A PROGRAM FOR THE CONSERVATION OF THE OIL AND GAS RESOURCES OF ECUADOR, SOUTH AMERICA

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A PROGRAM FOR THE CONSERVATION OF THE OIL AND GAS RESOURCES OF ECUADOR, SOUTH AMERICA

ABSTRACT

In the paper are outlined the conservation principles which may provide effective and rational utilization of crude oil and natural gas resources of the Republic of Ecuador, South America. Attention is called throughout the paper to the importance of conserving oil, preventing its waste, and to the necessity of a controlled rate of production under a program of conservation. The conservation measures insure a continuous and adequate supply of petroleum products at a reasonable cost and protect property rights at the same time.

Economic and technical phases are pointed out. Production of petroleum at a rate in excess of market demand brings physical waste and results in serious disturbance of the industry economy. Excessive capital expenditures, brought about by the drilling of unnecessary wells, lead inevitably to an excessive production rate, and frequently are opposed to efficient producing practices.

The technology of conservation consists in the selection of production methods which will reduce waste of oil to the lowest amount compatible with the interests of the industry, the consuming public, and the national welfare. This selection implies a proper understanding of the practical principles of conservation which are based upon a complete knowledge of the nature and behavior of oil reservoirs, and the manner in which operating con-

ditions influence the recovery of oil.

A major objective of all efficient production practice is to produce oil under the most efficient type of drive. Hence, the oil pools should be managed according to the reservoir energy in order to secure the optimum recovery. The common types of drive under which oil is produced are: water drive, dissolved-gas drive, gas-cap drive, and gravitational segregation.

The recovery obtainable from an oil reservoir depends not only upon the nature of the reservoir, but also upon the manner in which the reservoir is developed and operated. The factors include well spacing, well completion practice, and use of pressure maintenance and secondary recovery.

Authoritative regulation is needed to prevent waste in the oil production. Provisions of modern conservation statutes relating to oil and gas are stated in the paper. The allocation recommended within pools grants each operator an equal opportunity to recover the equivalent of the recoverable oil which underlies his property, preventing drainage across property lines. The allocation among pools should be observed in order that every pool may produce at an efficient rate and have its fair share of the total production allowable.

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INTRODUCTION

Location of the area: - The Republic of Ecuador lies between Colombia on the north and Peru on the south and southeast. It occupies the northwestern part of South America (see Fig. 1).

The country takes its name from the fact that the equator crosses the country approximately 25 kilometers from Quito, capital of Ecuador (see Plate 1). Continuing westward into the Pacific, the equator line crosses her island possessions, the Archipelago of Colon, better known as the Galapagos Islands.[(1)]

The country is in the tropics, extending from 1°21 N. latitude to 5° S. Fortunately, nearly half of the area is occupied by the mountains and high plateau of the Cordilleras so that it enjoys a temperate climate.

The area of the country, since the protocol of Rio de Janeiro of January, 1942, is 267, 844 square kilometers. This cypher includes the 13 Galapagos Islands lying 600 miles west of the Ecuadorean coast, which have an area of 7,844 square kilometers.

The population of Ecuador has been estimated at 3,740,871 (Teran, 1948 p. 174).

Physiography: - Ecuador comprises three sharply-defined topographic divisions: (a) the coastal plains or costa, (b) the Andean region or sierra, and (c) the Oriente region to the east

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1 Name "Galapagos" derived from Spanish word meaning tortoise for which the islands are noted.

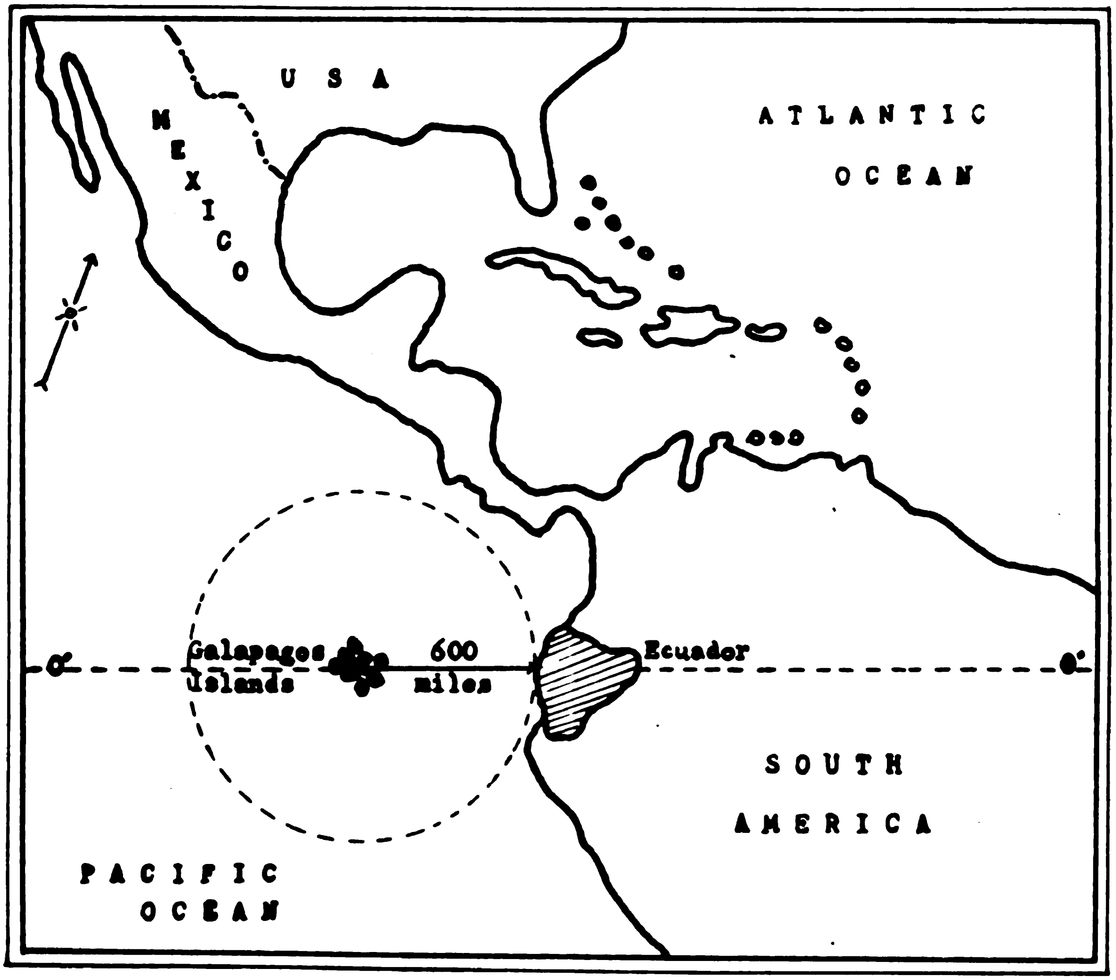

Figure 1.- Position of Ecuador and her Galapagos Islands.

of the Andes.

The coastal plains is a relatively flat country of tropical aspect, interrupted occasionally by groups of hills and ranges of less than 1700 feet altitude. Many of these hills are the spurs and outliers of the Andes (see Fig. 2).

The Andean region is the mountainous section between the coastal region and the flat Amazon basin of the Oriente region and extends the entire length of the country. It is comprised of three ranges known as the Cordillera Occidental to the west, the Cordillera Central in the middle, and the Cordillera Oriental to the east (see Fig. 3).

The two principal ranges of the Andes, the Cordillera Occidental and the Cordillera Central, form a double row of peaks about 30 kilometers apart with a high plateau between, and maintain this form to a surprising extent until its ranges become irregular and diffuse again near the Peruvian frontier to the south. At certain intervals the double row is joined by a crosswise ridge, or "knot" which forms connecting links between the Occidental and Central Cordilleras. Between this double row of peaks[2] and ridges connected by knots are the habitable valleys, called <u>hoyas</u>, drained by rivers that cut through one or another of the ranges. These valleys form only about three-eighths of the mountainous

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2 Among these peaks is an unequaled group of snowcapped volcanoes, most of them extinct. Some of the more important peaks are the Chimborazo (20,702 feet), the Cotopaxi (19,498 feet), and the Cayambe (19,160 feet). (Grosvenor, 1941).

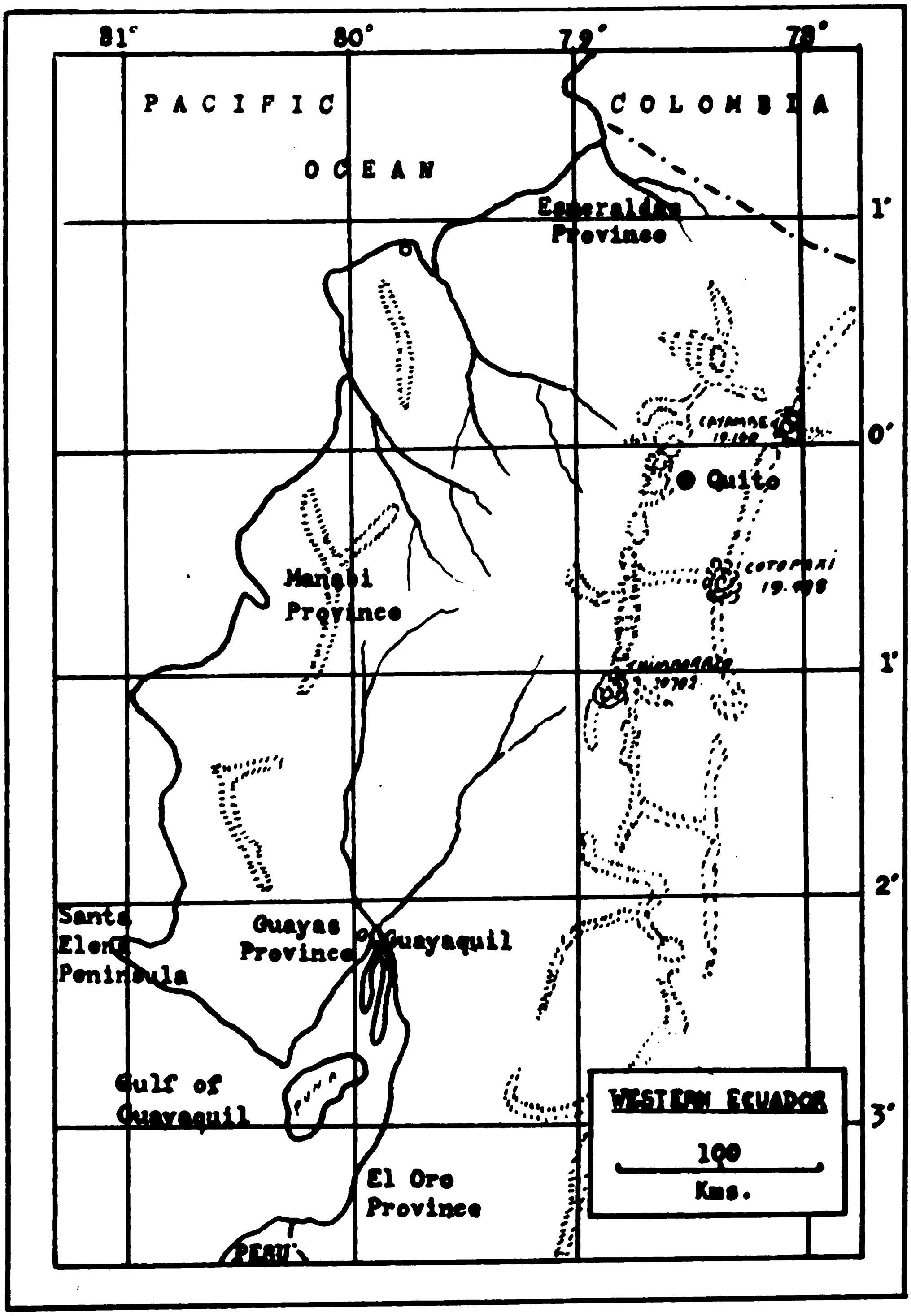

Figure 2.- Western section of Ecuador, South America. (After King , June 1948, p.10)

region, but they are the habitat of more than three-fourths of the population of Ecuador. The other five-eighths of the Andean Cordillera include land over twelve thousand feet in height on which grows only paramo grass.

The third cordillera, the Oriental, is less high and compact than the others, more irregular, and disconnected from the Cordillera Central. It was discovered in 1945 by the aerial survey of the Shell Ecuador Oil Company (Tschopp, 1945).

The Oriente region is divided (Teran, 1948 p. 135) into two sub-regions: one known as the region of the flanks or Andean plateaus, which slopes down from the base of the Cordillera Central, at about 4,000 feet altitude to the Cordillera Oriental; the other sub-region is the low, flat Amazon basin which extends to the Peruvian border, at about 850 feet altitude. The Oriente region is a vast region little known and inhabited by a sparse, partly Indian population.

