EXPERIMENTAL STUDIES OF SUBSURFACE RELATIONSHIPS IN OIL AND GAS FIELDS.¹

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INTRODUCTION.

During the writer's studies of subsurface problems in various oil and gas fields of the United States he has been impressed with the need for broad, systematic, and painstaking studies of subsurface relationships. New criteria for the interpretation of subsurface conditions must be established and new methods of work developed and applied in the search for oil and gas as well as in their recovery. The protection of our known fields against the inroads of water, and the development of more efficient methods of recovery are imperative, but both lines of endeavor depend primarily upon an understanding of subsurface principles and relationships. The drilling and operation of wells furnish valuable subsurface data, together with much costly experience, but the facts and relationships revealed through studies of materials and data collected in the field are not adequate because they are incomplete.

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The United States Bureau of Mines is endeavoring to meet this situation through systematic and scientific field and laboratory experimentation. While investigating various phases of the oil-field water problem for the Bureau of Mines the writer has pursued experimental studies in conjunction with his field work. This has led to the development of a simple apparatus for the laboratory study of subsurface relationships in oil and gas fields. A series of preliminary experiments, with the apparatus demonstrated its value in studying some of the fundamental principles and relationships governing the occurrence and recovery of oil and gas. As there is a growing demand for this type of work, the apparatus, together with the methods of study that have been developed and some of the results of the work, will be of interest to other investigators.

APPARATUS.

Construction.—The apparatus consists essentially of a rectangular steel tank with removable top and front plates, and with openings and cocks arranged as shown in Fig. 51 and the accompanying plates. Three of these tanks, two small and one large,

FIG. 51. Small experimental tank lying face down with cover plate attached.

are now in use by the Bureau of Mines. All pipe connections for the small tanks have $\frac{3}{8}$ inch (0.95 cm.) internal diameters, and those for the large tank $\frac{1}{2}$ inch (1.27 cm.) internal diameters. Standard brass service cocks are used on both sizes of tanks. All interior corners are slightly rounded through the bending of the steel members during construction, or through filling in corners with aquarium cement. The internal dimen-

sions of the two small tanks are 92 by 48 by 9 cm., or 36.22 by 18.90 by 3.54 inches; and of the large tank, 183.5 by 124 by 13.3 cm., or 72.24 by 48.82 by 5.24 inches. The fluid capacities of the two sizes of tanks are 39.7 liters (10.49 U. S. gallons) and 302.6 liters (79.94 U. S. gallons), respectively.

The steel bodies of the two sizes of tanks are built up of $\frac{5}{16}$ -inch plates riveted and welded to 4-inch and 6-inch channels respectively, the channels being bent so as to form the bottoms and ends of the tanks when standing vertically as shown in Plates XII.-XV. The surfaces of the steel members exposed on the insides of the tanks are enameled to prevent corrosion and to provide surfaces that approximate glass and quartz in their coefficients of friction with oil and water.² The legs of the channels, to which the plates are riveted, project outward as shown in the photographs. The backs of the small tanks are single plates, but the back plate of the large tank is equipped with two armholes and two removable plates to close them. Around the tops of the tanks there are planed flanges $\frac{5}{16}$ inches thick, to which the top or cover plates may be bolted. The cover plates, which are $\frac{5}{16}$ inches thick, fit snugly upon the flanges, the contacts being made tight by rubber gaskets. The cover plates are equipped with threaded openings and packing boxes which are closed unless in use. These openings serve principally to receive miniature wells. (See Fig. 51.)

The fronts of the tanks are removable glass plates that fit inside the steel frames and slide into place through the openings at the tops of the tanks when the cover plates are removed. The dimensions of the glass plates are $\frac{1}{2}$ by 16 by 36 inches for the small size, and $\frac{3}{4}$ by 48 by 72 inches for the larger size. The tanks are constructed so that thicker plate glass may be used if desired. These plates are made tight to the steel frames by aquarium cement, and are braced from the outside by buckstays when necessary.

Uses.—This type of apparatus can be readily transported to field laboratories where it is desired to make repeated use of large

² Experiments with different enamels are in progress.

volumes of the gases, oils, and waters there found. When a tank is in use, such materials as sand, clay, gas, oil and water can be placed in the tanks and arranged to simulate varied natural conditions. Loose sands can be compacted both by sedimentation and by tamping, and can be lithified through the use of different chemical reagents that react so as to cause cementation thus approximating the rock formations in nature.³ Fluids can be introduced and made to pass through at will. Jet-like currents can be induced or prevented through regulating the velocities of flow and through the use of baffles which break up such currents. Pipes representing wells can be inserted and the fluids extracted through them. Moderate pressures can also be exerted, but for high-pressure work an auxiliary apparatus, to be described later, is being developed. While in use, the apparatus can be tilted to any desired angle. The total surface of glass in contact with the fluids is practically negligible in comparison with the total sand-fluid contacts. In other words, the conditions of experimentation can be made to approach more nearly to deep-seated rock conditions than can the conditions of experimentation in glass tubes or in open vessels. The plate glass fronts of the tanks afford every facility for making observations and photographic records, and the dimensions of the areas of glass exposed in the frames, together with graduations on the edges of the frames around the glass, afford size scales for the pictures. Furthermore, if the glass plates become badly scratched or broken, they can be easily replaced without injury to the apparatus. These features, together with the wide range of experiments that can be performed in the apparatus, are decidedly advantageous.

