Montana Law Review

Volume 17
Issue 1 *Fall 1955*

Article 1

July 1955

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Recommended Citation
Jack Tarner, *Reservoir Mechanics,* 17 Mont. L. Rev. (1955).
Available at: https://scholarworks.umt.edu/mlr/vol17/iss1/1

MONTANA LAW REVIEW

VOLUME SEVENTEEN FALL, 1955 NUMBER ONE

Reservoir Mechanics

By JACK TARNER*

An understanding of the nature of oil and gas, their occurrence in the earth, and the mechanics by which they are produced from the sub-surface reservoir is materially helpful and even essential to those who are associated with the business of producing oil. The association may be one of acquiring land, drilling wells, operating producing wells, participating in hearings before regulatory bodies or with the various legal entanglements which occasionally grow out of the many operations connected with the business of producing oil. It is possible to measure or accurately define a surface property involved in a dispute. Property owned in the subsurface oil reservoir, by the various individuals having surface ownership, cannot be marked or delineated in a like manner because there is no access to the underground property except through indirect measurements. This is the principal cause for many of the disputes in the industry.

Considerable progress has been made in development of engineering methods and instruments for measuring reservoir rock characteristics and the nature of the oil and gas contained in the subsurface reservoir. From these it is possible to make reasonable deductions concerning the amount of oil, gas and water underlying the several surface properties in oil and gas pools and to predict what will take place when wells are drilled on those properties and allowed to produce. The amount of oil and gas that can ultimately be reduced to possession by each surface owner is dependent not only upon the position in the reservoir that is encountered by the well drilled upon his surface land, but also to a considerable extent on the manner and method employed in producing each well that has penetrated the same subsurface reservoir. It is possible to influence the production from one property by regulating producing conditions on an adjoining property. The surface properties may be separated; the subsurface property cannot be segregated or separated.

Oil and Natural Gas Are Volatile Hydrocarbons

In the subsurface reservoir, oil and gas are associated together and with water. When natural gas is brought into association with oil and the resulting mixture placed under pressure, gas goes into solution in the oil and becomes a part of the liquid reservoir crude oil. The amount in solution varies with pressure.

Pressure naturally occurs in most all subsurface reservoirs. Those found at shallow depths of 500 to 1,000 feet have initial pressures in the order of 200 to 500 pounds per square inch. The deep reservoirs occurring at depths of 10,000 to 15,000 feet have pressures which vary from 4,000 to 8,000 pounds per square inch. Because of these pressures, reservoir crude

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oil normally has natural gas as a liquid part of its volume. If there is more gas in the reservoir than can go into solution in the oil at the naturally occurring reservoir pressure, it will exist as free gas.

Oil and Natural Gas Are Found in Porous and Permeable Rocks

Most reservoir rocks are either sandstones or porous limestones. Oil and gas are contained in the void spaces that exist between sand grains or in the fractures and water-worked channels in limestones. Oil is not contained in underground lakes or rivers but is tightly held in the small, minute openings in the porous rocks.

Porosity is the term used to denote the amount of pore space available in a rock to hold fluids. A porosity of 25 per cent means that ¼ of the total rock volume is pore space and is available to oil, gas and water. About ⅓ of a barrel of water can be poured into a barrel of potatoes before water will overflow the barrel. A barrel of potatoes, therefore, has about 33 per cent porosity.

Permeability is the term which denotes the ability of a porous rock to conduct or transmit fluids. It is similar to using inches to denote the carrying capacity of pipe lines. A given fluid volume will flow more readily through a single 10″ pipe than it will through a bundle of 2″ pipes having the same total volume as the single 10″ pipe. This is because the single 10″ pipe has less frictional area than the bundle of 2″ pipes. The single 10″ pipe has greater permeability than the bundle of 2″ pipes. Permeability is expressed in millidarcies. A rock having permeability as low a 5 millidarcies is considered very tight and unless there is a thick section of such rock, commercial oil production from it will be very difficult. Permeabilities in the order of 1,000 millidarcies, even in porous rock sections of only a few feet, will permit completion of high productivity wells.

It is important to remember that porosity and not permeability is an indicator of the ultimate oil volume that will be produced from a reservoir. Permeability is an indication of the rate of production possible. The "gusher" well that will produce initially at a high rate from only a few feet of formation may deplete its reserves in a short time; the low productivity well that can be completed in a formation having low permeability but considerable thickness will never produce at a flashy rate but will be a steady producer over many years and can produce considerable oil and gas reserves.