Geologic features: - The geology of Ecuador has not been worked out in detail except in a few limited areas. At present only most general statements can be made. The broader geologic features of the western part of the country have been fairly determined, principally through the works of Wolf (1892 and 1912) and Sheppard (1927, 1937, and 1946). The eastern part of the country has been studied lately by the Shell Company geologists (Tschopp, 1945).

a) Coastal plain: Quaternary tablazos and Recent marine sediments occur along the western edge of the littoral belt. The

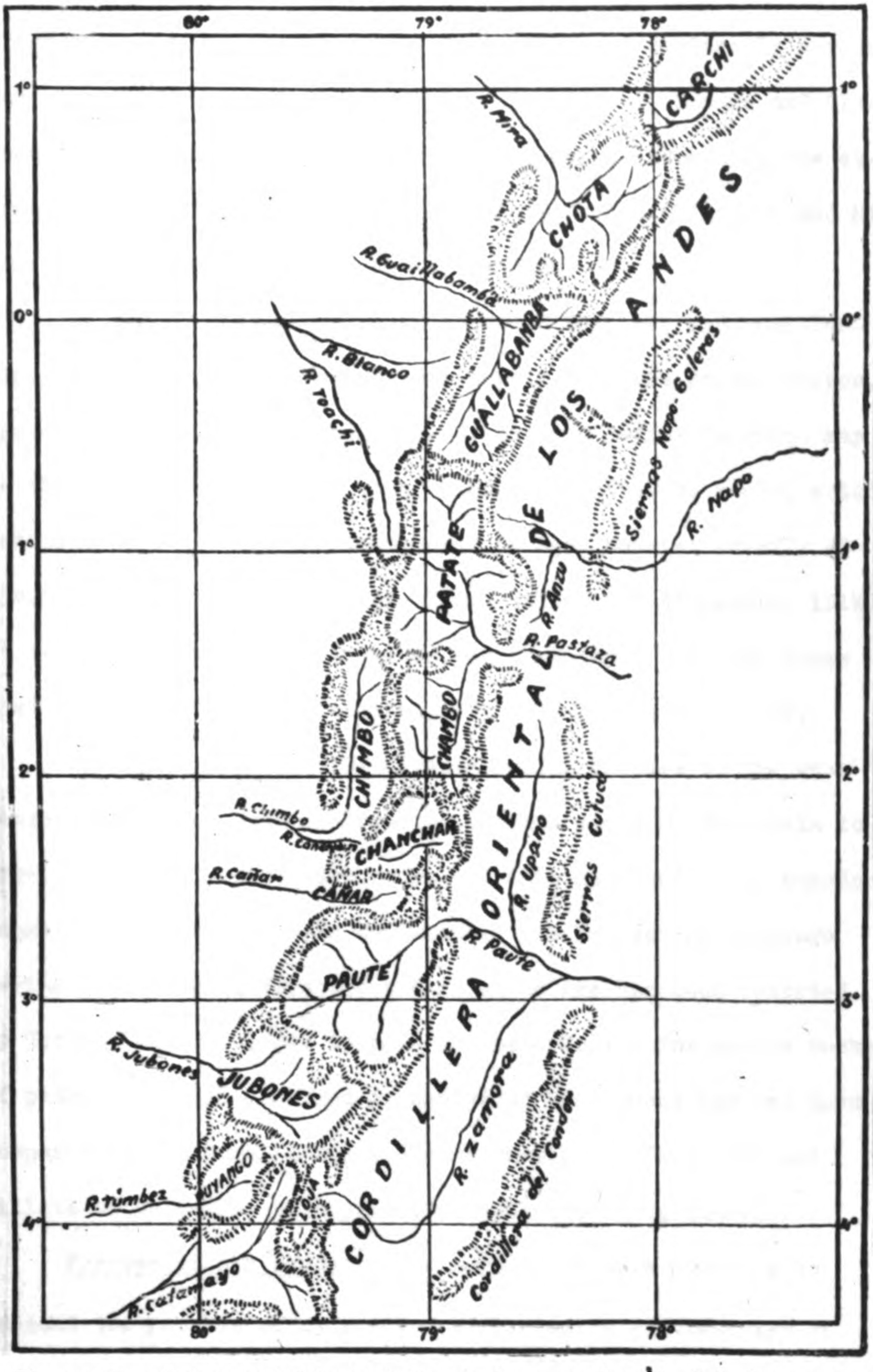

Figure 3.- Interpretation of the Andean region in Ecuador according to Wolf (1892) and the sections of the Cordillera Oriental according to Tschopp (1945). After Teran 1948, p. 96.

known Tertiary rocks on the Pacific coastal plains are of Eocene, Oligocene, Miocene, and Pliocene age. They are dominantly marine and are chiefly sandstone and shale. In general, Eocene and Oligocene rocks make up most of the coastal range, except in the extreme north of the province of Esmeraldas, where Oligocene and Miocene formations are exposed at the surface.

b) Andean region: Volcanic rocks of Tertiary and post-Tertiary age form almost a continuous mantle over the Andean region. Associated with the volcanics are Cretaceous sediments which may be observed throughout the entire length. Intrusive rocks, which authorities state are pre-Cretaceous in age, consist chiefly of diorites and porphyrites (Wolf, 1892; Miller and Singewald, 1919). It is in these ancient intrusives and associated intruded rocks that nearly all of the mineralization thus far known occurs.

c) Oriente region: The Oriente region belongs to the vast geosyncline which extends from the eastern Andes of Venezuela to Argentina. The sedimentary rocks, of this geosyncline in Ecuador, range in age from Triassic to Recent. The Ecuadorean Santiago marine formation of Triassic and Jurassic age has been reported by Tschopp (1945, p. 21) to have characteristics for source rocks of petroleum. And the Napo formation of Cretaceous age has been compared to the Cogollo-Luna-Colon formation in Venezuela and Villeta of Colombia, both productive petroliferous zones.

Purpose of the study: - The purpose of this paper is to present the results of my studies of the petroleum industry of Ecuador. This paper points out principles which may provide effective utilization of the oil and natural gas resources of Ecuador, and recommends factors that should be considered in the proper application of these principles.

The report is submitted in the hope that it will serve a useful purpose in promoting general recognition of these principles and the acceptance of these factors by the regulatory bodies of Ecuador in administering conservation laws pertaining to oil production.

Plate 1.- A monument erected over a point of the equator line, in San Antonio de Pichincha, 25 kilometers to the north of Quito.

Section II

PETROLEUM AND NATURAL GAS IN ECUADOR

Distribution: - Though oil and natural gas have been reported from the eastern slopes of the Andes in the Oriente region of Ecuador (Sinclair and Wasson, 1927; Tschopp, 1945) and oil springs in the coastal plain in the provinces of Esmeraldas and Manabi, and in spite of efforts to encourage further exploration in the province of El Oro (see Fig. 2), the only region of promise thus far discovered and developed is that of the peninsula of Santa Elena, about 64 miles west of Guayaquil in the Guayas province (see Fig. 4).

The principal oil accumulation occurs, in Santa Elena, in sandstones ranging in age from upper Cretaceous to lower Eocene. The source of this oil is controversial and it is believed that the oil itself is indigenous to the formation in which it now occurs (Thomas, 1946 p. 20).

Sheppard (1937, p. 250) assumed that the oil had its origin in the silty shales which make up the greater part of the Tertiary sediments. Seepages of petroleum and productive sands range from the upper Eocene to the Oligocene, and although it is quite possible that certain shales of the latter formation may have been the cause of the oil in these beds, it is the opinion of Sheppard that the majority of the oil occurrences which are found higher than the Eocene have been occasioned entirely by upward seepage, or migration, along joint or fault planes.

FIG. 4.

Geological Map of the Santa Elena and Colonche districts, Southwestern Ecuador. (After Sheppard 1937)

Geological features of Santa Elena Peninsula: - The Santa Elena region comprises plateaus, known locally as tablazos, and rugged hills generally less than 1,000 feet.

Below this surface formation, composed of soft sedimentary rocks of Quaternary age, a greenish-grey sandstone is found which passes laterally into sandy shales, and in certain localities (Ancon) the formation is saturated with a heavy, dark-colored oil. These sandstones and shales are distorted and crushed which makes it almost impossible to map the district satisfactorily. From the viewpoint of petroleum it is important to note that the most saturated oil sands in the Santa Elena region occur in these excessively shattered zones, and are often in close contact with the igneous dykes intruded into the Tertiary sediments.

The thickness of the Tertiary formation is not known. The earth's crust has been broken up into innumerable independent rock blocks. The main blocks are separated from one another by large faults (Report of the International Ecuadorean Petroleum Company, 1948). These fault-blocks have been tilted in various different directions and have undergone different vertical movements, so that some have sunk down while others have been upheaved. This region has been complicated by igneous intrusions, apparently dykes and sills, that have considerably baked and silicified the adjoining rocks.

In general the geology of this area has been very difficult to interpret owing to unconformities, faulting, intrusions, and the lack of diagnostic fossils which have impeded a correct age determination of its geological formations.

Geologists of the Ecuador Oilfield Ltd. Company have divided the peninsula into two areas: a) the north area and b) the south-east area (Geological report submitted by the company to the Bureau of Mines of Ecuador, 1940).

The north area (see Fig. 4) has sporadic occurrences of dolerite - a volcanic rock - and chert. The beds in many places dip very steeply as a result of past tremendous disturbances and crushing forces. The region has a fossiliferous formation, the tablazos of Quaternary age. Its thickness varies from 15 to 300 feet. Shallow wells drilled into the buried cherty low masses have found commercial oil accumulation in fissures.

The south-east area has sandstones, conglomerates, and clay of Eocene age. In this area are found the "Seca Shales" and "Socorro Series" - productive formation in local areas - of the upper Eocene age. These formations are covered mainly by deposits of Oligocene sands and shales. Below the Socorro Series lies the "Clay Pebble Bed" and below that the Atlanta formation of shales and sandstones which is the deeper pay in the important Tigre field area. The "Atlanta Sandstone" of the lower Eocene is over 3,000 feet thick, and wells usually penetrate this for 300 to 400 feet before reaching oil.

The stratigraphic formations of the Santa Elena Peninsula are shown in Table I, page 9.

Oil Companies operating in Ecuador: - The principal oil companies operating in Ecuador are: The Anglo-Ecuadorean Oilfields,

Table I

STRATIGRAPHIC COLUMN OF THE FORMATIONS IN SANTA ELENA[3]

Geologic age	Name of formation	Thickness (ft.) Max.	Min.	Character
Pleistocene	Tablazos	80	0	Calcareous deposits & gypsum.
Miocene	Progreso Fm. (local)	-	-	Sandstone
Oligocene	Ancon Fm. (local)	400	-	Sandstone
Oligocene	Oligocene Shales	-	2850	Clay & shale
Eocene	Seca Shales	600	0	Clay with concretions.
Eocene	Socorro Series	1100	0	Clay & sandstone (Petroliferous serie).
Eocene	Clay Pebble Bed	2200	100	Breccias & clay
Eocene	Atlanta Shale	2700	1000	Dark shale & quartziferous conglomerate.
Eocene	Atlanta Sandstone	3570	2500	Hard sandstone & some clay (Petroliferous serie).
Eocene	San Jose Shale	400	400	Hard, black clay.
Eocene	San Jose Sandstone	-	3460	Hard sandstone & some clay (Shows oil traces)

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(3) Taken from geological reports submitted to the Bureau of Mines and Petroleum of Ecuador by the Ecuador Oilfield Ltd. Company and the International Ecuadorean Petroleum Company (Coloma 1939, pp.112, 128), and the Anglo Ecuadorean Oilfields Ltd. (Piedra 1947, p. 81).

Ltd., and The Ecuador Oilfields Ltd. which have a backing of British capital. The Shell Company of Ecuador and Esso Standard Oil Company of Ecuador are American-owned concerns. The domestic companies are: Compania Petrolera Ecuatoriana, Carolina Oil Company, Petropolis Oil Company, Concepcion Oil Company, Tompkins Concession, and Ing. Hidalgo Concession (see Fig. 5).

With the exception of the Shell-Esso companies, which are exploring in the Oriente region, and Compania Petrolera Ecuatoriana, which is exploring in the lowlands of the El Oro province in the southwestern part of the country, the principal activity is confined to the Santa Elena Peninsula in the Guayas province.

In 1937, the Shell Company of Ecuador obtained a concession of 20,615,000 acres in the Oriente region of Ecuador. At the end of 1948, the Esso Standard Oil Company of Ecuador joined in oil exploration in the eastern region of Ecuador, where Shell has been working for some time. Under the concession Shell and Standard were authorized by the Ecuadorean Government to transfer between themselves any of their rights (The Oil and Gas Journal, Vol. 47 Nº 29, Nov. 18, 1948).