Three reservoir tanks for gases, oils, and solutions, together with an air pressure line connecting the reservoir tanks to an air receiver, form a part of the equipment. Pipe connections, gas meters, water meters, pressure regulators, thermometers, and gages, were arranged differently for the various experiments.

In using an apparatus of this kind it is imperative that the

³ This process involves the formation of interstitial silicates and carbonates. It is used for the manufacture of artificial sand stone.

limitations of the experimental values be recognized. The difficulties of reproducing subsurface conditions in the laboratory necessitate the development of experimental methods to establish broad principles and relationships rather than concrete facts. In this connection, it is recognized that laboratory data have indicative and relative rather than absolute values as criteria for the interpretation of subsurface conditions and relationships; but in conjunction with field studies, the laboratory experiments broaden our conception and strengthen the foundation of facts upon which valid conclusions must be based. Field investigations, together with the laboratory study of materials collected in the field,⁴ are therefore supplemented by experimentation in which comparisons are made between the behavior of different gases, oils, and aqueous solutions in different kinds of sands under different sets of conditions. The number of variables in each experiment is restricted so that the relative values of the factors and relationships under scrutiny, may, under the conditions of experimentation, be very definitely determined. In this respect, laboratory experimentation has a decided advantage over subsurface experiments in the field. Both types of work should be pursued; one or the other taking precedence according to the requirements of the problem. The reduction of the number of variables and the substitution of known for unknown values in formulating conclusions from both field and laboratory studies are just as important as the corresponding steps in solving an equation or a set of equations.

EXPERIMENTS.

Photographic Records.—To illustrate the use of the apparatus, photographs and brief descriptions of a few of the Bureau of Mines experiments in the laboratory are submitted for consideration. More complete descriptions of these experiments, together with notes showing the quantitative results, will be pre-

⁴ See U. S. Geol. Survey Bull. 693. The evaporation and concentration of waters associated with petroleum and natural gas, by R. Van A. Mills and Roger C. Wells.

sented in later papers and in Bureau of Mines publications that are in course of preparation.

Materials Used.—The oils and sands that were used in these particular experiments are recorded in Tables I. and II., the oils

TABLE I.
OILS USED FOR EXPERIMENTATION.

Num- ber.	Source of Oil.	Color.	Specific Gravity		Baume Gravity at 60° F. (15.6° C.).	Viscosity Expressed According to Engler.
			at 70° F. (21.1° C.).	at 60° F. (15.6° C.).		
1	Woodsfield, Ohio	Black	0.820	0.824	39.9	1.573
2	Tulsa, Oklahoma	"	0.861	0.865	32.0	2.073
3	Summerland, California	"	0.912	0.916	22.9	75.488

TABLE II.
SANDS USED FOR EXPERIMENTATION.⁵

Marks by which the Sands are Designated in the Photographs.	Ranges in Diameters of Grains Expressed in Millimeters. ⁶	Total Porosities Expressed as Percentages of the Vol- umes of the Sands. ⁷
<i>a</i>	6.350 to 1.651	36.00
<i>b</i>	0.833 to 0.589	38.00
<i>c</i>	0.417 to 0.074	37.00
<i>d</i>	1.168 to 0.833	37.00
<i>e</i>	0.589 to 0.074	38.00
<i>f</i>	6.350 to 0.833	37.00
<i>k</i>	0.295 to 0.074	40.00

being designated by numbers and the sands by letters which appear with the illustrations as well as in the tables. Only one quality of water, a chloride brine having a specific gravity of 1.100 was used. Air was substituted for natural gas. The temperature of experimentation was 70° F. (21.1° C.). In the different parts of each comparative experiment, equal volumes of air, oil, and water were used, under the same pressures and through equal periods of time, unless otherwise stated. With the apparatus arranged as shown in the accompanying photographs, the pressures never exceeded five pounds per square inch. The

⁵ These are white quartz beach sands with rounded and partly rounded grains, except *c*, which is a fine sandy material from drill sludge.

⁶ Screen analyses of these sands will be presented in later papers.

⁷ Averages from five tests upon each sand, expressed to the nearest per cent.

time periods varied from a few hours up to several months. In the recovery experiments illustrated by Plates XII.-XV., the miniature wells ($\frac{3}{8}$ inch pipes) extended 1 cm. (0.394") below the tops of the pay sands and were 1 cm. inside the glass fronts.

Notes and Conclusions.—The following notes and conclusions from the experiments illustrated by the accompanying photographs are abbreviated to meet the purpose of this introductory paper as already outlined.