Distribution of Oil, Gas and Water in the Reservoir

Oil in the reservoir rock is generally associated with gas and water. In the undisturbed state prior to discovery, those three fluids are more or less segregated in the reservoir in relation to their respective densities. Water, if present in sufficient quantities, occurs beneath the oil and gas. If there is gas in excess of that volume which will go into solution in the oil at the pressure prevailing in the reservoir, it will exist as free gas above the oil. These zones are referred to as the gas-cap, the oil zone, and the water zone; and the demarcations between the respective zones are referred to as the gas-oil contact and the water-oil contact.

Pore space in a reservoir rock is capillary in size and this fact prevents a definite or straight line demarcation between zones. The transition zone between the 100 per cent oil-productive and the 100 per cent water-productive zones may occur vertically over a few feet or over as much as 50 feet, depending on the rock characteristics. The water-oil transition zone is productive of both oil and water. The gas-oil transition zone between the gas cap and the oil zone is much thinner and generally occurs over only a few feet. The capillary size of the pore openings results in water being distributed throughout the entire thickness of the reservoir rock and many oil rerservoirs which produce all oil and no water may contain as much as 40 per cent of their pore space filled with water. The water generally clings to the rock surfaces and to the small spaces between grains and is not removed by ordinary production methods.

Energy to Produce Oil Comes From Compressed Gas and Water

Oil purchased in a gasoline station or found in the stock tanks on any oil lease contains no inherent energy by which it can expell itself from a reservoir rock. Removing the cap from a bottle of crude oil will not cause oil to gush from the bottle. However, had natural gas been associated with the oil and the mixture held under a pressure, the oil and gas would gush forth upon removing the cap in exactly the same manner as a carbonated beverage gushes from a warm pop bottle when the cap is removed. Energy of gas expansion brought about by releasing pressure causes oil to be produced from most reservoirs. Some reservoirs are connected to large volumes of water, and oil is expelled by releasing the energy contained in the body of water under pressure. The important consideration is that commercial production of oil requires energy brought about through release of pressure on fluids associated with the oil.

Behavior of Oil, Gas and Water in a Porous Sandstone Rock

The accompanying six figures portray the pore space in a sandstone, the initial distribution of fluids within a small section, and the distribution that occurs as natural pressures are depleted.

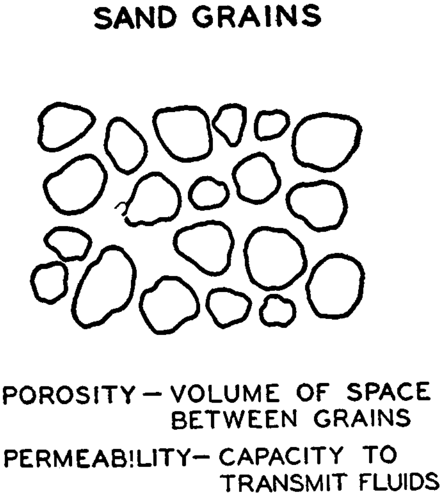

Fig. 1

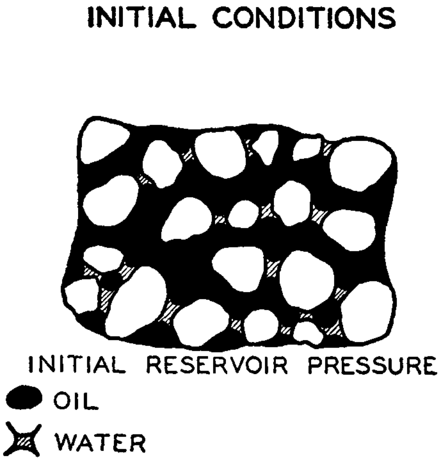

Fig. 2

Figure 1 shows the sand grains of varying sizes and the openings between those grains. This is necessarily a two-dimensional portrayal and it should be remembered that random sorting and packing of sand grains by nature results in the path of fluid flow between the grains being even more tortuous than that portrayed.

Figure 2 shows these same sand grains with the pore spaces filled with gas-saturated reservoir crude oil and its associated water. Water occurs as a film around each grain and as a small pendant or ring of water at the intersection between grains. The oil is more in the open channels between the grains. No gas is shown because this portrayal assumes that all the gas is in solution in the oil and becomes a part of the liquid volume at the prevailing natural pressure.