Tremendous difficulties and costly problems associated with thick vegetation have been a serious retarding factor in developing the oil exploration in eastern Ecuador (Showler, 1947). The Shell is carrying on a limited geological and geophysical survey in this region. Since 1937, four wildcats have been completed, two of which reached depths of 5,281 feet (Vuano Nº 1) and 7,019 feet (Macuma Nº 1)(Piedra 1947 p. 106). The tests were dry. The

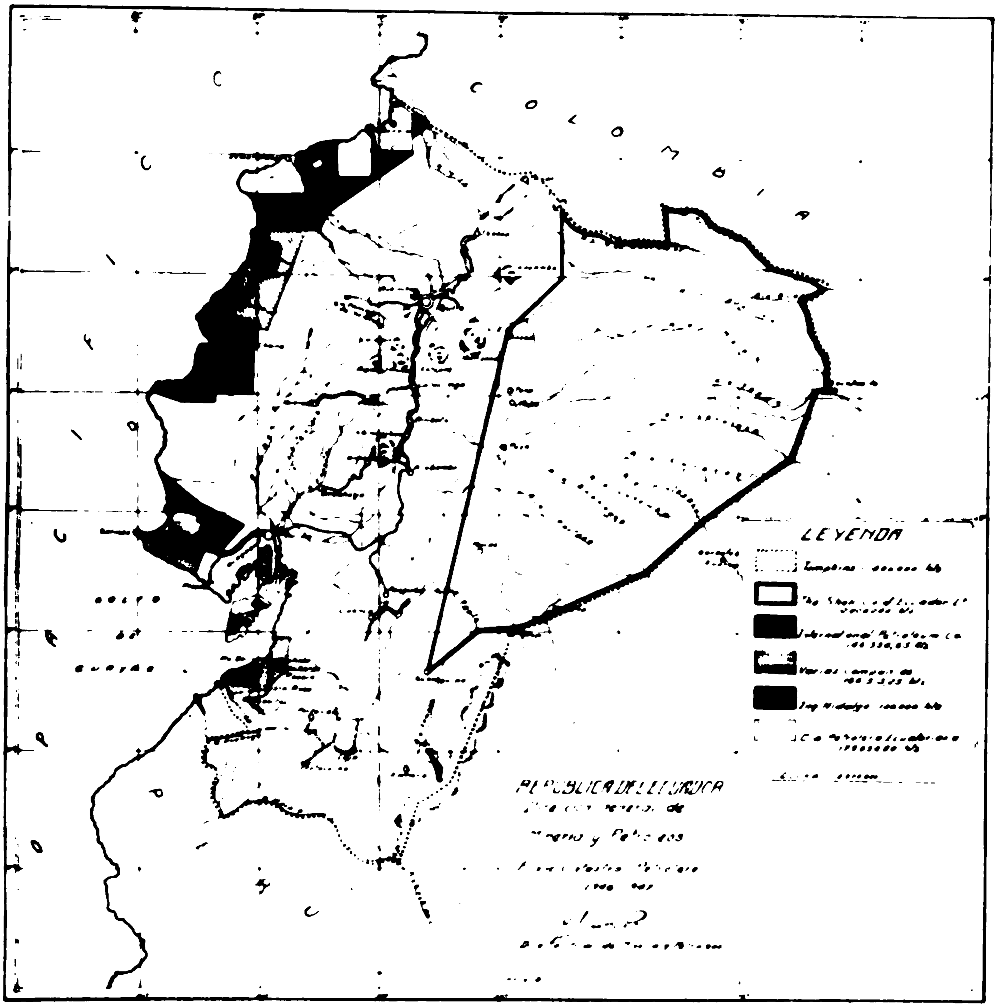

Figure 5.- Official Map showing the concessions granted by the **Ecuadorean** Government to the different oil companies (After Piedra, 1947 p. 14)

actual exploration for oil in this region is extremely difficult and results may be slow in materializing, but the outlook for possible large production is more favorable than in the already producing region of Santa Elena. If and when production comes about, it will be accompanied by improved transportation facilities that will open the way for general economic development of the region.

During 1947, the International Petroleum Company completed its extensive search for oil in the coastal regions of Ecuador in the provinces of Guayas, Manabi and Esmeraldas. In ten years of exploration the company drilled 20 wildcats, two of which reached depths of 13,206 feet (Bajada Nº 1), which is the deepest well drilled in South America, and 10,485 feet (Rodeo Nº 2) located in the Daule-Guayas concession of the Guayas province (Piedra, 1947 p. 104). All tests were dry.

The Anglo-Ecuadorean is Ecuador's largest oil producer. From 1935 to the present, shallow and deep drilling and development of the important Atlanta Sandstone formation at about 4,200 feet, have kept Anglo-Ecuadorean's yearly production at about 2,000,000 barrels. This company has a refinery, built in the north side of the peninsula at La Libertad, with a daily capacity of 2,700 barrels.

The Ecuador Oilfields Ltd. is the second largest producer of the country. This company discovered the important field, El Tigre, situated near the town of Santa Elena. Part of the Atlanta sand oil zone in its Tigre field has been developed into production at the rate of 1,400 barrels per day. The company has a small refinery at Cautivo, near La Libertad, with a daily capacity of 500 barrels. The company manufactures gasoline, naptha, kerosene, diesel oil and residual fuel.

The domestic companies are unimportant because of their insignificant production.

Ecuadorean Oil Production: - Petroleum in Ecuador is locally important and of unusual interest because the oil seepages of the Santa Elena peninsula seem to be the locality of the first discovery of petroleum in South America. The petroleum workings are of great antiquity. There is evidence for the belief that they were known to the Indians and later operated by the early Spaniards about 1500. In 1700 oil was reported from dug pits at Santa Elena (Hager, 1939 p. 30). In 1917-1922 the annual output ranged from 50,000 to 60,000 barrels, all derived from shallow pits. In 1923, a 45-barrel well was completed and the annual production rose to 87,000 barrels. At that time numerous hand-dug pits were made in San Lorenzo (in the Santa Elena region), the pits being grouped closely together, and the majority of these started in the Quaternary surface rocks. The pits were excavated to a depth of 15 to 50 feet. At the time when the pits of this area were in full operation (1926) the annual output was 350,000 barrels. The low costs of labor and production, and the steady market made this business very profitable in those days. However, after heavy rains in the years 1925-1926, these pits were completely flooded and the majority were ruined and abandoned. In 1928, deeper drilling, usually to 1500-2500 feet, showed other producing areas and zones and the output was 1,000,000 barrels. In 1937, it was 2,000,000 barrels, (Thomas, 1946 p. 20). During 1945, a 300-barrel well was completed at 4200 feet in the northern part of El Tigre field.

Of Ecuador's total production in 1946 (about 2,322,603 barrels) a single company, the Anglo-Ecuadorean, accounted for almost 75% of the total production. The company's annual production in 1946 was reported to be 1,673,915 barrels. Of this company's production, about 1,240,779 barrels were exported to Argentina and Uruguay, and the rest was refined and marketed in Ecuador (see Tables II and III).

Ecuador's cumulative production at the end of 1947, all from the Santa Elena peninsula, has been reported (Weeks, 1948 p. 1093) to be about 41,800,000 barrels. The annual production in the same year was 2,281,000 barrels (Egloff, 1948 p. 263).

Types of production: - Shallow production to depths of 1200 feet, and of relatively minor importance, is obtained by digging by hand or by drilling with cable tools at El Tambo, Cautivo, Carolina, and Santa Rita fields in the peninsula. The shallow production is obtained from Quaternary to upper Eocene beds (Socorro Series), (see Plate 2).

The deeper production, to depths of 5000 feet, is the more important and is drilled with hydraulic-rotary system at Concepcion, Ancon, and Tigre fields. These wells are producing from the Atlanta Sandstone formation of lower Eocene age (see Plate 3).

The oil which is produced from both the shallow and from

Plate 2.- A cable tool for shallow wells Commonly used in Cautivo (La Libertad).

Plate 3.- A standard rotary drilling machine used in deep wells in the Tigre field (Santa Elena), Ecuador.

Table II

SURVEY OF ECUADOR OIL FIELDS [4]

Name of field	Flowing wells	Pumping wells	Producing depths(ft)	Daily av. Production (bbl)	Gr. A.P.I.
Ancon	39	414	1200-3800	4750	36-41
Cautivo		28	500-1200	30	35
Carolina		15	30-600	95	18-28
Concepcion		10	3000-4000	30	38
El Tambo		6	1200	10	39
Santa Rita		34	500-1200	165	28
Tigre	10	5	2850-4350	920	39
TOTAL	49	512		6000	

Accumulative prod.: (bbl)	32,000,000	Ancon
	3,000,000	Tigre
	35,000,000	Total

(4) Taken from The Oil and Gas Journal, Dec. 28 1946, Vol. 48, p. 191.

Plate 4.- The Ecuador Oilfields Ltd. Co. in La Libertad, Ecuador. In the distance can be seen the puntilla of Santa Elena.

Plate 5.- Tank for crude oil (50,000 bbl.) La Libertad, Ecuador. Oil tank is without sand fire wall to prevent loss of oil or spread of fire in case of accidental break.

the deep wells, of the Santa Elena region of Ecuador, varies in color from black or brownish-green to green color. Although mixed-base types of oil occur, the majority fall into asphaltic-base oil and paraffin-base oil[5]. The specific gravity of the Ecuadorean oils range from 18° to 41° A.P.I.[6] (see Table II).

Although the gravities of the oils derived from the respective deep and shallow wells of the Santa Elena fluctuate between certain limits there are always slight differences in the oils from different wells, even though the wells are close together. The depth factor and more probably the phenomenon of faulting account for gravitational differences and paraffinic quality in the oil obtained from the same drilling area.

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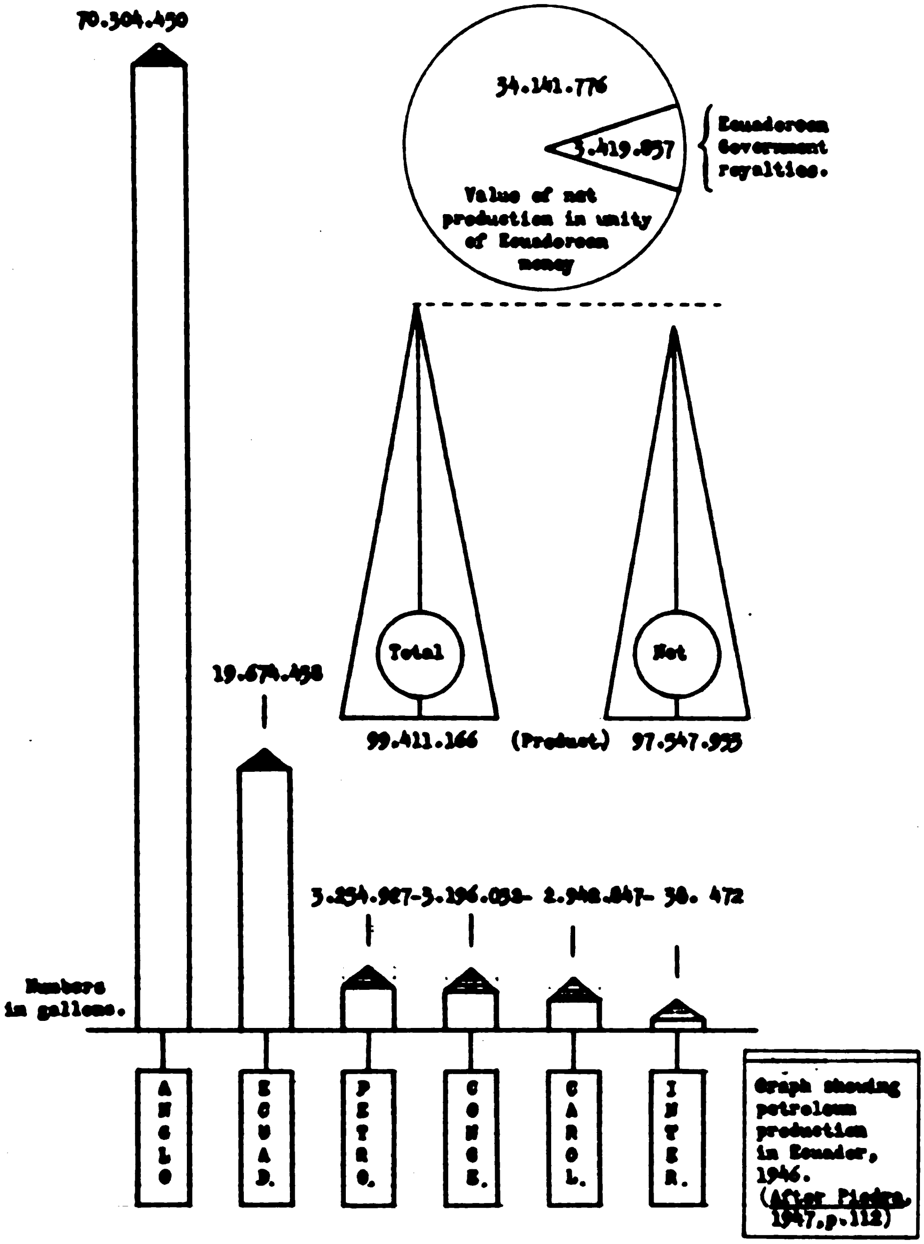
(5) Base is the predominating residual element held in solution in a petroleum. Petroleums are generally classified as to their predominating bases. Thus, the four principal divisions of crude oils are those of paraffin base, asphaltic base, napthenic base, and mixed base where both asphalt and paraffin qualities are included.