Experiment 1 (Plate XII., *a*) illustrates the "gravitational" segregation and accumulation of oil (1, Table I.) above water (chloride brine, sp. gr. 1.100) in a coarsely porous sand (*a*, Table II.) and in a finely porous sand (*d*, Table II.). The oil was introduced at the bottoms of the tanks and allowed to migrate upward through the water-saturated sands under the propulsive force of its buoyancey in the water. The experiment had been in progress 48 hours when the photograph was made. The cap sand (*e*, Table II.) was a water-saturated beach sand, finer but more porous than either of the pay sands. This relatively fine water-saturated sand constituted a barrier to further vertical migration of the oil. Except for the textures of the two pay sands, the conditions of experimentation were practically the same in each tank. The reader will observe the more complete segregation of oil above water in the coarse sand *a*; and the sharp angles of repose⁸ between oil and water in the finer sand *d*, as contrasted with the horizontal contact between the oil and water in the coarser pay sand *a*. In the finer sand *d*, the movements and adjustments of the fluids, especially the up-dip migrations of the oil, were slower and more restricted than in the coarser sand *a*.

Experiment 1 may be regarded as indicative of conditions in the crests of anticlines or in the upper parts of lenticular bodies of sand regardless of structure. Again, by tilting the apparatus, the experiment may be regarded as indicative of conditions in a single bed in which there are irregular textural variations. This

⁸ In the descriptions of experiments the term "angle of repose" is used in a relative rather than an absolute sense.

a.

b.

c.

a. The "gravitational segregation and accumulation of oil above water in sands of different textures. Tank 1 contained a relatively coarse pay sand (a), and tank 2 a relatively fine one (d). The cap sand (e) was water-saturated. Letters refer to materials in Table 2.

b and c. The "gravitational" and hydraulic segregation and accumulation of oil in sands of different textures. The arrows indicate the direction of flow.

a.

b.

c.

d.

a and b. "Gravitational" segregation and accumulation of oil and gas above water in accordance with configuration of tops of sands. A-Oil and gas migrating upward into dome-like top of coarse sand a. B-Oil and gas migrating upward from coarse sand a into finer sand b.

c. "Gravitational" segregation and accumulation of oil in anticline and terrace. The dark beds k were fine oil-bearing sand (see table 2) which gradually gave up its oil to the overlying coarser sand b.

d. Differential movements between oils of different viscosities, and water, under same conditions of hydraulic flow. Tank 1 contained relatively non-viscous Appalachian oil (1); tank 2 more viscous Mid-Continent oil (2).

experiment, supplemented by many others of the same type, indicates that, other conditions being equal, the textures of oil and water bearing sands, more especially the sizes of pores in the sands, are primary factors governing the migration, accumulation, and mode of occurrence of oil. The angles of repose between oil and water in sands depend, among other things, upon the sizes of pores in the sands. The degree of dip is also a primary factor influencing both the angle of repose between oil and water and the up-dip migrations of the oil. Under ordinary hydrostatic conditions in water bearing sands, oils of the Appalachian and Mid-Continent types (see oils 1 and 2, Table I.) migrate up dip until angles of repose between oil and water are established. These migrations are influenced and may be restricted or prevented by textural variations in the sands. Sharp reductions in the sizes of pores in water-bearing sands may, under favorable conditions, constitute textural barriers against which oil accumulates in the coarser pores. This is illustrated by the effects of the fine water-bearing cap sands *e* and *c* used in this and the other experiments herein described.

Experiment 2 (Plate XII., *b, c*) illustrates the "gravitational" and hydraulic segregation and accumulation of oil (1, Table I.) above water (chloride brine, sp. gr. 1.100) in a coarsely porous sand (*a*, Table II.) and in a finely porous sand (*d*, Table II.). The cap sand (*e*, Table II.) was a water-saturated beach sand, finer but more porous than either of the pay sands. This relatively fine water-saturated sand constituted a barrier to further vertical migration of the oil from the coarser sands *a* and *d*. At the beginning of the experiment the fluids were as shown by Plate XII., *a*. The migrations and rearrangements of oil and water yielding the conditions shown in Plate XII., *b* and *c*, were induced by hydraulic currents in the directions indicated by the arrows. Under the same pressure (3 foot head of water) and during the same time (10 minutes) the volume of water (25 liters) displaced from the coarse sand *a* was five times that displaced from the finer sand *d*, though the finer sand was the more porous of the two. The reader will observe the smaller volume of accu-

mulated oil, as well as the steeper, though less sharply defined, oil-water contact in the finer pay sand *d*. A large proportion of the oil in tank 2 was lost through retention in the fine pay sand. Effects similar to these were induced in the laboratory by currents having only one tenth the velocities used in this experiment but extending through longer periods of time.

Experiment 2 may be regarded as indicative of conditions resulting from hydraulic currents in the crests of anticlines or in the upper parts of irregular or lenticular bodies of sand regardless of structure. Again by tilting the apparatus, the experiment may be regarded as indicative of similar conditions in a single bed in which there are irregular textural variations. The experiment indicates that under favorable conditions, the oils of the Appalachian and Mid-Continent types (see oils 1 and 2, Table I.) migrate up or down dip under the influence of slight hydraulic currents. These migrations are, of course, influenced, and may be prevented, by the textural conditions in the sands. The slopes of the sands and the rates of the hydraulic currents are factors of primary importance. This and many other experiments indicate that the loss of oil through retention in the sands incident to induced movements of oil and water, depend among other things upon the sizes and shapes of the pores in the sands. The greatest losses by retention occur in the sands having relatively fine angular pores.

