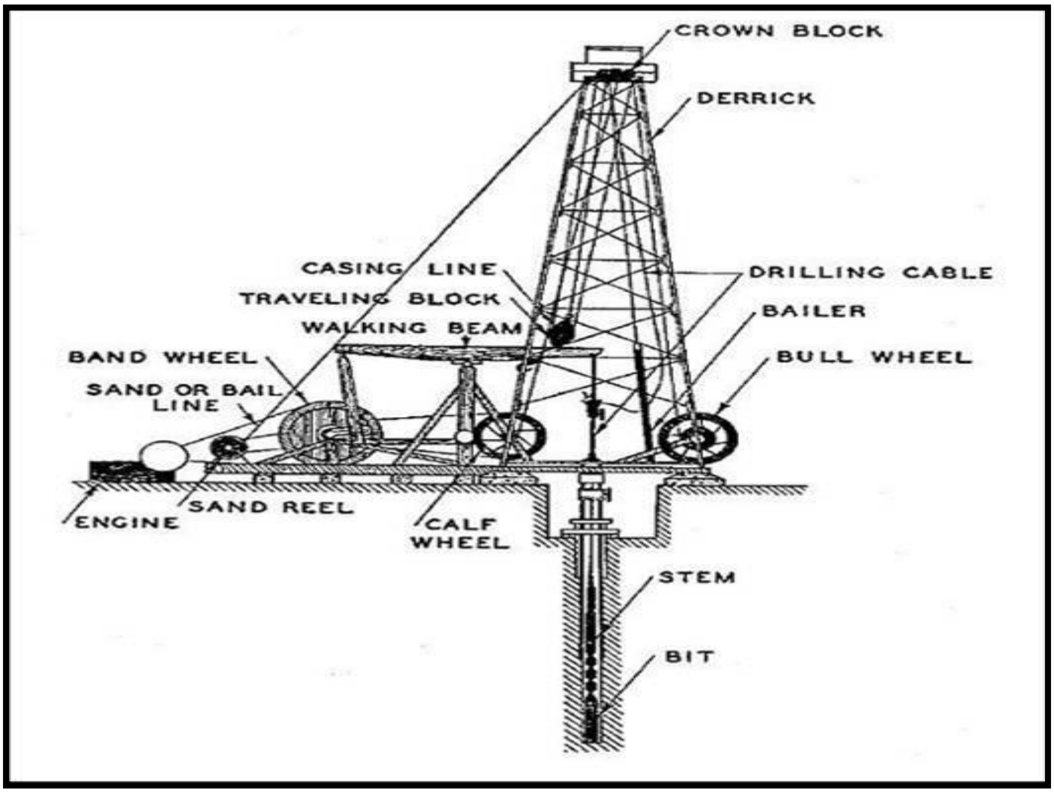



**Figure 6.2 Cable tool drilling method.**

Water is used in the borehole to combine with all of the drilled cuttings, and is periodically bailed out of the well when this "mud" interferes with the effectiveness of the drill bit. The limitations of this method are:

i) It is suitable only for shallow wells of small and invariable diameters.
ii) Only vertical wells can be drilled using this drilling method.
iii) There is no system to control the flow of formation fluids.

### 6.2.2 Rotary Drilling Method

The basic drilling equipment for the early rotary rig has not changed much as far as function is concerned, although its capabilities have been largely expanded to meet modern drilling needs. Rather simple stated, torque needs to be transmitted from a prime power source to a bit via drill stem; a drilling fluid needs to be able to circulated down the drill stem through the bit, and back up through the annulus to the surface; and a subsurface encountered pressure needs to be controlled. Performing these functions in various ranges of environments (offshore and onshore) has led to variety of rig designs. Rotary drilling rigs are generally are categorized as onshore (land) rigs or offshore (marine) rigs. Onshore rigs are all similar, while offshore rigs fall into one of several categories, each design to suit a certain type of offshore environment as shown in **Table 6.2** and **Figure 6.3**.

The advantages of rotary drilling method are:
i) It is suitable for both shallow and deep wells of variable diameters.
ii) Vertical, directional and horizontal wells can be drilled using this drilling method.
iii) The flow of formation fluids into wellbore can be controlled in this drilling method.

## 6.3 Basic Rotary Drilling Rig Components

The basic components of rotary drilling rig are:

i) The Rig (Derrick).
ii) Hoisting system.
iii) Rotating system.
iv) Mud circulating system.
v) Pressure controlling system.

### 6.3.1 The Derrick

The principal components of a rig that perform drilling function are shown in the attached figure. The derrick supports the crown block and traveling block, which are operated via the drawworks and its drilling line. The Kelly and swivel are connected to the drillstring and are suspended from the hook beneath the traveling block, allowing the Kelly and drillstring to be turned by the rotary table. A drilling fluid circulation system pumps mud from the bits through stand pipe, hose, swivel, and drillstem returning the mud and the cuttings up the annulus and back to the pits. The blowout preventer (BOP) stack and its operating equipment allow the drilling crew to maintain control over subsurface pressures.

### 6.3.2 Hoisting System

It is responsible for handling up and down drillpipes, drillcollars and drillbit during drilling operations. It includes drawworks, crown block, traveling block and the drilling string lines.

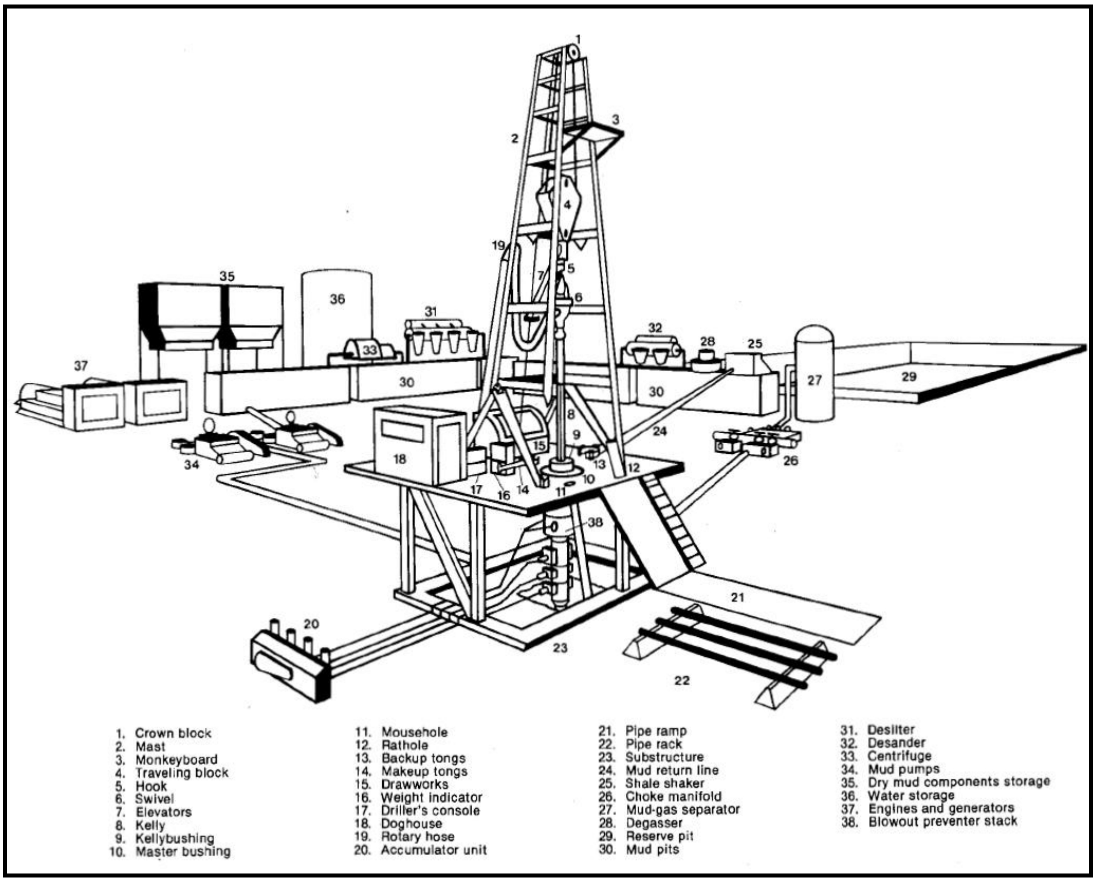



**Figure 6.3 Rotary drilling rig.**

**Table 6.2 Types of rotary drilling rigs.**

| Onshore rotary drilling rigs | Offshore rotary drilling rigs |
|---|---|
| • Light rigs (3000 ft – 5000 ft).<br>• Medium rigs (4000 ft – 10000 ft).<br>• Heavy rigs (12000 ft – 16000 ft).<br>• Ultra-heavy rigs (18000 ft – 25000 ft). | • Jack up rigs.<br>• Platform rigs.<br>• Submersible rigs.<br>• Drill ships. |

### 6.3.3 Rotating System

This system is responsible for the rotation of the drillstring (Bit, drillcollar and drillpipes) during drilling operations. The rotation action is done by:

i) A rotary table for shallow vertical wells drilling or

ii) A top-drive motor in case of deep vertical wells drilling or

iii) A downhole motor in case of highly deviated or horizontal well drilling.

### 6.3.4 Mud Circulating System

This system is responsible for the circulation of a drilling fluid necessary for carrying drilled cuttings from the borehole up to surface. Cooling and lubrication the drilling bit is important functions of any rotary drilling rig. It includes mud tank and pit, mud pump and shale shakers.

### 6.3.5 Pressure Controlling System

It is responsible for controlling the subsurface pressure that may encountered while drilling by means of a system called blowout preventer (BOP). The blowout preventer is a series of powerful sealing elements designed to close off the annulus between the pipe and hole, where the mud is normally returning to the surface. By closing off this rote, the well can be shut-in and the mud/or formation fluids forced to flow through a controllable choke.

## 6.4 Basic Functions of Drilling Fluid

The general functions of drilling fluids (mud) are:

i) To cool and lubricate the drillbit and the drillstring.
ii) To remove and transport rock cuttings from the bottom of the hole to the surface.
iii) To suspend rock cuttings during non-circulation periods.
iv) To control encountered subsurface pressure.

## 6.5 Type of Drilling Fluids

Drilling fluids are classified as follows:

i) Air or mist.
ii) Clear water (Fresh or Sea water).
iii) Water-base mud:
   a) Fresh water + Bentonite + Additives.
   b) Seawater + Attapulgite + Additives.
   c) Water + Polymers + Additives.

iv) Oil-base mud (Emulsion or Invert emulsion).

## 6.6 Optimum Drilling Fluid Density Design

Mud density design is a vital element in the overall drilling program design. Any miscalculation in mud density will cause series unrecoverable problems such as kick or in worst cases blowouts.

Step 1: Optimize formations pore fluid pressure using the following equation:

$$P_p = 14.7 + \left(W_g \times TVD\right) \qquad \ldots(6.1)$$

Where:

$W_g$ = Less than 0.433 psi/ft for subnormal pressure.

$W_g$ = Greater than 0.433 psi/ft and less than 0.465 psi/ft for normal pressure.

$W_g$ = Greater than 0.465 psi/ft and less than or equal to 1.0 psi/ft for abnormal pressure.

Usually, pore pressure of a subsurface formation is slightly different from values calculated based on the above assumptions. When impermeable rocks such as shales are compacted rapidly, their pore fluids cannot always escape and must then support the total overlying rock column, leading to abnormally high formation pressures. Excess pressure, called abnormal pressure, overpressure or geopressure, can cause a well to blow out or become uncontrollable during drilling. Severe under pressure or subnormal pressure can cause the drillpipe to stick to the underpressured formations.

Step 2: Calculate optimum drilling mud pressure using the following equation:

$$P_m = P_p + (\text{Safety margin between 100 to 200 psi}) \qquad \ldots(6.2)$$

The calculated mud pressure must satisfy the following conditions:

$$(P_p + 100 \text{ to } 200 \text{ psi}) \le P_m \le P_f \qquad \ldots(6.3)$$

Step 3: Optimum mud density can be calculated as follows:

$$\rho_m = \frac{P_m}{0.052 \times TVD} \qquad \ldots(6.4)$$

Where:

$P_p$ = Formation pore fluid pressure, psi.

$P_f$ = Formation fracturing pressure, psi.

$P_m$ = Drilling fluid (mud) pressure, psi.

$W_g$ = Water column pressure gradient, psi/ft.

$\rho_m$ = Drilling fluid (mud) density, ppg.

TVD = Well true vertical depth, ft.

## 6.7 Casing-Bit Design

Oil or natural gas well drilling process is divided into several steps. In each step part of the well is drilled, cased and cemented. After the completion of any section, the size of the drill bit must be reduced to drift inside the previously cemented casing. **Figure 6.4** is bottom-to-top casing-bit design chart.

To use this chart, production casing must be selected based on the completion requirements necessary for a given reservoir. Typical casing program is consisting from the following casing strings arranged from surface to full well depth (see **Figure 6.5**):

i) Conductor pipe: The conductor pipe may also be called drive pipe for offshore wells since it may be driven in to the seafloor with a pile driver until a specific refusal point is reached. The main function of the conductor pipe is to support the wellbore through the unconsolidated materials present in the surface hole. It is therefore desirable to set the conductor pipe either on solid rock or into solid rock. A second function of the conductor is to protect the wellbore near the surface from washout, which may result from circulation of the drilling mud from the lower section of the wellbore, and therefore to restrict the well diameter at the surface to the inside diameter of the conductor.

ii) Surface casing: The surface string serves a primary function of protecting the surface environment from contamination from downhole fluids such as hydrocarbons and drilling mud. This environmental protection requirement makes the cementing of the surface casing to the surface necessary. Once the surface string is run, a bolt flange connection is welded to the top of the casing to which the BOP stack will be attached. The combination of the casing head and BOP stack will protect against blowout during further drilling operations. It is important that the surface string be set at sufficient depth within solid rock to provide protection against downhole pressures.

iii) Intermediate casing: A primary function of intermediate strings or liners is to seal off zones of high fluid pressures. The determining factor for this casing point will be to drill through an impermeable rock formation below the high pressure reservoir, thereby permitting further drilling with a less dense drilling mud. A second function of intermediate strings or liners is to seal off zones of lost circulation, which can occur when drilling a low pressure reservoir. Another function of intermediate strings or liners is to seal off zones of wellbore washout in unconsolidated sandstones or sensitive shales.

iv) Production casing: The production string or liner is that casing through which the reservoir fluid will be produced. This casing is run all the way through the reservoir and set some depth below it. The casing depth is therefore dependent on the depth of the bottom of the reservoir and the amount of rat-hole required for that particular well. It is usually desirable to produce hydrocarbons through production tubing rather than through the production casing in order to minimize exposure to possible corrosion from the reservoir fluids. The production casing may also serve the functions of sealing off high pressure zones, zones of lost circulation, and zones of potential wellbore washout.

## 6.8 Wellheads, Chocks, and Subsurface Safety Valve

Wellheads are the connection points for the tubing and the surface flow lines as well as being the surface control point in all wells. The selection of the wellhead is based on the pressure, temperature and corrosivity of the produced fluids. Both the casing and tubing strings are landed in the wellhead.

The casing also acts as a conduit allowing for all types of workover operations. Wellheads plays a major role in preventing on controlled flow from downhole, through it's configuration of valves.

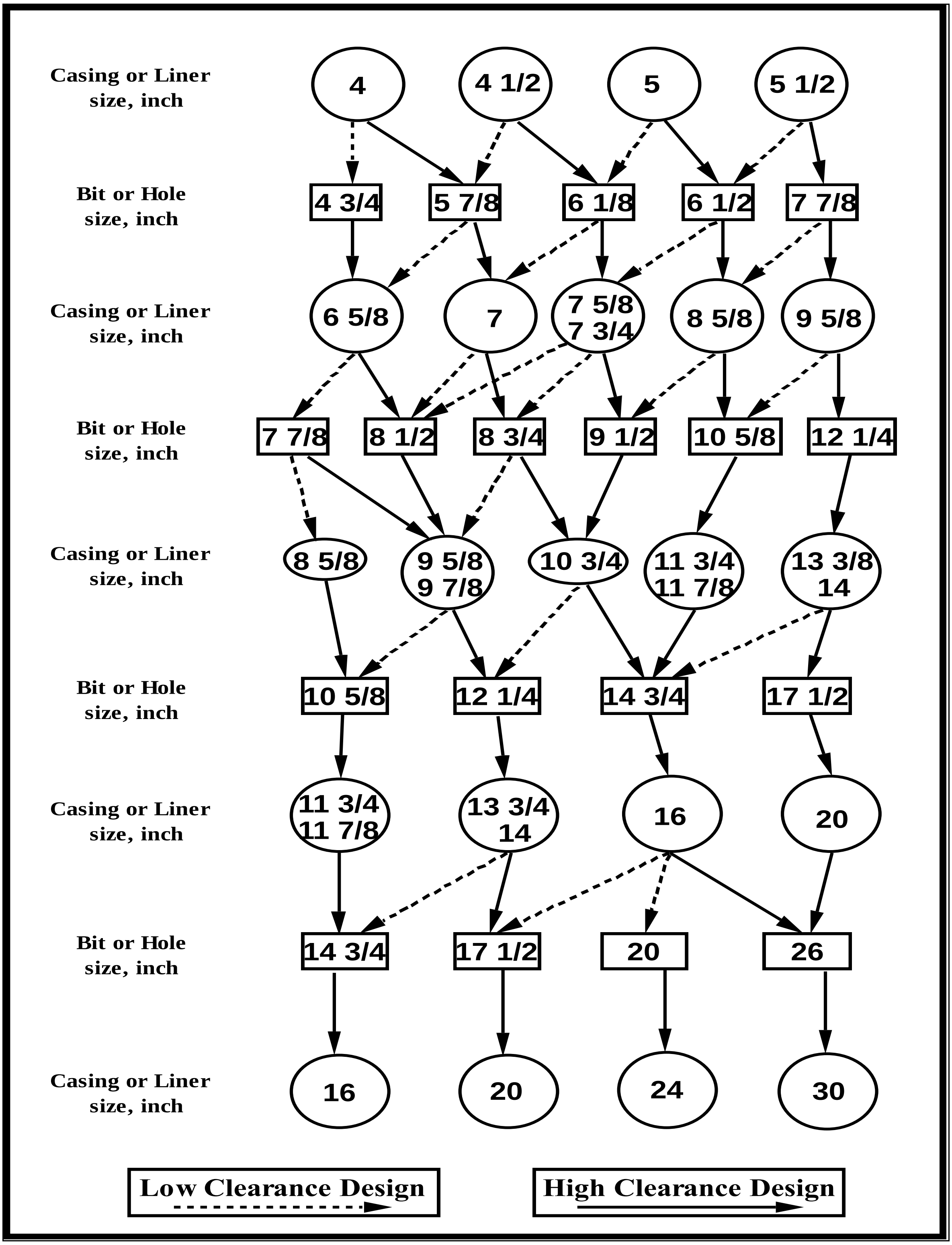



**Figure 6.4 Bottom to top casing-drill bit design configuration.**

The production choke can be used to control the production flow rate of the well and hence the drawdown. The drawdown is the difference between the reservoir pressure and the flowing bottomhole pressure. This is very important in preventing sand entry into the wellbore. If the drawdown is too high, the cohesive forces due to the cementing material between the sand grains within the rock can be exceeded. This will result in sand grains becoming loose and flowing into the wellbore. This can result in plugged tubing, washed out choke and plugged flow line. The choke could be either adjustable or fixed choke (with a bean inserted). Adjustment of the choke and hence the flow rate can maintain a bottomhole pressure above the bubble point, preventing the breakout of gas out of solution at the bottom of the well. This guarantees only liquids flowing into the well. A downhole safety valve refers to a component on an oil and gas well, which acts as a failsafe to prevent the uncontrolled release of reservoir fluids in the event of a worst case scenario surface disaster. It is almost always installed as a vital component on the completion. These valves are commonly uni-directional flapper valves which open downwards, such that the flow of wellbore fluids try to push it shut, while pressure from surface pushes it open. This means that when closed, it will isolate the reservoir fluids from surface. Most downhole safety valves are controlled hydraulically from surface, meaning they are opened using a hydraulic connection linked directly to a well control panel. In addition to manual control, the downhole safety valve operates automatically, in case of accidents, by means of the high pressure difference.

## 6.9 Petroleum Well Cementing Job

The purpose of primary cement job in an oil well is to fill the annular space between a string of casing and the openhole as shown in **Figure 6.5**. Squeeze cementing is selective cementing downhole, within the casing. This technique might be used to seal off casing leaks caused by corrosion or to repair channels that occur behind the casing during primary cementing.

The main functions of cement are:

i) Restriction of fluid movement between permeable zones.
ii) Provision of mechanical support of the casing string.
iii) Protection of casing from corrosion.
iv) Prevention of wellbore collapse by supporting the wellbore sides.

Major properties of oil and natural gas wells cement that taken into account during drilling design are: slurry density, thickening time, compressive strength, tensile strength, bonding strength, filtration, permeability, corrosion resistance and perforating quality.

## 6.10 Petroleum Well Completion

Well completion is a link between drilling and production stages. Well completion involves: treating to remove skin or permeability damage, equipping the well with screens, gravel packs, production tubing, subsurface safety valves, etc. Well completion is function of well type (production, injection of observation wells). The main types of well completion are:

i) Openhole Well Completion: This is the simplest of all completion types, where casing is run and cemented just above the producing zone. The pay section is drilled with a non-damaging fluid as shown in **Figure 6.6-i**.

ii) Single-zone Cased-hole Well Completion: In this completion, casing is run and cemented to the bottom of the pay zone. In some cases the well is drilled and cased beyond the pay zone, leaving a “rat hole” below the perforated zone as shown in **Figure 6.6-ii**.

iii) Multiple-zone Cased-hole Well Completion: Conventional Multiple Completion is utilized when there are two zones in a well that contain significantly different reservoir pressures.

If both are produced together and allowed to mix, some production from the higher pressure zone will preferably flow into the lower pressure zone, especially when the well is shut in. Thus it is necessary to isolate production from both zones. This is achieved by placing a dual packer between both zones and allowing flow up two different tubing strings as shown in **Figure 6.6-iii**. There are several other well completions that apply for special cases such as (iv) Gravel Packs and Screens Well Completion (**Figure 6.6-iv**) and v) Horizontal Well Completions (**Figure 6.7**).

### 6.11 Perforating

Perforations are holes through casing and cementing to permit entry of fluids. The perforations must be placed opposite the productive zones and are designed to penetrate both the casing and the cement placed behind it, thus allowing communication between the permeable part of the reservoir and the borehole. Perforating involve running in perforating guns, a string of shaped charges, down to the desired depth and firing them to perforate the casing or liner, the cement around it, and move deep into the formation.

### 6.12 Cores and Coring Techniques

Cores are the best source for petrophysical and geological information. Cores cane be obtained either during well drilling phase using coring bits or by side-well coring if open-hole completion the case as shown in **Figure 6.8**. Cores obtained by side-well coring method are small in size and limited in quantity. When cores are brought to surface, they must be stored in airtight containers to preserve them in the downhole state until the time of laboratory testing. Details such as well no., depth, coring interval, and reservoir name must be labeled on the storage container.

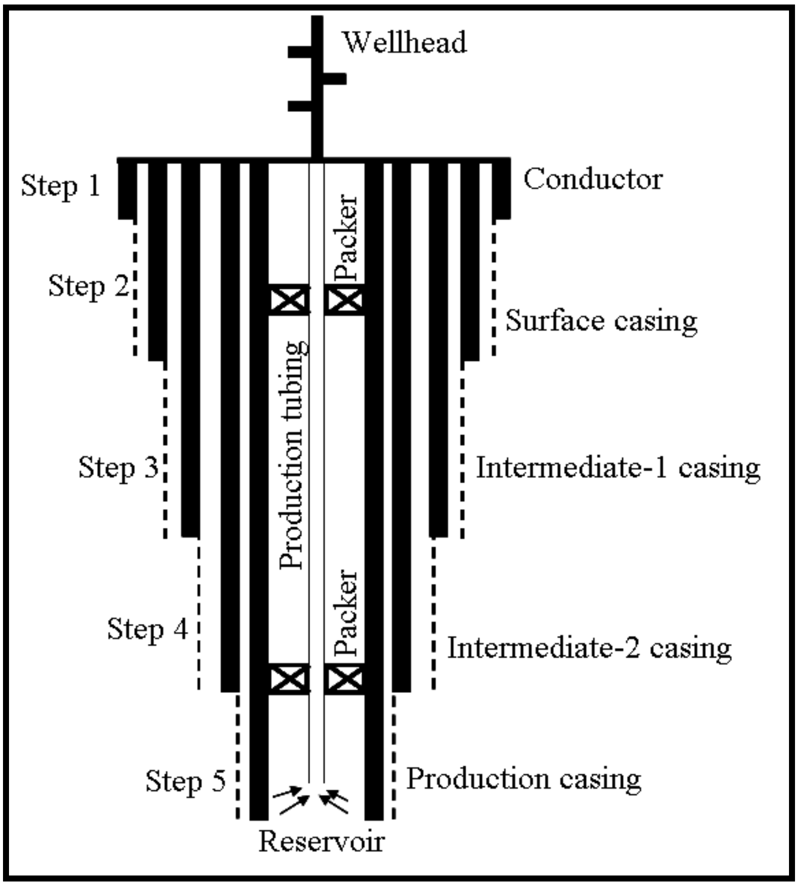



**Figure 6.5 Casing configuration for typical petroleum well.**

## 6.13 Offshore Drilling

A major difference between onshore and offshore drilling is the nature of the drilling platform. In addition, in offshore drilling the drillpipe must pass through the water column before entering the lake or seafloor. Offshore wells have been drilled in waters as deep as 10,000 ft. The following text provides an overview of drilling in offshore environments (see **Figure 6.9**).

Offshore drilling requires the construction of an artificial drilling platform, the form of which depends on the characteristics of the well to be drilled. There are two types of basic offshore drilling platforms:

i) The movable drilling rig (ship), and

ii) The permanent drilling rig.

The first type is typically used for exploration purposes, while the second is used for the extraction and production of oil and/or gas. A variety of movable rigs are used for offshore drilling.

i) Jack-up rigs are towed, but once on location three or four legs are extended to the lake bottom while the working platform is raised above the water surface; thus, they are much less affected by wind and water current.

ii) Submersible rigs are also employed in shallow waters and, like jack-up rigs, are in contact with the lake bottom. These rigs include platforms with two hulls positioned above one another, with the lower hull acting like a submarine. When being towed to a new location, the lower hull is filled with air and serves to float the entire platform. Once on location, the lower hull is filled with water, and the rig sinks until the legs make contact with the lake bottom.

iii) The most common movable offshore drilling rig is the semi-submersible rig. It functions in a similar manner to the submersible rig, with a lower hull that can be filled or emptied of water. However, this type of rig does not contact the lake floor but floats partially submerged and is held in place through a number of anchors. This type of rig provides a stable and safe working platform in deeper and more turbulent offshore environments, and when high reservoir pressures are expected.

iv) The final type of movable drilling rig is the drillship. These are ships designed to carry drilling platforms great distances offshore and in very deep waters. A drilling platform and derrick are located in the middle of a large, open area of the ship, and the drill is extended through the ship.

When exploratory drilling locates commercially viable oil or gas deposits, a more permanent drilling platform is required to support well completion and oil and/or gas extraction. A variety of such production platforms are used for offshore drilling. Fixed platforms are typically used in areas with water depths less than 1,500 ft and would be the most likely type of production platform that would be used in the Great Lakes. These platforms contact the bottom using concrete or steel legs and are either directly attached to, or simply rest on, the bottom. A variety of other production platforms are available for deeper water conditions and would probably not be applicable for use in the Great Lakes.