(6) Specific gravity is the relation the fluid bears by weight to the same volume of water. Water has a specific gravity of 1. As petroleum is lighter than water its specific gravity is expressed by decimals less than unity. Gravity of crude oil is determined with a hydrometer. The hydrometer, invented by Baume, is a glass column marked with graduations from 10 to 100. The scale bears an inverse ratio to the specific gravity scale, as is indicated in the degrees, which permits the translation of Baume gravity to specific gravity. When floated in pure water, the Baume hydrometer indicates 10 Baume, while the specific gravity scale reads 1000. The modulus 140 serves for liquids lighter than water, while a modulus of 145 is employed for liquids heavier than water. The standard scale used in the United States is called the A.P.I. (American Petroleum Institute) which is a variation of the Baume scale, using a modulus of 141.5 to specific gravity at 60°F.

$$\text{sp. gr.} = \frac{140}{130-\text{Be.}}$$

TABLE III



Graph showing petroleum production in Ecuador, 1946. (After Piedra, 1947, p.112)

Section III

PRINCIPLES OF PETROLEUM CONSERVATION

A. General Considerations

Importance of conserving crude oil: - Crude oil is a natural resource of great value. The supply now available is finite; it cannot be used without being consumed. At the present time Ecuador is depleting its reserves rapidly as is shown in figure 6.

The nation's known reserves of crude oil were estimated in 1944, by Petroleum Administration for War (Report of Subcommittee concerning investigations overseas, 1944 p. 8) at about 45,000,000 barrels. Theoretically, if the rate of Ecuadorean production is in excess of 2,000,000 barrels a year, the estimated known reserves will be exhausted in about 22 years.

The question thus arises as to what should be done in order to diminish the output of this product and thus make petroleum last as long as possible, since under the most favorable circumstances the period that it will be available will be very short as compared with the life of the nation.

With the oil accumulation found in the Santa Elena peninsula, it seems certain that others will be discovered in the favorable sedimentary basins of the Esmeraldas and Manabi provinces as yet undrilled on the coast of the country (see geological report of the International Ecuadorean Petroleum Company concerning the "Minero Concession ", 1948), or in the promising Oriente region (Tschopp, 1945). But while such finds may be made effective, we

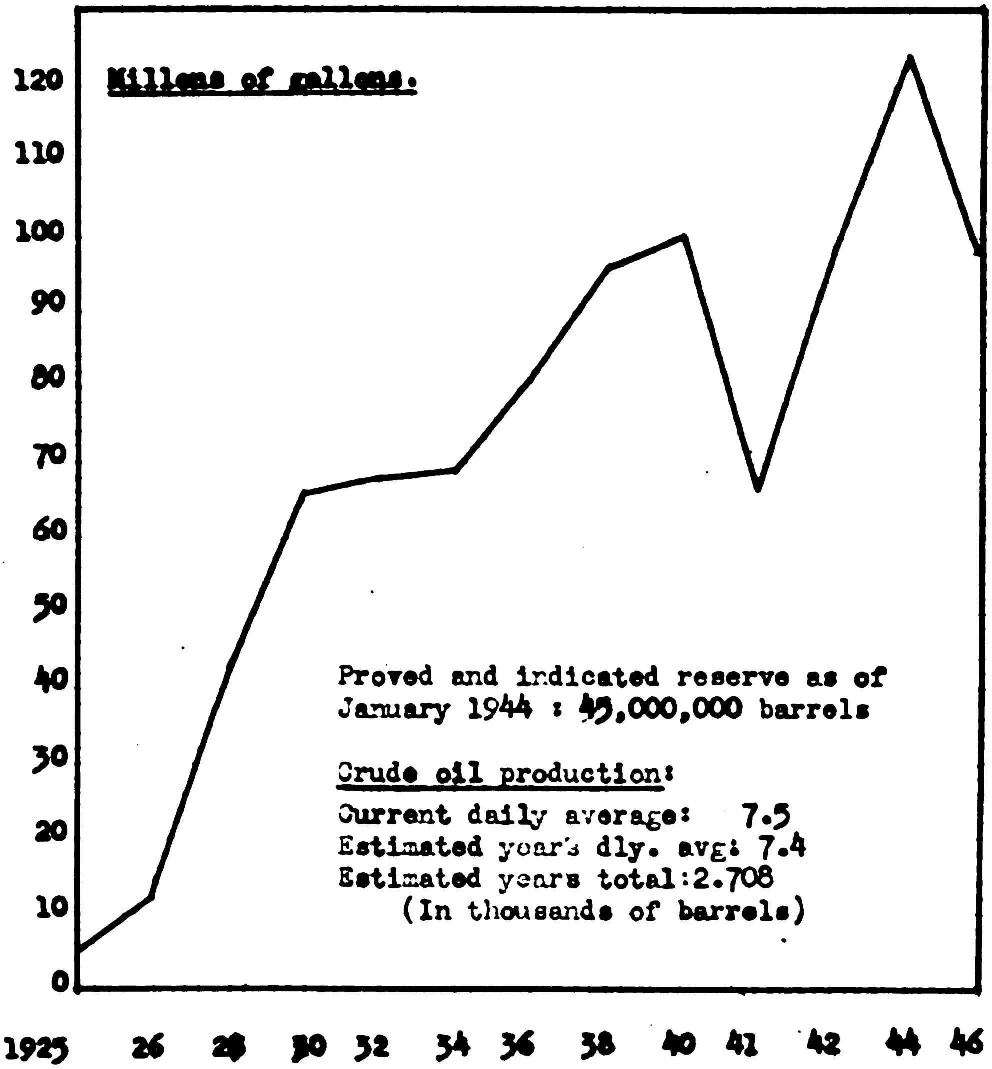


Figure 6.- Graph showing production of petroleum in Ecuador, 1925-1946. (Data from "Ecuador Petrolero", December 1946, vol. 1, Nº 2, p. 38)

can make no predictions regarding them.

Meaning and objectives of conservation: - The conservation policy according to Pogue (1942, p. 60) is:

> "to keep crude oil flowing to the consumer at low prices as long as possible, to encourage its wise use without imposing arbitrary restraints, and to rely upon the technological ingenuity of future generations to solve the inevitable problems of scarcity and high prices."

In view of the importance of crude oil, its efficient and rational utilization is obviously necessary. Conservation of petroleum resources is necessary; first, to insure a continuous adequate supply of petroleum products at reasonable cost; and second, to protect property rights. For this reason, the economic phases of the conservation problem are equally as important as the technical phases, and must be given adequate consideration in a conservation program.

B. Economics in Conservation

Market demand: - Production of petroleum at a rate in excess of market demand not only brings about appreciable physical waste, but also results in serious disturbance of the industry's economy.

Market demand is defined by the Michigan Law, Act 61, P.A. 1939, as follows:

> "(m) the words "market demand" as used herein shall be construed to mean the actual demand for oil from any particular pool or field for current requirements for current consumption and use within or outside the state, together with the demand for such amounts as are necessary for building up or maintaining reasonable storage reserves of oil or the products thereof, or both such oil and products and shall not be less than the actual purchasing commitments for oil from such pool or field."

Storage for petroleum is expensive to build and to maintain, and the cost of such storage in excess of that required for working stocks is a burden which an industry, obliged to make its products available at a reasonable price, should not be forced to carry. Furthermore, oil is subject to deterioration in storage, and may lose some valuable components through evaporation. Storage subjects the oil to the hazard of destruction by fire. In other words, unnecessary storage on the surface is uneconomical and inefficient, whereas the natural reservoirs provide the most efficient storage house for oil until the oil is required for current consumption needs.

Control of development costs: - The economic pressure to convert an oil reserve into capital encourages a policy of haste and waste. Excessive capital expenditures, brought about by the drilling of unnecessary wells, lead inevitably to strong pressure in the way of excessive production rates, and frequently go against the use of efficient producing practices.

Importance of production rate: - Crude petroleum has a variation of costs because of the varying nature of its occurrence. Some oil fields are shallow, others deeper; some have thick sands under high pressures and yield their oil easily, others are in thick sands and give up their oil reluctantly. Naturally these conditions are not subject to control. There also exists an additional factor: an unregulated rate of production that distorts costs, creating low costs in the flush period and consequently high costs thereafter.

The technology of conservation consists in the selection of an optimum producing and operating method which will reduce waste of oil. The prevention of waste is accomplished by the application of the most efficient production methods known and economically available. In the following section it will be shown that the control of production rate is essential to any effective method for improving production efficiency and, therefore, production rate is perhaps the most important single factor which must be regulated. The efficiency of a conservation program rests upon the ability to control properly the rate of production.

Need of oil reserves: - If the production rate must be controlled in order to prevent waste, it follows that productive capacity should always substantially exceed reasonable market demand. Therefore, there must be a reserve of oil capable of supplying the market demand within the range of the efficient production rate. To meet fluctuations in the demand and to hedge against the uncertainties of the discovery of new supplies, a reserve somewhat larger than that required to achieve a physically efficient rate of production should be maintained. It follows that the discovery of new reserves becomes an essential part of a comprehensive program of conservation.

Section IV

TECHNOLOGY OF PETROLEUM PRODUCTION

A. Oil Reservoirs

Introduction: - A proper understanding of the practical principles of oil conservation must be founded upon a knowledge of the nature and behavior of oil reservoirs, and the manner in which operating conditions influence the recovery of oil. Accordingly, a brief review of the pertinent composition, origin, and technology of petroleum production is presented herein.

Composition and origin of petroleum: - Petroleum is a mixture of naturally occurring hydrocarbons which may assume either the solid, liquid, or gaseous state. These three phases of petroleum are transmutable, one into the others by the application of moderate changes in temperature and pressure. Commonly, petroleum occurs in the liquid phase, as an oil somewhat lighter and more viscous than water, varying in color from black, through various shades of brown and green, to a light amber. The naturally occurring solid forms of petroleum include the mineral waxes, paraffin, and asphalt. Gaseous forms of petroleum, commonly called "natural gas", consist of mixtures of hydrocarbon gases and vapors, the more important of which are methane, ethane, propane, butane, pentane, and hexane, all of the paraffin series ($C_n H_{2n-2}$).

The origin of petroleum is still a subject of scientific controversy between chemists and geologists. Some of the theories seem to offer plausible explanations of the source and manner of formation of specific deposits, but apparently none are of general application.

The various theories dealing with the origin of petroleum are classified into two groups: the so-called "inorganic" and "organic" theories. The former attempt to explain the formation of petroleum as a result of geochemical reactions betwwn water or carbon dioxide and various inorganic substances, such as carbides and carbonates of the metals. The organic theory is generally accepted by most scientists as being the most logical one to explain the origin of oil. This theory assumes that petroleum is a decomposition product of vegetable and animal arganisms that existed within certain periods of geologic time.

<u>Accumulation and migration of petroleum</u>: - Whatever the theory accepted in explanation of the origin of petroleum, the rocks in which accumulation occurs are seldom those in which the petroleum was formed, and accumulation is occasionally found in formations stratigraphically unrelated with those containing the parent material, as in the case of the Santa Elena oil (see page 6).

The question of migration of oil has proved to be a controversial one among oil geologists. Some of them believe in vertical and lateral migration and a minority believe that there is practically no migration, except when a source bed is in direct contact with the reservoir (Athy, 1929).

Migration has been subdivided by Clapp (1927) and Heald (1940) into primary and secondary.

Primary migration is the initial process of oil and gas

movement by which the gas or fluid moves from the source rock to the reservoir rock. The process is selective in that the oil and gas enter coarser and more porous rocks in preference to fine compact ones.

Secondary migration is the movement of fluid within the coarser rocks, by which the gas, oil, and water are separated and come to rest in the reservoir rocks.

Reservoir for petroleum: - Oil and gas migrate from the source rock, in which the present organic matter was deposited, to the reservoir rocks in which they are accumulated and stored by nature. Upward escape of the reservoir fluids is prevented by an impervious "cap rock". An essential condition in the formation of a commercially important oil or gas accumulation, according to Uren (1946, p. 13), is that there must be:

> "a porous, fractured, cavernous or creviced stratum in which the fluids may accumulate; and this must be overlain by an impervious cap rock which prevents escape of the fluids after their concentration and segregation have been affected."

The lithologic properties of the reservoir rock are important in determining storage capacity, resistance to flow and the rate at which fluids may enter the wells. The size and shape of the pore spaces, their continuity and their percentage of the total volume of the rock are also important factors.

Forces causing migration of petroleum tend to concentrate oil and gas in the upper portion of folded porous strata, particularly in the crest of anticlines or domes or other structurally high portions of the reservoir rock to which they have access.

Occurrence and distribution of oil: - Oil is commonly associated with water and natural gas. Water underlies the oil and exerts a pressure on it (see Fig. 7). Gas occurs dissolved in the oil (see Fig. 8) and, in some cases, as a gas cap overlying the oil (see Fig. 9). Both the pressure of the water and the expansion of the gas provide energy for moving the oil through the sand to the well outlet and thence to the surface.

The amount of gas which can be dissolved in a certain amount of oil depends chiefly upon the pressure under which the oil and gas are confined. Under the pressure and temperature of the reservoir, all the gas associated with the oil may be in solution. On the other hand, more gas may be associated with the oil than the oil can dissolve; in this case the excess gas accumulation forms a gas cap. As the pressure in an oil reservoir is lowered, oil saturated with gas releases gas from solution.