Experiment 3 (Plate XIII., *a* and *b*) illustrates the "gravitational" segregation and accumulation of oil and gas above water in accordance with the configuration of the tops of the sands but not necessarily in accordance with structure. At the beginning of the experiment the sands were saturated with water (chloride brine, sp. gr. 1.100) except for entrapped air which slowly segregated and accumulated above the water. Oil (1, Table I.) was introduced in three equal volumes through the respective openings at the bottom of the apparatus while the water displaced by the oil escaped through the center opening in the top plate.

Plate XIII., *a*, shows oil and air migrating upward from the relatively fine water-saturated sand *b* into the dome-like top of

the coarser water-saturated sand *a*. The photograph was made thirty minutes after the oil was introduced. The upper bed of water-saturated sand *b* in contact with *a* constituted a temporary barrier to further vertical migration of the oil and air which migrated up the slope of the contact between *a* and *b*. Within 24 hours after this photograph was taken, the cumulative buoyancy of the oil and air accumulating in the dome-like top of *a* overcame the resistance to further upward migration. The oil and air broke through the contact along the crest of *a*, where the propulsive force of cumulative buoyancy was greatest.

Plate XIII., *b* shows the oil and air migrating "gravitationally" from the coarse sand *a* into the finer sand *b* and reaccumulating under the fine water-saturated cap sand *c*, 48 hours after the oil was introduced. The lateral migration of oil and air through the fine water-saturated sand *b* in the absence of any slope in the top of that sand is especially interesting. The relatively fine water-saturated sand *c* constituted an effective barrier to the further upward migration of the accumulating bodies of air and oil which flattened out to assume positions of repose above the water.

Experiment 3 indicates that under such conditions of retarded migration, the cumulative buoyancy of oil and gas in water-bearing sands is a primary factor in both the accumulation and the recovery of oil and gas. It further indicates that the so-called "up-dip" migrations of oil in regions of low dip and the deep-seated movements and rearrangements of oil and water incident to the drilling and operation of wells, more especially the elimination of water cones, are due in part to the flattening out of bodies of oil when they are assuming their angles of repose above water. The presence of gas in a water-bearing sand with the oil evidently facilitates the lateral as well as the vertical adjustments. The experiment further indicates that there is a tendency for oil and gas to migrate upward under hydrostatic conditions in water-saturated strata and to accumulate where further upward migration is prevented by structural or depositional doming, or by textural or other barriers, in ac-

cordance with the underlying principles of the anticlinal theory but not necessarily in accordance with structure.

Experiment 4 (Plate XIII., *c*) illustrates the "gravitational" segregation and accumulation of oil (1, Table I.) above water (chloride brine, sp. gr. 1.100) in an anticline and in a terrace. The dark bands *k* under the pay sands *b* were fine oil-bearing sand which gradually gave up its oil to the overlying coarser sand. In these oil and water saturated sands, the vertical migration and adjustments of the oil toward static equilibrium occurred more readily than the horizontal adjustments, thus giving rise to the inclined, though irregular, oil-water contacts. There was a tendency for the oil to migrate up dip and for the oil-water contacts to flatten until angles of repose between the oil and water were established.

The experiment indicates that the up-dip migration and segregation of a light, non-viscous oil above water, under the propulsive force of buoyancy, plays an important rôle in the accumulation of such oils in both anticlines and terraces. The entrapment of oil in terraces also depends upon the resistance to the lateral migration of the oil across and beyond the terraces. This resistance to lateral migration depends largely upon the textural conditions, more especially upon textural barriers in the sands and also upon the shape and extent of the terraces. Under favorable conditions, oils of the Appalachian and Mid-Continent types (oils 1 and 2) migrate up dip under the propulsive forces of their buoyancy in water. Structure and conditions that are analogous to structure are of primary importance both in the accumulation and in the recovery of such oils. This is one of the experiments in a series indicating that the angles of repose between oil and water, under hydrostatic conditions, in sands depend upon the summations of the effects of many factors among which the slopes of the tops of the sands, and the textural conditions in the sands, more particularly the bedding and sizes of pores are of primary importance.

Experiment 5 (Plate XIII., *d*) illustrates differential movements between oils of different viscosities and water under the

same conditions of hydraulic flow. Oils 1 and 2 were introduced into water-saturated pay sands of corresponding textures (*f*, Table II.) in tanks 1 and 2 respectively. The cap sand *c* was a fine water-saturated material described in Table II. At the beginning of the experiment the bodies of accumulated oil lay horizontally above the water. Under the influence of water currents passing through the pay sands, and involving the displacement of 15 liters of water from each tank during a time period of 30 minutes, both bodies of oil were moved in the direction of flow. The least viscous oil, in tank 1, underwent the most extensive movement and the most complete rearrangement. The water advanced most readily ahead of the more viscous oil in tank 2. Under practically the same conditions of experimentation, oil 3 was not moved by the hydraulic currents. It remained practically stationary while the water advanced ahead of it.