## 6.14 Drilling Operations Management

Drilling rigs vary in size depending on the environment and drilling program. A small onshore drilling rig may have crew of five to six individuals, while an offshore rig drilling a deep exploration well in remote location may have several crews and groups of specialists totaling forty to fifty persons. Job descriptions and the organization are universal and can be described as follows:

i) The Operator: is the company or organization responsible for conducting operations on a concession on behalf of holders or government.
ii) The Contractor: is the company responsible for conducting the drilling of the well for the specified target.

iii) The Drilling Engineer: is the operating company representative person on location who is responsible for the safe, efficient execution of the drilling program according to the operating company policies.

iv) The Tool Pusher: is the person in charge of rig and overall drilling operations and drilling rig and maintenance of its equipment.

v) The Driller: is an experienced person who is responsible for major drilling operations and equipment repairs.

vi) The Service company Personnel: They are ordered out to location by the drilling representative (drilling engineer) in most cases. These individuals and their equipment are on hand for special jobs such as running casing, cementing casing, logging and fishing for stuck pipe.

Modification to this general organization plan may be found in some cases. However, in all cases the primary goal is a team that works together safely and efficiently.

### 6.15 Petroleum Well Drilling Cost

Oil and natural gas wells drilling cost depends on several factors including:

i) Well depth.
ii) Lithology and Location (Offshore or Onshore).
iii) Well inclination (Vertical, Directional or Horizontal).
iv) Well diameter.

Normally, the drilling cost is estimated in $/ft. The total drilling cost includes, drill bits costs, drilling fluids cost, casing strings cost, cementing jobs cost, rig rental cost … etc.

### 6.16 Measurement While Drilling

The measurement while drilling tool (MWD) assesses the lithology and determines the presence of hydrocarbons as the drill-bit penetrates. Electric logs run at each casing seating point and at the total depth, help assesses the nature of the drilled through layer, the presence of oil and/or natural gas in the reservoir section and the quality of the reservoir rock. Mud logs provide a record of the well cuttings and hydrocarbon content as the well being drilled.

Core samples of the reservoir formation are retrieved to look for characteristics of reservoir. Usually, service companies perform these logging tests and petroleum engineers interpret the resulting logs to determine if the well is a success or failure (dry). After reaching the target depth, the drillstring is pulled out and the well is evaluated using drillstem test. A drillstem test is used to evaluate the openhole section of the well. Integration of drillstem data with other logs leads to completion type decision or abandonment of the well.

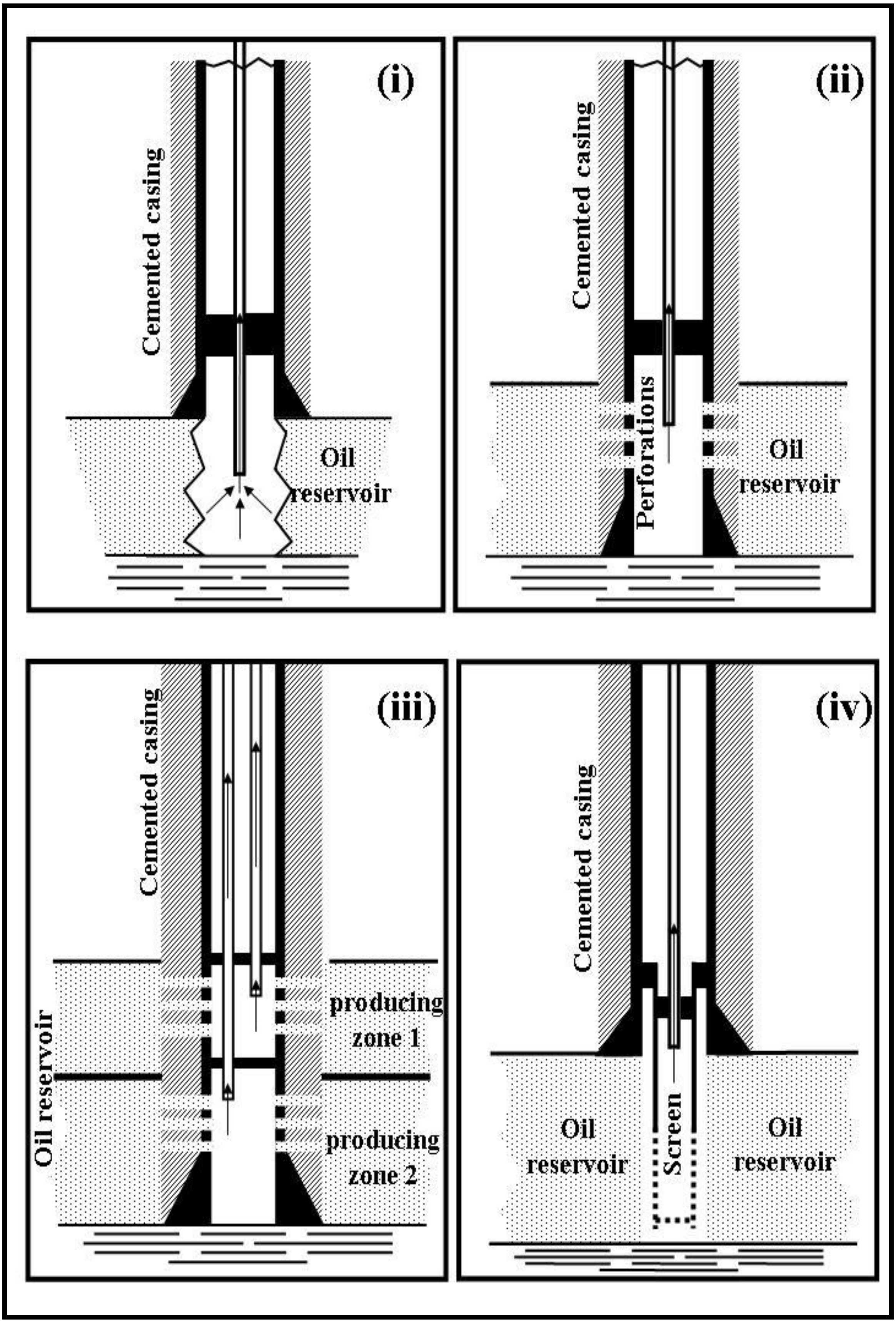



**Figure 6.6 Petroleum well completion types.**
**i) Open hole completion, ii) Conventional perforated completion,**
**iii) Multiple zone completion, and iv) Slotted liner screen or gravel packs.**

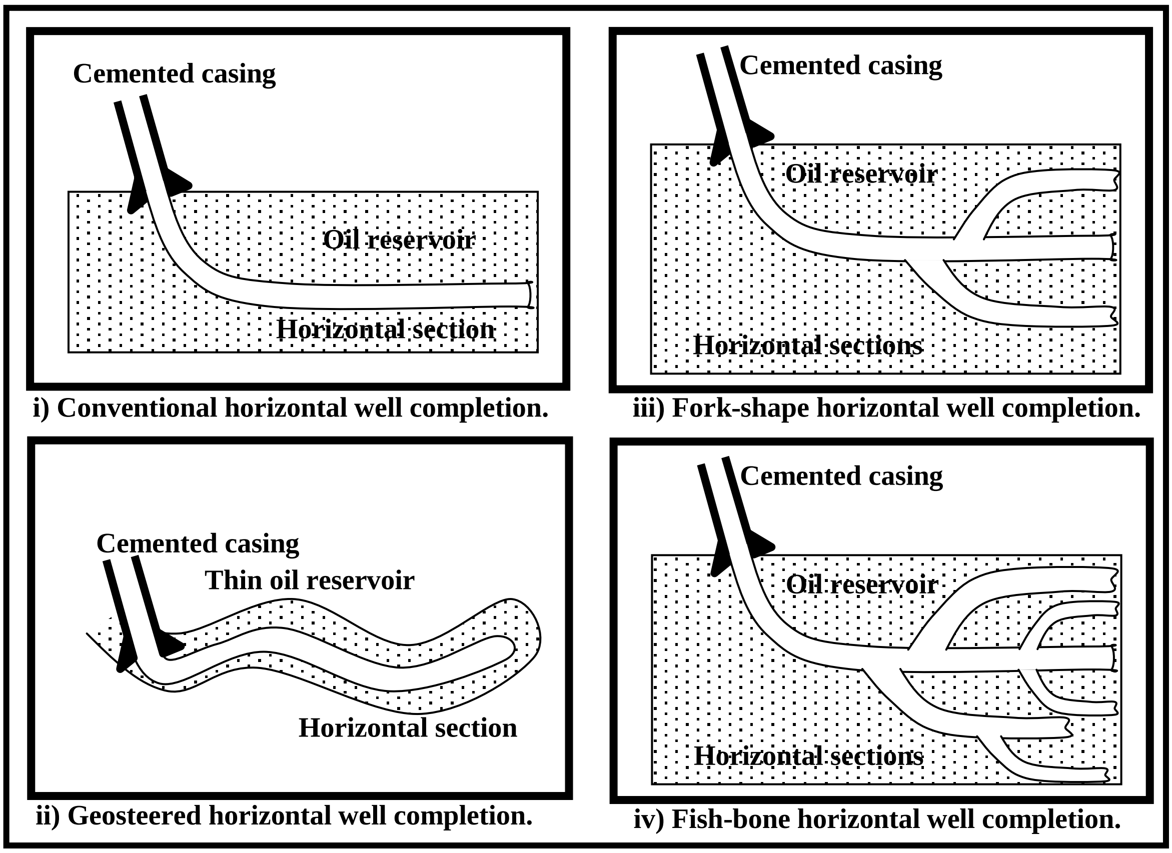



**Figure 6.7 Various types of horizontal well completions.**

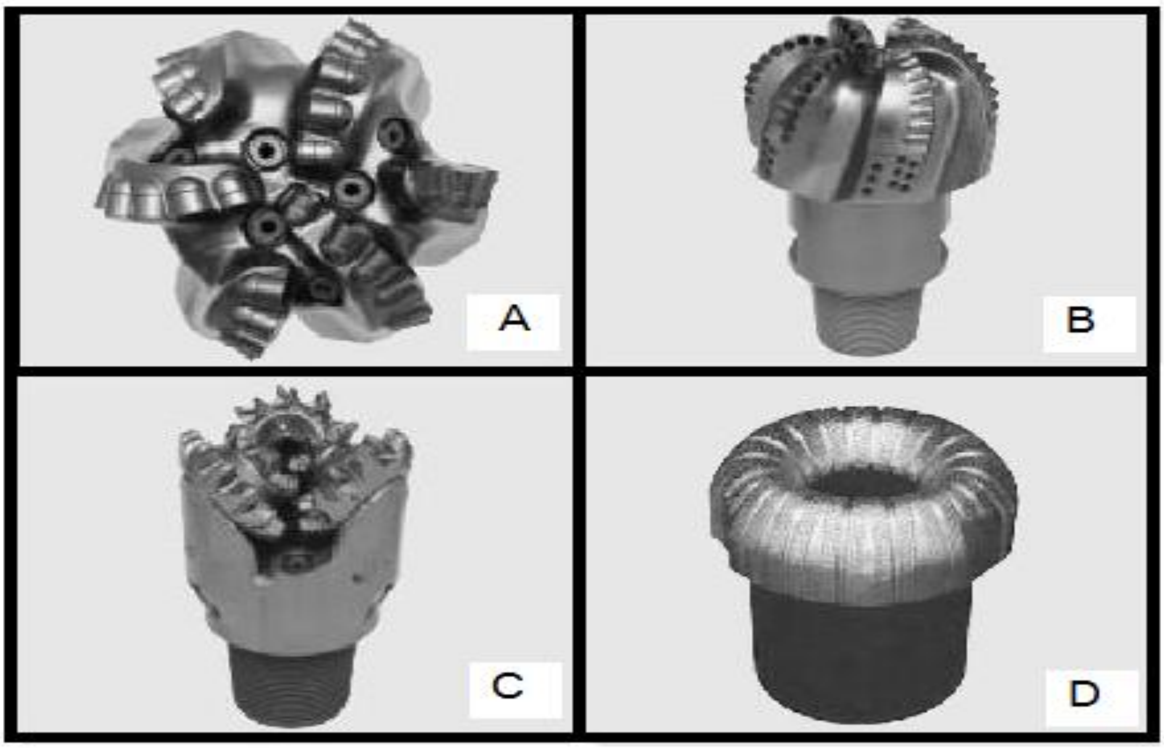



**Figure 6.8 Rotary drilling (A, B and C) and coring (D) bits.**

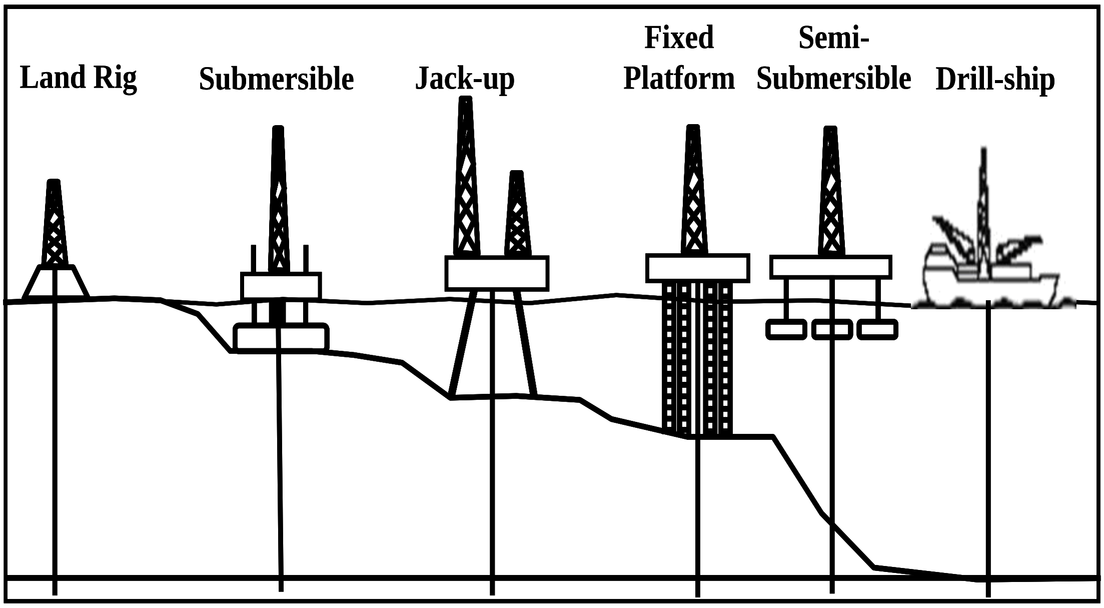



**Figure 6.9 Types of offshore drilling techniques.**

# CHAPTER SEVEN
# Oil and Natural Gas Reservoirs Rocks Properties

## 7.1 Introduction
The knowledge of reservoir rock properties such as porosity, permeability, and fluids saturations are essential for reservoir characterization, production calculations, and reserves estimation. Porosity represents the storage volume where water, oil and natural gas are stored while permeability represents the ease of which these stored fluids can move from one pore to another towards the production well.

## 7.2 Porosity
Porosity ($\phi$) is the voids between sand grains or matrix which is filled by petroleum and brine water. Porosity types are presented in the following sections.

### 7.2.1 Absolute Porosity
Absolute pororsity ($\phi_a$) is the ratio of the total pore volume (interconnected plus sealed pores) to the total bulk volume of the reservoir rock on percentage basis, that is:

$$\text{Absolute porosity} = \left[\frac{\text{Total pore volume}}{\text{Bulk volume}}\right] \text{x } 100 \qquad \text{or} \qquad \phi_a = \frac{V_p}{V_b} \text{ x} 100 \qquad \ldots(7.1)$$

The pores of the rock are very irregular in shape and size, and some pores are sealed. These sealed pores do not allow drainage of fluids from them.

### 7.2.2 Effective Porosity
Effective pororsity ($\varphi_e$) is the ratio of the interconnected pore volume to the total bulk volume of the reservoir rock on percentage basis:

$$\text{Effective porosity} = \left[\frac{\text{Effective pore volume}}{\text{Bulk volume}}\right] \text{x } 100 \qquad \text{or} \qquad \phi_e = \frac{V_p}{V_b} \text{ x} 100 \qquad (7.2)$$

Porosity of most reservoirs ranges from 5 to 40% and most commonly between 10 and 20%. The rock porosity can be evaluated as shown in **Table 7.1**. Carbonate reservoirs (limestone and dolomites) generally have slightly less porosity than sandstone reservoirs, but the permeability of carbonate rocks may be higher due to some compensating factors, such as fractures, fissures, vugs, and caverns. There are two types of porosities in sedimentary rocks, the first is called primary porosity and and the other is called secondary porosity.

### 7.2.3 Primary Porosity
It is established when sediment were deposited. Sandstone is a permeable rock having primary porosity, less permeable examples are shales and chalk. The primary porosity of a rock is largely dependent upon its packing characteristics, which in turn depends on the grain sorting, grain shape, and grain size. Also depends upon the compaction of grains,

the proportion of the matrix material, the degree of cementing, and the presence or the absence of fractures and vugs.

**Table 7.1 Porsity evaluation scale.**

| Scale | | Saudi reservoirs |
|---|---|---|
| Porosity Range, % | Evaluation | Sandstone: $\phi$ = 25 – 32%<br>Limestone: $\phi$ = 10 – 18%<br><br>Fluids in limestone reservoir like liquids in an Apple.<br><br>Fluids in sandstone reservoir like liquids in an Orange. |
| 0 – 5 | Negligible | |
| 5 – 10 | Poor | |
| 10 – 15 | Fair | |
| 15 – 20 | Good | |
| 20 – 25 | Very good | |

### 7.2.4 Secondary Porosity

It is prorosity of carbonate reservoir rocks. Secondary porosity may result from or modified by i) solution; ii) fractures and joints; iii) recrystallization and dolomitization; iv) cementation and compaction.

### 7.2.5 Induced Porosity

It is composed of an intentionally generated pore space to increase permeability of rocks surrounding wellbore. Artificial porosity includes perforations and hydraulic fracturs. Stimulation (acidization) of the reservoir rocks near the wellbore artificially increases both porosity and permeability of that section of the reservoir.

## 7.3 Measurement of Porosity

In laboratory, reservoir rock porosity can be calculated using core (plugs) by measuring any two of the following properties of the rock: i) Pore volume (Vp), ii) Bulk volume ($V_b$) or iii) Grain volume ($V_g$) as shown in **Figure 7.1**.

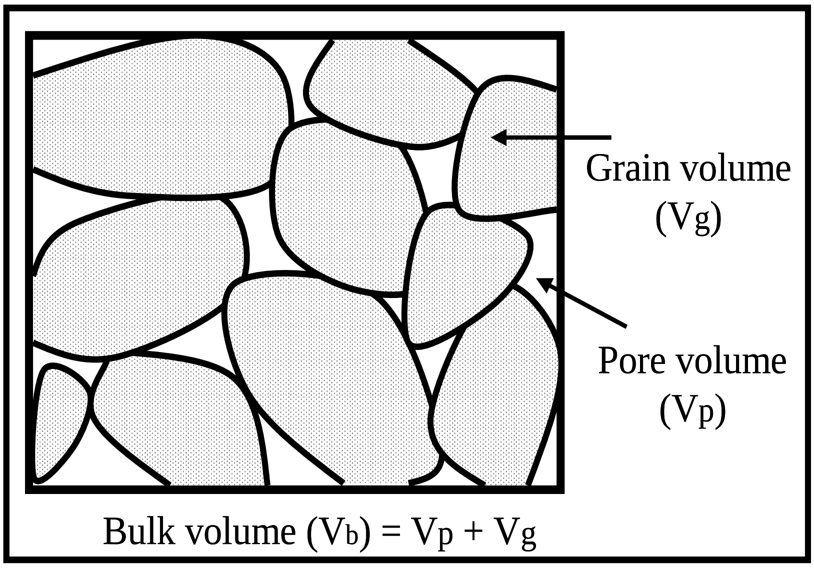



**Figure 7.1 Components of reservoir rock.**

Those three parameters are combined together in the following relationship:

$$V_b = V_p + V_g \qquad \ldots(7.3)$$

### 7.3.1 Measurement of Bulk Volume

i) Uniform Shaped Samples

For uniform shaped samples (cylindrical for example), bulk volume ($V_b$) can be easily calculated using standard mathematical expression such as the following one of cylindrically shaped samples:

$$V_b = \pi r^2 L = \frac{\pi}{4} D^2 L \qquad \ldots(7.4)$$

ii) Irregular Shaped Samples

For irregular shaped samples, the following methods are followed for bulk volume ($V_b$) calculation:

A) Immersion Method

i) Measure the weight of dry sample in air, $W_1$.

ii) Saturate the sample completely with fluid having a well known density, $\rho_L$.

iii) Measure the weight of the saturated sample in the air, $W_2$.

iv) Measure the weight of the saturated sample immersed in the fluid (see **Figure 7.2**), $W_3$.

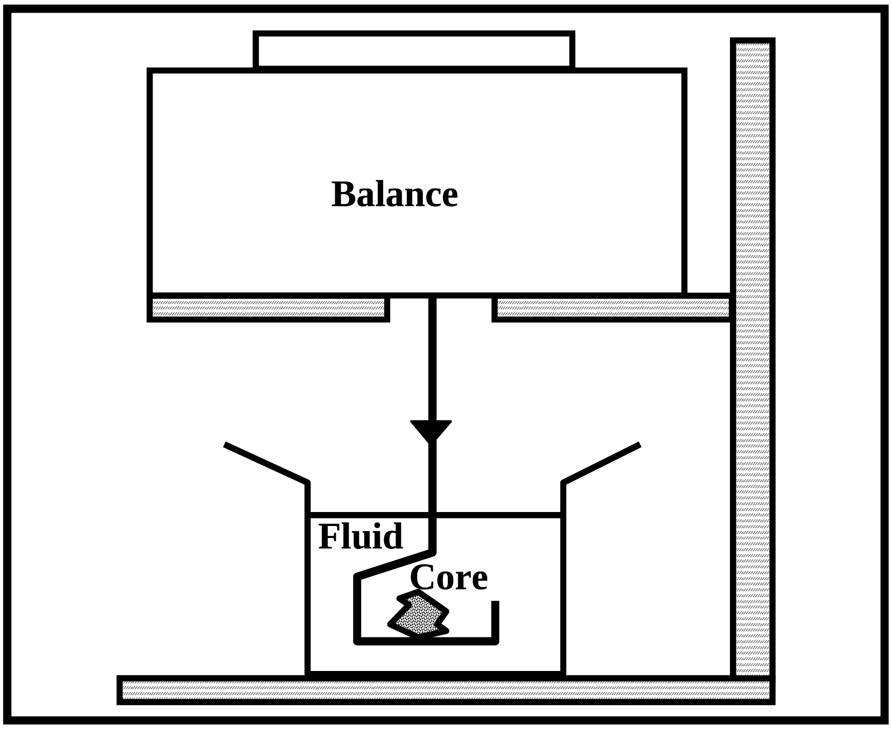



**Figure 7.2 Measurement of bulk volume using bouyancy technique.**

Using Archimedes rule, the bulk volume ($V_b$) of the sample can be calculated as follows:

$$V_b = \frac{W_2 - W_3}{\rho_L} \quad \text{and} \quad V_p = \frac{W_2 - W_1}{\rho_L} \qquad \ldots(7.5)$$

B) Mercury Pycnometer Method

To measure the bulk volume ($V_b$) using a mercury pycnometer (see **Figure 7.3**), the following steps are performed:

i) Weigh the dry sample in air, $W_1$.

ii) Weigh the pycnometer filled with mercury, $W_2$.

iii) Put the sample in the pycnometer (immersed in mercury by force) let excess mercury out. Clean the outside of pycnometer and weigh it again, $W_3$.

The bulk volume of the rock is equal to the volume of displaced mercury and can be written as follows:

$$V_b = V_{Hg} = \frac{W_1 + W_2 - W_3}{\rho_{Hg}} \qquad \ldots(7.6)$$

where:
$V_{Hg}$ = volume of displaced mercury, cc.
$\rho_{Hg}$ = mercury density at laboratory temperature, gm/cc.

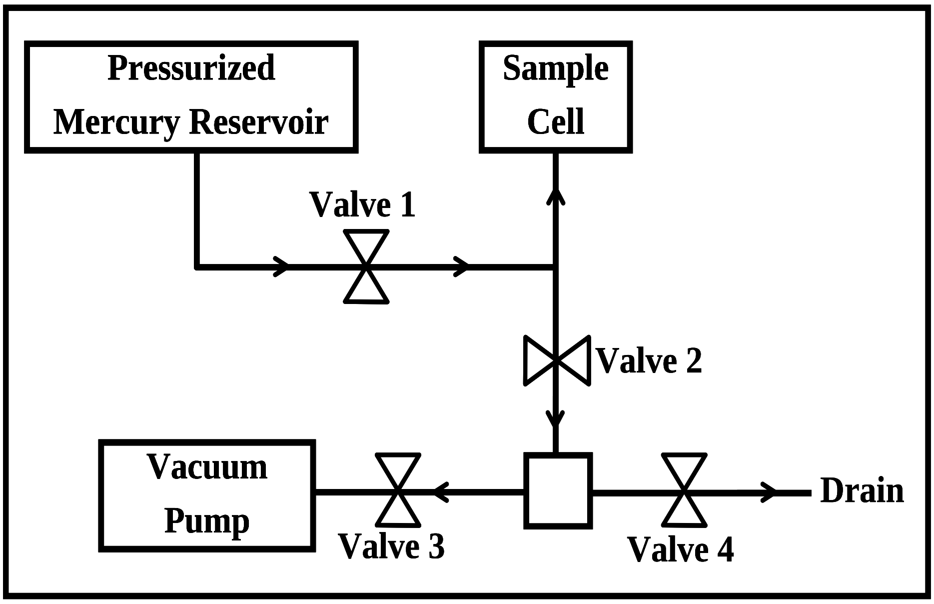



**Figure 7.3 Schematic diagram for mecury pycnometer.**

It must be noticed that, coating technique is used when rock samples contain reactive (swelling) clays and saturation technique is used when rock samples are free of reactive clays.

C) Coated Samples
In this method the sample is coated with a thin layer to prevent fluid invasion of the sample:

i) Weight the dry sample in air, $W_1$.

ii) Weigh the dry sample coated with substance such as paraffin, $W_2$.

iii) Weigh the coated sample in a liquid with a well-known density ($\rho_L$), $W_3$.

The bulk volume of the sample then is calculated as follows:

$$V_b = V_{coated} - V_{paraffin} \qquad \ldots(7.7)$$

$$V_{paraffin} = \frac{W_2 - W_1}{\rho_{paraffin}} \qquad \ldots(7.8)$$

$$V_{coated} = \frac{W_2 - W_3}{\rho_L} \qquad \ldots(7.9)$$

### 7.3.2 Measurement of Grain Volume

A) Crushed Sample Method
This method is used to measure sealed and interconnected pores.

i) Weigh the dry sample in air, $W_1$.

ii) Weigh the Pycnometer filled with fluid, $W_2$.

iii) Weight the Pycnometer filled with fluid and wet crushed sample $W_4$.

Then, the grain volume is given by:

$$V_g = \frac{W_1 + W_2 - W_4}{\rho_L} \qquad \ldots(7.10)$$

B) Gas Expansion Method
This method is used to measure the interconnected pores of intact samples. Two chambers are connected together via a valve. The pressure in the chamber containing the rock sample is higher than the pressure in the empty chamber as shown in **Figure 7.4**. The grain volume is calculated as follows:

$$V_g = V_2 + \left[\frac{P_3 - P_1}{P_3 - P_2}\right] V_1 \qquad \ldots(7.11)$$

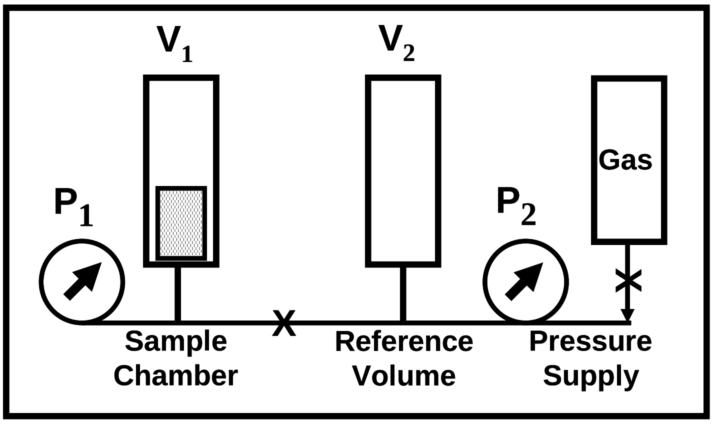



**Figure 7.4 Boyle's law porosimeter.**

In this test, the sample is placed in the sample chamber, and the valeve is opend to increase the pressure in the reference chamber. Then the valve for the reference volume chamber is closed and the valve between the two chambers is opend. Pressures in both chambers befor the connection valve and after pressure equilibrum are recorded and inserted into equation 7.11 to calculate sample grain volume.