The gas also has additional qualities. Its presence in solution renders the oil far more liquid than the oil we see above ground. In addition dissolved gas lessens the tendency of the oil to stick to grains of sand. It follows that an oil pool should be so managed that the maximum utilization shall be made of the reservoir energy and of the presence of the gas itself. Hence, production should be restricted to a rate that will restrain the gas from coming out of solution in the reservoir and will permit the oil to be replaced by water (Fig. 11 and 12). Optimum recovery of oil depends on a production rate that is regulated to conform with engineering principles rather than with

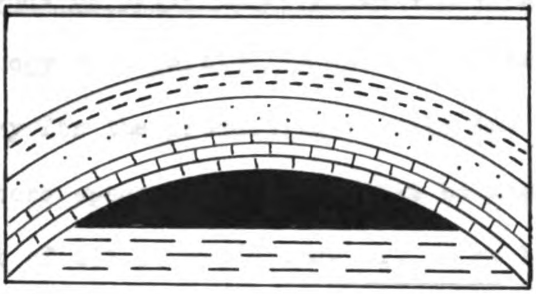


Fig. 7 - Water drive type of oil reservoir (water under oil)

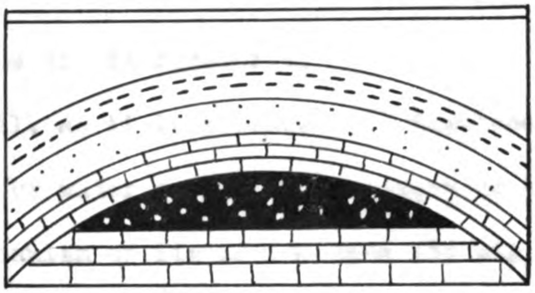


Fig. 8 - Dissolved gas drive (gas in solution with oil)

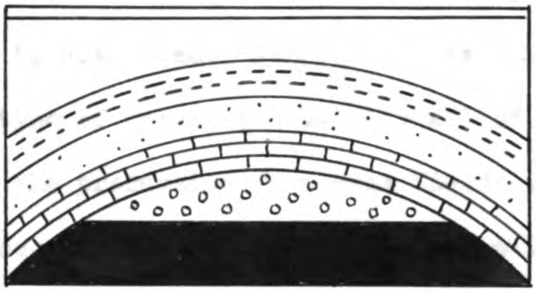


Fig. 9 - Gas-cap drive (gas over oil)

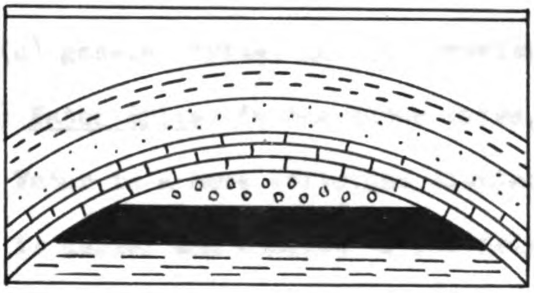


Fig. 10 - Gravitational segregation (gas, oil and water)

Figures 7-10.-Types of drive under which oil is produced the dictates of economic supply and demand.

Types of drive under which oil is produced: - Regardless of the geology of a particular reservoir, two major conditions are necessary for the production of oil: (a) the concentration of oil in the pore space of the rock must be high enough to permit the movement of oil in preference to, or at least along with, other fluids (Uren, 1946 p. 13); and (b) energy must be available to move the oil from the reservoir into the well outlets through which the oil is recovered.

Oil, as it is produced, is displaced in the reservoir principally by water or gas. The nature of the displacing medium and the mechanism of its action upon the oil largely determine the amount of oil recovery. Accordingly it is convenient to classify oil reservoirs according to the type of drive, or the mechanism by which the oil is displaced. Naturally, few oil fields operate under a single type of drive, and usually all of these mechanisms play some part in the production from most fields.

According to the type of drive, oil reservoirs have been classified by the Central Committee on Drilling and Production Practice (1942, p. 20) as: (a) water drive, (b) dissolved-gas drive, (c) gas-cap drive, and (d) gravitational segregation.

a) Water drive: In the water drive, oil is displaced by water. Water is a more efficient displacing fluid than gas in that it is denser and adheres to particles of sand, forcing oil from the pores. For this reason a properly controlled water drive is one of the best means available for the extraction of oil. To

secure the greatest ultimate recovery of oil requires restricting the field's producing rate to keep pace with the pressure of the expelling water. A low rate of production is usually necessary for utilization of a potential water drive (see Fig. 7).

A restricted rate of oil production from an oil field permits an even rise of water into the reservoir body. The water in its slow movement from its own porous rock bed will filter through the oil-bearing rock. Its pressure will reach into nooks and crannies, slowly flushing the oil from the rock pores, driving it ahead toward the well opening.

If the oil well is operated at too high a rate, gas separates from the gas-oil mixture and forms a cap in the dome of the reservoir. When gas separates from oil, the oil becomes heavier, less fluid, slower flowing, and less capable of draining. In such case the gas escapes out the tubing of the well, leaving more of the oil clinging in the rock pores, lost, and wasted underground.

b) Dissolved-gas drive: In the dissolved-gas drive, gas escapes from solution within the oil upon reduction of pressure and expels the oil from the sand. A unique feature of this type of drive is that the displacing gas is liberated from the oil itself, and forms throughout the oil zone. The gas, when it first appears, exists as isolated bubbles throughout the pores of the sand, held immobile by capillarity forces; and, therefore, it cannot flow to the well. However, a comparatively small quantity of gas in the pore spaces is sufficient to establish channels through which the gas may flow. Once such channels have been established, a rapid production of gas occurs. Dissolved-gas drive fields are characterized by comparatively rapid decline in reservoir pressure throughout the producing life of the field,and by a gas-oil ratio which begins to increase early in the life of the field. It increases at an accelerating rate, reaches a maximum, and thereafter declines as the gas remaining in the reservoir is exhausted. Because gas is a relatively inefficient medium for displacing oil from a partly depleted oil sand, and because the amount of gas is limited to that initially dissolved in the oil, the dissolved-gas drive gives comparatively low oil recoveries (see Fig. 8).

c) <u>Gas-cap drive</u>: - In the gas-cap drive, oil is displaced by the overlying expanding free gas. In most cases the efficiency of such a drive is less than that of an effective water drive, but greater than that of a dissolved-gas drive. Drives of this type often are brought about by pressure-maintenance operations (see Fig. 9).

d) <u>Gravitational segregation</u>: - Gravitational segregation, which is the stratification of gas, oil, and water according to their densities, is a factor which modifies all types of drive, usually in such a manner as to improve efficiency. The effect of gravitational segregation opposes the tendency of encroaching water or gas to advance irregularly into the oil zone and, hence, reduces somewhat the harmful effects of coning, channeling, and by-passing of the displacing fluid within the oil zone. The effect of gravitational segregation is to drain the upper part of the producing formations of some of the oil which otherwise would not be

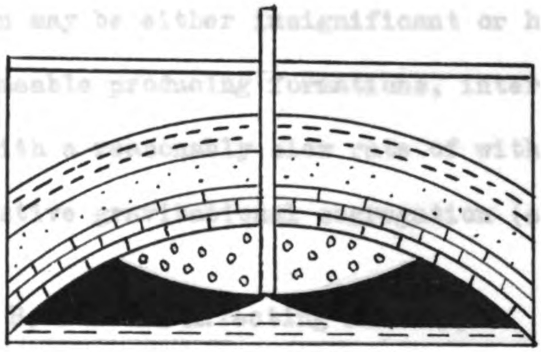


Figure 11. Too rapid rate of oil production pulls the water into the bottom of well, and shuts out the oil which is lighter than water.

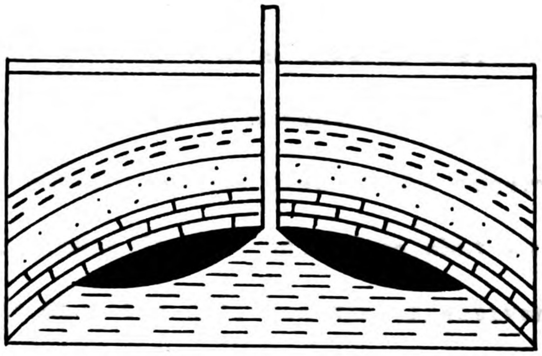


Figure 12. The flow of oil and gas is not restricted in this reservoir. (After Interstate Oil Compact Commission, "Oil in your future" p. 15)

recovered. This oil replenishes the lower part of the producing formations which have been partly depleted, and permits additional oil to be recovered from the replenished section. Depending upon the reservoir and the rate of production, the effect of gravitational-segregation may be either insignificant or highly important. Comparatively permeable producing formations, intercommunicating freely, coupled with a reasonably slow rate of withdrawal, are essential to effective gravitational segregation (see Fig. 10).

B. Factors Affecting Recovery

Control of factors affecting recovery: - The recovery obtainable from an oil reservoir depends not only upon the nature of the reservoir, but also upon the manner in which the reservoir is developed and operated. For this reason it becomes important, in a study of petroleum conservation, to inquire into the factors which control the recovery of oil. These factors are:

First: There is a group of uncontrollable factors, such as the geological and physical properties of the reservoir and of the fluids themselves. These factors determine what sources of energy are available to produce the oil, and the effectiveness with which the oil can be produced. Among the more important of these are: (a) the general geology of the area in which the field is located that influences the potency of the water drive, which may act on the field; (b) the amount of oil and gas in the reservoir; (c) the nature of the reservoir rock, its porosity, permeability, uniformity, and the amount of water retained in the oil and gas sands; and (d) the physical properties of the oil and gas, particularly the viscosity, since a highly viscous oil is much more difficult to extract than a light oil.

Second: There are the factors involving the development of the field, which, of course, can be controlled. Of these, well spacing, well completion practice, and the possible use of pressure maintenance and secondary recovery are particularly important. These are discussed later in more detail.

Third: There are the factors which can be controlled during the production of the field, in some degree at least. Discussion of the most important of these factors follows.

Rate of production: - A major objective of all efficient production practice is to produce oil under the most efficient type of drive. The most effective method of control is regulation of the rate of production. In many fields a sufficiently low rate of withdrawal permits a water drive to be effective, whereas, at higher rates, it would not be effective. Even in the absence of any effective water drive, a low rate of flow is desirable, inasmuch as it may bring about a desirable gravitational segregation of the oil and of the gas released from solution, tending to convert a dissolved-gas drive into a more efficient gas-cap drive. The extent to which recovery can be increased by maintaining a proper or optimum rate of production depends, of course, upon the nature of the field.

Production of water and gas: - Careful regulations of gas

and water production are necessary for adequate control of oil reservoirs and, hence, of the efficiency of oil extraction.

Production of excessive quantities of gas has three possible effects upon an oil reservoir: first, the rapid exhaustion of the pressure; second, a reduction in the size of any gas cap which may exist, causing oil to migrate into the area formerly occupied by the gas and to soak up into dry sands - from which a substantial part of the oil cannot be recovered - ; and third, undesirable changes in the physical properties of the oil.

In certain water-drive fields having limited water, the production of excessive quantities of water may reduce the effectiveness of the water drive, may accelerate the reservoir-pressure-decline, and may even result in the production of the remaining oil by the less efficient dissolved-gas drive. However, there may be circumstances under which production of water, as a practical matter, cannot be controlled, and where such water production is not particularly harmful. The effect of water production upon the recovery of oil must be carefully investigated, and such remedial measures as may be necessary and practical should be employed.

In searching for methods by which to control water and gas production, it is well to bear in mind the limitations imposed by the prevailing reservoir conditions. The relative production of the several fluids from any rock is controlled by the concentration of the various fluids present in the pores of the rock, and by the viscosities of the fluids. These are affected by the entire producing history of the reservoir, and are not subject to substantial

modification by any operation conducted within the well bore. Accordingly, if high gas-oil ratio, or high water production, is due to absorption of oil by the sand, the condition cannot be corrected by mechanical means. It should be remembered, however, that proper control of the reservoir may prevent absorption. However, excessive water or gas production may be due to the entrance of water or gas through only a portion of the sand open to the well, and in this case the condition can be remedied by shutting of that portion of the sand through which the water or gas is flowing.

Well completion practice: - Numerous methods have been devised for preventing water intrusion (oil-well cementing, oil-well shooting, acidization, gun perforating, etc.) and for plugging back wells with cement to shut out bottom water, (Brantly, 1940 p. 116; Millikan, 1940 p. 251; Suman, 1940 p. 160; Uren, 1946 p. 559). The success of any of these practices depends primarily on proper conditioning of the well for the job and on using the method most suitable for conditions in the well.

Proper practice in handling multiple producing zones in the same field is important. Usually, each producing zone should be regarded as a separate reservoir, and controlled as such in order to obtain the maximum economical recovery (Bennet, 1942 p. 9). The opening of multiple producing zones into a single flow string deprives the operator of an opportunity to control the reservoir behavior of any zone; hence, such practice usually is to be condemned as being potentially wasteful (Alcorn, 1942 p. 18; Lewis, 1941 p. 52; Uren, Feb., 1944 p. 82).