It has been assumed in Figure 3 that a well has been drilled to the right of the section of sandstone and the pressure lowered in the well bore. This creates a pressure drop with resultant fluid flow. Gas begins to break out of solution from the oil and form as little bubbles between the grains, forcing oil to the low pressure well bore.

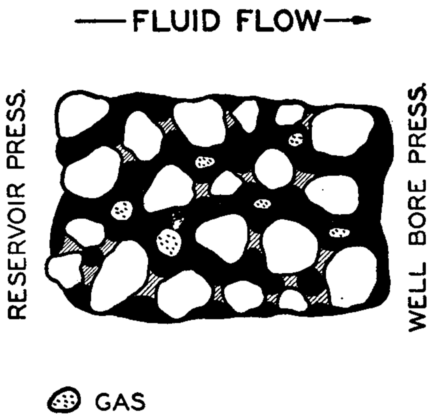

Fig. 3

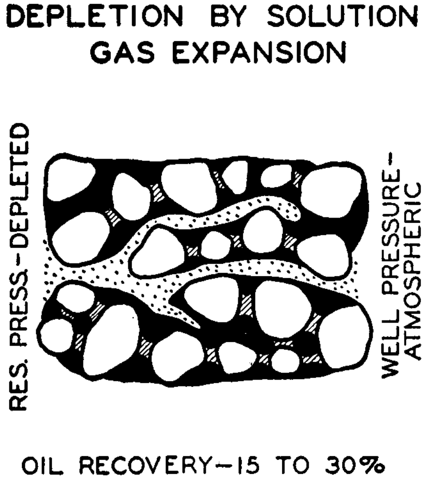

Fig. 4

The pressure release and driving of oil to the well bore by expanding gases is continued in Figure 4. In this figure reservoir pressure has depleted to the point where commercial production is no longer possible and the pressure in the well bore is approximately equal to atmospheric pressure. When reservoir pressure is exhausted, production must necessarily cease. This is a portrayal of the reservoir conditions at time of abandonment.

This type of oil recovery process is generally referred to as solution-gas expansion and it enables recovering from 15 to 30 per cent of the initial oil-in-place. The remaining 75 to 85 per cent will remain in the reservoir unless steps are taken to furnish additional energy to the reservoir by injecting either gas or water under pressure.

Figure 5 shows what can take place if additional energy in the form of injected gas is supplied to the reservoir. The injected gas will follow the old paths or gas channels created by the natural gas originally associated with the reservoir oil. If enough additional gas is injected it is possible to enlarge those channels and even to enter channels containing oil that was bypassed by the original solution gas. Furnishing additional gas energy can increase the ultimate oil recovery to 25 to 40 per cent of the initial content.

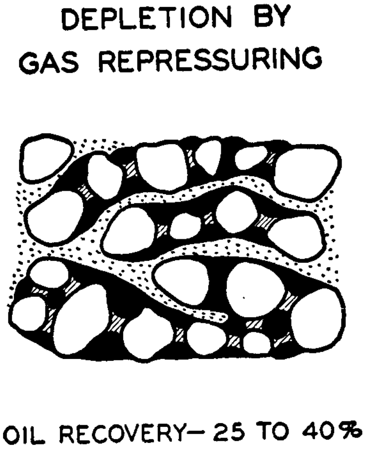

Fig. 5

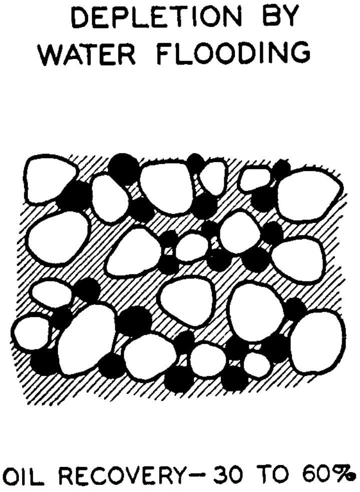

Fig. 6

In reservoirs of extremely high permeability and great structural relief it is possible to inject gas into the top of the reservoir and drive oil down structure. This type of gas-cap expansion drive takes advantage of gravitational forces working on the oil and is generally more efficient that a horizontal gas drive. Injecting gas into a gas-cap, lowering the gas-oil contact, and forcing oil into the down-structure wells, makes it possible to ultimately recover 35 to 50 per cent of the initial oil content.