## 7.4 Permeability

Permeability (k) is a measure of the fluid conductivity of a rock. Permeability is also defined as a rock characteristic that describes the ease with which liquid and gas may move through porous rock. High permeability indicates relative ease in moving through rock; low permeability indicates the opposite. Permeability of average reservoir rocks generally ranges between 5 and 1000 millidarcys and can be evaluated using the scale shown in **Table 7.2**.

**Table 7.2 Permeability evaluation scale.**

| Scale | | Saudi reservoirs |
|---|---|---|
| Permeability range, md | Evaluation | |
| 0.1 – 1.0 | Poor | k = 500 – 3000 md |
| 1.0 – 10 | Fair | |
| 10 – 100 | Good | |
| 100 – 1000 | Very good | |
| >1000 | Excellent | |

Commercial production has been obtained from rocks which permeabilities were as low as 0.1 md, but such rock may have highly permeable fracture system that are not revealed in the standard laboratory analysis. Permeability, as porosity, varies both laterally ($k_H$) and vertically ($k_V$) in the average reservoir rocks. Permeability in carbonate reservoir rock is often mainly due to fractures. In fractured reservoir, there are two systems of permeability: (i) the normal matrix permeability, where oil moves slowly through short distance into (ii) the high permeability fractures, where oil moves faster until it reaches the well bore.

The porosity of rock, the pore size, the type of connection between pores, and the size of connecting channels between pores are all related to permeability, which is measured in the unit called Darcy. However, a milliDarcy (one-thousandth of a Darcy), is commonly used unit for reservoir rocks. Permeability is classified as follows:

i) Absolute permeability: is the measurement of permeability conducted when a single fluid or phase is present. In other words, it is the permeability of a rock to a particular fluid at 100% saturation. Absolute permeability is independent of fluid type.

ii) Effective Permeability: is the ability of rock to transmit a particular fluid when other immiscible fluids are present. Effective permeability of a particular rock is dependent on fluid type.

iii) Relative Permeability: is the ratio of the effective permeability to a particular fluid to the absolute permeability.

### 7.4.1 Measurement of Absolute Permeability

In order to clarify the concept of the permeability and to see how it is defined, consider the following experiment. Suppose a cylindrical sample (core) of the porous rock is fully saturated with a liquid viscosity “$\mu$”.

Let "A" be the cross-sectional area of the rock sample and “L” be its length. Fit the core into a tube in such a way that there is a good liquid seal between the wall of the tube and the core. Now force through the core from one end to the other the same liquid that was used to saturate it (**Figure 7.5**).

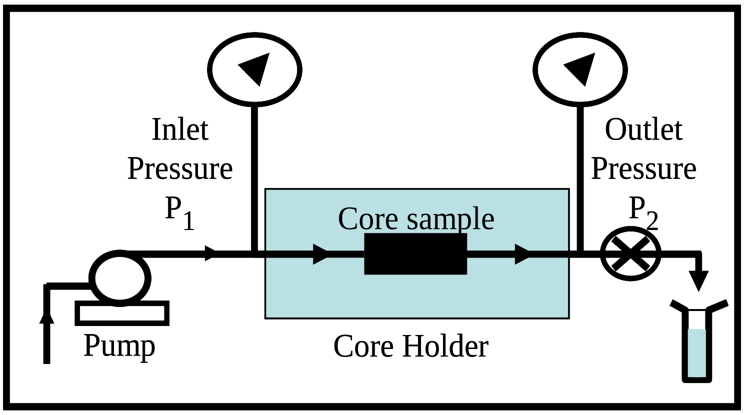



**Figure 7.5 Core holder for permeability measurements.**

Let "q" be the flow rate (volume per time) of the liquid through the core, "$P_1$" be the inlet (upstream) pressure on the liquid, "$P_2$" be the outlet (downstream) pressure. The flow rate "q" increases with the increase of the pressure drop across the sample "$\Delta P = P_1 - P_2$" and with the increase of sample's cross sectional area "A" and decreases with the increase of viscosity "$\mu$" of the flowing fluid and the increase of the core length "L". It is found experimentally that for a particular rock sample, the following expression is constant and independent of the type of the flowing fluid:

$$\frac{q\,\mu\,L}{A\left(P_1 - P_2\right)} = \text{constant} = k_{\mathbf{a}} \qquad \dots(7.12)$$

This constant being independent of the liquid used, the applied pressure drop, and the dimension of the core sample under viscous (laminar) flow conditions. The above expression is called Darcy law and given by:

$$q = \frac{k\,A\left(P_1 - P_2\right)}{\mu\,L} \qquad \dots(7.13)$$

### 7.4.2 Measurement of Effective Permeability

The permeability concept was defined in the previous section for a single-phase homogeneous fluid moving through the rock sample. The great majority of reservoirs in practice contain at least two fluids, namely oil and water. If free gas is also present, there will be three fluids in the reservoir. Evidently, there will be a greater resistance to the flow of oil through the rock containing say 20% connate water than through the same rock in which the connate water is 5%, because the connate water will block some of the flow channels. To explain the idea, suppose that a core sample is saturated with water and inserted into a core holder to generate a good seal between the wall of the rubber jacket and the core sample. And oil-water mixture is passed through the sample, the oil rate being held at $q_o$ and the water rate at $q_w$. In the late stages of the experiment, steady-state condition will be reached, i.e. the injected volumes of oil and water are totally produced from the other end of the core, or:

$$[q_O]_{in} = [q_O]_{out} \quad \text{and} \quad [q_W]_{in} = [q_W]_{out} \qquad \dots(7.14)$$

After equilibrium, the oil effective permeability and water effective permeability are calculated as follows:

$$k_o = \frac{q_o \, \mu_o \, L}{A \, (P_1 - P_2)} \qquad \ldots(7.15)$$

$$k_w = \frac{q_w \, \mu_w \, L}{A \, (P_1 - P_2)} \qquad \ldots(7.16)$$

It should be noticed that: At $S_w$=0.0 and $S_o$=1.0, $k_o = k_a$ and At $S_o$ = 0.0 and $S_w$ = 1.0, $k_w = k_a$. Also, the sum of $k_o$ and $k_w$ at any particular oil saturation is always less the absolute k, i.e.

$$k_g + k_o + k_w \le k_a \qquad \ldots(7.17)$$

Therefore, the effective permeability can be defined as: the permeability of a rock at a particular fluid when that fluid has pore saturation less than 100%.

### 7.4.3 Measurement of Relative Permeability

Relative permeability is another term that is used in reservoir engineering calculations. Relative permeability is the ratio of the effective permeability to a particular phase to the absolute permeability of the rock. Since the unit of effective and absolute permeability is in Darcies, then the relative permeability has no unit (dimensionless).

$$k_{ro} = \frac{k_o}{k_a} \quad , \quad k_{rw} = \frac{k_w}{k_a} \quad \text{and} \quad k_{rg} = \frac{k_g}{k_a} \qquad \ldots(7.18)$$

At $S_w$= 0.0 and $S_o$=1, $k_{ro}$ = 1.0 and at $S_o$ = 0.0 and Sw = 1.0, krw = 1.0

Residual (critical or interstitial) water saturation ($S_{wi}$), is the minimum water saturation, at which water in the rock pores will not move any more. Residual (critical) oil saturation ($S_{or}$) is the minimum oil saturation, at which oil in the rock pores will not move any more. Values of these parameters are estimated from relative permeability curves as shown in **Figure 7.6**.

## 7.5 Reservoir Fluids Saturations

Oil ($S_o$), water ($S_w$) and gas ($S_g$) saturations in the reservoir at any stage are given by the following relationship:

$$S_o + S_w + S_g = 1.0 \qquad \ldots(7.19)$$

$$S_o = \frac{V_o}{V_p} \qquad \ldots(7.20)$$

$$S_w = \frac{V_w}{V_p} \qquad \ldots(7.21)$$

$$S_g = \frac{V_g}{V_p} \qquad \ldots(7.22)$$

## 7.6 Reservoir Pressure Distribution

Normally, pressure at the wellbore is much smaller than pressure at the near wellbore formation. This difference is called "pressure drop" which is the energy required to perform fluid flow into wellbore and then to the surface. Pressure distribution at the reservoir is given by the following relationship:

$$P_r = P_w + \left(P_e - P_w\right)\left(\frac{\ln\left(r/r_w\right)}{\ln\left(r_e/r_w\right)}\right) \qquad \ldots(7.23)$$

From equation 7.23, it is clear that maximum pressure drop is located near wellbore as shown in **Figure 7.7**.

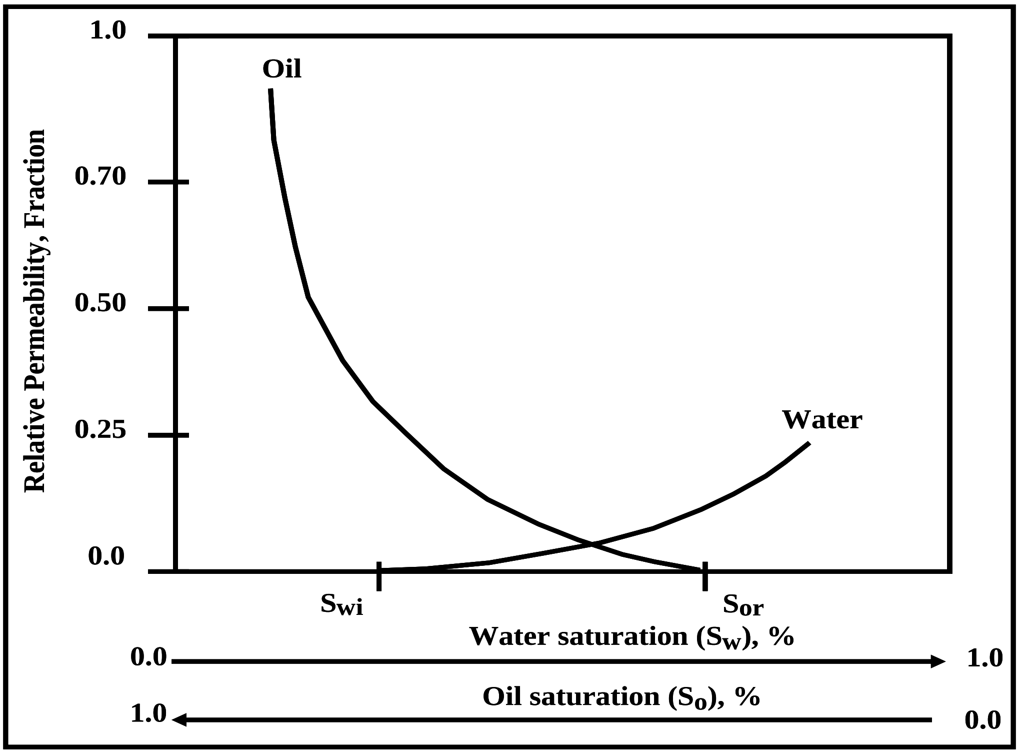



**Figure 7.6 Oil and water relative permeability curves.**

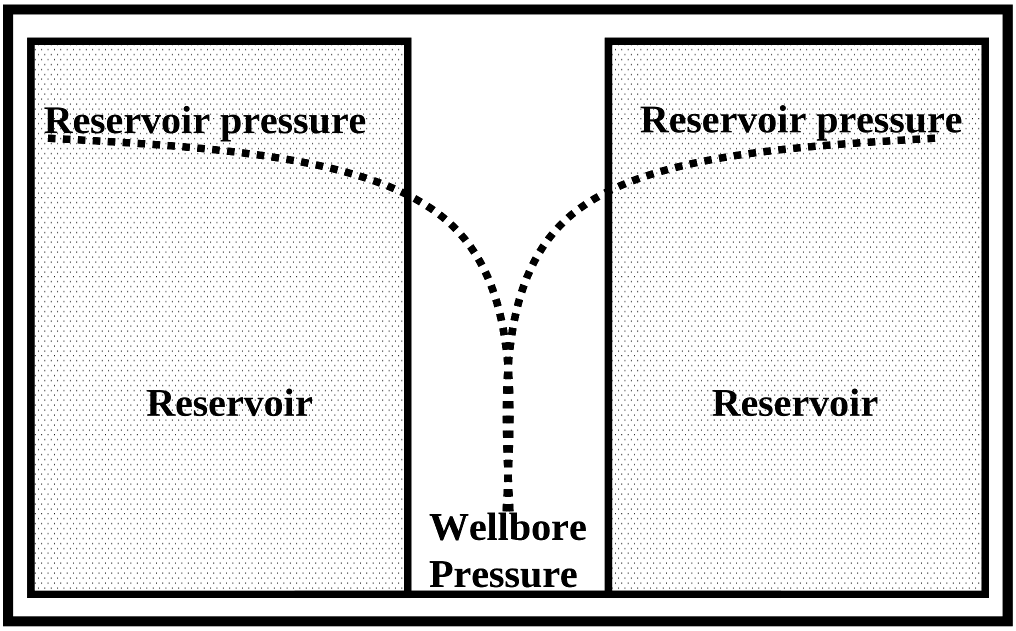



**Figure 7.7 Reservoir pressure distribution scheme.**

## 7.7 Darcy Law for Linear Flow

Linear Darcy law for fluid flow through porous media is the most important relationship required to measure reservoir rock permeability at laboratory using core samples as follows:

$$q = \frac{k\,A\,\Delta P}{\mu\,L} \qquad \ldots(7.24)$$

## 7.8 Darcy Law for Radial Flow

Field calculations of well productivity is done using Darcy law for radial fluid flow through porous media as follows:

$$q = \frac{7.081\,k\,h\,\Delta P}{\mu\,\ln\left(r_e / r_w\right)} \qquad \ldots(7.25)$$

## 7.9 Gas Permeability

When test rock samples contain reactive clays, or some times for simplicity even if they are free of reactive clays, gas injection (Helium) is used to measure the absolute permeability. Liquid permeability is then calculated based on Klinkenberg principal using the following relationship:

$$k_L = k_g\left(1 + \frac{1}{P_m}\right) \qquad \ldots(7.26)$$

By plotting gas permeability versus the inverse of the applied gas mean pressure ($1/p_m$) and the straight line fitting data points is extrapolated to the origin point, liquid permeability is estimated as shown in **Figure 7.8**.

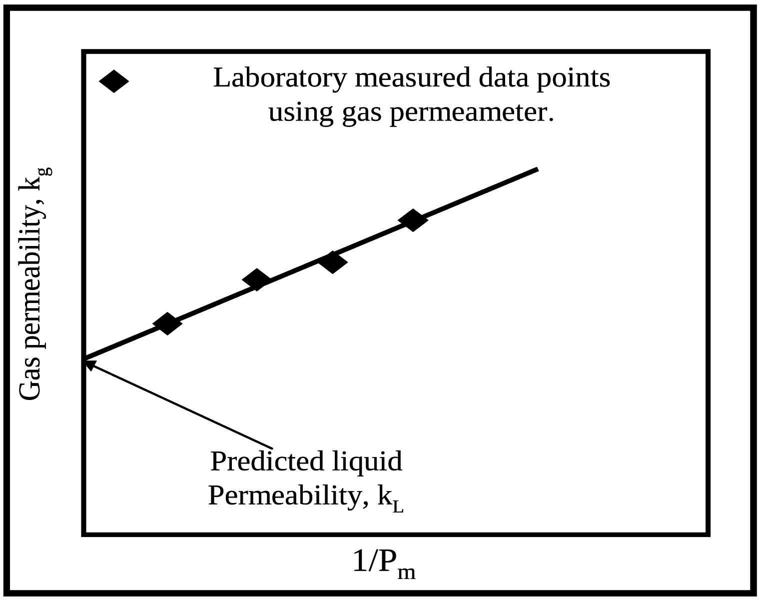



**Figure 7.8 Rock gas-liquid permeability relationship.**

## 7.10 Permeability of Combination of Layers

Sometimes, the heterogeneity of the hydrocarbon pay-zone are treated as the reservoir is consisting from more than one productive layers arranged either in series or in parallel as shown in **Figure 7.9** for linear and radial systems. The average permeability in each case is calculated as follows:

Parallel combination of layers:

$$\bar{k}=\frac{\sum_{1}^{n}(k_i\,h_i)}{\sum_{1}^{n}(h_i)}=\frac{\sum_{1}^{n}(k_i\,h_i)}{h_{total}} \qquad \ldots(7.27)$$

Series combination of layers:

$$\bar{k}=\frac{\sum_{1}^{n}(L_i)}{\sum_{1}^{n}(\frac{L_i}{k_i})}=\frac{L_{total}}{\sum_{1}^{n}(\frac{L_i}{k_i})} \qquad \ldots(7.28)$$

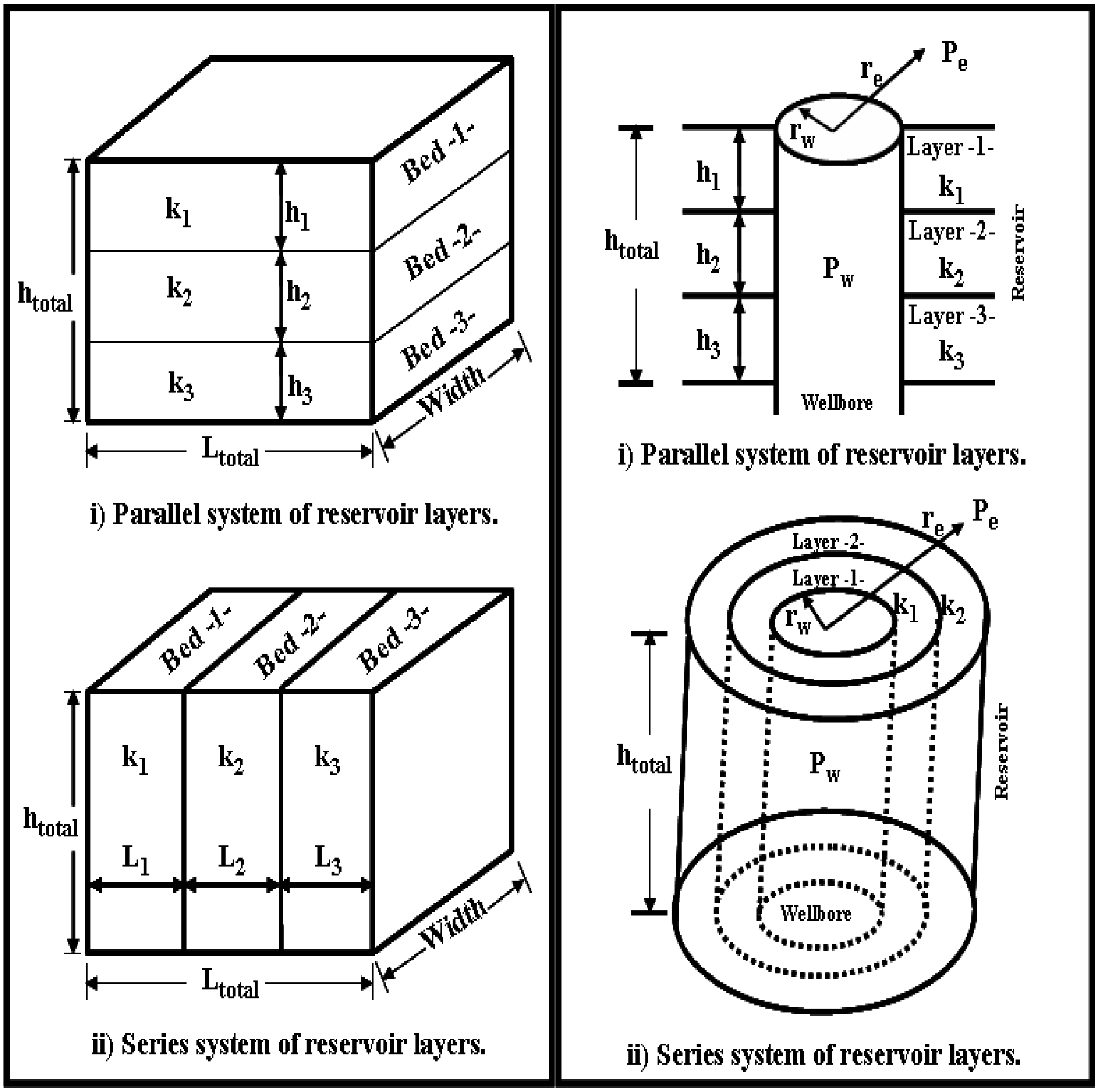



**Figure 7.9 Linear and radial beds in series and parallel configurations.**

# CHAPTER EIGHT
# Oil and Natural Gas Reserves Estimation

## 8.1 Introduction

The estimation of oil and gas reserves is not an exact science. There is always uncertainty in making these predictions, with the magnitude of the uncertainty dependent upon the quantity and quality of the data and on the experience and knowledge of the evaluator.

Reserves estimation is a continuous process throughout the life of a producing oil or natural gas field. Reserves estimates will generally be revised as additional geologic or engineering data becomes available or as economic conditions change.

## 8.2 Types of Reserves

Petroleum and natural gas reserves estimate are normally classified as follows:

i) Proved Reserve: Known accumulation of oil or natural gas by conclusive exploration data which can be produced at high degree of certainty at the present time by current technology and prices.

ii) Possible Reserve: Known accumulation of oil or natural gas by conclusive exploration data which can not be produced at high degree of certainty at the present time by current technology and prices.

iii) Probable Reserve: Known accumulation of oil or natural gas by analogy with nearby reservoirs with less exploration data and no definite economical feasibility studies.

Based on development stage, proved reserves are classified into:

i) Developed Reserves: Are those reserves that are expected to be recovered from existing wells and installed facilities or, if facilities have not been installed, that would involve a low expenditure (e.g., when compared to the cost of drilling a well) to put the reserves on production. The developed category may be subdivided into producing and non-producing.

ii) Developed Producing Reserves: Are those reserves that are expected to be recovered from completion intervals open at the time of the estimate. These reserves may be currently producing or, if shut-in, they must have previously been on production, and the date of resumption of production must be known with reasonable certainty.

iii) Developed Non-Producing Reserves: Are those reserves that either have not been on production, or have previously been on production, but are shut in, and the date of resumption of production is unknown.

iv) Undeveloped Reserves: Are those reserves expected to be recovered from known accumulations where a significant expenditure (e.g., when compared to the cost of drilling a well) is required to make them capable of production. They must fully meet the requirements of the reserves classification (proved, probable, possible) to which they are assigned.

### 8.3 Reserve Estimation Techniques

Petroleum and natural gas reserves estimate are normally made by one of the following methods:

i) Educated estimate (guess) and comparison of nearby, similar production history.

ii) Material balance calculations and simulation.

iii) Production decline method.

iv) Volumetric calculations.

#### 8.3.1 Material Balance Method

Material balance is an indirect method of dynamic estimation of oil and natural gas reserves. It involves the analysis of pressure behavior as reservoir fluids are withdrawn, and generally result in more reliable reserves estimates than volumetric estimates. Reserves may be based on material balance calculations when sufficient production and pressure data are available. Confident application of material balance methods requires knowledge of rock and fluid properties, aquifer characteristics, and accurate average reservoir pressures. In complex situations, such as that involving water influx, multi-phase behavior, multi-layered, or low permeability reservoirs, material balance estimates alone may provide erroneous results. The material balance relationship is derived based on the law of conservation of mass converted to volume relationship as follows:

$$\text{Volume in} - \text{Volume out} = \text{Net change in volume} \qquad \ldots(8.1)$$

The above relationship can be restated in terms of reservoir fluids quantities. For a given amount of production and the associated pressure change, the formula is as follows:

Reservoir withdrawal = Expansion of oil and originally dissolved gas +
Expansion of gas cap + Reduction in hydrocarbon pore volume due to rock and water expansion + Water influx …(8.2)

As a relationship between pressure drop and volume change, the material balance equation is very valuable because it enables one to make estimate of the original volume of the hydrocarbons based on the pressure-production performance.

#### 8.3.2 Production Decline Method

Production decline analysis is an indirect method of reserves estimation. It involves the analysis of production behavior as reservoir fluids are withdrawn. Confident application of decline analysis methods requires a sufficient period of stable operating conditions after the wells in a reservoir have established drainage areas. In estimating reserves, evaluators must take into consideration factors affecting production decline behavior, such as reservoir rock and fluid properties, transient versus stabilized flow, changes in operating conditions (both past and future), and depletion mechanism. Production decline analysis is a traditional means of identifying well production problems and predicting well performance and life based on real production data. It uses empirical decline models that have little fundamental justifications. These models include: i) exponential decline (constant fractional decline), ii) harmonic decline, and iii) hyperbolic decline.

#### 8.3.3 Volumetric Method

Volumetric method is a direct method of static estimation of oil and natural gas reserves. It involves the calculation of reservoir rock volume, the hydrocarbons in place in that rock volume, and the estimation of the portion of the hydrocarbons in place that ultimately will be recovered. For various reservoir types at varied stages of development and depletion, the key unknown in volumetric reserves determinations may be rock volume, effective porosity, fluid saturation, or recovery factor.

Consider a reservoir, which is initially filled with liquid oil (see **Figure 8.1a**). The oil volume in the reservoir (initial oil in place) is given by:

$$\text{Initial oil in place (IOIP)} = \frac{7758\ V\ \phi\,(1-S_{wi})}{\beta_{oi}} \qquad \ldots(8.3)$$

Similarly, for natural gas reservoirs (see **Figure 8.1b**), the volume of initial gas in place is given by:

$$\text{Initial gas in place (IGIP)} = \frac{43560\ V\ \phi\,(1-S_{wi})}{\beta_{gi}} \qquad \ldots(8.4)$$

The percentage of oil or natural gas that can be produced using current technology is given by:

$$R_{fo} = \frac{(1-S_{wi}-S_{or})\times 100}{(1-S_{wi})} \qquad \ldots(8.5)$$

$$R_{fg} = \frac{(1-S_{wi}-S_{gr})\times 100}{(1-S_{wi})} \qquad \ldots(8.6)$$

Finally, the recoverable oil or gas can be calculated as follows:

$$\text{Recoverable oil} = R_{fo} \times \text{IOIP} \qquad \ldots(8.7)$$

$$\text{Recoverable natural gas} = R_{fg} \times \text{IGIP} \qquad \ldots(8.8)$$

Where:
IOIP = Initial oil in place, stock tank barrel (STB).
IGIP = Initial gas in place, standard cubic foot (SCF).
V = The bulk reservoir volume in acre-feet.
43560 = A conversion factor from acre-feet to cubic feet.
7758 = A conversion factor from acre-feet to barrels.
$\phi$ = The porosity from core testing or logs.
$S_{wi}$ = The connate water saturation, fraction.
$S_{or}$ = The residual oil saturation, fraction.
$R_f$ = Recovery factor of oil or gas that can be produced by current technology, %.
$\beta_{oi}$ = The initial oil formation volume factor, bbl/STB.
$\beta_{gi}$ = The initial gas formation volume factor, $ft^3$/SCF.
1 $km^2$ ≈ 4.1 acres.
Acre-ft = 43560 $ft^3$ = 7758 bbls.