Several satisfactory methods are available for handling multizone reservoirs, and in most cases one of these methods provides for the efficient and economical production of the field. These are: (a) dual completions where mechanically feasible, providing for the separate production of two zones through separate flow strings of a single well; (b) successive production of the several zones, accomplished by recompletion of wells in a producing zone after the exhaustion of the zone in which the well was completed originally; and (c) drilling separate wells to each zone. Of course, if any of the zones are not sufficiently permeable to permit completion of a commercial well, sufficient pay section must be included in each completion to support production at an economical rate.

If possible, all the operators in each field should agree upon the producing intervals to be separately maintained, and the casing and water-exclusion program necessary to accomplish it. A uniform program is advisable to prevent possible intercommunication of fluids from zone to zone through differently cased wells. According to Uren (Feb., 1944 p. 82; 1946 p. 86) this is particularly important in the vicinity of actively encroaching edge water which might develop troublesome water incursion in edge wells, to the detriment of continued production from other oil-yielding strata in the same producing interval.

<u>Time of development</u>: - Under competitive conditions, there are powerful incentives which compel the operator to drill and produce his wells as rapidly as possible. Maximum ultimate recovery

is secured by prompt and complete development of wells especially when the field is produced under water drive or gas drive. Where expulsion of oil from the reservoir rock is primarily by gas expansion, the early wells enjoy the advantages of high reservoir pressure and greater production time, and their initial and ultimate productions are substantially greater than those of later drilled wells. In unrestricted fields (Uren, Jan., 1944), delay of even a few months may mean substantial losses for the later drilled wells.

C. Secondary Methods for Increasing Oil Recovery

Methods: - Secondary recovery has been defined by Torrey (1940, p. 289) as:

> "the application of various methods and processes for artificially increasing the production of oil."

The two most commonly employed secondary recovery methods are water-flooding and gas-repressuring. Closely allied to gas-repressuring are pressure maintenance and crude stabilization.

Water-flooding: - Under certain conditions, water-flooding is the most efficient method devised for increasing oil recovery, and in some instances effective water-flooding results in better recovery than is obtained by natural flow or pumping.

Intentional water-flooding should be clearly differentiated from natural water-flooding, or water encroachment, in that water is introduced into the sand by artificial means. Under conditions of efficient production control, uniform water encroachment tends to maintain the bottom-hole pressure of the field, thereby prolonging the flowing life of the wells as well as increasing oil recovery by the flushing action of the water.

The most successful results that can be realized from water-flooding naturally will be obtained where the producing formation is a continuous and uniform body. Marked variations in porosity and permeability, in thickness, and in shale breaks will be responsible for irregular flooding action. The presence of appreciable quantities of water in the producing formation is unfavorable for successful water-flooding, since the water will reduce the oil content of the sand and the excess water endangers the effectiveness of the water drive. In addition to increasing recovery, water-flooding has been adopted as a satisfactory method for the disposal of salt water.

Gas-repressuring: - Gas-repressuring for increasing oil recovery has wider application than water-flooding. Many of the geologic factors that must be considered in water-flooding operations, and espedially the geologic structure of the field, have equal importance in gas-repressuring, although their actual effect on the success or failure of either method may be quite different.

Gas-repressuring is useful under the following conditions: (a) In fields which have no active water drive, in order to avoid production by the inefficient mechanism of a dissolved-gas drive. (b) In fields with potentially active water drive, which fields, for various reasons, must be produced faster than the rate at which the water drive is effective. (c) In fields with a large gas-cap in which the gas-oil ratio cannot be controlled effectively by mechanical means, to prevent migration of oil into a contracting gas cap. And (d) in areas where conservation of gas for future use is economical.

Pressure maintenance: - Pressure maintenance differs from repressuring or pressure restoration in that gas is returned to the reservoir during the primary production of the field. The term pressure maintenance refers only to supplying energy artificially in order to maintain pressure.

Pressure maintenance may be commenced shortly after the discovery of a field. This method is particularly adapted to deep fields where the pumping of the wells, after natural production by flowing has ceased, presents a serious production problem.

Pressure maintenance has a most beneficial effect on retarding water encroachment; and where gas pays are present in the upper part of the sand, the movement of the oil into these barren pays, should the gas be withdrawn, is definitely prevented, thereby eliminating a loss that otherwise would certainly take place. In addition to these protective effects, when the reservoir is depleted of its oil content the field will still be a source of high-pressure gas that will be available for marketing.

Pressure maintenance in gas-distillate fields is of the utmost importance. In fields of this type, the distillate originally occurs in the reservoir entirely in the vapor state. As the pressure declines, owing to the withdrawals of gas, the heavier fractions will condense, wetting the grains of the sand, and thus be lost. But, if the gas is returned to the reservoir and the pressure maintained, no condensation will take place, and by continued recycling of the gas, most of the distillate should be recovered.

Stabilization of crude: - Crude stabilization is a controlled evaporation of the mixture of gas and oil as it comes from the well, by which all desirable fractions of the mixture are preserved and held in the crude rather than partly wasted in the atmosphere.

Crude stabilization can be most effectively carried on in connection with pressure maintenance. According to Bennet (1938) and Torrey (1940, p. 305), crude stabilization results in the recovery of up to 50 per cent of the lighter hydrocarbons as salable products, that otherwise would be lost by evaporation, thereby increasing the volume of the crude produced. In addition, the maintenance of the specific gravity of the crude will provide a greater return to the operator in fields where the oil is sold on a gravity scale.

D. Spacing of Oil and Gas Wells

Function of wells: - Careful studies of the theoretical and practical aspects of the well spacing indicate that, under the efficient operating methods made possible by restricted production rates, ultimate recovery is in many cases substantially independent of the number of the wells. Muskat (1940, p. 37) reaches the conclusion that from the energy standpoint the interval between wells is of little consequence in its influence upon oil recovery. Shatford and Crowley (1942, p. 79) conclude that well spacing is solely a device to prevent waste of capital, not waste of oil.

Wells in a reservoir serve two important functions: (a) that of providing conduits from the reservoir to the surface, and (b) that of providing connections into a reservoir. Thus, information essential to the efficient operation of the reservoir may be obtained.

The relation of well spacing to ultimate recovery depends upon many factors, such as permeability, porosity, texture, degree of cementation and other lithologic properties of reservoir rocks. The geologic structure, drainage and the type of drive under which the reservoir operates is perhaps the most important.

Influence of geologic structure and structural position on well spacing: - Geologic structure influences oil and gas accumulation and drainage in many ways and should be taken into account in planning a development program. Several different types of geologic structure are productive of oil and gas, each of which presents its own peculiar problems of well location and spacing. Position on structure is also an important consideration; thus, a property situated at the crest of a structure may require a different plan of development than another on its flank near the edge-water line.

An accumulation on domal or anticlinal structure, producing under hydraulic control, if operated as a unit, may yield a high percentage recovery if exploited by a few widely spaced wells situated along the crest of the structure. Wells in this position will produce throughout the economic life of the field and will not be flooded with edge-water until nearly all of the available oil has been produced.

In a field where oil is expelled from the reservoir rock by gas pressure and the formation pressure declines as exploitation proceeds, there is often a gas cap at the crest of the structure. (see Fig. 9). If there is no primary gas cap at the structural crest, one is likely to form as a result of depletion of the reservoir (see Fig. 11). In a gas-cap area, according to Uren (1946, p. 74), wells should be widely spaced, if drilled at all. Production should be taken from down-dip wells, so situated that they will drain as little gas as possible from the crestal area. Wells should be spaced in accordance with some uniform pattern that will make approximately equal areas of reservoir rock tributary to each well.

Well spacing in fields under water-drive or gas-cap-drive: - In water-drive and in gas-cap-drive fields, and likewise in secondary recovery operations, the oil is displaced by an advancing body of water or gas pressure, and the efficiency of extraction depends upon the completeness with which the displacing fluid is made to advance through all parts of the reservoir. The problem in this case is to control the direction and uniformity of advance of the water or gas. An adequate number of properly located wells is essential for control of the movement of the displacing fluids through the reservoir.

Where the field is under hydraulic control and the reservoir rock is highly permeable and continuity of pore spaces permits rapid equalization of pressures, wells may be widely spaced without adversely influencing the ultimate recovery. Late completion of wells will not greatly influence their initial production and rate of production; however delay in drilling must diminish their ultimate production. It has often been suggested (see page 36) that, in such a reservoir, one well situated at the crest of the structure would in time produce all of the drainable oil. Additional wells need be drilled only when competitive conditions exist between different tracts producing from the same reservoir, or where it is desired to produce at a more rapid rate than is possible with a single well. Where gas energy is furnishing the expulsive force, the interval between wells may have an influence on the effectiveness of oil recovery as a result of inefficient application of gas energy in moving oil through the reservoir rock, and this may operate disadvantageously in cases where the wells are widely spaced. At points remote from the wells, where fluids are moving slowly through the reservoir rock, gravitational force tends to segregate the gas from the oil; thus, gas may escape to the wells through oil-drained spaces without doing useful work in moving oil. Gas drainage of this sort may occasion serious wastage of reservoir energy that could be largely avoided by closer spacing of wells and rapid production of oil.

Well spacing in fields under dissolved gas-drive: - It has been demonstrated theoretically that in the dissolved gas-drive type of field, if production is carried on for an indefinitely long time, recovery is independent of well spacing over the range of spacing ordinarily employed in practice. However, the recovery at some economic limit of production rate may vary with well spacing, and it is probable that, if economic factors are introduced into the problem, recovery may depend in some degree upon well spacing.

Under unrestricted flow, or under a proration plan which places emphasis upon number of wells or upon well potentials, a given tract will recover more with close spacing than will similar tracts with wider spacing. The greater recovery with close spacing is due usually to the fact that the closely spaced areas produce oil more rapidly and, through drainage from other tracts, obtain a greater share of the total production than the more widely spaced areas.

Effect of plugged sand: - Under certain conditions, not often encountered, well spacing may have a great effect upon recovery. Usually these conditions arise when asphalt, paraffin, or chemical deposits plug the sand for so great a distance around the well that they cannot be cleaned out. High rate of production causes release of gas from solution, a lowering in the temperature around the well, an excessive pressure gradient in the neighborhood of the well. These combine to bring about these undesirable conditions which cause a sealing off of productive areas.

E. Summary of Good Practices in Extraction of Oil

Principles for good practice in well spacing may be stated as follows:

a. The drilling of sufficient wells and test-holes to furnish adequate information of the size and nature of the reservoir; and,

b. The drilling of sufficient wells and in such locations as will adequately drain the reservoir in an economical manner.

<u>Efficient production methods can be achieved by</u>:

a. Drilling of the necessary number of properly located wells.

b. Proper well completion and maintenance of wells in proper repair.

c. Well completion providing for separate control of multiple producing zones.

d. Production of the wells at such rate as to prevent the escape of excessive gases.

e. Production of the wells in a manner so as to prevent the production of excessive water and to prevent the trapping of oil by channeling.

f. Prevention of migration of oil into gas zones.

g. Application of secondary recovery and pressure maintenance methods where needed and where economically feasible.

Section V

CONSERVATION STATUTES

Administration: - The legislatures of several states in North America have recognized the fact that conservation statutes cannot be self-administered (American Bar Association, 1939). They have found it necessary to set up administrative agencies to enforce the statutes and to promulgate necessary or convenient rules and regulations designed to carry out the policies of the laws.

Most state proration laws are administered by an administrative agency which has been set up and has been granted broad administrative powers. In most cases the official regulatory body is assisted by an advisory board consisting of representatives of the industry.

In theory the power of the regulatory body is defined by statute. They apparently define the powers of the regulatory bodies with some precision, but the exercise of those powers is a matter of discretion.

Functions of the state regulatory bodies: - The state regulatory bodies have authority with respect to: (a) restriction of flow; (b) balance of supply with market demand; (c) equitable apportionment; and (d) regulation of oil-pool development (King, Dec., 1948).

a) Restriction of flow: Under proration each flowing well is assigned a daily quota of production or allowable. Usually the restriction is accomplished by introducing a "choke" in the flow line of the oil well or by enforcing shut-downs in certain fields for a short period of time. In most states, wells having less than a certain minimum potential production, stripper wells, are exempted from all restrictions on production (see page 53).

Periodic tests enable the regulatory bodies to determine exactly how the bottom-hole pressure and gas-oil ratio are holding up under various conditions of restricted flow. It is also possible to determine with a fair degree of accuracy the location and content of the oil-bearing formations and the surface condition in the pool.