The most effective means known today to commercially and economically recover additional oil from a subsurface reservoir is by the flushing action of water entering the porous rock. Most reservoirs initially contain water, identified as connate water. Figure 2 shows the usual manner in which connate water is held by a porous rock—as a film around each grain and at grain contacts. When additional water enters the rock it tends to coalesce with the water already present and effect a thorough removal of the oil. Figure 6 shows a portrayal of sandstone after it has been completely flushed with water. This process can recover from 30 to 60 per cent of the initial oil.

Some oil reservoirs, referred to as active water-drive reservoirs, initially are associated with sufficiently large volumes of water or aquifers to naturally flood the entire oil reservoir with release of pressure. Many other reservoirs, and those that are in the majority, do not have fully active natural water-drives and must be furnished water energy for producing oil by either drilling or converting a well for the purpose of injecting water into the reservoir.

By way of review, oil recovered by solution-gas drive forces amounts to 15 to 30 per cent; by gas repressuring, 25 to 40 per cent; by gas-cap injection and gravity drainage, 35 to 50 per cent; and by waterflooding, 30 to 60 per cent of the initial oil-in-place volume. These are average recovery ranges; fields are known that will produce as little as 5 per cent and as much as 80 per cent of their initial oil content.

Comparison of Oil Recoveries in Field Operations

The knowledge of the behavior of reservoir oil when subjected to the various energy forces brought about through pressure release or through injecting extraneous fluids into the reservoir must be used to advantage in actual operations if the most oil is to be recovered. This can be illustrated by considering the next series of three figures.

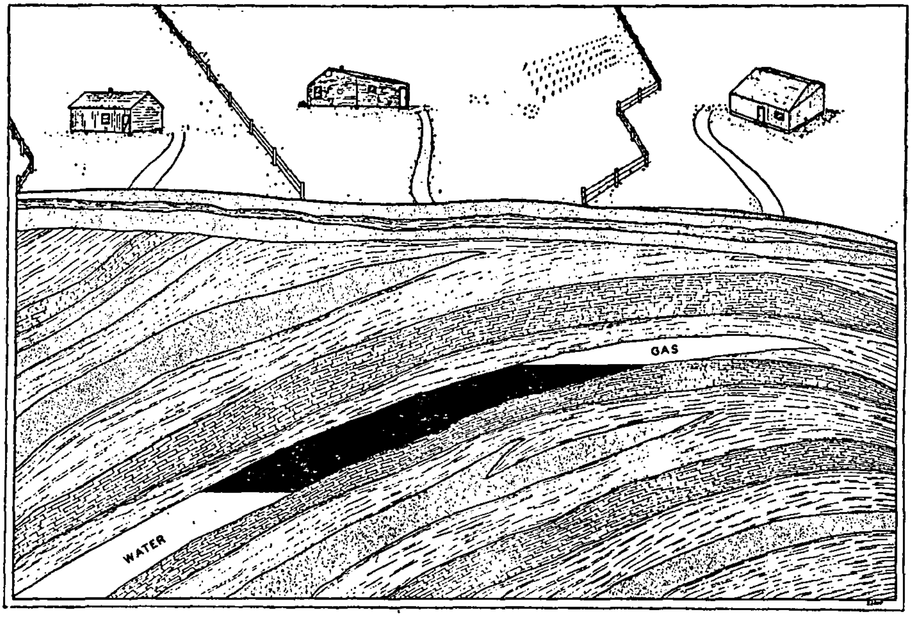

Fig. 7

Figure 7 shows the surface of an oil and gas field and a cut-away view of the subsurface reservoir. It is a steeply dipping structure with the high, or up-structure portion on the right and the low, or down-structure portion on the left. The attitude or structure of the subsurface reservoir bears no relationship to the contours of the surface. A water-oil contact is shown on the left and a gas-oil contact on the right.

On the surface are three separate farms. The owners of these farms have about the same amount of natural energy and consequently have about the same status in life and social position within the community. Their houses and farms are about the same and there is no question about ownership because their presently known worldly goods can be separated by fences and by possession. There is no possible means of separating the property owned in the subsurface reservoir by the individual owners because it is all contained in a single vessel, the reservoir, common to each owner. The owner on the left has his farm mainly underlaid by water. He does, however, have some oil saturation within his property boundary. The farmer in the middle has his entire farm richly underlaid with oil. The farmer on the right owns mostly gas but some oil also occurs within his property line.