## 8.4 Evaluation of Reserves Estimation Parameters

To perform reserves estimation calculations, several properties must be evaluated. Some of these properties are measured at laboratory and the others are evaluated using field measurements as shown in **Table 8.1**. Oil and natural gas recovery pass in several stages from the development of the field until abandonment. Recovery stages are as follows (see **Table 8.2**):

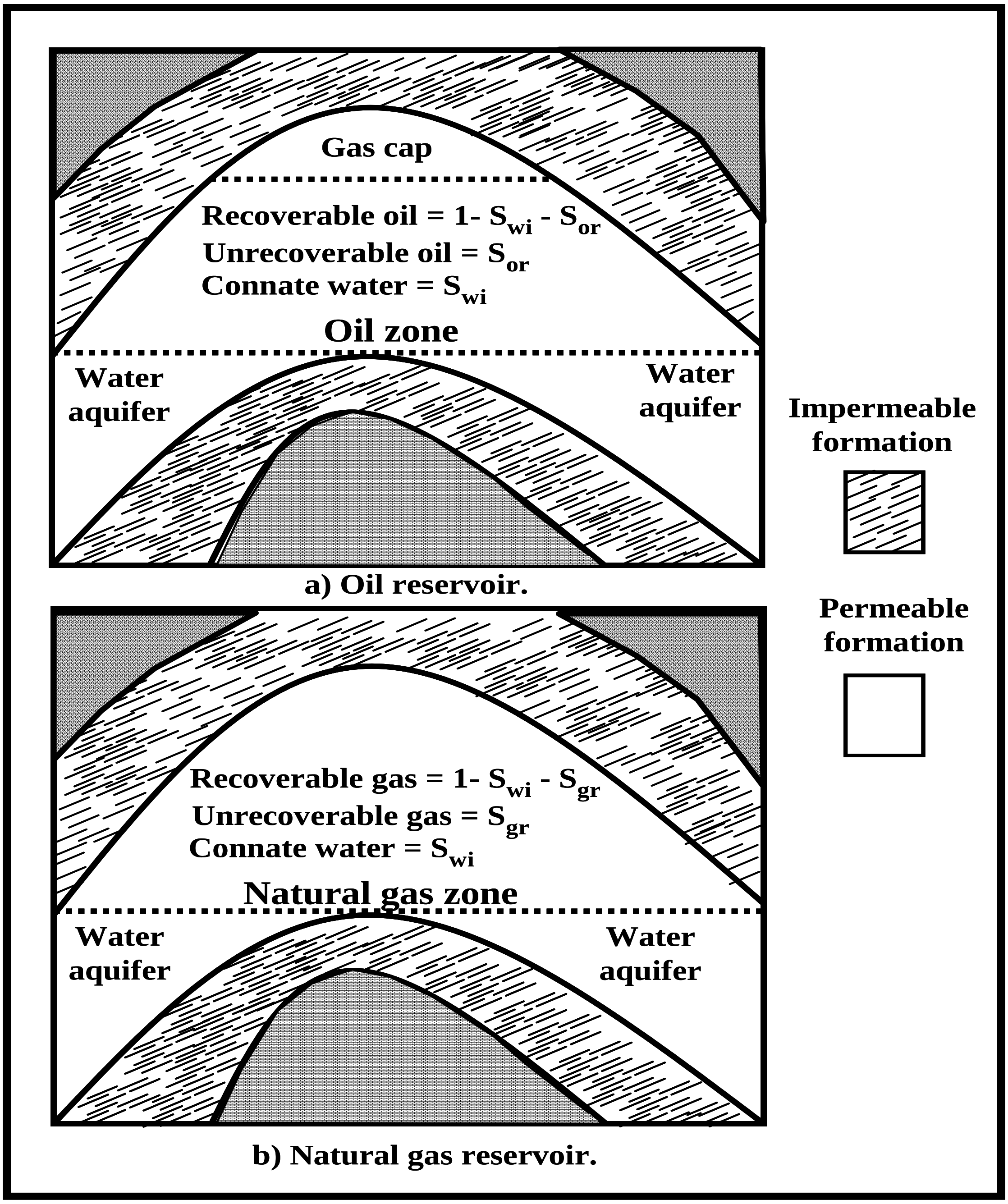



**Figure 8.1 Distribution of fluids in oil and gas reservoirs.**

i) Primary Recovery: This is the first stage of oil or gas production when the natural pressure of gas, water or rock elasticity of the reservoir forces the hydrocarbons to the surface naturally. There are many sources of this primary recovery energy of which three are dominant: gas-cap drive, compaction drive, gravity drainage drive, aquifer drive (water influx) mechanism, and solution-gas drive. As the pressure drops, it is necessary to bring in pumps or injecting natural gas into the wellbore (gas left) to assist but this is still classed as primary production. Only about 10 to 20% of the source is produced in this stage and it ends when the production rates are too low to be economical or the amount of gas (gas cut) or water (water cut) is too high.

**Table 8.1 Parameters necessary for petroleum reserves estimation.**

| Parameters | Symbols | Evaluation method | |
|---|---|---|---|
| | | Field | Laboratory |
| Reservoir volume | V | √ | |
| Porosity | $\phi$ | √ | √ |
| Oil formation volume factor | $\beta_{oi}$ | | √ |
| Gas formation volume factor | $\beta_{gi}$ | | √ |
| Irreducible water saturation | $S_{wi}$ | | √ |
| Residual oil saturation | $S_{or}$ | | √ |
| Residual gas saturation | $S_{gr}$ | | √ |

**Table 8.2 Percentage recovery from petroleum reservoirs.**

| Recovery stage | Percentage hydrocarbon recovered | |
|---|---|---|
| | Low estimate | High estimate |
| Primary | 10 | 20 |
| Secondary | 15 | 40 |
| Tertiary | 5 | 15 |
| Remaining | 70 | 25 |

ii) Secondary Recovery: Here an external fluid such as natural gas is injected into reservoir gas cap or water into the water aquifer (water injection) or into the oil section (water flooding) to create an artificial pressure, enough to drive the hydrocarbons to the surface. 15 to 40% of the source can be produced by secondary recovery and it ends when too much of the injected fluid is being returned at the wellhead.

iii) Tertiary Recovery: In the last stage, sophisticated techniques are used to increase pressure and improve fluid flow. These involve altering the original properties of either the reservoir fluids (water, oil and natural gas) or reservoir rocks or both. The four main methods in tertiary recovery are chemical flooding (alkaline, polymer, surfactant flooding), miscible, immiscible hydrocarbons injection, thermal recovery (steam-flooding or combustion), and others (bacterial EOR, vibration, etc.). 5 to 15% may be recovered using tertiary production. Tertiary recovery is also known as "Enhanced Oil Recovery" (EOR) or "Improved Oil Recovery" (IOR).

Usually one could not expect to get more than about 20 to 60% from an oil field and 50 to 80% from a natural gas fields.

## 8.5 Estimation of Oil and Gas Reserves Depletion

Most of published predictions for oil peak periods and depletion durations are based on proved reserves (see **Table 8.3**), which represent about 25% from the total volume of the total existing hydrocarbon reserves (including possible and probable reserves). Therefore, more years can be added to these predictions when new enhance oil and gas recovery methods are developed.

**Table 8.3 Oil and natural gas proved reserves lasting predictions.**

| Region | Oil | | Natural Gas | |
|---|---|---|---|---|
| | Share, % | Reserve/Production Ratio, years | Share, % | Reserve/Production Ratio, years |
| Middle East | 61.7 | 82 | 40.6 | >100 |
| Europe and Eurasia | 11.7 | 22 | 35.7 | 61 |
| Africa | 9.4 | 33 | 7.8 | 97 |
| South and Central America | 8.5 | 41 | 4.0 | 44 |
| North America | 5.1 | 12 | 4.1 | 10 |
| South Asia and Pacific | 3.5 | 14 | 7.9 | 55 |

# CHAPTER NINE
# Petroleum Production and Formation Evaluation

## 9.1 Introduction

Before production of oil and natural gas from a reservoir starts, a complete production system must be installed and set-up including: wellbore completion, tubing string, artificial lift system, surface control devices, gathering pipelines, separators, treatment equipment, storage tanks, metering devices, …etc. as shown in **Figure 9.1**.

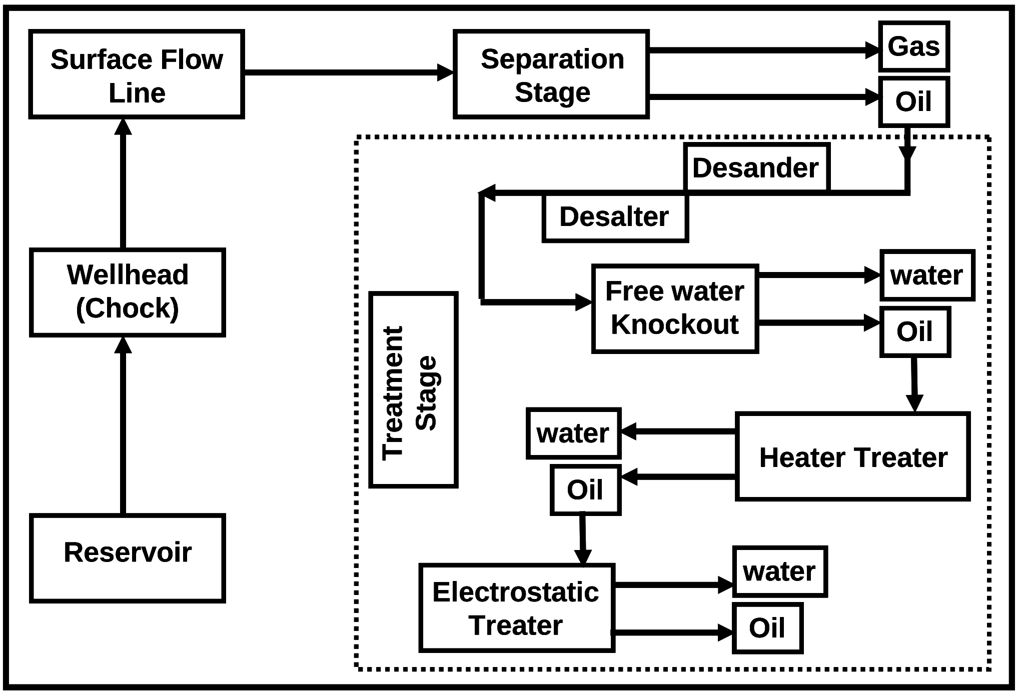



**Figure 9.1 Oil production system flowchart.**

All of those elements behave according to their own specific performance, but, in turn, also depends on the influence of other production elements. The job of production engineers is concerned with the interaction, performance change, and design of the production elements as production occurs over time to maximize recovery of petroleum and natural gas economically. From the time of starting production from a reservoir until it is depleted and abandoned, production type and performance is changing. Production from a reservoir will pass through three successive periods including primary recovery, secondary recovery and tertiary recovery.

## 9.2 Components of the Production System

The damaged formation around the wellbore must be treated and several types of equipment must be installed in the wellbore and in the wellhead before production is commenced:

i) Well Completion: completion involves: treating to remove skin or permeability damage, equipping the well with screens, gravel packs, etc.

ii) Tubing and Packers: tubing is a small diameter pipe used to transport reservoir fluids to surface. Tubing is supported into casing by means of a rubber packer. Packers also used to prevent annular flow.

iii) Surface Flow Control Equipments: including wellhead, gathering pipelines, separators, treatment equipment, metering devices, etc. Separators and treatment equipment are used to separate solids, water, sulfur and gas from the produced hydrocarbons.

iv) Storage Tanks: are used to store crude oil or natural gas after separation.

## 9.3 Production Equations

The following is a simplification of procedures for predicting well performance. Damaged well and/or other factors will affect the flow efficiency and could change the well's productivity.

i) Productivity Index: When the well flowing pressure is greater than bubble -point pressure, the fluid flow is similar to single phase flow, and the inflow performance curve is a straight line with slope, as given by the productivity index, PI:

$$PI = \frac{Q}{\overline{P}_r - P_{wf}} \qquad \ldots(9.1)$$

Where:
Q = the fluid test production rate.
$P_{wf}$ = the well flowing pressure @ test rate.
$\overline{P}_r$ = the well static pressure.

ii) Inflow Performance Relationship: If the well flowing pressure is smaller than bubble -point pressure, resulting in multi-phase flow, the inflow performance relationship **(IPR)** method should be used. The relationship is given by the following equation:

$$Q_{max} = \frac{Q}{1.0 - 0.2\left[\frac{P_{wf}}{\overline{P}_r}\right] - 0.8\left[\frac{P_{wf}}{\overline{P}_r}\right]^2} \qquad \ldots(9.2)$$

## 9.4 Formation Damage and skin factor

Wellbore damage occurs when filtrate (liquid) or solids from drilling mud or completion fluids interact or plug the formation near the wellbore. Mud filtrate can swell the clays or fines and plug the pore throats. Both result in a reduction in the size of the flow channels and hence a reduction in the near wellbore permeability. This is referred to as skin damage. The skin factor is a numerical representation of skin damage. If the skin factor is positive, then the flow efficiency is less than 1 indicating that the well is damaged. If the skin factor is negative, then the flow efficiency is greater than 1 indicating that well is stimulated.

## 9.5 Artificial Lift

In most fields, the new wells flow under its natural pressure until such time that the reservoir pressure is reduced to the point that the well can no longer flow under its natural pressure. The well now becomes a prime candidate for artificial lift. Artificial lift is simply a method of adding energy to lift liquid to the surface of a well, and can be accomplished by any of the following means: gas lift, plunger lift, downhole electric or hydraulic pump, and rod pump. The selection of artificial lift depends on type of hydrocarbons, flow rate and the reservoir pressure. The design of lift systems also depends on the economics of the project.

### 9.6 Remedial Well Work

At various stages other reservoir and well life, remedial work is needed to restore production or to overcome encountered problems.

i) Gravel packing: Gravel packs can be performed in either open hole or cased hole completions, in well deviations from 0° to 110° and in zone lengths up to a few thousand feet. Systems are available for virtually any well temperature, pressure, and environment. Gravel packed wells can be produced under high drawdown without concern of sand production. Productivity of the open or cased hole gravel packed completion is determined in part by the condition of the reservoir behind the filter cake, quality of the filter cake, and stability of the wellbore. Sand-free production, high productivity, and completion longevity are primary objectives for gravel pack operations. To achieve these objectives, operators must be able to perform gravel pack applications under various well conditions. Several techniques are available for dealing with sand production from wells. These range from simple changes in operating practices to completions such as sand consolidation and gravel packing. The sand control method selected depends on site specific conditions, operating practices, and economic consideration.

ii) Acidizing: The purpose of acidizing is to stimulate or effectively increase the flow capacity of wells. The increase in flow capacity is accomplished by the acid's ability to dissolve rock, certain scale, mud and other soluble material, which may be blocking the flow channels. Acids that are commonly used for stimulation are: Hydrochloric acid (HCl), Hydrofluoric acid (HF), Acetic Acid, Formic Acid, and Other Acid Additives. Among the four acids mentioned above, hydrochloric acid is the most widely used due to its high carbonate dissolving ability and low cost. It reacts with limestone to form water, carbon dioxide and calcium chloride. HCI/HF, also known as mud acid, is used exclusively for sandstone reservoirs with little calcium. A pre-flush of 10% HCl is used to dissolve any calcium which is in the pore throats. A mixture of 3% HF and 12% HCl, known as mud acid, is used to dissolve clays and remove mud cakes created during the drilling process. Acetic and Formic acids are used in stimulations where their slower reaction time and ease of inhibition is required. On the basis of cost, these acids are 3 to 5 times more expensive than HCl.

iii) Acid Fracturing: In acid fracturing, the acid is injected at higher rates and pressures, which fractures the reservoir. The acid then travels along the newly created flow path and etches sides of the fracture as well as the matrix pores along the fracture. This method is useful where deep penetration is required.

iv) Hydraulic Fracturing:
Hydraulic fracturing is a technique used to allow oil and natural gas to move more freely from the rock pores where they are trapped to a producing well that can bring them to the surface. The technology was developed in the late 1940s and has been continuously improved and applied since that time. Hydraulic fracturing is used to create small cracks A fracture acts much like a road, speeding up the journey of oil or gas molecules on their

way to the wellbore that will produce them. If only water was being pumped into the well, the fracture would gradually close when the operator stopped pumping, and within minutes the formation would be back to its original non-fractured condition. In a hydraulic fracturing job, the fluid pumped into the well contains a proppant (usually sand) to keep the fracture open. This proppant collects inside the created fracture, so when the fracture tries to close, it cannot, because the proppant is holding it open. The operator has now "constructed a road" that molecules of gas far out in the formation can use to travel to the well. Some of these gas molecules might not have been able to make it to the well otherwise. Even though this new fracture is full of proppant, it is still much more permeable and easier to travel through than the formation itself. The extent of the fracture is controlled by the characteristics of the geologic formation, its depth, the fluid type, and pumping pressure. The fracture will grow if the operator continues to pump fluid at higher rates, or if the operator pumps a more viscous fluid into the formation (e.g., molasses = high viscosity, water = low viscosity). Whether the fracture grows higher or longer is determined by the surrounding rock properties. When the fracture reaches the shale above (or below) the geologic formation being fractured, it will stop; shale does not fracture easily. In nature, fluids that are under pressure (such as fracturing fluids) will follow the path of least resistance. A hydraulically created fracture will always take the path of least resistance, which means staying within the formation that fractures easiest.

## 9.7 Processing of Produced Fluids

For oil wells and gas wells, surface processing is proposed to reduce the presence of undesirable produced fluids and other materials to a sufficiently low level to make transportation of the desirable fluids (hydrocarbons) economic to facilities at other locations for further processing and conversion into marketable products. In the case of crude oil it is normally desirable to reduce water content to a level no greater than two percent of the total volume of the liquids to be transported. In some instances, however, it is necessary to completely remove contaminants during the initial processing. This would be the requirement if hydrogen sulfide should be present, in that not only does it create a corrosive environment in the presence of water, but also it is toxic and potentially deadly. Additionally, salt, and solids must be removes. Fluids produced from high-pressure wells normally have a high solution gas-oil ratio, consequently resulting in a higher producing gas-oil ratio. There are several options for this gas, and the option selected will affect specifications for the surface processing equipment. The three most common options for the gas are:

i) Sell the gas or use the gas as a fuel at the locally.
ii) Re-inject the gas into the suitable nearby hydrocarbon reservoir.
iii) Flare the gas as waste.

If significant gas is being produced, the third option is not normally permitted be government regulations, in that a natural resource would be destroyed, with adverse effect on the environment. Either of the first two options is more likely to be selected. Therefore, the surface system is designed so that gas produced at the surface is maintained as nearly as possible at the pipeline pressure or the re-injection pressure to minimize cost of recompression of the gas.

## 9.8 Formation Evaluation Techniques

In petroleum exploration and development, formation evaluation is used to determine whether a potential oil or natural gas field is commercially viable or not. The formation evaluation problem is a matter of answering the question: what are the lower limits for porosity, permeability and upper limits for water saturation that permit profitable production from a particular formation or pay zone; in a particular geographic area; in a particular economic climate. These limits are known as “cutoff values”.

It is complicated by the impossibility of directly examining the formation. It is, in short, the problem of looking at the formation indirectly. The following tools to detect oil and gas have been evolving for over a century:

i) The simplest and most direct tool is well cuttings examination. Reservoir formations are evaluated directly using conventional or unconventional (special) core analysis or indirectly by well testing or by running well logs.

ii) Formation evaluation provides valuable data such as porosity, permeability, saturations, strength, etc. Conventional core analysis provides values for porosity, permeability and water, oil and gas saturations. Special core analysis provide values for capillary pressure, wettability, resistivity, two phase flow, relative permeabilities, composition, grain size distribution, pore size distribution, etc.

iii) Reservoir can be evaluated by well testing method. It is aimed to estimate reserves in case of exploration well. Testing of a production well is monitoring the cumulative production on the reservoir. Well tests basically consist of a series of measurements of pressure, fluid flow, time, and temperature downhole (PVT) in a controlled sequence of flowing and shut-in periods. Using well testing reservoir pressure and temperature, formation fluids types, and formation damage can be evaluated.

iv) There are too many logging tools nowadays available for evaluation; each tool has strengths and weaknesses.

Therefore, a combined evaluation data gained from different logging tools may provide clear picture of the formation matrix and fluids properties. The following are the most used well logs as shown in **Figure 9.2**:

i) Spontaneous Potential Log (SP): This log measures the natural current occurs at the interface when foreign ions from the drilling fluid have invaded the pay-zone. Therefore, this log provides data on the thickness of the invaded (damaged) zone and used in detecting permeable formations and their thickness.

ii) Gamma Ray Log: This log measures the natural gamma radiation of formation rocks. Gamma ray of most rocks such as sandstone and carbonates are very low. Shale contains small amounts of radioactive elements, therefore, it is radioactively hot compared to sandstone and carbonates.

iii) Resistivity Log: Dry rocks and rocks containing hydrocarbons are very poor conductors to electric current. Therefore this tool functions well in water saturated zones. This log is used when water-base mud is used in drilling operation.

iv) Induction Log: This log is basically induces current into formations generating a magnetic field. This log is used when oil-base mud or air are used in drilling operation.

v) Sonic (Acoustic) Log: This log is used to measure the velocity of generated sound waves. This log is used to predict lithology and porosity.

vi) Density Log: This log is used to measure formation density, porosity and type of enclosed fluids by emitting energy into the formation and measuring the returned gamma ray generated due to electrons collisions.

vii) Neutron Log: This log emits high-energy neutrons and measures some sort of resulting radiation that is a function of elemental hydrocarbon content in the logged formation.

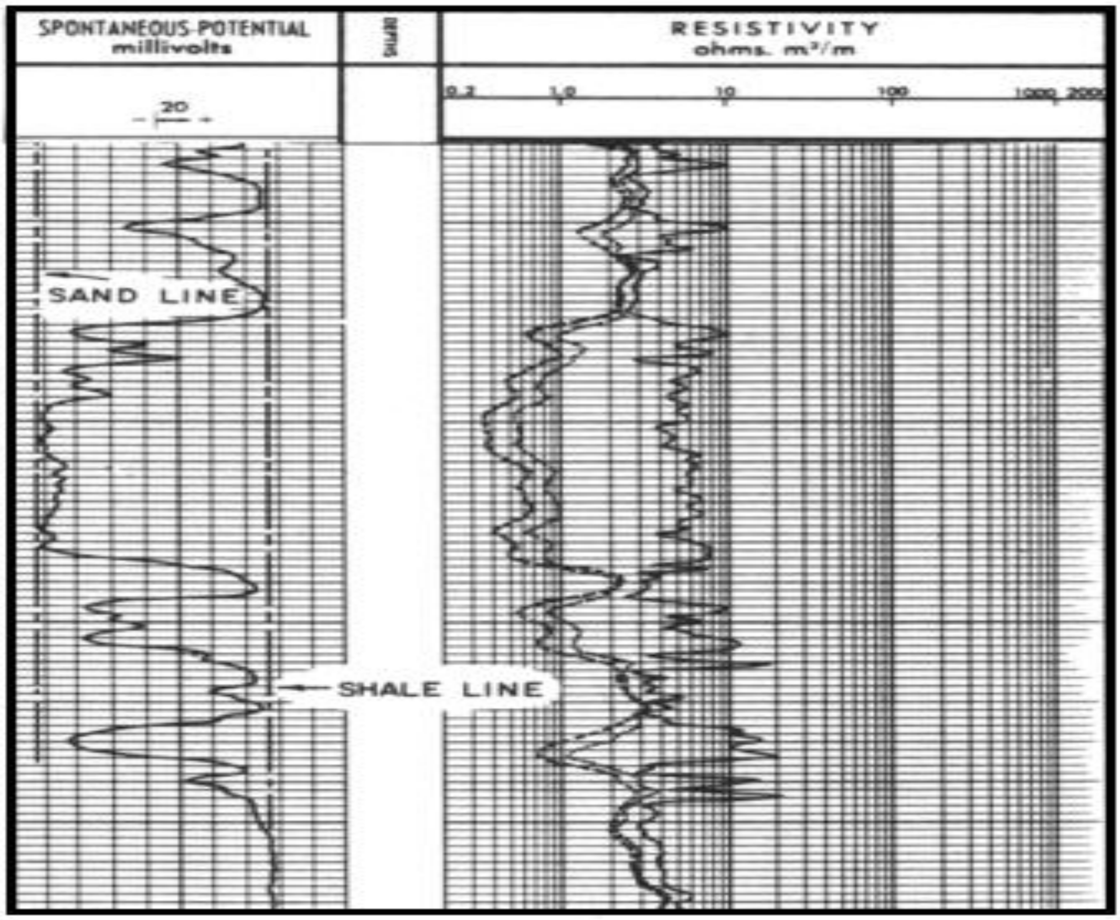



**Figure 9.2 SP log in sand and shale formations.**

viii) Other Logs: The continuous development technology adds new tools and/or modifies existing logging tools. NMR, Permeability Log, Mechanical Logs, etc. are examples of such recently developed logs.

After completing formation evaluation and installing the necessary production facilities, critical production rate for each well must be calculated. Critical production rate is the upper limit after which either gas or water coning starts. Water coning increases water cut and hence reducing the volume of produced oil while gas coning leads to loosing the reservoir driving energy.

# CHAPTER TEN
# NATURAL GAS PROPERTIES

## 10.1 Introduction

Liquefied natural gas (LNG) is called the liquid form of natural gas. Liquefaction procedure involves the cooling of natural gas to a temperature of -161$^o$ C, at atmospheric pressure. LNG is odorless, non-corrosive, smokeless and non-toxic. LNG is predominantly methane, $CH_4$. The reason of liquefying natural gas is mainly for transportation and storage purposes, since one volume unit of LNG is 600 times smaller than a volume unit of natural gas. It is therefore more economical to transport LNG between continents instead of using traditional pipelines systems which are uneconomical for distances more than 8000 km, due to technical and political constraints.

On the other hand, even though liquefaction cost has been decreased over the last years, it still remains expensive making LNG transportation for short distances. The major stages of the LNG value chain consist of exploration and production of natural gas from dry gas fields or associated gas fields. Gas is transported via pipelines to liquefaction plants in which natural gas is cooled down to cryogenic temperatures (-161$^o$ C) and converted to a liquid known as LNG. The liquefaction plants consist of processing units called "trains". The size of each train depends on the capacity of compressors and varies between 2 million tonnes to 4 million tonnes. A typical LNG process the gas is first extracted and transported to processing plant, then purified by removing condensates such as water, oil, mud, as well as other gases like $CO_2$ and $H_2S$ and some times mercury.

## 10.2 Natural Gas Types

Natural gas can occur by itself or in conjunction with liquid crude oils. It consists mainly of the more volatile members of the paraffin series containing from one to four carbon atoms per molecule. In addition, natural gases may contain varying amounts of carbon dioxide, nitrogen, hydrogen sulphide, helium and water vapor. Most natural gases consist predominantly of methane, the percentage of which may be as high as 98%.

Hydrocarbon gases are classified into:

i) Petroleum (Refinery) gas such as butane and propane which is extracted from the crude oil by cracking, and

ii) Raw natural gas which is rich of methane and ethane.

Raw natural gas may be one of the following types based on its state (existence) as found in the reservoir:

i) Associated Natural Gas: It is the raw natural gas that comes from crude oil wells. This gas can exist separate from the crude oil in the top of the same underground reservoir (Gas Cap), or dissolved in the crude oil (Solution Gas).

ii) Non-Associated (Free) Natural Gas: This gas typically comes from reservoirs that contain raw natural gas and does not contain any hydrocarbon liquids. Such gas is called

"Non-Associated Dry Gas". Part of the dry gas is condensed into liquid and produced along with free dry natural. This condensed gas liquid is called Gas Condensate. Such gas is also non-associated gas and often referred to as "Non-Associated Wet Gas". The natural gas condensate is also referred to as simply "Condensate", or "Gas Condensate", or sometimes "Natural Gasoline" because it contains hydrocarbons within the gasoline boiling range.

Natural gas also classified based on its composition and contents as follows:

i) Dry Gas: The gas that contains more than 98% Methane of its total composition,

ii) Wet Gas: The gas that is rich of Ethane,

iii) Sour Gas: That gas contains more than hydrogen sulfide ($H_2S$), and

iv) Sweet Gas: That gas free of hydrogen sulfide ($H_2S$).

v) Synthetic Gas: This type of gas is produced from coal or any other feedstocks.

Similar to crude oil, natural gas must be purified from hydrogen sulfide (4 ppm maximum), mercaptan sulfur (8 ppm maximum), total sulfur (17 ppm maximum), carbon dioxide (maximum 2 to 5% by weight) solids and water before exporting. Natural gas value is mainly dependent on its composition, i.e. its calorific value. Natural gases must be distinguished from "petroleum gases" produced in refineries during distillation process. Petroleum gas is mainly composed from propane and butane, while natural gas is mainly composed from methane and ethane.

## 10.3 Natural Gas Volume Calculation

Knowing gas volume at specific pressure and temperature is vital element in calculating natural gas reserves and in knowing the required gas volumes to be produced at those conditions. Natural gas is normally composed from Methane, Ethane and traces of other gases, while Petroleum gases; mainly produced in refineries from crude oil distillation; are composed from Propane, Butane plus traces of other gases.