The regulatory bodies thus have available all the data necessary for determination of the rate of flow that will produce maximum utilization of the natural driving forces and oil.

b) Balancing supply with market demand: The proration laws are not yet administered purely on an engineering basis. In most states the exact amount of restriction on each pool is determined by reference to the demand for crude oil (McKeithan, 1942 p. 57). This demand is determined in the first instance by asking the purchasers of crude oil in each pool for monthly "nominations", showing the amount of crude oil they will need during the ensuing month. The regulatory bodies then check the sum totals of the nominations for all pools against monthly estimates of demand and "advisory quotas" prepared by the Bureau of Mines.

c) Equitable apportionment: Having determined the amount of production which shall be permitted in a pool, the next problem is to apportion that production among the operators in the pool by assigning an "allowable" amount to each pool. In assigning such allowables the regulatory bodies have in consideration two factors: first, to allot to every operator in the field an equitable share of the oil, preventing cross-drainage from one property to another, and, second, to maintain a production pattern which will permit maximum utilization of the natural driving forces.

In the early days of proration the conservation authorities attempted to treat each well alike; i.e., each well was allowed to produce the same amount of oil regardless of its potential; or, the wells were classified according to their bottom-hole pressure, regardless of the nature of the reservoir rock, its porosity and permeability. Each well in the same class was treated alike. Such practices, naturally, put a premium on drilling as many wells as possible.

The present practice is to base allowables on a combination of wells and acreage. The allowables are based upon an optimum pattern of production preventing cross-drainage from one property to another. The authorities have to calculate the number of acre-feet of oil underlying each operator's plot, and apply some formula which will produce: first, the maximum recovery for the pools as a whole, and, second, the ultimate recovery by each operator of approximately his share of the total oil in the pool.

d) Regulation of oil pool development: In addition to calculating market demand and assigning allowables, most state conservation authorities have at least some authority to regulate drilling and production practices.

Some of these regulations are merely for purposes of safety.

In Texas the conservation authorities control the drilling equipment, maintain a constant guard against "cratering", grant, as is done in Michigan, drilling permits, and supervise the actual work of bringing the well into production. In Arkansas they regulate the building and use of storage facilities.

In Michigan and in other states the conservation authorities have the power to regulate the number and the spacing of wells, preventing in this way the enormous economic waste involved in excessive drilling, and so increasing ultimate recovery (Act 326, P.A. 1937; Act 61, P.A. 1939).

Under any system of well spacing any tracts will obviously contain less than the minimum acreage which the conservation authorities have prescribed for the drilling of a well. To resolve this situation the authorities may require the operators of two or more small tracts to obtain their oil from a single-well-unit operation. The authorities may also designate the tract on which the well is to be drilled. In that case the operators can share equitably the benefits of production and costs.

Unit operation: - According to De Golyer (1942, p. 68) the unit operation is defined as follows:

> "... in a true unit operation the various operators in the field exchange their leaseholds for undivided interests in the pool, and the pool is developed and operated by an agent, trustee, or committee representing all the holders of undivided interests."

Unit operation permits maximum utilization of reservoir energy and the field is developed in the best possible way. Stabler (1942, p. 68) contends that the unit operation results in substantially lower production costs by lowering drilling costs, equipment and auxiliary services. Stabler estimated that it would produce from 25 to 30 per cent greater recoveries than present methods of operation.

The unit operation or "compulsory unitization" has been described by conservation authorities as the goal toward which the conservation law is directed (German, 1931). Nevertheless, to this date such operation has not been accepted in the United States. The unit operation could be employed successfully in Ecuador, where an entire pool is included, generally, in a single concession.

Provisions of the modern conservation statutes: - The principal provisions of the modern conservation statutes relating to oil and gas may be stated as follows:

a) Waste is prohibited. Such waste is defined in general and in specific terms; usually there is included, as a specific definition of waste, the production of oil in excess of the reasonable market demand.

b) An agency, such as a commission, is created with authority to administer the act in the light of specific directions and limitations and, subject thereto, to make such rules, regulations, and orders as are reasonably necessary to prevent waste and otherwise make the act effective.

c) Penalties are provided for in connection with violations of the statute or of any rule, regulation, or order of the administrative agency.

d) Court review of the acts of the administrative agency is authorized specifically.

e) Finally, the regulation contemplated by the statute is designed to increase ultimate recovery, and to insure a continuous, adequate supply of petroleum products at reasonable cost, justified in the public interest. Such regulations afford a reasonable method of protecting and adjusting conflicting property rights of individuals.

The statutes, regulations, and provisions dealing with conservation discussed on the preceding pages have been taken from the Michigan Conservation Law (Act 326, P.A. 1937 and Act 61, P.A. 1939) and from a public hearing held by the Supervisor of Wells and the Advisory Board in the city of Lansing, on February 2, 1949, with the purpose of hearing evidence and testimony pertaining to the necessity of promulgating general regulations governing oil and gas operations in Michigan.

Section VI

POOL'S ALLOCATION

A. Introduction

We have seen in the previous pages of this report (pages 19-43) that conservation of petroleum is the prime objective in the control and restriction of oil and gas production. To attain the desired results, we have seen also in page 17, that it is not only necessary to distribute production in a manner to permit the greatest ultimate recovery, but also to limit current supply to consumptive requirements. The most difficult problem involved is the equitable distribution of restricted production to the various pools and wells within the respective states.

The term "proration" applies to the broad process of imposing restrictions on production, whereas "allocation" applies to the more specific procedure of distributing regulated production to wells and pools within a state. Proration is essential to the attainment of effective conservation, and, as such, is the principal instrument used in the prevention of waste and the promotion of good production practices.

The need for proration has been demonstrated amply, and now is accepted widely as necessary to the general welfare. To meet this necessity a comprehensive plan of allocation is essential. However, only in recent years have the principles of allocation been developed from a scientific and engineering standpoint, and these principles have yet to be embodied firmly in the regulatory process. For this

reason, proper allocation of production is the most important and commanding phase of the current proration problem.

In the following discussion on allocation practices, only a brief outline of the principles which would provide a reasonable basis for allocation within and among pools, will be attempted. It is suggested that the excellent work which is done by the members of the American Petroleum Institute (Special Study Committee on Well Spacing and Allocation of Production) be followed closely while applying the proration activities in Ecuador. The work of the Interstate Oil Compact Commission of the United States in dissemination and coordination of information also should be of great value and assistance in this effort.

B. Principles of Allocatiom Within Pools

Definition: - Allocation within a pool is the division of the oil currently produced from the pool among those persons holding interests in the pool. It consists in the determination of the amount of oil which each property will be allowed to produce currently.

Principles: - The authorities of the state may be called upon to regulate production of oil and gas for the purpose of preventing waste and protecting property rights.

The preceding principles are too general to be of much assistance in working out an allocation plan under a particular case and for this reason more specific principles have been formulated:

a. Physical waste should be prevented (see page 49).

b. Within reasonable limits, each operator should have an opportunity, equal to that afforded other operators, to recover the equivalent of the amount of recoverable oil underlying his property. The aim should be to prevent reasonably avoidable drainage of oil and gas by the wells of adjacent operators.

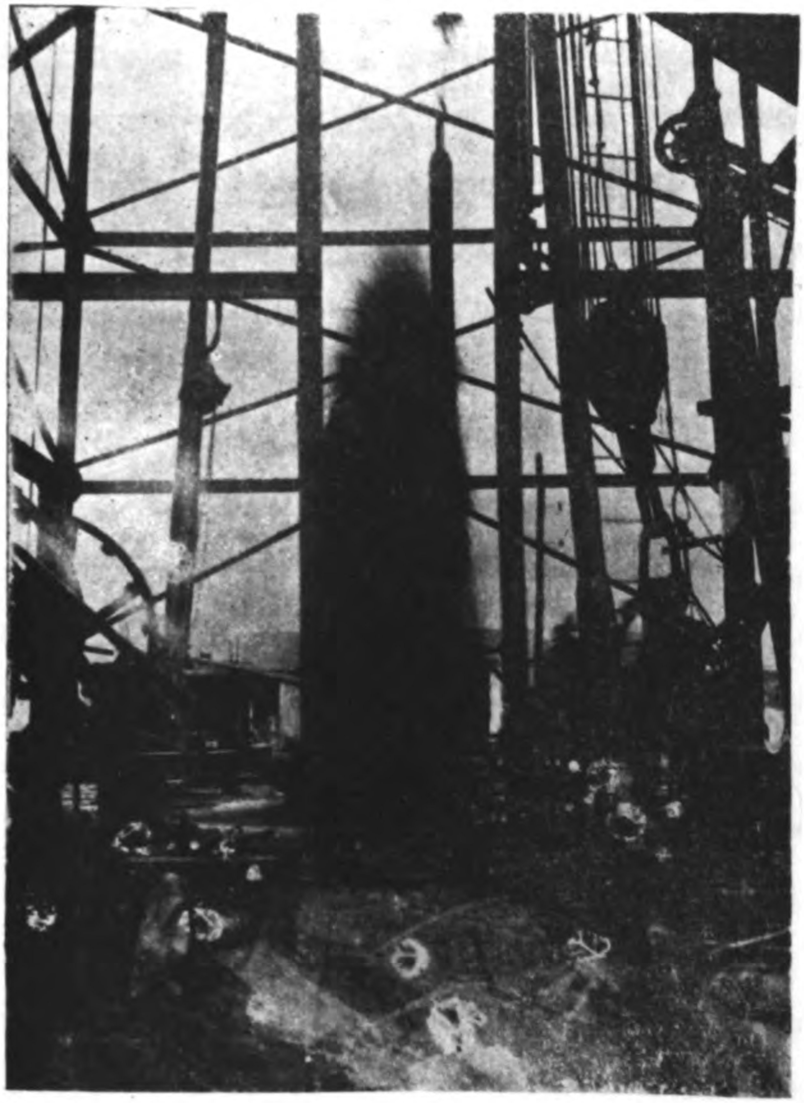
c. Allocation of production within each pool should be based on specific conditions in that pool. The producing life of a property depends partly upon structural position, and its effect on regional migration; this regional migration must be taken into account in order to permit the properties whose drainage is the result of unavoidable regional migration to recover oil at a faster rate than the properties which ultimately benefit from such migration (see page 52).

d. Under certain circumstances, some of these principles may be incompatible with others. In such cases, compromise or adjustment must be made (see page 53).

C. Factors Pertaining to Waste Prevention

Field rules: - Rules should be established in each field to provide for the safe drilling of wells and for proper development of the field. Where the necessities of the case justify the action, certain equipment, such as blow-out preventers, specifications for the "drilling mud", and any other special provisions necessary to safe drilling operations should be required.

Provisions should be made for the completion of wells in an efficient manner. Strict regulation by the regulatory commission of all the mechanical operations and equipment used in drilling and completing wells is impractical and undesirable, but the rules should be sufficient to eliminate inefficient well completion due to incompetence or negligence (see Plate 6). In some cases, proper well completion regulations can be enforced through penalties for the production of excessive amounts of gas or water. Particular



Campamento Petrolífero de la "Anglo Ecuadorian Oilfields Ltd."
Ancón, Península de Santa Elena. Provincia del Guayas.

Plate 6.- A gusher. During the early development period, wells were drilled in without any preparations for control to prevent waste, oil pollution, or fire hazard. (Courtesy of the Mines and Petroleum Bureau of Ecuador).

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attention should be given to the problem of well completion in fields with multiple producing zones, in order that well-completion practice may provide for efficient control of the several producing zones.

Well spacing: - Drilling should be regulated in order to provide a proper number of wells and an efficient well-spacing pattern. Oil well sites in Ecuador are arbitrarly located, and certain customs have been followed for years. Thus, a common interval between wells in some fields of Santa Elena (Anglo-Ecuadorean Oilfields, Ltd. and Ecuador Oilfields, Ltd. in El Tigre field) is 660 feet, but this merely resulted from the fact that any well, according to the Ecuadorean regulations (Ley del Petroleo, Aug. 6, 1937) has to be drilled 330 feet (100 meters) back from its boundary line (see Fig. 13).

The best method for regulating well spacing in a field order appears to be that of fixing drilling units, or designated areas, upon which a single well is to be drilled. The area of a unit should be the maximum area which, in the light of all the pertinent economic and physical facts (see pp. 36-38), a single well can drain efficiently.

In many fields there are tracts that are smaller than a proper-sized drilling unit. In order to avoid the drilling of unnecessary wells on small tracts, that have a right to a fair share of the field's production, it is believed desirable to coördinate such tracts with adjacent tracts in order to make a drilling unit that would permit efficient and economical development.