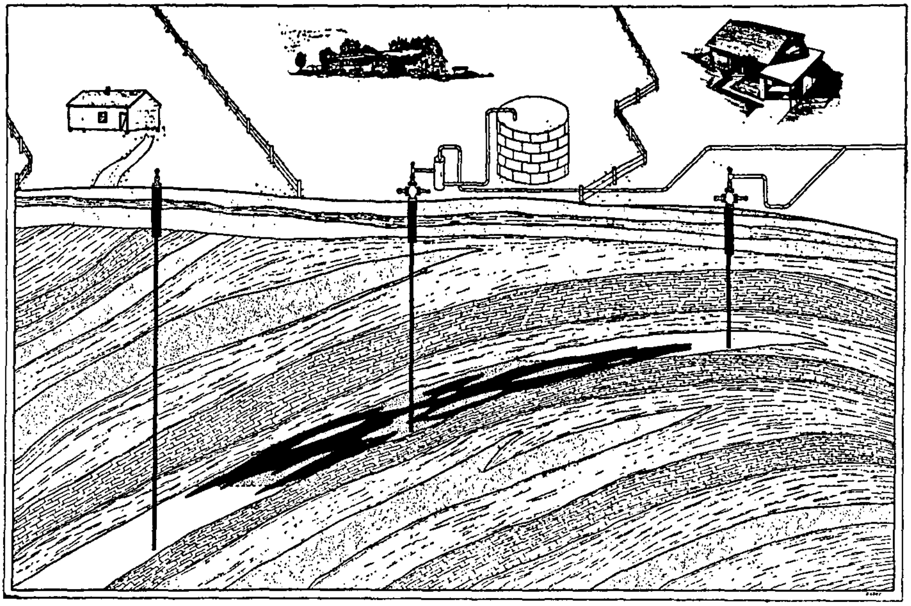

Fig. 8

Figure 8 shows what can happen to these three farms when individual oil leases are taken and wells drilled. A well drilled on the property to the left encounters 100 per cent salt water. This is referred to in the industry as a "dry hole." However, it is far from dry as it would be a prolific producer of salt water if there was an economic use for salt water. This owner will not benefit from oil productions or in any other way as a result of an oil well having been discovered in the vicinity of his farm. The property owner in the middle cannot miss. A well drilled anywhere on his land will encounter rich oil saturation and become a prolific producer. This owner can produce through the well on his land a considerable volume of the initial oil content in the reservoir. The property owner on the right did not drill a well that penetrated the oil zone but did encounter gas. Gas is commercially valuable and he too was able to improve his position but not to the extent of the man in the center. The pool, as shown by the development in Figure 8, will produce all its oil to the interests of the lessor and lessee of the center property.

Oil wells could have been completed on the edge farms by drilling very close to the property lines, in which event the owners on each side would have produced some oil contained originally under the property owner in the center unless the producing rates of those wells had been regulated to a rate commensurate with the relative volumes of oil in the reservoir beneath the respective properties.

Drilling of oil wells at unregulated distances from property lines to gain a part of the common oil supply for each owner has proved to be a very unprofitable and disastrous practice except when an authority has been created to carefully regulate the practice and the number of such wells allowed in each pool. It has in the past led to the doctrine of equi-distant offset wells to protect against drainage and it can create an indiscriminate race to determine which owner can drill the greatest number of wells and thus gain the most oil from the common supply. The number of wells determines only who will get the most oil, not the ultimate volume to be recovered, and if too many wells are drilled it may be impossible to recover enough oil to pay all the costs of development. Drilling more wells than is necessary to recover the oil in a reasonable period of time leads to both economic and physical waste.

Reservoir crude oil was gas-in-solution moves freely in the direction of the lowest pressure. Figure 8 shows that production from the gas well was able to lower the pressure and draw oil into the gas-cap. This oil will enter the small pore spaces in the dry gas-cap rock and be retained. It is oil that could have been recovered by proper producing practices. It has been possible in the past for some operators to produce a gas well at such a high rate that gas-cap pressures will be lowered to the point where oil will eventually migrate into the gas well and be produced. This was known as "blowing a well into oil." It enabled the owner of the gas well to become richer because of oil production, but it decreased the ultimate oil recovery from the entire common source of supply because it required oil to wet a tremendous expanse of dry gas-cap rock before it could reach the gas well and be produced.

Figure 8 is a portrayal of the reservoir after its depletion by primary pressure depletion methods. Each owner produced the well on his land to his sole advantage and with but a minimum regard for the effect that his operations might influence the well being of his neighbors. About two-thirds of the initial oil content remains in the reservoir and all the pressure has been depleted. No further recovery can be expected unless secondary recovery methods can be instituted to return additional pressure and energy to the reservoir.