The experiment indicates that the influence of natural or induced water currents upon the migration, accumulation, and recovery of oil depends primarily upon the physical properties of the oil, more especially its viscosity, together with the numerous other subsurface conditions and relationships. Other conditions being equal, the differential movements between relatively viscous oils and water are more pronounced and under certain conditions, are more detrimental to the recovery of the oil than are such movements and rearrangements between non-viscous oils and water.

Experiment 6 (Plate XIV., *a*) illustrates the formation of water cones through the differential movements of oil and water to wells. Oils 1 and 2 were used in pay sands of corresponding textures (*f*, Table II.) in tanks 1 and 2 respectively. The cap sand *c* was a fine water-saturated material described in Table II. At the beginning of the experiment, the accumulated bodies of oil lay horizontally above the water. The propulsive force was exerted by the pressure of the advancing water. The rates of extraction from wells 2 and 4 were more rapid than from wells 1 and 3. In both tanks, water advanced to the wells ahead of the oil, thus forming the so-called water-cones. This was most pro-

nounced with the relatively viscous oil in Tank 2. Again, in both tanks, the advance of water ahead of the oil was most pronounced where the rates of extraction through wells were most rapid. Also the light non-viscous oil in Tank 1 moved most readily to the wells thus giving rise to greater interference between wells in tank 1 than in tank 2. The loss of the relatively viscous oil in tank 2 by retention in the pay sand was greater than with the non-viscous oil in tank 1. These relationships are illustrated by Plate XIV., *a*, the photograph having been made 30 minutes after continuous extraction through the wells commenced. As production from the wells continued, the proportions of water recovered with the oil increased. This was especially noticeable with the more viscous oil in tank 2. Under the conditions of experimentation there appeared to be direct relationship between the oil-water ratios and the rearrangements of the fluids in the sands.

This experiment, together with many others of the same type, upon water-cone phenomena, indicate that the formation and effects of water cones depend primarily upon the qualities as well as upon the modes and proportions of occurrence of the fluids; the qualities of the reservoir rocks, more especially the bedding, thickness, and sizes of pores; and upon the practice of drilling and operating wells, more particularly upon the manner and rates of extraction. Rapid and continued extraction tends to accentuate the formation of water cones.

Experiment 7 (Plate XIV., *b* and *c*) illustrates the formation of water cones through differential movements between oils and water when the propulsive force was exerted by expanding gas. Oils 1 and 2 were used in pay sands of corresponding textures (*f*, Table II.) in tanks 1 and 2 respectively. The cap sand *c* was a fine water-saturated material described in Table II. At the beginning of the experiment, the accumulated bodies of oil with small proportions of absorbed gas (air) lay horizontally above the water. In the recovery of oil, gas, and water through the wells, the propulsive force was exerted by compressed air admitted at the bottoms of the tanks. The extraction was more

rapid through wells 2 and 4 than through wells 1 and 3. During periods of 30 minutes, 25 cubic feet of air under pressure of one pound per square inch were admitted into each tank; the oils and water thereby displaced being recovered from the wells as foams of oil and water with air.

Attention is called to the ebullition of gas (compressed air) through the oils, and to the greater tendency of the gas to cut across the top and ahead of the less viscous oil in tank 1. The propulsive work of the expanding gas upon the relatively viscous oil in tank 2 was the more efficient because the viscous oil became more readily entangled with the gas thus preventing its free passage and escape to the wells. This advantage of the viscous oil was offset by the greater force required to propel it through the sand.

This experiment, together with a series of experiments of the same type, emphasizes the need for underground conservation of the compressed gases accompanying oils, especially viscous oils, in their "pays." The experiments also indicate that to obtain the maximum increase in the recovery of viscous oils by the Smith-Dunn compressed air process,⁹ comparatively high air pressures should be used to overcome the greater resistance to the movements of these oils. By maintaining high pressures, either natural or artificial, and by letting the wells flow intermittently, advantage may also be had from the oil coning and skimming phenomena illustrated by the next experiment (see Plate XV., *a*).

Experiment 8 (Plate XV., *a*) illustrates the formation of an oil cone through the differential movements of oil, gas, and water when the propulsive force was exerted by expanding gas. In this experiment there was a greater proportion of gas to oil and a smaller proportion of water to oil than in the preceding experiment (see Plate XIV., *b* and *c*). At the beginning of the experiment the accumulated body of oil (1, Table I.) lay horizontally above the water and below an accumulated body of gas. The compressed gas that exerted the propulsive force, and which

⁹ See Lewis, J. O., "Methods for Increasing the Recovery from Oil Sands," U. S. Bureau of Mines Bull. 148, 1917.

was admitted at the ends rather than at the bottom of the apparatus, became absorbed and entangled with the oil which was propelled toward well No. 2 ahead of the water. In this experiment the oil was literally skimmed from above the water, the ratio of oil to water recovered being better than in any of the preceding experiments. During a period of 20 minutes, at the end of which the photograph (Plate XV., *a*) was taken, 122 cubic feet of compressed air under a pressure of one pound per square inch were admitted into the apparatus.