Natural or petroleum gases composition is identified using gas chromatograph device. Natural gas price is function of gas quality which depends on the calorific value per volume, i.e. GJ/m$^3$ or MMBTU/ft$^3$. Natural gas types and reserves have been discussed in chapter two.

## 10.4 The General Gas Law

The general gas equation represents an important theoretical expression for most engineers and it can be derived from basic considerations as is done in thermodynamics.

$$V \alpha \frac{1}{P} \quad \rightarrow \quad P \times V = \text{Constant @ constant temperature} \qquad (\text{Boyle's law}) \text{ or } P_1 V_1 = P_2 V_2$$

and

$$V \alpha T \quad \rightarrow \quad \frac{V}{T} = \text{Constant @ constant pressure} \qquad (\text{Charles' law}) \text{ or } \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Boyle's law and Charles' law can be combined together to describe the behavior of ideal gas when pressure and temperature are altered. Therefore, for one mole of ideal gas:

$$\frac{PV}{T} = R = 10.72 = \text{Constant} \qquad \ldots(10.1)$$

For n moles of ideal gas:

$$\frac{PV}{T} = nR \qquad \text{or} \qquad PV = nRT \qquad \ldots(10.2)$$

Therefore, the behavior of ideal gases is given by:

$$n = \frac{Wt}{MW} \qquad \ldots(10.3)$$

Pressure, volume, and temperature are represented by the symbols, P, V, and T where the temperature is in absolute units. The number of moles of gas is n, R is the numerical constant that makes the equation correct for a particular set of units. Value of the gas constant (R) depends on the applied system of units as shown in **Table 10.1**.

**Table 10.1 Gas constant values.**

| Pressure (P) | Volume (V) | Temperature (T) | Gas constant (R) |
|---|---|---|---|
| atm | cc | $^{o}$k | 82.1 |
| atm | Liter | $^{o}$k | 0.0821 |
| atm | ft$^3$ | $^{o}$R | 0.73 |
| psi | ft$^3$ | $^{o}$R | 10.72 |
| psf | ft$^3$ | $^{o}$R | 1545 |
| g/cm$^2$ | cc | $^{o}$k | 8.135 |
| mm mercury | cc | $^{o}$k | 62369 |

## 10.5 Evaluation of Gas Deviation Factor

Gas deviation factor can be estimated using well-established relationships as that shown in the **Figure 10.1**. Petroleum reservoir gases are different in behavior than ideal gases and normally are called real (or perfect) gases, therefore a new term called gas deviation factor (Z) is introduced into equation (10.2) to correct it for real gases behavior as follows:

$$PV = ZnRT \qquad \ldots(10.4)$$

Where:

P = Pressure, psi.

V = Volume, ft$^3$.

T = Absolute temperature.

n = Number of moles.

Z = Gas deviation factor, dimensionless.

R = Gas constant = 10.72 for the above units.

Wt = Weight, lb/mole.

MW = Molecular weight, lbs.

AMW = Apparent molecular weight, lbs.

To estimate Z factor from this figure, Pseudo-reduced pressure ($P_r$) and Pseudo-reduced temperature ($T_r$) must be known. These two values can be calculated as follows:

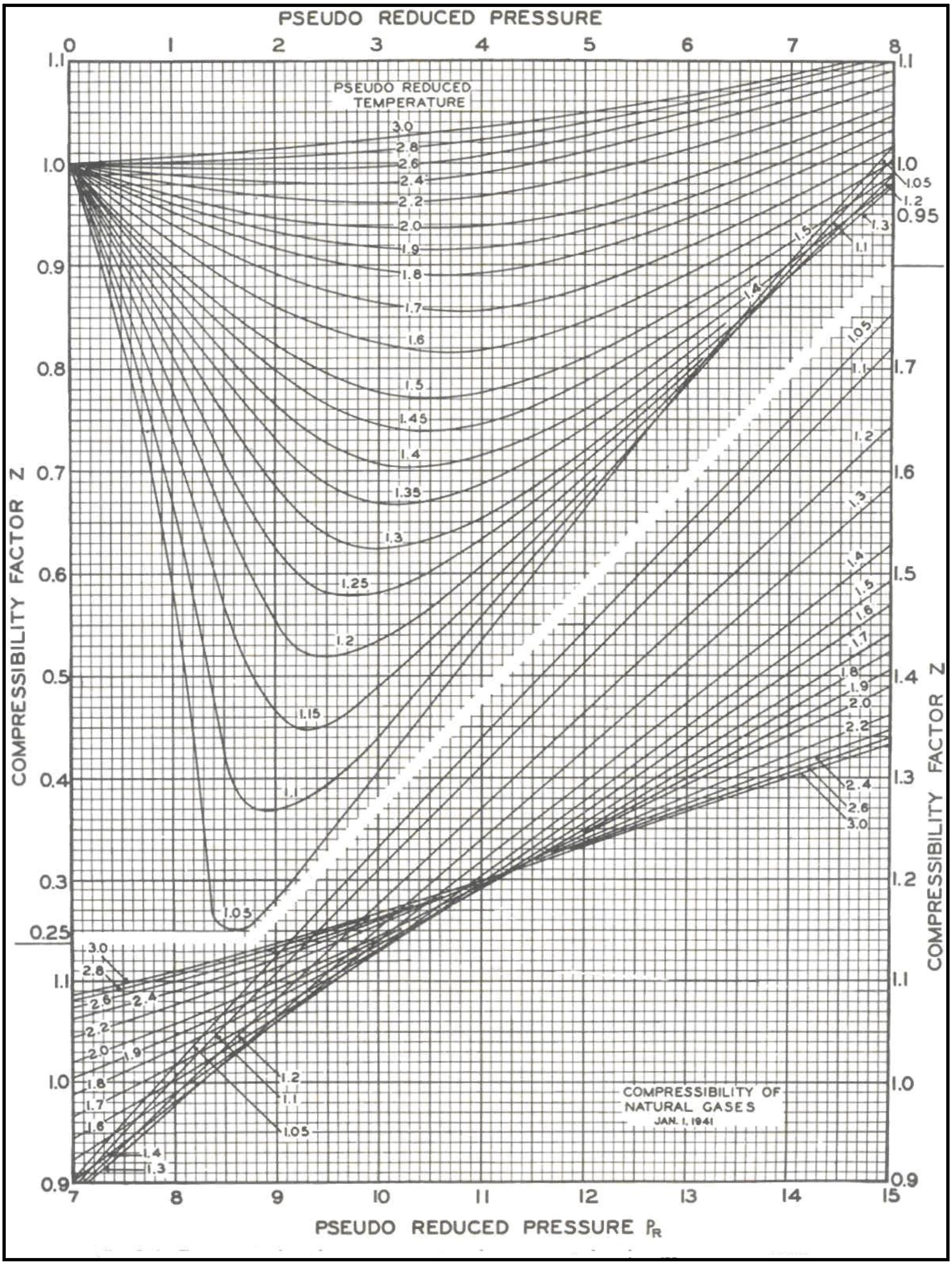



**Figure 10.1 Compressibility factor (Z) for natural gases.**

$$T_r = \frac{T}{T_c} \qquad \text{and} \qquad P_r = \frac{P}{P_c} \qquad \ldots(10.5)$$

Where, $T_c$ and $P_c$ are the true critical temperature and pressure at which liquid and vapor cannot be distinguished. **Table 10.2** contains the critical pressure and temperature of most known gases. For gas mixtures, **Figure 10.2** is used to find the critical pressure and temperature using gas mixture specific gravity.

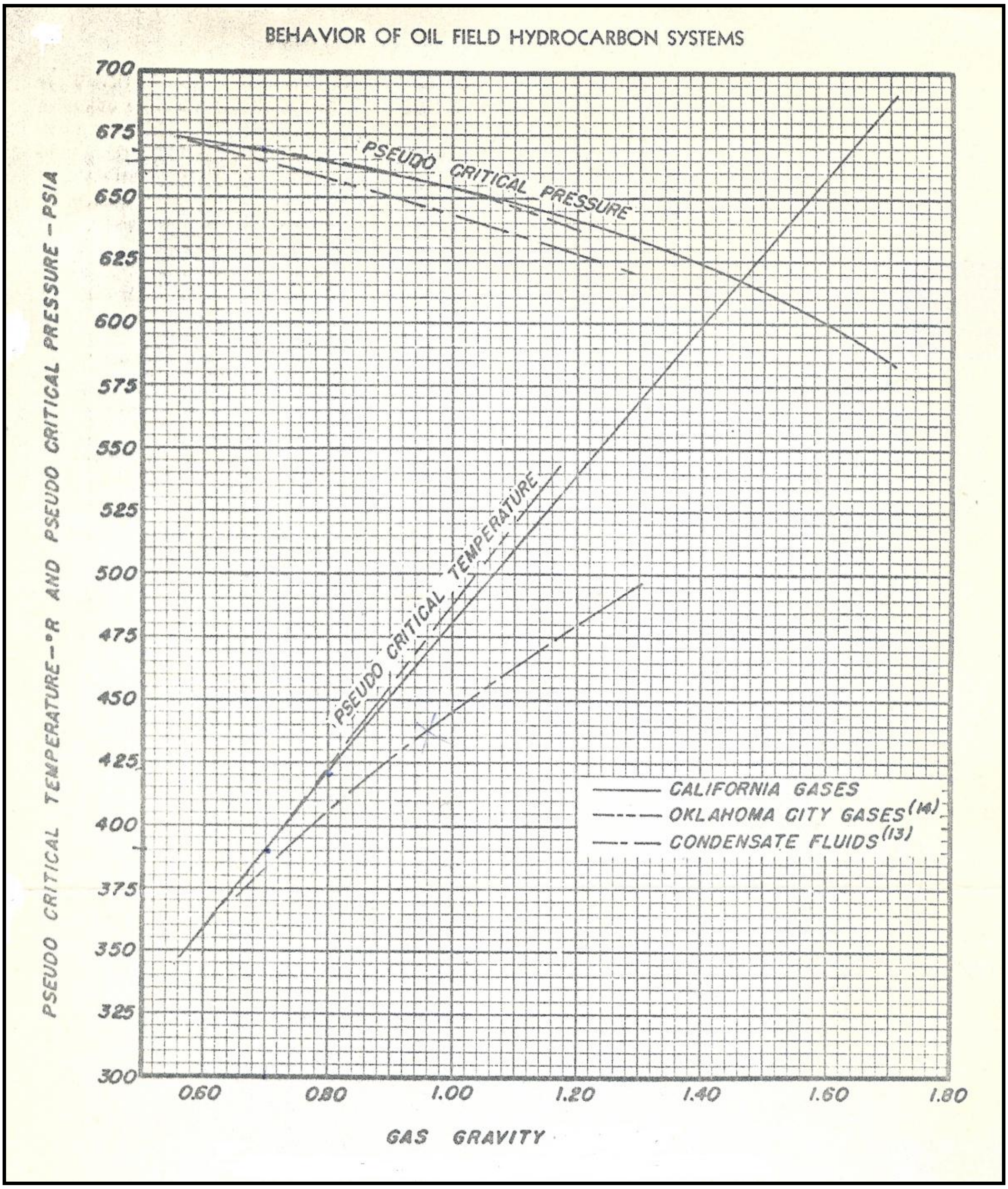



**Figure 10.2 Pseudo reduced pressure and temperature for gases.**

Specific gravity of gases ($\gamma_g$) is defined as the ratio of the density of gas ($\rho_g$) to the density of dry air ($\rho_{air}$) at the same temperature and pressure. This relationship is expressed in the following equation:

$$\gamma_g = \frac{\rho_g}{\rho_{air}} = \frac{MW}{29} \qquad \text{...(10.6)}$$

$$\rho_g = \frac{MWP}{ZRT} \qquad \ldots(10.7)$$

Natural gases are mixtures of different hydrocarbons (methane, ethane, propane and butane) and consequently they do not have a true critical pressure and temperature like a single gas. The critical pressure and temperature of gas mixtures can be calculated as follows:

$$P_C = \sum_{i=1}^{i=n}\left[(MF)_i \times (P_C)_i\right] \quad \text{and} \quad T_C = \sum_{i=1}^{i=n}\left[(MF)_i \times (T_C)_i\right] \qquad \ldots(10.8)$$

For gas mixtures, density and specific gravity can be calculated using equations 10.6 and 10.7 in terms of the apparent molecular weight (AMW). The molecular weight of gas mixtures can be calculates as follows:

$$AMW = \sum_{i=1}^{i=n}\left[(MF)_i \times (MW)_i\right] \qquad \ldots(10.9)$$

Where:
MF = Mole fraction of component "i" in the gas mixture.

**Table 10.2 Physical properties of petroleum components.**

| Compound | Molecular weight, Lb/mole | Boiling point at 14.7 psi, $^oF$ | Critical constants | |
|---|---|---|---|---|
| | | | Pressure, psi | Temperature, $^oR$ |
| Methane | 16.00 | -258.70 | 673.10 | 343.20 |
| Ethane | 30.00 | -127.50 | 708.30 | 549.90 |
| Propane | 44.00 | -43.70 | 617.40 | 666.00 |
| Butane | 58.00 | 31.10 | 550.10 | 765.70 |
| Pentane | 72.00 | 96.90 | 489.80 | 846.20 |
| Hexane | 86.00 | 155.70 | 440.10 | 914.20 |
| Heptane | 100.00 | 209.20 | 395.90 | 972.40 |
| Octane | 114.00 | 258.20 | 362.20 | 1024.90 |
| Nonane | 128.00 | 303.40 | 334.00 | 1073.00 |
| Decane | 142.00 | 345.40 | 312.00 | 1115.00 |
| Air | 29.00 | -317.70 | 547.00 | 239.00 |
| Carbon dioxide | 44.00 | -109.30 | 1070.20 | 547.50 |
| Helium | 4.00 | -452.10 | 33.20 | 9.50 |
| Hydrogen | 2.00 | -423.00 | 189.00 | 59.80 |
| Hydrogen sulfide | 34.00 | -76.60 | 1306.50 | 672.40 |
| Nitrogen | 28.00 | -320.40 | 492.20 | 227.00 |
| Oxygen | 32.00 | -297.40 | 736.90 | 278.60 |
| Water | 18.00 | 212.00 | 2109.50 | 1165.20 |

It must be recognized that natural gas composition and BTU value are vary from field to field and sometimes vary even in the same field.

# CHAPTER ELEVEN
# Storage and Transportation of Petroleum

## 11.1 Introduction

The rates charged for cargo transportation depend upon many variables including location of the movement, distance of the movement, type of tank required, type of commodity moved, competitive aspects of other modes of transportation, special services required, and cost of registration fees and taxes. Transportation of petroleum by water is desired wherever possible, for it is the lowest-cost worldwide.

The cost ratio of the principal forms of volume petroleum transportation, in monetary units, is: tank truck, 1.0 per ton-mile; railroad tank cars, 0.6 per ton-mile; pipeline, 0.3 per ton-mile; by water, 0.1 per ton-mile.

## 11.2 Strategic Storage of Petroleum

Oil consumption is growing rapidly in world. Oil consumers (see **Table 11.1**) are located far from main exporters, which necessitate the establishment of strategic oil reserves (see **Table 11.2**) for use during shortage periods or crises.

**Table 11.1 World top 20 countries by oil consumption, 2010.**

| Country | Oil consumption, millions bbl/day | Country | Oil consumption, millions bbl/day |
|---|---|---|---|
| USA | 20.000 | Mexico | 1.932 |
| China | 6.500 | Italy | 1.881 |
| Japan | 5.450 | United Kingdom | 1.699 |
| Germany | 2.814 | Spain | 1.465 |
| Russia | 2.531 | Saudi Arabia | 1.415 |
| India | 2.300 | Iran | 1.109 |
| South Korea | 2.126 | Indonesia | 1.063 |
| Brazil | 2.123 | Netherlands | 0.881 |
| Canada | 2.048 | Australia | 0.879 |
| France | 2.040 | Taiwan | 0.846 |
| World total : 75.988 bbl/day | | World annual: 28,460 bbl/day | |

The environmental and security advantages of underground storage of oil and gas are well documented. Natural gas may be stored in a number of different ways. It is most commonly held in inventory underground under pressure in three types of facilities. These are: i) depleted reservoirs in oil and/or gas fields, ii) aquifers, and iii) salt cavern formations. (Natural gas is also stored in liquid form in above-ground tanks.

In many cases, underground storage have proven to be cost effective when compared to storage in steel tanks constructed for that purpose on the surface. In good rock conditions, underground storage of large quantities of hydrocarbon products in normally less costly up to 50–70% of the surface alternative.

## 11.3 Liquefied Natural Gas Transportation

Liquefied Natural Gas (LNG) is called the liquid form of natural gas. Liquefaction procedure involves the cooling of natural gas to a temperature of -161$^o$ C, at atmospheric pressure. LNG is odorless, non-corrosive, smokeless and non-toxic. LNG is predominantly methane, $CH_4$. The reason of liquefying natural gas is mainly for transportation and storage purposes, since one volume unit of LNG is 600 times smaller than a volume unit of natural gas. It is therefore more economical to transport LNG between continents instead of using traditional pipelines systems which are uneconomical for distances more than 8000 km, due to technical and political constraints. On the other hand, even though liquefaction cost has been decreased over the last years, it still remains expensive making LNG transportation for short distances. The major stages of the LNG value chain consist of exploration and production of natural gas from dry gas fields or associated gas fields. Gas is transported via pipelines to liquefaction plants in which natural gas is cooled down to cryogenic temperatures (-161$^o$ C) and converted to a liquid known as LNG. The liquefaction plants consist of processing units called “trains”. The size of each train depends on the capacity of compressors and varies between 2 million tonnes to 4 million tonnes.

A typical LNG process the gas is first extracted and transported to processing plant. Purified by removing condensates such as water, oil, mud, as well as other gases like $CO_2$ and $H_2S$ and some times mercury.

## 11.4 Petroleum Transportation Methods

The largest quantities of oil and gas discovered are to be found in developing countries, far from the major consumers. These producer countries easily meet their own needs and export the greater part of their production. On the other hand, developed countries, major energy consumers, are not self-sufficient in oil and gas, far from it: they are therefore hydrocarbon importers. As a result, for several decades now, enormous quantities of oil and gas have been transported all over the world by sea and on land. Oil and natural gas transportation methods are numerous and depend on the geographical locations of exporters and importers.

**Table 11.2 Strategic oil reserves, 2010.**

| Country | Strategic reserves, millions bbl | Strategic reserve satisfaction, days |
|---|---|---|
| USA | 658 | 33 |
| Japan | 321 | 59 |
| Germany | 191 | 73 |
| South Korea | 77 | 36 |
| France | 71 | 36 |

### 114.1 Sea Tankers

Waterborne traffic is a vital factor in the transportation of petroleum and its products in domestic and worldwide markets. The principal water movement in the world-wide oil markets is in large vessels especially constructed to carry petroleum in bulk, widely known as sea tankers (**Figure 11.1**). The freight rates depend on the state of the tanker market and the daily fluctuations in tanker supply and demands.

The factors affecting tanker-freighting costs are complex, covering as they do the original purchase price of the ship, its size, speed, mode of propulsion (force), type of fuel, pumping capacity and manning scale. The general rule is that a large ship freights more cheaply than a small one, since building and operating costs do not rise proportionately with increase in size.

### 11.4.2 Pipelines

The pipeline has over the years become more and more a transporter of energy. Pipelines used for transporting crude oil from the producing fields to tanker terminals or directly to refineries have been complemented by product pipelines from refineries to the consumer. There has been a further increase in natural gas transmission and distribution lines, also stimulated by increasing objections to wasting energy by flaring and by continued conversion of energy consumers from coal and oil to natural gas. The economics of pipelines are characterized by large investments; relatively low operating costs, and decreasing unit cost for higher volumes. The fixed cost is usually related to capital charges arising from initial investment; the variable cost to the energy consumed for pumping, which will be higher for high throughputs than for low ones. Labor costs are low compared with other forms of transport and do not change much with increasing capacity of the line. This means that the costs of transportation by pipeline are more inflation-resistant than those of other means of transport. In Saudi Arabia, the pipeline named “The Tapeline” is a good example. Tapeline transports oil from the oil fields in the eastern province to the western province for export from Yanbu port in the Red sea.

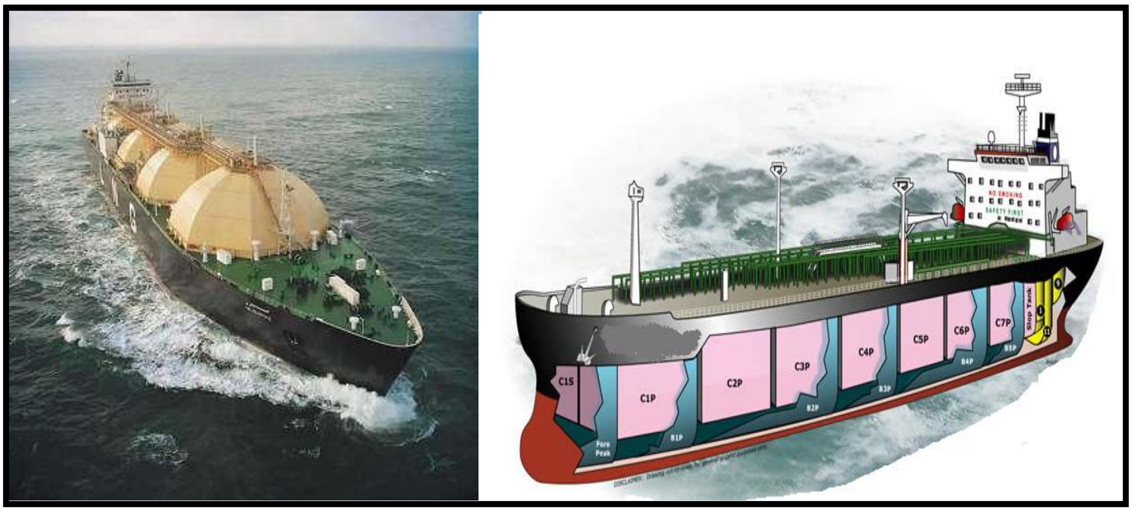



**Figure 11.1 Seawater tankers for oil and gas transportation overseas.**

### 11.4.3 Railways

In many countries, the railways are still the mainstay of the internal distribution system. Products are distributed in bulk by rail wagons from refineries or ocean terminals to installations or depots, or in some cases direct to customers. Bridging of large quantities of products from refineries or ports to installations is now being by liner trains made up entirely of operate at high speeds with rapid turn-round at each end achieved by large capacity loading and discharge arrangements. Although freight tariffs for liner trains are much lower than for single wagons, much higher capital investment is required at loading and discharge points and liner trains made up of bulk with brakes and running gear designed to operate at high speeds.

### 11.4.4 Tank Truck

Movement of petroleum in commerce by tank truck has become a major factor in the total oil traffic in the past two decades. In general tank trucks are not competitive with pipelines or waterborne transportation of petroleum. For-hire carriers compete, in many movements, against railroad tank cars and they must also operate so as to compete with actual or potential private carrier transportation. If tank-truck carriers provide special services such as dropping part of their load at different points, they generally attempt to recoup their extra expense through surcharge. Studies in some areas have shown tank trucks to operate at 1ower costs than railroads up to 300-mile distances.

## 11.5 Evaluation of Petroleum Transportation Methods

Each of the above mentioned petroleum transportation methods have their merits. The overall advantages and disadvantages are summarized in **Table 11.3**.

**Table 11.3 Summary of oil and gas transportation methods.**

| Transportation type | Cost ratio per ton-mile | Reduction in cost relative change to *Tank Truck* / Remarks |
|---|---|---|
| Tank Trucks | 1.00 | $\Delta = 0$ |
| | | Unsafe, Expensive, Small capacity, Local, Special care is required, Variable cost. |
| Railways Tanks | 0.60 | $\Delta = 40\%$ |
| | | Local, Expensive, Unsafe, Large capacity, Variable cost. |
| Pipelines | 0.30 | $\Delta = 70\%$ |
| | | Cheap, Safe, Medium distance, Fixed cost, Large capacity. |
| Sea Tankers | 0.10 | $\Delta = 90\%$ |
| | | Huge capacity, Variable cost, Long-distance (Overseas), Cheap, Relatively safe. |

From the analysis shown in **Table 11.3**, it is clear that pipelines are the most effective method for oil and natural gas transportation in land, while sea tankers are the most effective method of transportation overseas.

# CHAPTER TWELVE
# Offshore Pollution by Petroleum

## 12.1 Introduction
Oil spills are the harmful release of oil into the environment, usually in the water, sometimes killing area flora and fauna. Oil is the most common pollutant in the oceans. More than 3 million metric tons of oil contaminates the sea every year. The majority of oil pollution in the oceans comes from land. Runoff and waste from cities, industry, and rivers carries oil into the ocean. Ships cause about a third of the oil pollution in the oceans when they wash out their tanks or dump their bilge water. It is an unfortunate by-product of the storage and transportation of oil and petroleum is the occasional spill. Oil spills are very difficult to clean up.

The kind of oil spill we usually think about is the accidental or intentional release of petroleum products into the environment as result of human activity (drilling, manufacturing, storing, transporting, waste management), that floats on the surface of water bodies as a discrete mass and is carried by the wind, currents and tides. They have destructive effects on coastal ecosystems.

Examples of an oil spill would be things like well blowouts, pipeline breaks, ship collisions or groundings, overfilling of gas tanks and bilge pumping from ships, leaking underground storage tanks, and oil-contaminated water runoff from streets and parking lots during rain storms. Marine oil spill is a serious consequence of off-shore oil drilling and its oceanic transportation. Spill control firms specialize in the prevention, containment and cleanup of industrial oil spills. The first step taken for offshore pollution treatment is to control the source of pollution before applying clean up techniques. Most of the spilled oil in offshore is in suspension because it is heavy crude, the water is warm so the volatile material has evaporated increasing its density and finally most of it is still connected to the seabed. Because the oil floats under sea surface it cannot be burned regardless of the thermal pollution, which will occur.

## 12.2 Behavior of Oil Spill in Marine Environment
When oil spill into marine environment, the following stages are followed:

i) Spreading: Spreading of crude oil on water is probably the most important process following a spill. Apart from chemical nature of oil, the extent of spreading is affected by wind, waves and currents. Under the influence of hydrostatic and surface forces, the oil spreads quickly attaining average thickness of less than 0.03 mm within 24 hours. Once a spill has thinned to the point that surface forces begin to play an important role, the oil layer is no longer continuous and uniform but becomes fragmented by wind and waves into spots.

ii) Evaporation: Evaporation and dissolution are the major processes degrading petroleum crude when spilled on water. The composition of oil, its surface area and physical properties, wind velocity, air and sea temperatures, turbulence and intensity of solar radiation, all affect evaporation rates of hydrocarbons. Evaporation alone will remove about 50% of hydrocarbons in a crude oil on the ocean's surface.

iii) Photo-oxidation: The natural sunlight in the presence of oxygen can transform several petroleum heavy hydrocarbons into compounds of ultimately to low molecular weight.

iv) Dispersion: Dispersion is oil-in-water emulsion resulting from the incorporation of small globules of oil into water column. Oil begins dispersing immediately on contact with water and is most significant during the first ten hours.

v) Dissolution: Dissolution is another physical process in which the low molecular weight hydrocarbons as well as polar non-hydrocarbon compounds are partially lost from the oil to the water column.

vi) Degradation: Bio-degradative processes influencing fate of petroleum in aquatic environment include microbial degradation. Microorganisms capable of oxidizing petroleum hydrocarbons and related compounds are widespread in nature. The rate of microbial degradation varies with the chemical complexity of the crude, the microbial populations and many of the environmental conditions.

Saudi Arabia as the main world’s oil producer, encounter numerous sources of offshore pollution as indicated in **Table 12.1**. It must be realized that treatment of an oil barrel spill in offshore costs around one thousands US dollars.

Between 1973 and 1993, there were over 200,000 oil spills in USA waters, dumping over 5.5 million barrels of crude oil. Incredibly, that is as average of 28 incidents per day, spilling 753 barrels per day over 20 years into water ways. Oil intentionally released from Kuwaiti refineries and terminals during the second gulf war amounted to 6 million barrels.