Control of gas production: - Control of excessive gas production is urgently necessary for the prevention of waste. A common

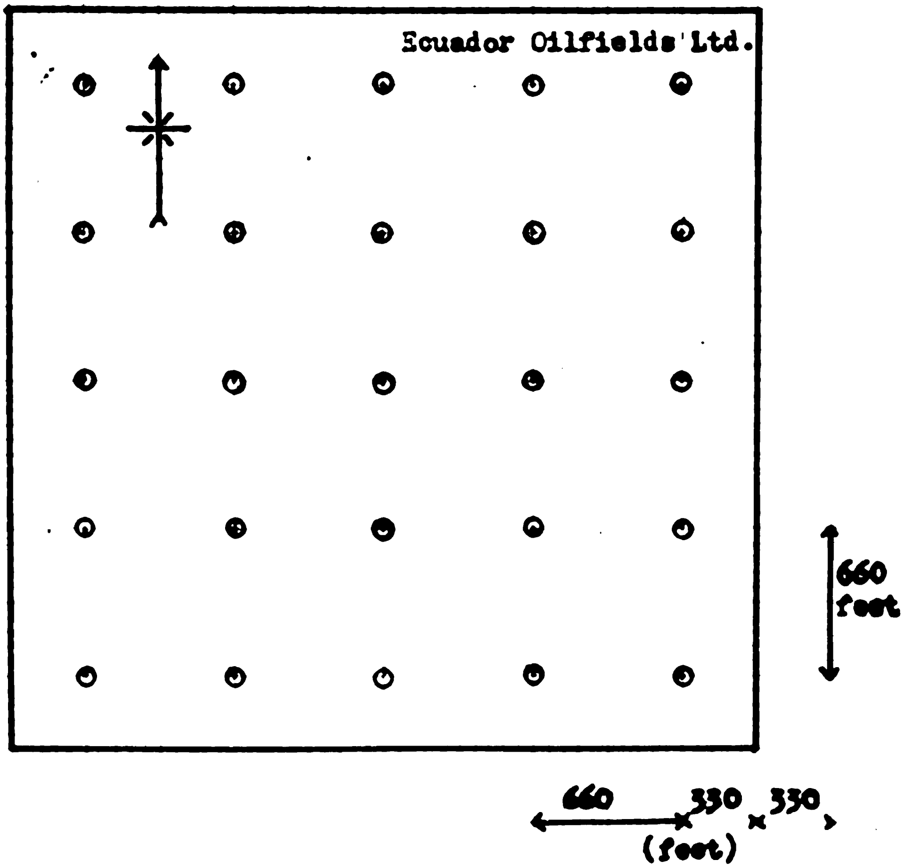

Figure 13.—Arrangement of wells providing 10 acre spacing adopted for exploitation of Ecuador Oilfields Ltd., Company, Santa Elena, Ecuador.

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practice in gas control is to fix a maximum gas allowable, determined on the basis of a limiting gas-oil ratio which cannot be exceeded without penalty in the oil allowable. The limiting gas-oil ratio should be adapted to the specific conditions of each field.

Control of water production: - Excessive water production sometimes may result in lower oil recovery by virtue of the fact that the produced water cannot displace additional oil from the sand. The effect of water production upon the reservoir behavior should be investigated carefully; if there is likelihood that water production is causing waste, the production of excessive quantities of water should be prohibited.

The regulatory commissions, except in rare instances, have not seen fit to control water production, possibly because control is too complex or because specific cases of waste due to excessive water production have not been forcibly called to their attention. In some fields water production is a serious problem that needs control.

Uniformity of withdrawals: - Excessive localized withdrawals result in irregular encroachment or in causing the water or gas to cone up; the result is by-passing or trapping of recoverable oil in the reservoir. In the interest of conservation, such heavy withdrawals from small areas should be eliminated.

Pressure maintenance: - In some fields the recovery of oil can be increased materially by returning gas or water to the reservoir. Usually these operations can be conducted successfully only on a field-wide basis. Regulatory commissions should encourage the adoption of conservation measures of this type wherever they are economically applicable.

Inasmuch as economic considerations dictate that most repressuring, pressure-maintenance, or secondary-recovery methods be undertaken cooperatively by all producers in a field, a satisfactory agreement among the producers is highly desirable in conducting these operations. If such an agreement cannot be obtained, the benefits can be realized only by legally compelling disagreeing operators to participate in the necessary operations.

Regional migration: - In the majority of the fields, efficient operation of the reservoir demands that the oil be displaced by an injected water drive displacing oil upstructure, an injected gas-cap drive displacing oil downstructure, or combination of these drives. In any of these cases a regional migration of oil occurs, and some properties are depleted of their recoverable oil before others. This condition is desirable from the standpoint of preventing waste, but the unequal life of the producing properties leads to complications in developing allocation methods that will please operators.

The ultimate production that will be obtained by each property depends upon the producing life of the property and the rate of production during the productive life of the property. Hence, the recovery can be made high or low, or the life can be made long or short, by the method of allocation.

If the allowable is so adjusted that each property will ultimately produce the equivalent of the recoverable oil underlying it, many properties will suffer undue hardship by being assigned unreasonably low current allowables. Clearly, this situation calls for compromise and adjustment. A just order would permit the properties which are drained as a result of unavoidable regional migration to recover oil at a faster rate. The method by which this is accomplished and its quantitative result must and can be determined only by examination of all the facts and circumstances of the particular field in question.

D. Principles of Allocation Among Pools

General considerations: - The problem of allocation among pools has not received yet the intensive study that has been given to other phases of the allocation problem.

In the present discussion it is assumed that the allowable for the country will be fixed at a value substantially equal to the reasonable market demand for the country, and the discussion will be confined to the development of principles and procedure for distributing the allowable among the pools within the country.

Principles: - The following principles should provide a reasonable basis for allocation among pools:

a) Stripper production: Stripper pools (pools nearing the end of their productive lives), which would ultimately yield less oil due to premature abandonment of wells if any restriction as to producing rate were imposed, should be exempt from such restriction.

b) Restriction to prevent waste: Other pools should be restricted at least to a rate which will permit the use of the most efficient producing practices.

It has been argued that there is an "optimum production rate" at which each field will produce a maximum amount of oil. It is doubtful that this is true. Geologists and engineers have not yet developed or determined the optimum rate with the accuracy required for allocation purposes. It is true that a rate can be determined for most fields at which waste would occur due to an excessive production rate; but there is a wide range of rates in which efficient operation is possible, and within this range it is not possible to select the exact point of maximum recovery, even if such a point exists.

Each field should be produced at a rate not to exceed that which would bring the field up to the threshold of waste. If this rate is more than the field's fair share of the reasonable market demand, the rate should be reduced to that which would permit the field to produce only its fair share.

c) <u>Allocation to groups of pools</u>: The problem of distributing the total state allowable among the pools is complicated greatly by the facts that different pools produce different grades of oil, and that all pools are not located similarly with respect to market and transportation facilities. Thus, it will be quite different to distribute the "allowables" in the pools of the Santa Elena region which is near to the Pacific coast and the populated city of Guayaquil, than in the pools (if oil is found) of the distant and uninhabited Oriente region.(7)

A practical approach to allocation of the state allowable on an equitable basis among pools would be to classify the pools of the state according to a few groups of pools producing similar grades of oil. For instance, the Ecuador Oilfields, Ltd., operating at Santa Elena, Ecuador, has classified its oil production in three groups: light, medium, and heavy oil, according to the density. The former ranges from 36° to 39° grades A.P.I., the medium is of 28° A.P.I., and the heavy has 18° A.P.I. The allowable of the state would be distributed among the groups of pools with due consideration to the relative needs for the several grades of oil.

d) Equitable allocation to each pool: Having determined the total allowable for a group of pools producing oil of similar grade, it becomes necessary to fix the allowable for each pool in the group. In order that each pool may share

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(7) According to the Ecuadorean Hydrocarbon Laws, the state is sole owner of mineral rights. Any person or company, foreign or national, can obtain a concession or a small pertenencia, provided such a person or company has sufficient capital and the official approval of the government. When oil is found, the land is leased on a royalty basis. Our taxation is fixed according to the distance between the oil well producers and the nearest port for its exportation. The government receives from 11% to 5% of the value of the sale of the oil after deducting operating expenses. In distances between 0 to 50 kilometers it receives 11% and this scale runs to 5% in distances of 600 kilometers or more.

equitably in the allowable attributable to its group, the recoverable oil reserves would provide a satisfactory primary standard for allocation among pools. It would be necessary also to have in mind a reasonable adjustment of allowable, the operating costs, in order to favor pools in which development and operating costs are high. In making such adjustment, appropriate factors such as depth may properly be considered.

Section VII

CONCLUSIONS

The following conclusions have been formulated from the studies upon which this paper is based:

1. Conservation of petroleum resources is necessary: first, to insure a continuous, adequate supply of petroleum products at reasonable cost; and second, to protect property rights.

2. Oil produced in excess of reasonable market demand is oil wasted.

3. Production rate is one of the most important factors governing oil recovery, and production at excessive rates commonly causes waste.

4. Waste also results from the following causes:

    a. Development of improper well-spacing patterns or with improper well density.

    b. Improper well completion.

    c. Improper production of multiple producing zones.

    d. Excessive, localized withdrawals, resulting in irregular encroachment of water or gas, or development of areas of unduly low pressure.

    e. Excessive production of water and gas.

    f. Migration of oil into free gas zones.

    g. Improper control of reservoir energy.

    h. Failure to apply suitable methods of pressure maintenance and secondary recovery where economically justified.

5. Authoritative regulation is needed to prevent waste.

6. Allocation of production among pools, and within a single pool, should be on the basis of sound principles of law, economics, and engineering.

Section VIII

RECOMMENDATIONS FOR ECUADOREAN OIL CONSERVATION

Conservation practices and legislation have been enacted in the United States in the most important oil-producing states, such as Arkansas, California, Kansas, Louisiana, Michigan, New Mexico, Oklahoma, Texas, etc. All that need be done in Ecuador is to utilize the experience and progress which have been achieved in those states. Invitations to engineers and geologists of recognized standing, but not directly associated with companies operating in Ecuador should be extended these men to remain until a personnel of native Ecuadoreans were trained to take over.

The success of conservation depends upon the application of proved and studied principles.

A. Waste Prevention

1. Regulation of production by government authority for the prevention of waste should be initiated.

2. Each oil reservoir should be controlled in such a manner as to utilize to best advantage the natural agencies and sources of energy by which oil is produced. To achieve this, a detailed and continuous study of each reservoir should be made, beginning with the early development of the pool.

3. A sound basis for gas conservation, adapted to the specific needs of the individual oil fields, should be required.

4. Water production should be controlled in those fields in which water is an important source of reservoir energy, and in which its production in excessive quantity would lead to waste.

5. Pressure maintenance, repressuring, and other field-wide conservation methods should be employed, whenever such methods are economically applicable.

B. Allocation Within Pools

1. Principles of allocation should be interpreted in a manner that they may approach more closely the ideal of allowing each operator an equal opportunity to recover the equivalent of the recoverable oil which underlies his property; and to prevent reasonably avoidable drainage acrosss property lines.

2. Well spacing should be controlled. It can be accomplished in areas of subdivided ownership by voluntary or compulsory pooling of adjacent tracts in order to permit wells to be drilled in conformity with a proper spacing pattern. The purposes of this control are:

   a. Protection of tracts whose recoverable reserves would not, under a reasonable allocation formula, justify the drilling of wells.

   b. Elimination of unnecessary wells, and adoption of more efficient and economical well-spacing patterns.

   c. Reduction of drilling hazards.

   d. Simplification of administration.

3. Generally the allowable of a pool should be allocated to designated areas or units. If there be more than one well on such a unit, it may be necessary to distribute the unit allowable among the wells on the designated area or unit in such a manner as to fix definitely the allowable for each well.

C. Allocation Among Pools

1. The basic principles of allocation among pools should be observed in order that all pools may produce at efficient rates, and in order that each oil production unit may have its fair share of the total allewable.

D. Procedure

1. Promptly enact adequate conservation laws and set up the administrative machinery to carry them into effect.

2. The oil exportation should be controlled or limited in view of its limited duration. Further exportation could be permitted if additional oil were found in the country.

3. Orders establishing field rules and setting out a basis of allocation should include the following:

   a. Field regulations governing the drilling and completion of wells.

   b. Specification of the location and spacing of wells and the tolerances allowed therein.

   c. Provision for penalties to be imposed on wells that produce in such a manner as to cause waste.

   d. Provision for prevention of fires and pollution and danger to, or destruction of, property or life.

   e. A formula for distribution of the field allowable among various units of production.

   f. Provisions for testing wells in a specified manner in order to determine:

      (1) Factors necessary for the application of the allocation formula.

      (2) The amount of gas and water produced, in order to determine whether or not the prescribed penalties are applicable.

      (3) That the well can produce its daily allowable.

4. Enact those laws which are most conducive to stimulating additional exploration and development in Ecuador.

5. Encourage free competitive enterprise with tax reforms to provide incentives for the risk of private capital in new ventures.

6. Maintain favorable conditions for foreign capital. Discourage artificial restraints and restrictions, both political and private, which deny full opportunity to participate beneficially in the production and distribution of petroleum and petroleum products.

7. Utilize the facilities of government and technical institutions to promote study and research of the oil industry.

8. The formation of representative cooperative engineering associations or committees among directly interested operators of a pool or concession should be encouraged. Such associations can study a specific pool or pools, and can prepare and recommend rules and regulations as may seem advisable. The formation of such associations or committees should be encouraged whether or

not the regulatory body includes technical staff engineers.

9. The governmental regulatory body should employ, or have available for consultation, competent technical advisors.

10. The recommendations in this report concern the application of basic principles only. For this reason no attempt is made herein to devise administration or to suggest organization of a governmental office. Working within the framework of the principles herein stated, operators and regulatory agencies should cooperate in the development of oil production, procedures, and formulas to enact technically competent and equitable conservation laws.

Section IX

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