This and many other experiments of the same type indicate that under favorable conditions, oil under the propulsive force of expanding gas, advances to wells ahead of the associated water. As the gas is exhausted, these advantageous relationships change, and water may advance ahead of the oil. The mode of occurrence of the fluids, the proportions in which they occur, and the movements and rearrangements that they undergo incident to the drilling and operation of wells are of primary importance in recovery problems.

Experiment 9 (Plate XIV., *d*) illustrates the entrapment of oil and gas in irregularities at the top of a water-bearing or flooded pay sand (*b*, Table II.). At the beginning of the experiment the gravel at the base of the apparatus was saturated with water (chloride brine, sp. gr. 1.100) which was overlain by a horizontal body of oil (1, Table I.) in the coarse sand *a*. The sands overlying the gravel were moistened with water when they were packed into place. These sands were slowly flooded by admitting water through the openings at the bottom of the tank. A large part of the air displaced during this procedure was allowed to escape through the center opening in the cover plate. As the water-level rose, a part of the oil was floated upward, while a large proportion was also retained throughout the pay sand, the water advancing ahead of it. Part of this retarded oil continued to migrate upward, as in the other experiments. Upon reaching the water-wet cap sand *e*, the oil assumed an inclined position against that barrier. The further upward migration of the oil with its included air was diagonal rather than vertical. The

a.

b.

c.

d.

a. Water cones formed through the differential movements of oil and water to wells, when the propulsive force was exerted by advancing water. Tank 1 contained a relatively non-viscous Appalachian oil (1); tank 2 more viscous Mid-Continent oil (2).

b and c. Water cones formed through differential movements of oil and water to wells when the propulsive force was exerted by expanding gas. Tank 1 contained a relatively non-viscous Appalachian oil (1, table 1). Tank 2 contained a more viscous Mid-Continent oil (2, table 1).

d. Entrapment of oil and gas in irregularities at top of water-bearing pay sand.

a.

b.

c.

a. Oil cone formed during recovery of oil and gas under propulsive force of the expanding gas.

b and c. Injury to an oil and gas well by infiltrating water; b, water leaking into pay sand through well No. 1; c, water being recovered through well No. 1 and oil through well No. 2.

photograph (Plate XIV., *d*) shows the oil and air migrating upward and accumulating in the entrapments above the water at the end of the 30 minute period of flooding.

The experiment was repeated by first saturating the sands with water and then introducing air and oil through the openings at the base of the apparatus. The water displaced during this procedure was allowed to escape through the center opening in the cover plate. Under the propulsive force of their buoyancy in the water, the gas and oil migrated upward into the entrapments, the movements being slower but of the same order as those just described. In both parts of the experiment the accumulating bodies of oil flattened out until they assumed angles of repose with the water. The oil in the uppermost entrapment was not displaced by hydraulic currents through the underlying sands but was readily displaced by air segregating and accumulating in the top of the entrapment.

This experiment indicates that the entrapment and retention of oil and gas along the irregular tops of water-bearing or flooded pay sands may be a common cause of underground loss of oil and gas. Much of the oil so entrapped should be recoverable by the Smith-Dunn compressed air process.¹⁰ Numerous experiments of this type indicate that air segregating above the oil liberates the oil from such entrapments. The experiment also indicates that under favorable conditions the wells tapping such irregularities at the tops of water-bearing pay sands may be benefited by induced migration, segregation, and accumulation.

Experiment 10 (Plate XV., *b* and *c*) illustrates the injury to an oil and gas well by infiltrating water. Water-bearing cap sand *c* and pay sand *f* were used. Plate XV., *b*, shows water leaking in through well No. 1 and flooding the pay sand *f*. Part of the water thus leaking into the pay sand was retained, by capillarity, in the pores of the sand around the well. Plate XV., *c*, illustrates an advanced stage in the recovery of oil from the flooded pay sand, the leak through well No. 1 having been stopped before production was commenced. Water with only a trace of

¹⁰ Described by J. O. Lewis in U. S. Bur. of Mines Bull. 148.

oil (2) was recovered from well No. 1, whereas oil with very little water was recovered from well No. 2. Practically all of the oil recovered came from well No. 2 because the sand around well No. 1, while permeable to water, was relatively impermeable to oil. The propulsive force was exerted by the pressure (3 foot head) of water admitted through the bottom of the apparatus. A large proportion of the oil, originally present, was lost by retention in the pay sand as is shown in the photograph (Plate XV., c) by the black patches of oil throughout the otherwise white pay sand. The injury to well No. 1 was remedied in the laboratory by introducing enough of oils 1 or 2, and under sufficient pressure, to displace the water from the pay sand around the well; and then, by operating the well very slowly with long periods of rest to prevent water coning.

This experiment indicates that the selective or differential permeability of sands to water or oil is an important factor in the recovery of oil from sands. The selective or differential permeability of a sand to oil or water depends very largely upon the order and degree with which the sand has been wet or saturated with one fluid or the other. The infiltration of water into a pay sand may render the sand selectively permeable to water and relatively impermeable to oil at that place. This appears to be one of the primary causes of injury to oil wells and to productive sands by infiltrating waters. Other causes of injury to wells and to productive sands, such as the salting up of wells, the corrosion of casing, and the plugging of the pores of productive sands by organic and inorganic matter, through the agencies of water, together with modes of preventing and remedying these injuries, have been studied through other experiments that will be presented in later papers.