In addition, more than 700 wells producing hundred tons of smoke, toxic chemicals into air were left producing for long time before repairing. It is estimated that almost 24 million barrels of crude oil are spilled into the world’s oceans and water ways each year. Bad sea tankers spilled are amounted to only 13% of the total world oil spill. Municipal and industrial wastes, urban runoff, leaking pipelines and storage tanks and standard tankers operations such as ballast water all contribute to marine pollution.

**Table 12.1 Pollution causes in offshore Saudi Arabia, 2010.**

| Origin of spill | Location | | Total | Percentage |
|---|---|---|---|---|
| | Red sea | Arabian Gulf | | |
| Oil sea tanker | 1 | 1 | 2 | 4% |
| Commercial ship | 1 | 1 | 2 | 4% |
| Pipeline | 0 | 1 | 2 | 2% |
| Offshore oil field | 0 | 2 | 2 | 4% |
| Industry | 5 | 11 | 16 | 34% |
| Offshore drilling rig | 0 | 4 | 4 | 9% |
| Offshore oil well | 0 | 9 | 9 | 19% |
| Oil exporting terminals | 2 | 2 | 4 | 9% |
| Unknown | 1 | 6 | 7 | 15% |
| Total | 10 | 37 | 47 | 100% |

## 12.3 Effects of Oil Spills

Oil spills have affected many people and many industries. They affect both the economy and the environment. Some of the things affected are:

i) Marine life: The adverse effects of oil spills on the marine environment are well known. If spilled oil escapes the booms and skimmers reaching the shore, it contaminates the inter-tidal zone and the beaches.

ii) Local industries: Oil, dead fish and birds all get washed up on the shores and the oil slick interferes in activities such as fishing, sailing, swimming etc. The local tourist industry suffers, as aesthetic beauty of seashore is lost due to oil slick. Industries that rely on clean seawater for routine operations such as desalination of seawater can also suffer because operations have to be stopped while the water is cleaned.

iii) Fishing industry: The fishing industry suffers badly when an oil spill occurs. Firstly because the fish are often covered in oil, or have swallowed oil making them poisonous. Also a large number of fish die, decreasing the number of fish that could have possibly been caught.

## 12.4 Major Classification of Oil Spill

Offshore oil spill may come from numerous sources of offshore and onshore activities including:

### 12.4.1 Offshore Production Spill

i) Accidents associated with drilling (blowout, mud leaks).

ii) Accidents associated with production (fire, pipelines, storms, equipment failure).

### 12.4.2 Oil Transport Spill

i) Bilge oil: This collects in the Ship bottom through seepage or leakage.

ii) Slop oil: Oil-water emulsion that is normally collected at the rear center tank as the residue of tank cleaning operations.

iii) Overflows: This occurs during the loading or discharge of cargo and the transfer of cargo from one tank to another.

iv) Ballast water: That is seawater taken into empty cargo tanks to give the vessel stability.

v) Collisions: Causes major spills.

### 12.4.3 Oil Refining Spill

i) Cooling water.

ii) Water softener and boilers blow down.

iii) Refinery processes (direct contact with oil and treating chemicals).

Undesirable components of refinery waste water are: floating and dissolved oil, suspended solids, dissolved solids, phenol and other organics, cyanide, chromate, organic nitrogen, phosphate, sulfides and mercaptans, caustics and acids color and turbidity.

## 12.5 Oil Pollution Treatment Techniques

At the past we do not have the technology to perform this huge task of controlling and stopping the pollution we have to depend on the foreign help to perform this task. But at present, part of this job can be done based on local experienced staff.

### 12.5.1 Skimming Treatment Process

This method is to surround the oil with special designed fences and skim it with huge tankers transferring it to the place where it is burned or may be re-used. The only disadvantage of this process is that it is limited to a certain capacity, which is small compared to our case.

### 12.5.2 Adsorption Treatment Process

This is done using charcoal or chalk-like stones, which are grounded, spread over the oil spot with a screen under the spot so that the stone absorbs oil (oil that sticks on the stone surface) and settles and then remove by the screen. The disadvantage of this process is that it may take two months to be done and a whole year to make sure that pollution is not transferred from the surface to the bottom.

### 12.5.3 Chemical Treatment Process

This method is using solvents with dispersing agents to be sprayed on the oil to change the oil to droplets that will be spread by wave action and the danger of pollution is reduced to minimum. This method is mainly used in open seas or oceans; therefore, it can not be used in our area because of the size of the spot and the nature of the Arabian Gulf.

### 12.5.4 Bacterial Treatment Process

This method is to spray bacteria, which will feed on oil turning it into energy. After the process is completed bacteria starve and leave nothing. The disadvantage of this process is that it is very expensive and not every company or organization can do it properly.

### 12.5.5 Burning Treatment Process

It is the oldest process being used to remove oil pollution. The disadvantage of this process is air pollution and the generated energy (temperature) kills inhabitant in the seawater.

## 12.6 Pollution Control and Treatment Capabilities in Saudi Arabia

The main government body responsible for environment protection and pollution records is the Presidency of Meteorology & Environment Protection (PME). Additionally, the government of Saudi Arabia has established the national committee for oil spills response from Ministry of Petroleum and Mineral Resources, Saudi Aramco, Water Desalination Establishment, Boarders Defense Force and PME. Saudi Arabia government holds stocks of equipment in Jubail, Jeddah and most ports in the Red sea and the Arabian Gulf for responding to offshore oil spills and ascendants. In the private sector, the Arabian Oil company (Saudi Aramco) holds the largest of oil pollution control and clean-up equipment in the country including offshore aerial spraying and mechanical recovery capability. Saudi Arabia has experienced a number of moderate-to-large oil spills during the last ten years, culminating in the large oil spill during the Gulf war in 1990. PME and Saudi Aramco coordinated major international response efforts during which more than one million barrels of oil were recovered from the Saudi shoreline.

## 12.7 Waste Management

Wastes generated during oil and gas exploration and production fall into four general categories:

i) Drilling mud and Cuttings: Drilling rigs that use drilling mud will generate a large volume of used drilling mud. Drilling muds that are oil- or synthetic oil-based are typically recycled, although over time the oil or synthetic materials may degrade and render the mud unusable for further drilling. Most water-based muds are disposed of after the completion of drilling although they can be managed to allow the water to be recycled.

Drill cuttings are bits of rock that are ground up during the drilling process and brought to the surface with the drilling mud as the well is being drilled. Most drill cuttings are managed through disposal, although some are treated and beneficially reused. In some circumstances, drill cuttings can be beneficially reused for stabilizing road surfaces, as landfill cover material, or as a construction material. For example, oily cuttings have been used to provide the same service as tar-and-chip road surfacing, although not all regulatory agencies allow for such a reuse

ii) Produced Water: In subsurface formations, naturally occurring rocks are generally permeated with fluids such as water, oil, or gas (or some combination of these fluids). Reservoir rocks normally contain both petroleum hydrocarbons (liquid and gas) and water. Extraction of oil or natural gas from reservoirs also generates produced water. Produced water is any water that is present in a reservoir with the hydrocarbons and is brought to the surface with the crude oil or natural gas. When hydrocarbons are extracted, they are brought to the surface as a produced fluid mixture. The composition of this mixture is dependent on whether crude oil or natural gas is being produced and generally includes a mixture of either liquid or gaseous hydrocarbons, produced water, and dissolved or suspended solids.

As reservoir pressure declines over time, additional water is often injected into the reservoirs to help force the oil to the wells. This process is known as enhanced oil recovery. Both formation and injected water are brought to the surface along with the hydrocarbons and as the reservoir becomes depleted, the amount of produced water increases as the reservoir fills with the injected water. Produced water is usually very salty and may contain residual hydrocarbons, heavy metals, naturally occurring radionuclides, numerous inorganic species, suspended solids, and chemicals used in hydrocarbon extraction.

At the surface, produced water is separated from the hydrocarbons and treated to remove as much oil as possible. At offshore facilities, this treated water is generally discharged into the sea. At most onshore locations, produced water cannot be discharged and is therefore injected underground either for enhanced oil recovery or for disposal. In some parts of the western United States, produced water can be discharged if it is not too salty and it can be beneficially reused. In recent years,

iii) Associated Waste: The process of producing, treating, storing, and transporting crude oil and natural gas generates low volumes of a variety of wastes, such as sludges, scales, produced sand, and other process-related wastes. These wastes, referred to as "associated wastes," make up less than 1% of the total volume of waste generated by oil and gas exploration and production. These wastes are managed in much the same way as other operational wastes.

iv) Other Wastes: Waste soils may also be generated as a result of oil and gas activities. These would include soils contaminated by releases of crude oil, produced water, or other materials. Contaminated soils are frequently managed along with other operational wastes. Oil and gas separators are used to separate produced water and gases from the extracted oil. Disposal of the produced water is conducted in the manner described previously.

## 12.8 Well Abandonment

If well logs determine that there is insufficient hydrocarbon potential to complete an exploratory well, or after production operations have drained a reservoir, the well must be plugged and abandoned. Following removal of production equipment, onshore and offshore wells are plugged and abandoned in a similar manner, although different regulatory bodies have their own requirements for plugging operations. Typically, cement plugs are placed and tested across any open hydrocarbon-bearing formations, across all casing shoes, across freshwater aquifers, and possibly several other areas near the surface, including the top 20 to 50 ft of the well bore. This is accomplished by pumping cement slurry to the desired location within the well bore. For plugging at locations above the well bottom hole (such as at aquifer locations), bridge plugs are used to prevent the cement from falling into the well bore. The bridge plug is set below the well section to be plugged, and cement is pumped on top of the plug.

At onshore locations, after the well has been plugged the casing is cut below the ground surface and a steel plate is welded to the top of the casing. The area around the sealed well is then backfilled with clean fill and a marker is installed indicating the presence of an abandoned well. For abandoned offshore wells, after the well has been plugged and abandoned the casing and production platform supports are cut at or below the bottom surface and the production rig is often toppled where appropriate and permissible to provide an artificial reef.

## 12.9 Some of the Major Global Marine Oil Spills

i) Argo Merchant: On December 15, 1976, the Argo Merchant ran aground on Fishing Rip (Nantucket Shoals), 29 nautical miles southeast of Nantucket Island, Massachusetts in high winds and ten foot seas. Later, the vessel broke apart and spilled its entire cargo of 7.7 million gallons of fuel oil.

ii) Amoco Cadiz: The Amoco Cadiz encountered stormy weather and ran aground off the coast of Brittany, France on March 16, 1978. Its entire cargo of 68.7 million gallons of oil spilled into the sea.

iii) Burmah Agate: On November 1, 1979, the Burmah Agate collided with the freighter Mimosa southeast of Galveston Entrance in the Gulf of Mexico, resulting explosion and a fire that affected an estimated 2.6 million gallons of oil to release into the environment, and another 7.8 million gallons to consume by the fire.

iv) Ixtoc I: The 2-mile-deep exploratory well, Ixtoc I, blew out on June 3, 1979 in the Bay of Campeche off Ciudad del Carmen, Mexico. By the time the well was brought under control in March, 1980, an estimated 140 million gallons of oil had spilled into the bay.

v) Exxon Valdez: On March 24, 1989, the Exxon Valdez ran aground on Bligh Reef in Prince William Sound, Alaska. It spilled 10.8 million gallons of oil into the marine environment, and impacted more than 1,100 miles of non-continuous Alaskan coastline. This was the largest oil spill in the U.S. history.

vi) Barge Cibro Savannah: On March 6, 1990, the Cibro Savannah exploded and caught fire while departing the pier at the Citgo facility in Linden, New Jersey. About 127,000 gallons of oil remained unaccounted for after the incident.

vii) Megaborg: The Megaborg released 5.1 million gallons of oil as the result of a lightering accident and subsequent fire. The incident occurred 60 nautical miles south-southeast of Galveston, Texas on June 8, 1990.

viii) Jupiter: On September 16, 1990, the tank vessel Jupiter was offloading gasoline at a refinery on the Saginaw River near Bay City, Michigan, when a fire started on board and the vessel exploded.

ix) Arabian Gulf Spills: In January of the 1991 Gulf War, the Iraqi Army destroyed tankers, oil terminals, and oil wells in Kuwait, causing the release of about 900,000,000 barrels of oil. This was the largest oil spill in the World's history.

x) Barge Bouchard 155: On August 10, 1993, three ships collided in Tampa Bay, Florida: the barge Bouchard 155, the freighter Balsa 37, and the barge Ocean 255. The Bouchard 155 spilled an estimated 336,000 gallons of fuel oil into Tampa Bay.

xi) Prestige: On 13th November 2002, the tanker PRESTIGE (81,564 DWT), carrying a cargo of 77,000 tonnes of heavy fuel oil, suffered hull damage in heavy seas off northern Spain. In all, it is estimated that some 63,000 tonnes were lost from the PRESTIGE.

## 12.10 Oil Spill Response in Saudi Arabia

The Saudi petroleum industry, represented by Saudi Aramco, is committed to preventing oil spills, in all of its operations, facilities and projects. It is also committed to effectively fighting any oil spill that may take place in any of its areas of operations; considering the magnitude of the Kingdom's oil resources and the massive oil production and marine terminal handling operations, hence, Saudi Aramco continuously monitors, by air and sea, its offshore operating areas to prevent any oil spill and ensure immediate response. Additionally, the company exerts great efforts to train its employees and properly maintain all of its vessels; to protect the natural marine environment, comply with governmental instructions for the prevention of oil spills, conform to the related international laws and standards and to maintain its impressive record in this area. To this end, the company has drawn up regional and global contingency oil spill plans that would enable it to respond effectively and in a timely manner to any incident anywhere in the company's operating areas. Draft plans have been formulated for the Arabian Gulf, the Red Sea, and the Gulf Coast, The Eastern Coast of the U.S.A., the Caribbean Sea, Europe, the Mediterranean Sea, South Africa and the Far East. Regular drills make up an important part of these plans.

Moreover, Saudi Aramco is a founding member in a number of regional and global organizations concerned with oil spill control activities, such as the Gulf Area Oil Companies Mutual Aid Organization (GAOCMAO), which is concerned with protecting the Arabian Gulf resources from oil pollution, and the UK-based Oil Spill Services Center which provides oil spill response services on a worldwide scale.

# CHAPTER THIRTEEN
# Basics of Petroleum Refining

## 13.1 Introduction
Petroleum refining is the process of separating the many compounds present in crude petroleum. This process is called fractional distillation where the crude oil is heated; the various compounds boil at different temperatures and change to gases; and are later re-condensed back into liquids. The principle which is used is that the longer the carbon chain, the higher the temperature at which the compounds will boil as shown in **Table 13.1**. The crude petroleum is heated and changed into a gas. The gases are passed through a distillation column, which becomes cooler as the height increases. When a compound in the gaseous state cools below its boiling point, it condenses into a liquid. The liquids may be drawn off the distilling column at various heights. Although all fractions of petroleum find uses, the greatest demand is for gasoline. One barrel of crude petroleum contains only 25-35% gasoline. Transportation demands require that over 50% of the crude oil be converted into gasoline. To meet this demand some heavier petroleum fractions must be converted to gasoline.

## 13.2 Refining Process
An oil refinery is an industrial process plant where crude oil is processed and refined into more useful petroleum products, such as gasoline, diesel fuel, asphalt base, heating oil, kerosene, and liquefied petroleum gas. Oil refineries are typically large sprawling industrial complexes with extensive piping running throughout, carrying streams of fluids between large chemical processing units. An oil refinery is a more than just a complicated construction of steel towers and pipes. It is actually a factory that takes crude oil and turns it into gasoline and other products necessary for our modern society to function. A typical refinery costs billions of dollars to build, and millions more just to maintain and upgrade. Large refineries are complex operations that run 365 days a year, employ as many as 2,000 people, and occupy huge areas. How does refining or transformation of crude oil to various valuable products take place? Actually, there are three basic steps common to all refining operations, whether big or small, simple or complex as follows:

### 13.2.1 The Separation Process
In this step, crude oil is separated into various chemical components by heating. Separation starts by pumping crude oil into pipes running through hot furnaces and heating the oil to vaporize it. The resulting vapors and liquids are discharged into distillation towers, the tall, narrow columns that give refineries their distinctive skylines. Inside the towers, the liquids and vapors separate into components or fractions according to their density and boiling point. The lightest fractions, including gasoline and liquid petroleum gas (LPG), vaporize and rise to the top of the tower, where they condense back to liquids. Medium-weight liquids, including kerosene and diesel oil, stay in the middle. Heavier liquids, called gas oils, separate lower down. The heaviest fractions with the highest boiling points settle at the bottom. These tar-like fractions, are called residues. The various fractions are then piped to different stations or plants within the refinery. Some fractions require relatively little additional processing to become road asphalt or jet

fuel. However, fractions destined to become high-value products, such as gasoline, typically require much more additional processing.

### 13.2.2 The Conversion Process

The conversion process goes a step further by breaking these chemicals down into molecules called hydrocarbons (cracking and reforming). Conversion is where fractions from the distillation towers are transformed into streams (intermediate components) that eventually become finished products. This also is where a refinery makes money, because only through conversion can most low-value fractions become gasoline.

The most widely used conversion method is called cracking, which uses heat and pressure to literally "crack" heavy hydrocarbon molecules into lighter ones. A cracking unit consists of one or more tall, thick-walled, bullet-shaped containers, called reactors, and a network of furnaces, heat exchangers, and other vessels. Cracking, coking and Alkylation are the important parts of conversion. Reforming uses heat, moderate pressure, and catalysts to turn naphtha, a light, relatively low-value fraction of the oil, into high-octane gasoline.

### 13.2.3 The Treatment Process

The treatment process combines and transforms hydrocarbon molecules, and other chemicals “additives” to create a collection of new products.

## 13.3 The Main Refinery Products

The products separated in the crude oil distilling unit (**Figure 13.1**) of a modern refinery may be broadly classified, in order of decreasing volatility, into: (i) gases, (ii) light distillates, (iii) middle distillates and (iv) residues as shown in **Table 13.1**.

i) The petroleum gases:
The gases consist chiefly of propane and butane and usually called petroleum gases. Propane and butane may be supplied, together as a town gas or liquefied by compression and marketed as liquefied petroleum gas (LPG). Butane may to some extent be added to motor gasoline. Generally, the refineries products are as follows:

**Table 13.1 Typical crude oil fractions.**

| Crude oil fractions | | Boiling points, $^oF$ | Chemical composition | Usage |
|---|---|---|---|---|
| Gases | Hydrogen gases | -ve | $C_1 – C_4$ | Petroleum gas |
| Light distillates | Petroleum ether | Up to 160 | $C_5 – C_6$ | Cleaner and solvent |
| | Gasoline | 160 – 400 | $C_7 – C_8$ | Motor fuel and solvent |
| | Kerosene | 400 – 575 | $C_{1o} – C_{16}$ | Motor and jet fuel |
| Middle distillates | Light oil | 575 – 850 | $C_{16} – C_{30}$ | Lubrication oil |
| | Heavy oil | 850 – 1100 | $C_{30} – C_{50}$ | Lubrication oil |
| Residues | Residues | 1200+ | $C_{80}$ + | Tars, Asphalts |

ii) The light distillates comprise fractions, which may be used directly in the production of motor and aviation gasoline. The heavier, higher-boiling-point fractions in this range are the lighting, heating and jet engine kerosene and the feedstock for reforming or cracking. The special boiling point spirits and white spirits are obtained by further distillation of an appropriate gasoline fraction in a special plant designed to give a high degree of fractionation, so as to produce the narrow boiling point ranges required. The heavier fractions falling within the gasoline range are sometimes referred to as naphtha.

iii) The middle distillates are used as gas-oil and diesel fuel and also for blending with residual products in the preparation of furnace fuels. The distillates used as feedstock for cracking purposes may be obtained from the middle distillate range.

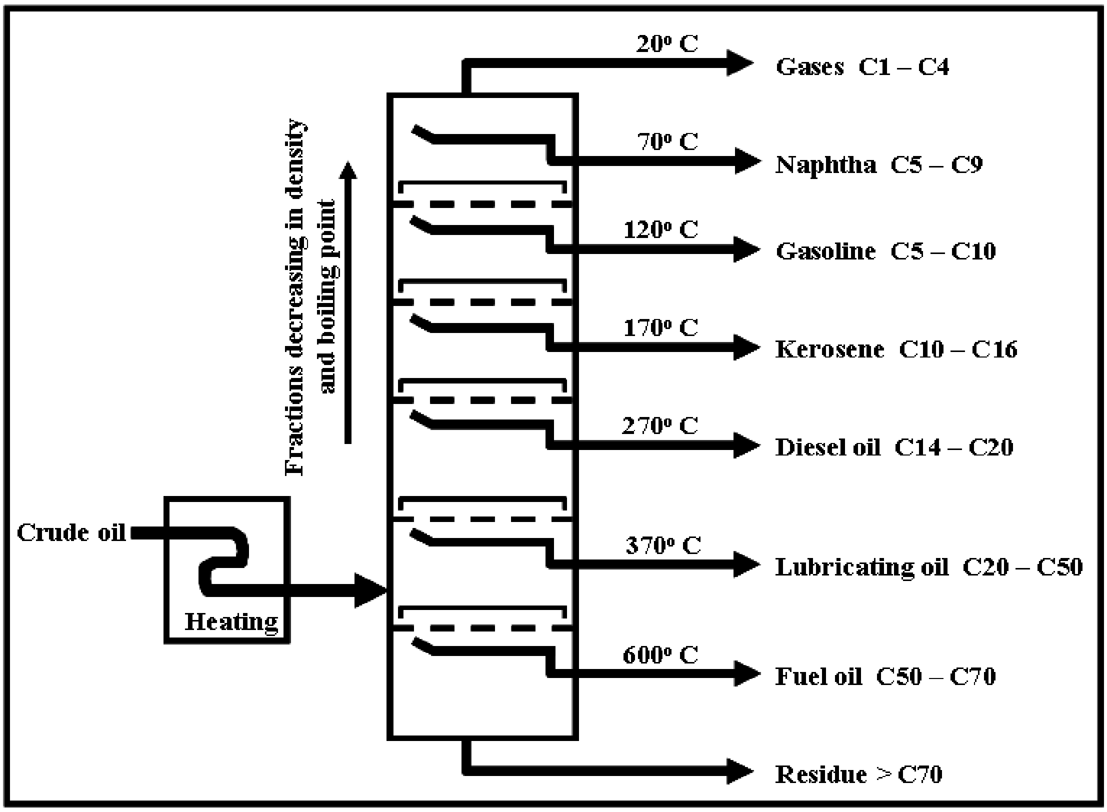



**Figure 13.1 General scheme of crude oil distillation.**

iv) The residues, consisting of the components that are not removed as distillates, are used as fuel oil or for the manufacturing of lubricating oils, wax and bitumen. Usually, the residues are cracked again to produce lighter products. Others may be reformed to produce new petrochemical products. **Table 13.2** shows refineries average yields from a barrel of crude oil. One barrel contains 42 gallons of crude oil.

**Table 13.2 Average yields from a barrel of crude oil.**

| Products | Gallons/bbl |
|---|---|
| Gasoline | 19.5 |
| Distillate fuel oil<br>(Includes both home heating oil and diesel fuel) | 9.2 |
| Kerosene-type jet fuel | 4.1 |
| Residual fuel oil (Heavy oils used as fuels in industry, marine transportation and for electric power generation) | 2.3 |
| Other heavy products | 9.1 |
| Total | 44.2 |

The total volume of products made is 2.2 gallons greater than the original 42 gallons of crude oil. This represents a "processing gain."

## 13.4 Petrochemical Products

Petrochemicals are chemical products made from raw materials of petroleum (hydrocarbons) origin. Although some of the chemical compounds which originate from petroleum may also be derived from other sources such as coal, petroleum is a major source of many. The two main classes of petrochemical raw materials are olefins (including ethylene and propylene) and aromatics (including benzene and xylene isomers), both of which are produced in very large quantities. World production of ethylene is around 110 million tonnes per annum, of propylene 65 million tonnes, and of aromatic raw materials 70 million tonnes. The largest petrochemical industries are to be found in the USA and Western Europe, the Middle East (Saudi Arabia) and Asia. Thousands of petrochemical products are existing nowadays few of them are shown in **Figure 13.2**.

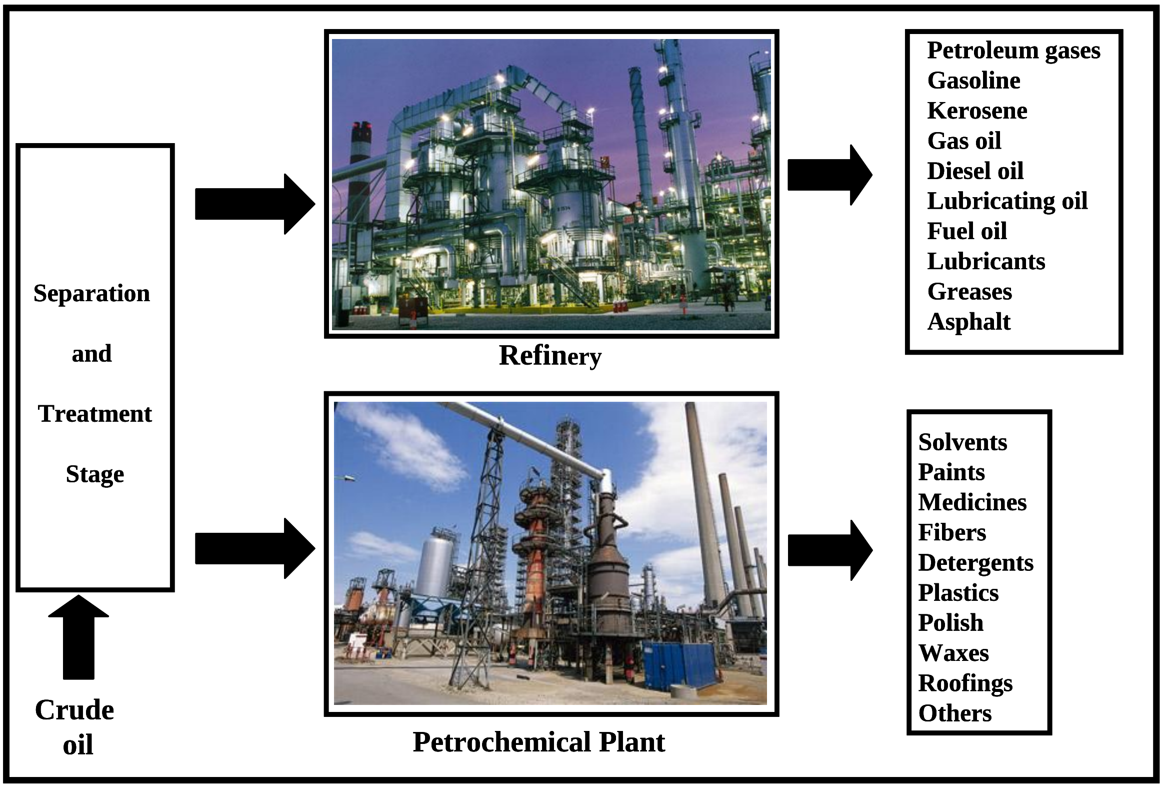



**Figure 13.2 Products from refineries and petrochemical plants.**

## 13.5 Jubail and Yanbu Industrial Complexes

Jubail and Yanbu in Saudi Arabia constitute a unique experiment in development, which has proved outstandingly successful. These are two cities, which were conceived on the drawing board and were planned to provide a purpose-built and highly efficient environment for modern industrial production. These industrial complexes, built at Jubail on the Arabian Gulf and Yanbu on the Red Sea by the Royal Commission for Jubail and Yanbu, are the key to the Kingdom of Saudi Arabia national industrialization plans. These two industrial cities provide the basis for the Kingdom's program to develop hydrocarbon-based and energy intensive industries. The massive investment in these industrial cities has as its major objective a reduction in the Kingdom's dependence on oil revenues by gaining access to the world's petrochemical markets. This route to industrialization exploits the Kingdom's natural advantages, in terms of cheap energy and cheap raw materials for petrochemical manufacture. These two industrial cities are governed by the Royal Commission for Jubail and Yanbu.