Methods and Technique.—The results of such experiments depend largely upon the methods employed, but to fully describe the methods and technique that have been developed by the Bureau of Mines would require more space than is here available. Only a few points upon methods and technique demand brief consideration at this time.

In attacking obscure subsurface problems, especially those of oil and gas migration, accumulation, and recovery, the investigator should proceed with an open mind without being unduly influenced by preconceived ideas which may hold true in one locality but not in another. Efforts to prove ideas before submitting them to adequate and unprejudiced field and laboratory study have too frequently led to conclusions that are worse than wrong because they are misleading.

The fact is emphasized that laboratory experiments on the movements of oil, gas, and water, through sands must be performed upon a scale sufficiently large to avoid the misinterpretation of capillary phenomena. The effects of capillary forces must be compared with the effects of other forces, but for this kind of work, the conditions of experimentation, more especially the size scale of the experiments, must be adequate. To restrict the work to the conditions and dimensions of movements by capillarity may lead to serious errors. In meeting these requirements, the writer works with saturated¹¹ as well as unsaturated sands in the two sizes of tanks that have been described.

Experimentation should be conducted systematically, directed toward elucidating first principles, and then working in accordance with them. In all of the Bureau of Mines experiments in the laboratory, the first step is to study the physical and chemical properties of the materials to be used, and to plan, approximately at least, the physical conditions of experimentation that are to be maintained. Unless the qualities of the various materials used in the experiments are studied, there can be no adequate basis for comparing different experiments or for drawing conclusions from single experiments. It is not sufficient to regard pay sands merely as sand, or to regard oils, gases, and waters merely as oil, gas, and water. The chemical and physical qualities of the reservoir rocks and fluids they contain have a wide range of variation; consequently their subsurface relationships are rarely, if ever, alike in different localities or at different

¹¹ These terms are used in a relative rather than an absolute sense, to indicate the degree with which the pores are filled with oil and water.

depths in the same locality. Experimentation must be conducted in the light of these facts.

In order to restrict the number of variables in the laboratory experiments, certain known conditions in the parts of experiments that are under comparison are maintained as nearly identical as possible. To satisfy this requirement, uniform methods of preparing, loading, and tamping sands and clays into the tanks and of introducing oils, gases, and aqueous solutions into these sands and clays, were devised and followed for each comparison. For the experiments illustrated in this paper, the sands were introduced in thin layers through the open tops of the tanks, and uniformly tamped as they were being loaded. Tamping must be done very carefully, as otherwise there may be a subsidence of the sand or clay during the experiment, which may give entirely misleading results. The use of compressable rubber gaskets under the cover plates is advantageous to take care of slight subsidences that may occur. The fluids are loaded together with the sands or are introduced through openings in the tanks after the sands and clays are in place. In some of the experiments, not here illustrated, perforated pipes extending through the sands are used to introduce the fluids. Fresh, clean sands are used in each experiment and strict cleanliness is observed. These sands are screened and washed alike and practically all extraneous material is removed to prevent the deposition of silt in the pores. These and the other precautions that have been outlined are necessary for making accurate comparisons.

Photographic records of the experiments furnish convincing evidence to accompany the notes and facilitate detailed studies and comparisons subsequent to experimentation. Phenomena that escape observation during the experiments are made apparent and can be studied through these records. Certain precautions are, however, necessary to make clear photographs. Smudges of oil, and finger marks upon the glass fronts of the tanks must be avoided or removed, and high-lights together with other reflections seen from the camera must be eliminated. It must be emphasized that careful, painstaking work, close ob-

servation, and adequate, systematic notes, in the laboratory as well as in the field, are imperative.

APPLICATION OF EXPERIMENTS.

Through the methods that have been outlined, the Bureau of Mines is now studying the induced effects¹² in oil and gas fields, or in other words, the deep-seated effects that are induced by man's activities. It has long been recognized that physical and chemical equilibrium in the reservoir rocks are disturbed by the drilling and operation of wells, but the importance of studying these effects to establish primary causes for underground losses of oil and gas is only beginning to be recognized. Such studies of causes and effects throw important light upon underground problems, and facilitate the development of better methods of recovery. The primary causes of injury to wells and to the productive sands themselves through the agency of water are being established and methods of preventing and remedying these injuries are being developed. The modes of occurrence of oils, gases, and waters in their reservoir rocks and the factors governing these modes of occurrence are being studied. Special attention is being given to the study of deep-seated movements and rearrangements that the fluids undergo incident to the drilling and operation of wells and to the factors and relationships governing these movements and rearrangements. This work is important because the recovery of oil and gas depends directly upon the movements of the fluids to the wells. The relative efficiencies of various methods of recovery under different sets of conditions and means of improving these methods are also being studied. The scope of this work is broad but it lies mainly within the provinces of geophysics and geochemistry together with their applications. These lines of field and laboratory investigation are so interrelated that sharp divisions between them are impossible. In the efforts that the Bureau of Mines is mak-

¹² Mills, R. V. A., Discussion of paper by R. O. Neal, "Petroleum Hydrology Applied to the Mid-Continent Field," *Transactions of American Institute of Mining and Metallurgical Engineers*, vol. 61, 1919.

ing to diminish underground losses and to develop more efficient methods of recovery, all three lines of investigation are necessary because very little progress has been previously made in the study of fundamental subsurface relationships.

SUMMARY.

To enumerate the various relationships indicated by the investigations herein described would require a longer paper than is appropriate at this time. Consequently in addition to the conclusions from the experiments the present contribution is summarized by a statement of a few of the broad facts and relationships that have been established.

One of the most important things to be realized is that all of the phenomena observed in the laboratory, as well as in the field, are brought about through the influence of various factors with differing effects. In other words, we are obliged to deal with the summations of the effects of many factors; not with the effect of any single factor. The values of the different factors that influence the migration, accumulation, mode of occurrence, and the recovery of oil and gas are extremely variable and are relative one to another. Different factors have predominating influences according to the different sets of limiting conditions into which enter, collectively, the porosities, fineness of pores, textural variations, and degrees of dip of the sands, the qualities of the fluids, more especially the viscosities of the oils, the degrees of saturation of the strata by water and oil, the temperatures, pressures, and many other conditions. Thus, it is recognized that there is a wide range of variation in the nature and extent of induced movements, especially the differential movements of gases, oils, and waters upon which recovery together with the effects of water upon recovery very largely depend. It is further recognized that gas mixed with oil facilitates lateral as well as vertical migrations of oil in water-bearing strata. Again, it is recognized that there may be a limit to the fineness of water-filled interstices beyond which viscous oils do not appear to migrate "gravitationally" under ordinary conditions.

It is further recognized that in a medium grained water-saturated sand (such as *b*, Table II.) a single globule of oil (such as 1, Table I.) fails to migrate "gravitationally" but as more globules of oil are added to it, there is formed an aggregation of globules whose *cumulative buoyancy* is sufficient to overcome the resistance to upward migration. Such relationships are important in the consideration of up-dip migrations. We must keep constantly in mind the critical conditions up to which certain phenomena hold true but beyond which there are absolutely different phenomena.

The field and laboratory investigations that the writer has so far made, indicate that under ordinary field conditions the up-dip migration of oil and gas under the propulsive force of their buoyancy in water, as well as the migration of oil, either up or down dip, caused by hydraulic currents, are among the primary factors influencing both the accumulation and the recovery of oil and gas.

The terms, "up-dip migration" and "down-dip migration," as used in this paper, apply to migrations that are in accordance with the configuration of the tops of the sands, regardless of actual structures. It must be remembered that there are many subsurface conditions such as the dome-like tops of lenses, irregularities in the tops of sands, and irregular textural barriers, which bear no consistent relations to structure, but whose influence upon oil and gas accumulation are analogous to those of true anticlines and domes. The writer's remarks apply to these conditions which he terms *structural analogies*.

In concluding this paper, the writer calls attention to the views recently set forth in the literature¹³ that the migration and accumulation of oil in water-saturated strata are caused mainly by capillary forces; that oil does not migrate up the dip, due to the differences in specific gravity between oil and water; and that oil is not propelled through sands by hydraulic currents. It

¹³ McCoy, A. W., "Notes on Principles of Oil Accumulations," *Jour. of Geology*, vol. 27, 1919, pp. 252-262.

Jones W. F., "The Relation of Oil Pools to Ancient Shore Lines," *ECONOMIC GEOLOGY*, vol. 15, 1920, pp. 81-87.

is further maintained that oil has been forced out of the fine bituminous shales adjacent to the reservoir rocks, by the capillary action of water and that no wide lateral movements of oil have subsequently taken place.

The writer can not accept these views as generalizations. They may appear to hold true under exceptional conditions, as in small scale laboratory experiments where the conditions of experimentation are especially favorable to the hypotheses, but they do not generally hold true, either in the laboratory or in the field. Capillary adjustments between oil and water in saturated strata are restricted within short lateral ranges, amounting to only a few centimeters in the writer's experiments. The principal rôle of capillarity, in saturated strata, is to retard rather than to promote fluid movements.

NEED FOR FURTHER EXPERIMENTATION.

Systematic and scientific experimentation upon subsurface problems in oil and gas fields, in conjunction with intensive field work, is imperative. It throws invaluable light upon the fundamental principles and relationships governing the occurrence, accumulation, and recovery of oil and gas, and opens the way for more intelligent and efficient subsurface conservation and recovery.

The necessity for this work is emphasized by the progressive depletion of our deposits of petroleum and natural gas under an ever increasing demand for these hydrocarbons. Hasty and wasteful field methods accelerate this depletion through enormous underground losses.

The utmost effort must be made to eliminate these losses. Producing fields must be conserved against premature abandonment. Development must be intelligently extended. Maximum ultimate yields, with profit, must be obtained, and oil left underground by wasteful methods in old and abandoned fields must be recovered. Under the stimulus of the rising prices of oil, these things can be done profitably through scientific methods of work in which petroleum experimentation must play an important part. If they

are not done the consequence will be a disastrous waste of invaluable resources.

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