# CHAPTER FOURTEEN
# Basics of Petroleum Economics

## 14.1 Introduction

The oil sector is the key of domestic production sector; oil revenues constituted of more than 70% of total budgetary revenues. The kingdom of Saudi Arabia input on the development of oil and natural gas sector is estimated to be around 10% of total budgetary expenditures. Export oil revenue represents a large portion of the Kingdom's gross national products (GNP) that is accounted for 90% of total exports. Saudi Arabia is the world's most important oil producer. Given its relatively high production levels, accounting for nearly 13% of world output and 35% of total OPEC output, and, more significantly, its small domestic needs, the kingdom's dominance of international crude oil markets is unchallenged. Although reluctant to play the role, Saudi Arabia has become the "swing producer" balancing international oil demand and supply. Therefore, within limits, Saudi oil production policies can have a profound impact on international prices. Since the early 1970s, the kingdom has occasionally used this dominance to influence oil prices, usually to further its objectives of sustaining long-term oil consumption and ensuring economic stability in the industrialized world.

## 14.2 Organization of Petroleum Exporting Countries (OPEC)

OPEC is an international organization of eleven developing countries, which are heavily reliant on oil revenues as their main source of income. Membership is open to any country which is a substantial net exporter of oil and which shares the ideals of the organization. The current members are Algeria, Indonesia, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates and Venezuela.

OPEC is a permanent, intergovernmental organization, created at the Baghdad conference on September 10–14, 1960, by Iran, Iraq, Kuwait, Saudi Arabia and Venezuela. The five founding members were later joined by eight other members: Qatar (1961); Indonesia (1962); Libya (1962); United Arab Emirates (1967); Algeria (1969); Nigeria (1971); Ecuador (1973–1992) and Gabon (1975–1994). OPEC had its headquarters in Geneva, Switzerland, in the first five years of its existence, and then was moved to Vienna, Austria, on September 1, 1965. OPEC's objectives are to:

i) Co-ordinate and unify petroleum policies among member countries.
ii) Secure fair and stable prices for petroleum producers for an efficient, economic and regular supply of petroleum to consuming nations; and a fair return on capital to those investing in the industry,
iii) Assign the possible oil quota for its members.

The OPEC conference of ministers meets in ordinary session twice a year, and is responsible for the formulation of the general policy of the organization. Since oil revenues are so vital for the economic development of these nations, they aim to bring stability and harmony to the oil market by adjusting their oil output to help ensure a balance between supply and demand. Twice a year, or more frequently if required, the oil and energy ministers of the OPEC members meet to decide on the organization's output level, and consider whether any action to adjust output is necessary in the light of recent and anticipated oil market developments. OPEC's eleven members collectively supply about 40 to 50% of the world's oil output, and possess almost three-quarters of the world's total proven crude oil reserves. As indicated by **Table 14.1** and **Figure 14.1**, OPEC spare oil production will satisfy the world's demand until 2022; after that, new discoveries must be found if the World's oil demand continues increasing. OPEC - produces 40 percent of the world’s oil and possesses 70 percent of its reserves - some of which, according to present estimates, should last for well over another hundred years. This assures the Gulf States, as well as Iran and Iraq, of a continuing global importance far beyond their still puny domestic economic strength, so long as:

i) Oil, however environmentally damaging, is perceived as a more useful fuel than coal;
ii) The cost of alternatives, like wind and biofuels, remains high; and
iii) Nuclear power stations continue to be beset by environmental and other political concerns.

## 14.3 Organization of Arab Petroleum Exporting Countries (OAPEC)

OAPEC was established in 1968 with permanent headquarters in Kuwait It is an instrument of Arab cooperation whose objective is to provide support to the Arab oil industry. OAPEC established by an agreement amongst Arab countries which rely on the export of petroleum. OAPEC is a regional inter-governmental organization concerned with the development of the petroleum industry by fostering cooperation among its members.

**Table 14.1 OPEC spare production record, 2010.**

| Country | Spare production, bbl |
|---|---|
| Saudi Arabia | 3,200,000 |
| Iran | 400,000 |
| Kuwait | 300,000 |
| Nigeria | 310,000 |
| Angola | 340,000 |
| Algeria | 110,000 |
| UAE | 100,000 |
| Qatar | 140,000 |
| Total | 4,900,000 |

OAPEC contributes to the effective use of the resources of member countries through sponsoring joint ventures. The organization is guided by the belief in the importance of building an integrated petroleum industry as a cornerstone for future economic integration amongst Arab countries. On January 9, 1968, Kuwait, Libya and Saudi Arabia signed in Beirut an agreement establishing OAPEC. The three founding members agreed that the organization would be located in the state of Kuwait.

By 1982 the membership of the Organization has risen to eleven Arab oil exporting countries: Algeria (1970), Bahrain (1970), Egypt (1973), Iraq (1972), Kuwait (1968), Libya (1968), Qatar (1970), Saudi Arabia (1968), Syria (1972), Tunisia (1982) and United Arab Emirates (1970). In 1986, Tunisia submitted a request for withdrawal. The ministerial council deliberated the request and it was agreed to suspend Tunisia’s rights and obligations in OAPEC, until such a time that Tunisia chooses to reactivate its membership. OAPEC activities are developmental in nature, and its membership is restricted to Arab countries with oil revenues that constitute a significant part of their GNP. Furthermore, it concerns for issues that relate to energy in all members of the Arab league, and for that purpose a meeting is organized every four years.

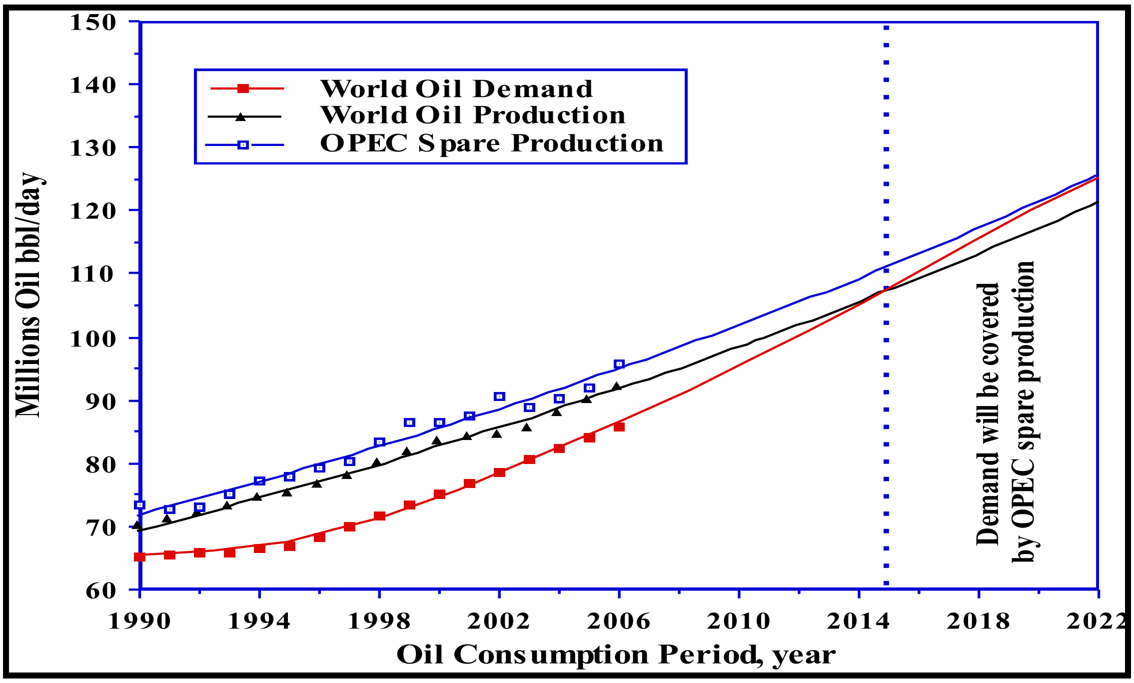



**Figure 14.1 Projected oil supply and demand.**

## 14.4 International Energy Agency (IEA)

This agency was organized in November 1974. Current members are Australia, Austria, Belgium, Canada, Portugal, Spain, Sweden, Swaziland, Turkey, Greece, Ireland, Japan, Luxembourg, Holland, Newzeland, Italy, Norway, UK, Germany, France, Finland, and USA.

The main objectives of this organization are:

i) Cooperation between members to lower their consumption from oil dependent energy,
ii) Search for alternative energy sources such as nuclear energy, solar energy, wind energy, Hydrodynamic energy, coal, and wastes,
iii) Construction of an energy database storing the oil market data,
iv) Cooperation with the oil producing countries for oil prices stability,
v) Preparation of their countries for any shortage in oil demand by strategic storage of oil, gas, and products,
vi) Financing exploration in the third world countries, and
vii) Funding EOR research projects.

## 14.5 History of Oil Prices

Economical and political issues in addition to weather change continuously impose up and down oil prices. **Figure 14.2** summarizes the history of oil prices in the period between 1970 and 2010. From this brief history, it is clear that oil process is not following the role of supply and demand; instead it is affected by embargos, wars, political issues, etc.

OPEC oil basket price, is the arithmetic average of the following crudes: Saharan Blend (Algeria), Girassol (Angola), Oriente (Ecuador), Iran Heavy (Iran), Basra Light (Iraq), Kuwait Export (Kuwait), Es Sider (Libya), Bonny Light (Nigeria), Qatar Marine (Qatar), Arab Light (Saudi Arabia), Murban (UAE) and Merey (Venezuela).

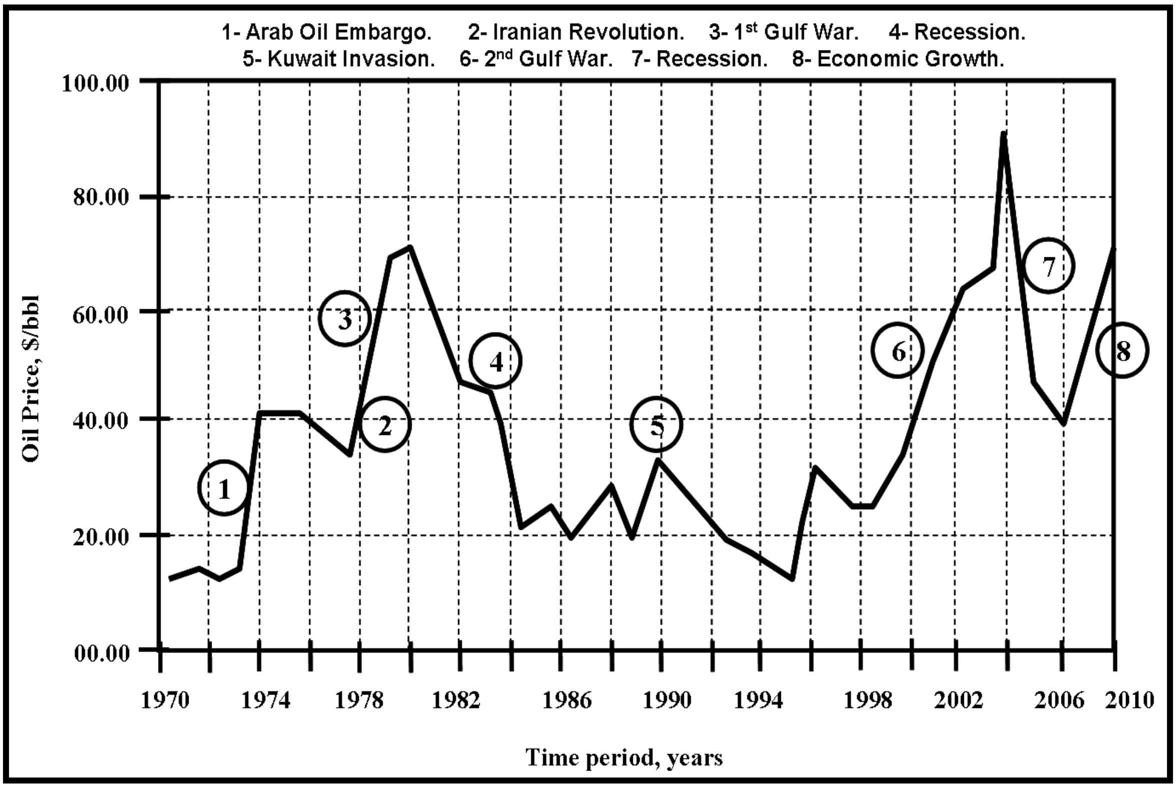



**Figure 14.2 Oil prices fluctuation history.**

Normally, crude oil prices are referenced against bench-mark crudes such as Arabian light, Brent blend, Dubai, OPEC basket, etc. For example, Brent oil blend properties are as follows: API =38.3$^o$, sulfur content =0.37% by weight and total acid number (TAN) =0.07. Therefore, any difference from these three properties makes the either decrease or increase in price of the compared crude oil.

## 14.6 Forms of Petroleum, Natural Gas and Minerals Ownerships

There are two types of petroleum and minerals ownerships, private and public. Except in U.S.A., public ownership is predominant in the global.

i) Private Ownership: The landowner owns any minerals found beneath his land, providing that a previous owner has not sold or retained these mineral rights.
ii) Public Ownership: Ownership of the minerals in place (except in USA) is almost completely in control of the national government.

## 14.7 Types of Petroleum Well Drilling Contracts

The operating companies can have their wells drilled under several contract alternatives including:

i) Turnkey Contract: The operator pays a fixed (lump sum) to the contractor on completion of the well, while the contractor furnishes all the material and labor and handles the drilling operation independently.

ii) Footage Contract: Payment is on a penetration rate per foot basis. This type of contract is given in well-known areas. The main goal of this contract is to pursue operators to drill the well faster.

iii) Daywork Contract: Payment is on a penetration rate per day basis. The purpose of this contract is to encourage the drilling contractor to reach the target depth quickly.
Actual contracts often involve several of these bases of payments.

## 14.8 Reservoir Development Practices

All information gathered through drilling and completion of the wildcat and appraisal wells and analysis of data obtained is used to prepare a reservoir development plan. This plan includes not only spacing of development wells, as affected by surface and subsurface conditions, but also the control procedures determined for manipulating the reservoir fluid pressure changes and flow characteristics over the productive life of the reservoir.

For flowing wells, this involves choke sizes and variations, in order to manipulate the flowing bottomhole pressure of the wells within technical and economic limits. It also involves fluid injection into the reservoir, to manipulate that pressure and therefore control the production of hydrocarbons from the reservoir and encroachment of external fluids such as water and gas into the reservoir. The onshore development plan will be quite different than the offshore development plan. One of the major decisions in preparing the offshore development plan is selection of offshore platform locations and number of platforms, to optimize production within economic limits from the reservoir in a reasonable lifetime. If an offshore platform is placed in the wrong location, as determined by later drilling, this will result in a major economic loss compared to drilling a single well in the wrong onshore location. The decision, therefore, for offshore development may be far more critical than decisions foe development of an onshore reservoir. Economics, both at the time of development, and that anticipated over the productive life of the reservoir, place limits on the extent to which the best technology can be applied. For example, an offshore reservoir might be best developed on a 40-acre spacing (16 wells per square mile).

However, the cost of the platforms as related to hydrocarbon prices may justify the drilling of only three wells per mile on an average basis, by directional drilling from centralized platforms. It cannot be anticipated, therefore, that as high a percentage of the original hydrocarbon in place will be recovered during the life of production of the reservoir with three wells per mile as would have been recovered has the best available technology been applied, requiring 16 wells per mile.

## 14.9 Principles of Engineering Economy

Engineering economy is a decision assistance tool (yardsticks) by which one project or investment will be chosen as the most economical one. The most important economical assisting tools are the net present value and the payout time yardsticks. In this section, definitions of the main engineering economy terms are presented. These terms are the basis of the economical analysis that is discussed in the next sections.

- Investment: An investment is an expenditure that will generate benefits for more than one period. Investment in the oil industry includes: exploration, drilling, well development (including drilling fluids, casing, cementing, logging, wellhead, tubing, etc.) as well as the cost of surface equipment including tanks, pumps, separators flow lines, etc.

- Market Clearing Price: At higher prices, lower quantities will be demanded if other factors being constant (law of demand) and at higher prices, higher quantities will be supplied if other factors being constant (law of supply). Therefore, the price at which demand=supply is called market clearing price as shown in **Figure 14.3**.

- Interest Rate: It is a single value interest rate which when applied on the total investment yields income distributed on the duration of the project.
- Economic Limit: The point at which there will be no profit, i.e. cost equal to income. In oil and natural gas industry, the economic limit point may change with rise in prices or discovery of new technologies.
- Inflation (Discounting Rate): It is a continuous rise in the general price level. In other words, it is a drop in the purchasing power of money.

The role of economics is fundamental to evaluation, development and abandonment of oil and natural gas reservoirs and wells.

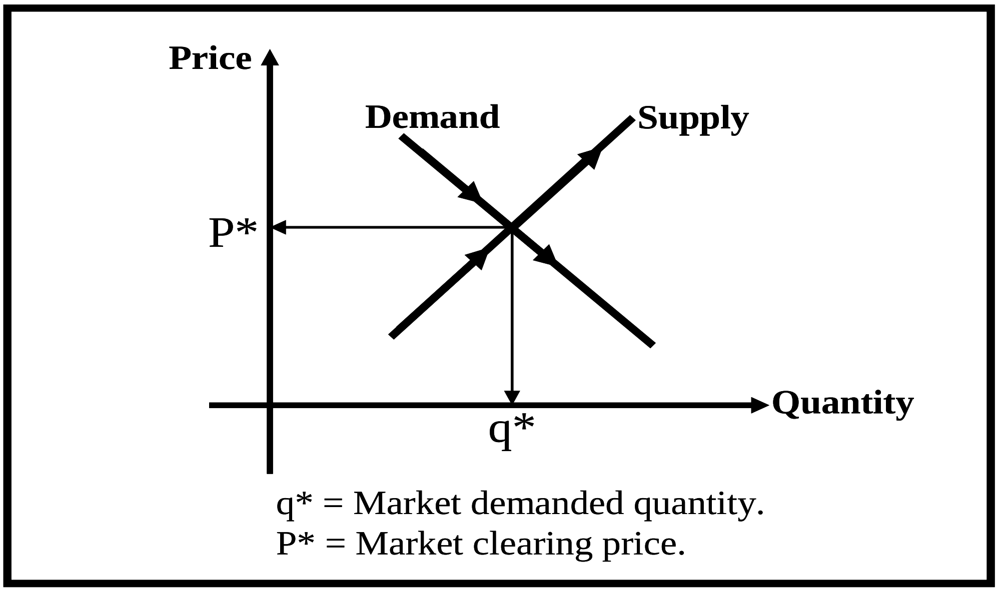



**Figure 14.3 Market clearing price determination plot.**

### 14.9.1 Net Present Value

Net present value (NPV) is the algebraic sum of total investment, income and the assets value (salvage value) at the end of the project. This definition is converted into a mathematical expression as follows:

$$NPV = -I + \left(\frac{A}{r}\right)\left(1 - e^{-rn}\right) + Se^{-rn} \qquad \ldots(14.1)$$

Where:
NPV = Net present value, \$.
I = Investment, \$.
A = Net income, \$.
r = Discounting rate, %/year.
S = Salvage value, \$.
n = Duration, years.

For example, assume a sum of 700 million Saudi riyals (I) is invested in a project for five years (n) at an annual income (A) of 150 million Saudi riyals. The salvage value (S) of the assets after seven years is 200 millions Saudi riyals and the inflation rate (r) was constant at 7% per year. Then by applying the above equation, the net present value (NPV) of this project will be 73.75 millions Saudi riyals. If the calculation yields positive NPV, this means the project is profitable.

### 14.9.2 Payout Time

Payout time (POT) is the time required to recover the paid investment (see **Figure 14.4**). Typical payout periods are in the range from 2 to 3 years. Payout time is calculated using the following expression:

$$POT = \left( \frac{(\sum I)}{\left(\sum \frac{A}{n}\right)} \right) \qquad \ldots(14.2)$$

For example, if we consider the same example mentioned previously, the payout time is equal to 4.67 years. Most of investors prefer to payback their invested money as soon as possible to overcome inflation growth or to start new projects.

## 14.10 Reservoir Management Economics

Petroleum reservoirs management economics requires economic evaluation and analysis of the property and associated projects throughout the life of the reservoir. Making rational investment decision requires that the project is economically viable, i.e., it will produce profits satisfying the applied economical yardsticks. Economical analysis of petroleum projects requires several input parameters such as:

i) Setting an economical objective.
ii) Collecting production and operation data.
iii) Selecting an economical yardstick for analysis.
iv) Making risk analysis and choosing optimum project for investment.

In addition to the previously mentioned requirements, investment in petroleum projects requires knowledge of the recovery scheme (primary, secondary or tertiary), number of wells and platforms, initial oil in place (IOIP), recovery factors, etc.

## 14.11 Cost-Per-Drilled Foot Analysis

The introduction of advanced drill bit designs has not always had the effect of obsolete existing designs. Instead, the availability of new designs has increased the number of types of bits available from the various bit manufacturers. Selection of the bit best suited for a specific use is further complicated by the variable performances and prices of the many types of bits. Thus, the question, which needs to be answered, is: How can the correct bit be selected for a given application? The decision concerning which bit to use often based on some performance criteria, such as total rotating hours, total footage, or maximum penetration rate. Other times, the least expensive bit is chosen. This approach may be satisfactory in areas where practices and costs are constants but it may not be satisfactory where drilling costs are changing, and drilling practices and bit selection vary.

A realistic approach to bit selection is to base the final decision on the minimum cost-per-foot. In this way, it is possible to achieve an optimum relationship between penetration rate, bit footage, rig cost, trip time and bit cost. Cost-per-foot as related to these variables can be determined by the equation:

$$C = \frac{HRRC\,[TT + DT] + BC}{FD} \qquad \ldots(14.3)$$

Where:
C = Cost, $/ft.
HRRC = Hourly rig rental cost, $/hr.
TT = Trip time, hr.
DT = Drilling time, hr.
BC = Bit cost, $.
FD = Footage drilled, ft.

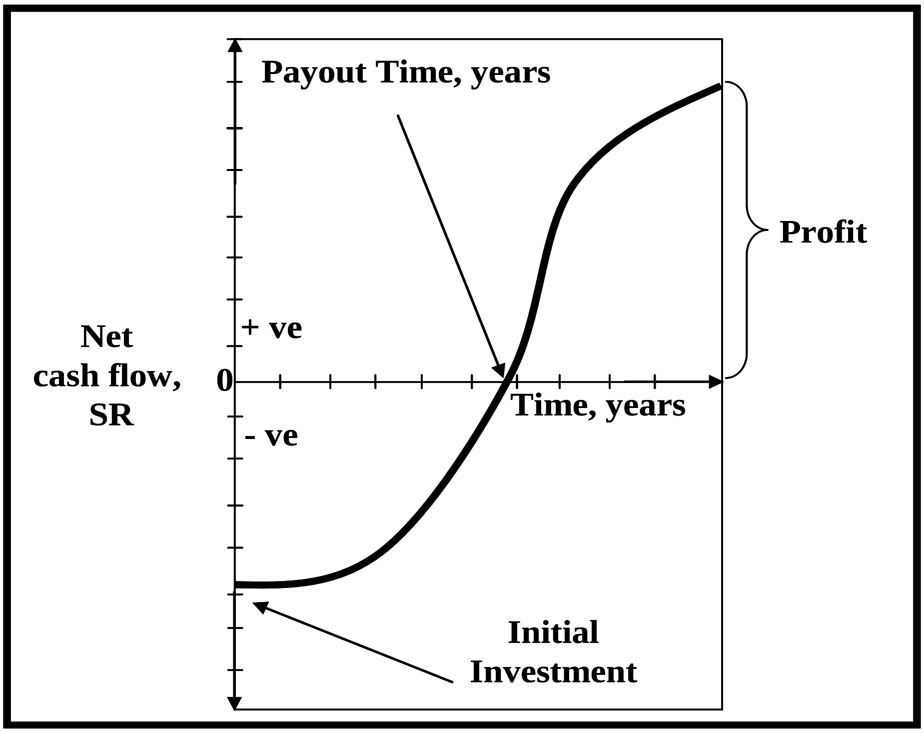



**Figure 14.4 Typical payout time determination plot.**

The example below (**Table 14.2**) illustrates how this formula evaluates the performance of two different bits. From the bit record, A and B are evaluated. Bit number A is a journal-bearing milled-tooth bit. Bit number B is a journal-bearing insert bit.

**Table 14.2 Example data for bit performance calculations.**

| Bit No. | Bit Cost, $ | Depth Out, ft | Footage, ft | Rotating Time, Hours | Penetration Rate, ft/hr | Cost/foot, $/ft |
|---|---|---|---|---|---|---|
| A | 950 | 7547 | 264 | 18.5 | 14.3 | 42.99 |
| B | 3145 | 8510 | 963 | 76.0 | 12.7 | 38.36 |

Rig Cost = $400/hour Trip Time = 1 hr/1000 feet

If performance is based on using penetration rate as the criteria, bit #15 would appear to be superior. Referring to the cost-per-foot comparison, bit "A" gave the best performance, at $4.63/ft cheaper than bit "B". It has been demonstrated that by using this cost-per-foot formula, a bit can be pulled when it no longer becomes economical to drill.

### 14.12 Oil Pricing Method

Crude oils prices are set in the world markets based on three crude oil markers (Benchmarks) as shown in **Table 14.3**. Therefore, oil produced in Asia will be affected by the price of Dubai marker crude oil, while oil produced in Europe and Africa will be affected by the price of Brent blend marker crude oil. Similarly, oil produced in America will be affected by the price of WTI marker crude oil. Price of the above three marker crude oils are changed according to supply and demand as well other numerous factors such as political issues, disasters, wars, etc. Prices of other crude oils are set based on the following properties: i) Sulfur content in weight percent basis, ii) Specific gravity expressed in API scale, and iii) Total acid content (TAN) in mg KOH/g basis.

Additionally, iv) distance between producing and importing countries (transportation cost) must be taken into account when crude oil is being priced. Price of crude oil other than the three marker crudes shown in **Table 14.3** is predicted using the following expression:

$$P_x = P_m \pm A_f \qquad \text{...(14.4)}$$

$P_x$ = Price of crude oil type x, \$/bbl.

$P_m$ = Price of Marker (benchmark) crude oil, \$/bbl.

$A_f$ = Adjustment factor, \$/bbl.

Adjustment factor shown in equation 14.4 is function of the above four factors and calculated as follows:

$$A_f = \text{function of}\left[\pm\Delta(\text{i}),\ \pm\Delta(\text{ii}),\ \pm\Delta(\text{iii}),\ \pm\Delta(\text{iv})\right] \qquad \text{...(14.5)}$$

According to equations 14.4 and 14.5, a crude oil may be higher or lower in price than the corresponding marker crude oil based on its properties and production and market locations.

### 14.12 Equivalent Oil Barrel Price

It must be realized that crude oil price is not only the cost of moving oil from the reservoir to surface, but it is the sum of many other expenses including: exploration cost, development cost, overall facilities maintenance cost, royalties and taxes, operating cost, spare production facilities cost, environment protection cost, reservoir pressure maintenance cost, and cost of consuming non-renewable economic resources (oil and gas reserves).

**Table 14.3 World crude oil markers.**

| Geographic Location | Marker Crude Oil | Price Exchange Market |
|---|---|---|
| Europe and Africa | Brent Blend<br>API = 38.3$^o$.<br>Sulfur content = 0.37 wt%. | 1) London Petroleum Exchange (LPE).<br>2) Singapore International Monetary Exchange (SIMEX).<br>3) New York Mercantile Exchange (NYMEX). |
| Middle East and Asia | Dubai-Oman<br>API = 32$^o$.<br>Sulfur content = 2.13 wt%. | |
| America | West Texas Intermediate (WTI)<br>API = 39.6$^o$.<br>Sulfur content = 0.24 wt%. | |

# CHAPTER FIFTEEN
# Units and Conversion Factors

## 15.1 Introduction

Units are essential in any mathematical calculations. The most systems of units worldwide used are the imperial system and the SI system. The fundamental units from which all other basic units are derived are the mass, length and time as shown in **Table 15.1** and defined as follows:

i) Meter (m): Meter is the basic unit of length. It is the distance light travels, in a vacuum, in 1/299792458*th* of a second.

ii) Gram (g): The gram is the basic unit of mass. It is the mass of an international prototype in the form of a platinum-iridium cylinder kept at Sevres in France. It is now the only basic unit still defined in terms of a material object.

iii) Second (s): The second is the basic unit of time. It is the length of time taken for 9192631770 periods of vibration of the caesium-133 atom to occur.

**Table 15.1 Units systems and their abbreviation.**

| Category | Abbreviation | |
|---|---|---|
| | SI system | Imperial system |
| Mass (M) | g | $lb_m$ |
| Length (L) | m | ft |
| Time (T) | s | s |

Other units derived from the above three fundamental units are shown in **Table 15.2**. Petroleum engineers have defined their own systems of units called Darcy units and Field units. Darcy units are applied in laboratory calculations while field units are used in field operations. The SI system is now the standard system in all countries except the United Kingdom and United States. The American Petroleum Institute (API) is supporting an orderly transition to SI units. The SI system of units allows the sizes of units to be made bigger or smaller by the use of appropriate prefixes as shown in **Table 15.3**.

**Table 15.2 Basic parameters for SI, Darcy and field systems of units.**

| Parameter | Symbol | Dimensions | SI units | Darcy units | Field units |
|---|---|---|---|---|---|
| Length | L | L | m | cm | ft |
| Mass | m | M | g | g | $lb_m$ |
| Time | t | T | s | s | hr |
| Velocity | u | L/T | m/s | cm/s | ft/s |
| Rate | q | $L^3/T$ | $m^3/s$ | $cm^3/s$ | STB/d & MSC/d |
| Pressure | p | $(ML/T^3)/L^2$ | $N/m^2$ .. Pa | atm | psi |
| Density | ρ | $M/L^3$ | $kg/m^3$ | g/cc | $lb_m/ft^3$ |
| Viscosity | μ | M/LT | kg/(m.s) | cp | cp |
| Permeability | k | $L^2$ | $m^2$ | Darcy | Darcy |
| Temperature | T | t | $^oK$ | $^oR$ | $^oR$ |

**Table 15.3 Prefixes used in SI system of units.**

| Prefix | Value | Prefix | Value |
|---|---|---|---|
| yotta [Y] | 10^24 | deci [d] | 10^-1 |
| zetta [Z] | 10^21 | centi [c] | 10^-2 |
| exa [E] | 10^18 | milli [m] | 10^-3 |
| peta [P] | 10^15 | micro [μ] | 10^-6 |
| tera [T] | 10^12 | nano [n] | 10^-9 |
| giga [G] | 10^9 | pico [p] | 10^-12 |
| mega [M] | 10^6 | femto [f] | 10^-15 |
| kilo [k] | 10^3 | atto [a] | 10^-18 |

## 15.2 Basic Symbols in Petroleum Engineering

As in other engineering branches, there are several special parameters routinely used in calculations. **Table 15.4** lists these parameters and their commonly used symbols.

**Table 15.4 Petroleum engineering parameters and their commonly used symbols.**

| Parameter | Symbol | Parameter | Symbol |
|---|---|---|---|
| Porosity | $\varphi$ | Permeability | k |
| Production rate | q | Relative permeability | $k_r$ |
| Flow rate | q | Effective permeability | $k_e$ |
| Compressibility | c | Oil formation volume factor | $\beta_o$ |
| Oil-water contact | OWC | Gas formation volume factor | $\beta_g$ |
| Pressure drop | $\Delta P$ | Gas-oil contact | GOC |
| Capillary pressure | $P_c$ | Viscosity | $\mu$ |
| Wellbore pressure | $P_w$ | Reservoir pressure | $P_r$ |
| Initial oil in place | IOIP | Gas-oil ratio | GOR |
| True vertical depth | TVD | Initial gas in place | IGIP |
| Density | $\rho$ | Gas deviation factor | Z |
| Productivity index | PI | Barrel | bbl |
| Standard cubic foot | SCF | Stock tank barrel | STB |

## 15.3 Linear Interpolation

Interpolation is the process of filling in intermediate values of a series between known values. The practicing engineer find it constantly necessary to refer to tables as source of information, consequently interpolation or that procedure of " reading between lines of the table" is necessary topic.

Linear interpolation is done using the following formula:

$$x = x_o + \left(x_1 - x_o\right)\left[\frac{f(x_1) - f(x)}{f(x_1) - f(x_o)}\right] \qquad \ldots(15.1)$$

Equation 15.1 can be used for linear interpolation as shown in the following example (**Table 15.5**):

**Table 15.5 Example on linear interpolation.**

| f(x) | x |
|---|---|
| $f(x_o) = 10$ | $x_o = 20$ |
| $f(x) = 30$ | $x = ?$ |
| $f(x_1) = 50$ | $x_1 = 40$ |

$$x = 20 + (40-20)\left[\frac{50-30}{50-10}\right] = 30$$

## 15.4 Conversion Factors

Conversion factor between various systems of units for area, pressure, flow rate, distance, force, time, viscosity, mass, permeability and density necessary for petroleum engineers are tabulated in **Tables 15.6** to **15.15**. Other conversion factors are available in most books.

### 15.4.1 Equation Balancing

Any mathematical equation is balanced and contains no numerical terms if SI system of units is used. If the same equation is to be applied using different system of units, a numerical conversion factor must be added to the equation to balance it with the new units. For example Darcy equation for fluid flow through porous media using SI system or Darcy units (see **Table. 15.2**) is written as follows:

$$q = \alpha \frac{2\pi k h \Delta P}{\mu \ln\left(r_e / r_w\right)} \qquad \ldots(15.2)$$

If the above equation to be used with field units (see **Table 15.2**), then a conversion factor of 1.127 is inserted to the left-hand side of the equation. This conversion factor is derived as follows:

i) Substitute all the terms in the given equation by the required non SI units and insert the term alpha ($\alpha$) as a conversion factor as follows:

$$(\text{bbl}/\text{day}) = \alpha \frac{2\pi(\text{Darcy})(\text{ft})(\text{psi})}{(\text{cp})\ \ln\left((\text{ft})/(\text{ft})\right)} \qquad \ldots(15.3)$$

ii) Covert all units to SI or Darcy units as follows:

$$\left(\frac{\text{bbl}}{\text{day}}\ \frac{\text{day}}{24 \text{ x } 3600\,\text{s}}\ \frac{1.59 \text{ x } 10^5\,\text{cc}}{\text{bbl}}\right) = \frac{2\pi(\text{Darcy})(\text{ft x }\frac{30.48\,\text{cm}}{\text{ft}})(\text{psi x }\frac{\text{atm}}{14.7\,\text{psi}})}{(\text{cp})\ \ln\left((\text{ft x }\frac{30.48\,\text{cm}}{\text{ft}}) / (\text{ft x }\frac{30.48\,\text{cm}}{\text{ft}})\right)} \qquad \ldots(15.4)$$

iii) Now Combine all numericals together in the right hand side and remove SI or Darcy units as follows:

$$\left(\frac{\text{cc}}{\text{s}}\right) = \left[\frac{24 \text{ x } 3600 \text{ x } 30.48}{1.59 \text{ x } 10^5 \text{ x } 14.7}\right] \frac{2\pi(\text{Darcy})(\text{cm})(\text{atm})}{(\text{cp})\ \ln\left((\text{cm})/(\text{cm})\right)} \qquad \ldots(15.5)$$

ii) Then, alpha to be used in equation 15.2 with field units is equal to: $\alpha = 1.127$.

It must be noticed that if equation 15.2 is to be used with SI or Darcy units then, no conversion factor is required or the conversion factor alpha is equal to one ( $\alpha$ =1.0 ). The above procedure can be followed for any other units or equations.

### 15.4.2 Basic Conversion Factors

**Tables 15.6** to **15.15** can be used to find conversion factors between various systems of units.

**Table 15.6 Conversion factors for pressure (A= conversion factor x B).**

| | B \ A | psi (Pound/in$^2$) | atm | Pa (Newton/ m$^2$) | inch Hg |
|---|---|---|---|---|---|
| Pressure | psi (Pound/in$^2$) | 1 | 6.81 x $10^{-2}$ | 6.897 x $10^{3}$ | 2.036 |
| | Atm | 14.7 | 1 | 1.0133 x $10^{5}$ | 29.921 |
| | Pa (Newton/ m$^2$) | 145 x $10^{-4}$ | 9.87 x $10^{-6}$ | 1 | 2.953 x $10^{-4}$ |
| | inch Hg | 0.4912 | 0.49511 | 3.3421 x $10^{-2}$ | 1 |

**Table 15.7 Conversion factors for flow rate (A= conversion factor x B).**

| | B \ A | cc/s | m$^3$/s | bbl/day | gal/day |
|---|---|---|---|---|---|
| Flow rate | cc/s | 1 | 1 x $10^{-6}$ | 0.54343 | 22.824 |
| | m$^3$/s | 1 x $10^{6}$ | 1 | 5.4343 x $10^{5}$ | 2.2824 x $10^{7}$ |
| | bbl/day | 1.8401 | 1.8401 x $10^{-6}$ | 1 | 42 |
| | gal/day | 5.3813 x $10^{-2}$ | 4.3813 x $10^{-8}$ | 2.3810 x $10^{-2}$ | 1 |

**Table 15.8 Conversion factors for distance (A= conversion factor x B).**

| | B \ A | cm | m | inch | ft | yard | km | mile |
|---|---|---|---|---|---|---|---|---|
| Distance or Length | Cm | 1 | 1 x $10^{-2}$ | 0.3937 | 3.2808 x $10^{-2}$ | 0.9144 x $10^{-2}$ | 1 x $10^{-5}$ | 6.2137 x 10-$^{6}$ |
| | M | 1 x $10^{2}$ | 1 | 39.37 | 3.2808 | 0.9144 | 1 x $10^{-3}$ | 6.2137 x $10^{-4}$ |
| | Inch | 2.54 | 2.54 x $10^{-2}$ | 1 | 8.3333 x $10^{-2}$ | 1.0936 | 2.54 x $10^{-5}$ | 1.5783 x $10^{-5}$ |
| | Ft | 30.48 | 0.3048 | 12 | 1 | 0.028 | 3.048 x $10^{-4}$ | 1.8939 x $10^{-4}$ |
| | Yard | 91.44 | 1.09361 | 36 | 3 | 1 | 0.9144 x $10^{-3}$ | 5.682 x $10^{-4}$ |
| | Km | 1 x $10^{5}$ | 1 x $10^{3}$ | 3.937 x $10^{4}$ | 3.2808 x $10^{3}$ | 1.094 x $10^{3}$ | 1 | 0.62137 |
| | Mile | 1.6093 x $10^{5}$ | 1.6093 x $10^{3}$ | 6.336 x $10^{4}$ | 5.28 x $10^{3}$ | 1.76 x $10^{3}$ | 1.6093 | 1 |

**Table 15.9 Conversion factors for area (A= conversion factor x B).**

| | B \ A | $cm^2$ | $m^2$ | $inch^2$ | $ft^2$ | acres | $mile^2$ |
|---|---|---|---|---|---|---|---|
| Area | $cm^2$ | 1 | 1 x $10^{-4}$ | 1.55 x $10^{-1}$ | 1.0764 x $10^{-3}$ | 2.471 x $10^{-8}$ | 3.861 x $10^{-11}$ |
| | $m^2$ | 1 x $10^{4}$ | 1 | 1.55 x $10^{3}$ | 1.0764 x $10^{1}$ | 2.471 x $10^{-4}$ | 3.861 x $10^{-7}$ |
| | $inch^2$ | 6.4516 | 6.4516 x $10^{-4}$ | 1 | 6.9444 x $10^{-3}$ | 1.5942 x $10^{-7}$ | 2.491 x $10^{-10}$ |
| | $ft^2$ | 9.2903 | 9.2903 x $10^{-2}$ | 1.44 x $10^{2}$ | 1 | 2.2957 x $10^{-5}$ | 3.587 x $10^{-8}$ |
| | acres | 4.0469 x $10^{7}$ | 4.0469 x $10^{3}$ | 6.2726 x $10^{6}$ | 4.356 x $10^{4}$ | 1 | 1.5625 x $10^{-3}$ |
| | $mile^2$ | 2.59 x $10^{10}$ | 2.59 x $10^{6}$ | 4.0145 x $10^{9}$ | 2.7878 x $10^{7}$ | 6.40 x $10^{2}$ | 1 |

**Table 15.10 Conversion factors for density (A= conversion factor x B).**

| | B \ A | $lb/in^3$ (psi) | $lb/ft^3$ | lb/gal (ppg) | $g/cm^3$ (g/cc) | $kg/m^3$ | lb/bbl |
|---|---|---|---|---|---|---|---|
| Density | $Lb/in^3$ (psi) | 1 | 1.728 x $10^{3}$ | 2.31 x $10^{2}$ | 27.68 | 2.768 x $10^{4}$ | 9.702 x $10^{3}$ |
| | $lb/ft^3$ | 5.787 x $10^{-4}$ | 1 | 0.13368 | 1.6018 x $10^{-2}$ | 16.018 | 5.6146 |
| | Lb/gal (ppg) | 4.329 x $10^{-3}$ | 7.4805 | 1 | 0.1983 | 1.1983 x $10^{2}$ | 42 |
| | $g/cm^3$ (g/cc) | 3.6127 x $10^{-2}$ | 62.428 | 8.3454 | 1 | 1000 | 3.5051 x $10^{2}$ |
| | $kg/m^3$ | 3.6127 x $10^{-5}$ | 6.2428 x $10^{-2}$ | 8.3454 x $10^{-3}$ | 1 x $10^{-3}$ | 1 | 0.35051 |
| | Lb/bbl | 1.0307 x 10-$^{4}$ | 0.17811 | 2.381 x $10^{-2}$ | 2.853 x $10^{-3}$ | 2.853 | 1 |

**Table 15.11 Conversion factors for force (A= conversion factor x B).**

| | B \ A | dyne | poundal | pound | Newton |
|---|---|---|---|---|---|
| Force | dyne | 1 | 7.233 X $10^{-5}$ | 2.2481 x $10^{-6}$ | 1 x $10^{-5}$ |
| | poundal | 1.3826 x $10^{4}$ | 1 | 3.1081 x $10^{-2}$ | 0.13826 |
| | pound | 4.4482 x $10^{5}$ | 32.174 | 1 | 4.4482 |
| | Newton | 1 x $10^{5}$ | 7.233 | 0.22481 | 1 |

**Table 15.12 Conversion factors for mass (A= conversion factor x B).**

| Mass: B \ A | lb | gm | kg | slug | grain |
|---|---|---|---|---|---|
| lb | 1 | 4.5359 x $10^{2}$ | 0.45359 | 3.1081 x 10-$^{2}$ | 7000 |
| gm | 2.2046 x $10^{-3}$ | 1 | 1 x $10^{-3}$ | 6.8521 x $10^{-5}$ | 15.432 |
| kg | 2.2046 | 1000 | 1 | 6.8521 x $10^{-2}$ | 1.5432 x $10^{4}$ |
| slug | 32.174 | 1.4594 x $10^{4}$ | 14.594 | 1 | 2.2522 x $10^{5}$ |
| grain | 1.4286 x $10^{-4}$ | 6.4799 x $10^{-2}$ | 6.4799 x $10^{-5}$ | 4.4401 x $10^{-6}$ | 1 |

**Table 15.13 Conversion factors for viscosity (A= conversion factor x B).**

| Viscosity: B \ A | cp, or $\left(\frac{gm}{m\ s}\right)$ | poise | $\left(\frac{lb}{ft\ s}\right)$ | $\left(\frac{kg}{m\ s}\right)$ | $\left(\frac{slug}{ft\ s}\right)$ |
|---|---|---|---|---|---|
| cp or $\left(\frac{gm}{m\ s}\right)$ | 1 | 0.01 | 6.7197 x $10^{-4}$ | 1 x $10^{-3}$ | 2.0885 x $10^{-5}$ |
| poise | 100 | 1 | 6.7197 x $10^{-2}$ | 0.1 | 2.0885 x $10^{-3}$ |
| $\left(\frac{lb}{ft\ s}\right)$ | 1488.2 | 14.882 | 1 | 1.4882 | 3.1081 x $10^{-2}$ |
| $\left(\frac{kg}{m\ s}\right)$ | 1000 | 10 | 0.67197 | 1 | 2.0885 x $10^{-2}$ |

**Table 15.14 Conversion factors for volume (A= conversion factor x B).**

| Volume: B \ A | $m^3$ | $cm^3$ | liter | $ft^3$ | $in^3$ | gallon | bbl |
|---|---|---|---|---|---|---|---|
| $m^3$ | 1 | 1.0 x $10^{9}$ | 1.0 x $10^{6}$ | 35.31 | 61.023 x $10^{3}$ | 3.785 x $10^{-2}$ | 6.2893 |
| $Cm^3$ | 1.0 x $10^{-9}$ | 1 | 1.0 x $10^{-3}$ | 30.48 | 16.39 | 3.7853 x $10^{3}$ | 162.763 x $10^{3}$ |
| liter | 1.0 x $10^{-6}$ | 1.0 x $10^{3}$ | 1 | 0.03048 | 61.024 | 3.7853 | 158.983 |
| $ft^3$ | 0.0283 2 | 2.832 x $10^{4}$ | 30.48 x $10^{6}$ | 1 | 6.39 x $10^{-3}$ | | 5.615 |
| $in^3$ | 1.639 x $10^{-5}$ | 0.061 | 61.013 | 5.787 x $10^{-4}$ | 1 | 4.239 x $10^{-3}$ | |
| gallon | 3.785 x $10^{-3}$ | 0.264 x $10^{-3}$ | 0.2642 | | | 1 | 0.02381 |
| Bbl | 0.159 | 6.29 x $10^{-6}$ | 6.29 x $10^{-3}$ | 0.1781 | | 42 | 1 |

**Table 15.15 Conversion factors for temperature.**

| | | |
|---|---|---|
| Temperature | $^oF = 1.8\ ^oC + 32$ | Degree Fahrenheit. |
| | $^oC = (^oF - 32)/1.8$ | Degree Celsius. |
| | $^oK = ^oC + 273$ | Degree Kelvin. |
| | $^oR = ^oF + 460$ | Degree Rankin. |

## 15.5 Measurement of Oil and Gas Volumes

Oil volume for production, exporting or importing is measured using US barrel. Us barrel is equal to 42 US gallons. On the other hand, refined oil products and chemicals are distributed using barrels equal to 55 US gallons. Therefore, the volume of an oil barrel is two-third the volume of chemicals and refined products barrel.

Natural and petroleum gases are measured in standard cubic foot while liquefied petroleum gas is measured in pounds. Since in the early days, oil was shipped in blue painted barrels suggests the strange abbreviation for barrel "bbl". Natural gas is measured in standard cubic foot (SCF). Natural gas is measures by standard cubic foot (SCF).

# PETROLEUM GLOSSARY TERMS

**Acre-Feet**: Unit of volume; one acre of producing formation one foot thick. One acre-foot equals 7,758 barrels, 325,829 gallons or 43,560 cubic feet.

**Annulus**: The space between the wellbore and casing or between casing and tubing, where fluid can flow.

**API Gravity**: Gravity (weight per unit volume) of oils as measured by the API scale. This standard was adopted by the API 5/4/22 as the standard for the American petroleum industries

**Barrel**: A measurement used in the oil industry for a unit of volume of oil equivalent to 158.978 liters or 42 US gallons. Abbreviated to "bbl".

**Blowout**: An uncontrolled flow of reservoir fluids into the wellbore, and sometimes to the surface.

**Cap Rock**: A layer of impervious rock above a porous and permeable formation that contains oil or gas.

**Casing**: Pipe cemented in the well to seal off formation fluids or keep the hole from caving in.

**Cement**: Fluid cement is mixed at the surface, pumped to the bottom of a cased well, forced to flow around the lower end of the casing and up into the space between the casing and the borehole. When the cement solidifies (sets), it holds the casing in place, and provides support.

**Cementing Material**: The binding material in sedimentary rocks that precipitates between grains from pore fluids. Calcite and quartz are common cement-forming minerals.

**Crude Oil**: Crude petroleum and other hydrocarbons produced at the wellhead in liquid form

**Connate Water**: The water present in a petroleum reservoir in the same zone occupied by oil and gas considered by some to be the residue of the primal sea, connate water occurs as a film of water around each grain of sand in granular reservoir rock and is held in place by capillary attraction.

**Core**: Samples of subsurface rocks taken as a well is being drilled. The core allows geologists to examine the strata in proper sequence and thickness.

**Cracking**: The process of breaking down the larger, heavier and more complex hydrocarbon molecules into simpler and lighter molecules, thus increases the gasoline yield from crude oil. Cracking is done by application of heat and pressure, and in modern time the use of a catalytic agent.

**Development Well**: A well drilled in an already discovered oil or gas field.

**Discovery Well**: The first oil or gas well drilled in a new field. The discovery well is the well that is drilled to reveal the actual presence of a petroleum-bearing reservoir, Subsequent wells are development wells.

**Drilling Mud**: A special mixture of clay, water, and chemical additives pumped down hole through the drill pipe and drill bit. The mud cools the rapidly rotating drill bit; lubricates the drill pipe as it turns in the well bore; carries rock cuttings to the surface; and serves as plaster to prevent the wall of the bore hole from crumbling or collapsing. Drilling mud also provides the weight or hydrostatic head to prevent extraneous fluids to entering the well bore and to control down-hole pressures that might be encountered.

**Directional Drilling**: Drilling at an angle, instead of on the perpendicular, by using a whipstock to bend the pipe until it is going in the desired direction. Directional drilling is used to develop offshore leases, where it is very costly and sometimes impossible to prepare separate sites for every well; to reach oil beneath a building or some other location which cannot be drilled directly; or to control damage or as a last resort when a well has cratered. It is much more expensive than conventional drilling procedures.

**Drill bit**: Located at end of drill-string cutting head is generally designed with three cone-shaped wheels tipped with hardened teeth. Drill bits used for extra-hard rock are studded with thousands of tiny industrial diamonds.

**Drilling Platform**: An offshore structure with legs anchored to the sea bottom that supports the drilling of up to 35 wells from one location.

**Dry Hole**: A well that either produces no oil or gas or yields too little to make it economic to produce.

**Enhanced Oil Recovery**: Injection of water, steam, gases or chemicals into underground reservoirs to cause oil to flow toward producing wells, permitting more recovery than would have been possible from natural pressure or pumping alone.

**Field**: An area consisting of a single reservoir or multiple reservoirs all grouped on, or related to, the same individual geological structural feature or stratigraphic condition. The field name refers to the surface area, although it may refer to both the surface and the underground productive formations.

**Heavy Oil**: A type of crude petroleum characterized by high viscosity and a high carbon-to-hydrogen ration. It is usually difficult and costly to produce by conventional techniques.

**Horizontal Drilling**: The newer and developing technology that makes it possible to drill a well from the surface, vertically down to a certain level, and then to turn at a right angle, and continue drilling horizontally within a specified reservoir, or an interval of a reservoir.

**Hydrocarbons**: A large class of organic compound of hydrogen and carbon. Crude oil, natural gas, and natural gas condensate are all mixtures of various hydrocarbons, among which methane is the simplest.

**IEA:** A term stands for the international energy agency.

**Injection Well**: A well employed for the introduction into an underground stratum of water, gas or other fluid under pressure.

**Infill Drilling**: Wells drilled to fill in between established producing wells on a lease to increase production.

**Isopach Map**: A geological map showing the thickness and shape of underground formations. A tool used to determine underground oil and gas reservoirs.

**Limestone**: Sedimentary rock largely consisting of calcite. On a worldwide scale, limestone reservoirs probably contain more oil and gas reserves than all other types of reservoir rock combined.

**LNG (Liquefied Natural Gas)**: Natural gas that has been converted to a liquid through cooling to -260 degrees Fahrenheit at atmospheric pressure.

**Lost Circulation**: A serious condition that occurs when drilling mud pumped into the well does not return to the surface, but goes into the porous formation, crevices, or caverns instead.

**LPG (Liquefied Petroleum Gas)**: Hydrocarbon fractions lighter than gasoline, such as ethane, propane and butane, kept in a liquid state through compression and/or refrigeration, commonly referred to as "bottled gas.

**Mud**: Drilling fluid used to lubricate the drill string, line, the walls of the well, flush cutting to the surface and create enough weight to prevent blowouts.

**Natural Gas**: A mixture of hydrocarbon compounds and small amounts of various non-hydrocarbons (such as carbon dioxide, helium, hydrogen sulfide, and nitrogen) existing in the gaseous phase or in solution with crude oil in natural underground reservoirs.

**Net Present Value**: The present value of the dollars (income, or stream of income) to be received at some specified time in the future, discounted back to the present at a specified interest rate.

**Offshore:** Situated in the land area.

**Oil Spill:** The release of a liquid petroleum hydrocarbon into the environment due to human activity or accidents.

**Onshore:** Situated in the sea area.

**Open Hole**: An uncased well bore; the section of the well bore below the casing; a well in which there is no protective string of pipe.

**OPEC:** An abbreviation for the organization of petroleum exporting countries.

**Pay-Zone**: The term to describe the reservoir that is producing oil and gas within a given wellbore. Pay zones (or oil reservoirs) can vary in thickness from one foot to several hundred feet

**Perforating:** To make holes through the casing opposite the producing formations to allow oil and gas to flow into the well.

**Petrochemicals:** Chemical products made from raw materials of petroleum or other hydrocarbon origin**.**

**Permeability**: A measure of the resistance offered by rock to the movement of fluids through it.

**Perforations**: Holes through casing and cement into the productive formation.

**Petroleum**: A complex mixture of naturally occurring hydrocarbon compounds found in rock.

**Pollution:** The introduction of contaminants into an environment that causes instability, disorder, harm or discomfort to the ecosystem.

**Porosity**: The state or quality of being porous; the volume of the pore space expressed as a percentage of the total volume of the rock mass.  Porosity is an important property of oil-bearing formations. Good porosity indicates an ability to hold large amounts of oil in the rock. Porosity must be coupled with good permeability to allow the oil to flow to the well bore.

**Productive Well**: A well that is producing oil or natural gas or that is capable of production.

**Refining**: Refining is the process of converting crude oil into usable fuel products. A full description of refining and refining processes is available.

**Refining**: Manufacturing petroleum products by a series of processes that separate crude oil into its major components and blend or convert these components into a wide range of finished products, such as gasoline or jet fuel.

**Reserves**: An economically recoverable quantity of crude oil or gas.

**Reservoir**: A porous, permeable sedimentary rock formation containing quantities of oil and/or gas enclosed or surrounded by layers of less permeable or impervious rock.

**Reservoir Pressure**: The pressure at the face of the producing formation when the well is shut-in. It equals the shut in pressure at the wellhead plus the weight of the column of oil in the hole.

**Sandstone**: A clastic sedimentary rock whose grains are predominantly sand-sized.

**Sedimentary Rock**: Rock formed by the laying down of matter by seas, streams, or lakes; sediment deposited in bodies of water through geologic ages. Limestone, sandstone and shale are sedimentary rocks.

**Source Rock**: Sedimentary rock, usually shale containing organic carbon in concentrations as high as 5-10% by weight.

**Structure (Trap)**: Subsurface folds or fractures of strata that form a reservoir capable of holding oil or gas.

**Stratigraphic Column:** is a representation used in geology and its subfield of stratigraphy to describe the vertical location of rock units in a particular area. A typical stratigraphic column shows a sequence of sedimentary rocks, with the oldest rocks on the bottom and the youngest on top.

**Water-Drive Reservoir**: An oil reservoir or field in which the primary natural energy for the production of oil is from edge, or bottom-water in the reservoir.

**Well Killing**: To overcome downhole pressure by adding weighting elements to the drilling mud.

**Wellhead**: A device on the surface used to hold the tubing in the well. The wellhead is the originating point of the producing well at the top of the ground.

**Well Completion**: To finish a well so it is ready to produce oil or gas.

**Wildcat Well**: A well drilled for the purpose of discovering a new field or reservoir.

**Workover**: Operations on a producing well to restore or increase production.

**Water Flooding**: A secondary recovery method in which water is injected into a reservoir to force additional oil into the wells.

**Workover**: To clean out or work on a well to restore or increase production.

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