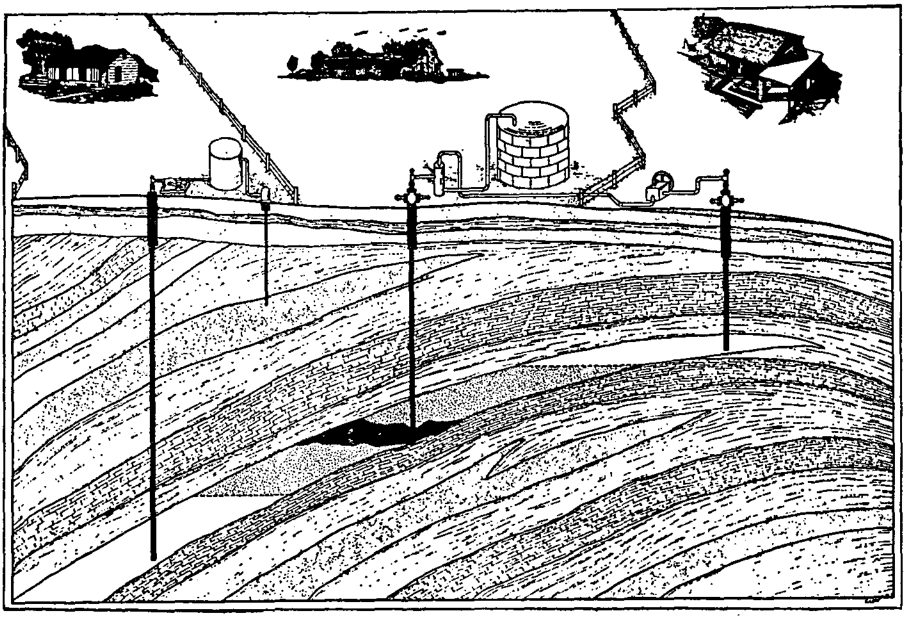

Fig. 9

The results of producing this same reservoir by employing the knowledge of the behavior of fluids under pressure and what happens when additional energy is supplied to a reservoir is illustrated in Figure 9. The gas that normally would be produced through the gas-cap well can be diverted through the oil zone where its energy can be utilized in producing additional oil. The gas itself will eventually be produced through the oil well but this time its production will occur only after expending some of its energy in a downward direction through the oil zone. An agreement between the owner of the oil well and the owner of the gas well will be necessary because the gas well must be shut in and the gas produced through the well on the oil man's property. Unless there is some agreement on a distribution of the products produced from the oil well the gas well owner will lose from the process. If they do reach agreement, however, they both can gain by sharing in the additional oil production that can be recovered by reversing the direction of the gas flow.

The dry hole drilled in the down-structure position of the reservoir can be used as a water injection well to inject water into the reservoir and drive additional oil into the producing well. This step may not be necessary if the reservoir is one that has a naturally active water encroachment zone. A further conservation step can be achieved by collecting the gas produced with the oil, taking it through a compressor, and injecting it under pressure back into the reservoir where its additional energy can further be utilized in the production of additional oil.

The effect of using these advanced producing methods will be to squeeze the oil zone between a downward moving gas-cap and an upward moving water zone. This is probably the most effective means of recovering oil in a reservoir of this type and 60 per cent or more of the initial volume should be recovered. In addition, the reservoir remains filled with gas that is available for sale when oil production reaches abandonment rates. A reservoir with less structure and having lower permeability rock can be subjected to the same water and gas injection operations but the movement of oil will be horizontally through the reservoir and with little or no vertical movement.

Conclusion

Optimum use of reservoir energy and of gas and water injection operations requires the several owners to agree upon a division of the oil and gas reserves prior to their being produced. The oil field must be operated as a single lease—as the common source of supply nature intended it to be. Some wells must be shut in, others must be converted to injection service, and only those wells permitted to produce that can best use the energy from compressed gas or water. No owner can be expected to discontinue production from his well and forego income from sale of gas or oil unless assured income from the sale of products from those wells that do remain as producers.

Engineering methods and instruments permit a reasonably accurate determination of the proper share of the common reservoir that underlies the several surface properties in an oil field. Cooperation in any oil field can bring about increased oil recoveries that benefit royalty owners, working interest owners, the state, nation, and public as a whole. Oil reserves are a diminishing supply and it is inherent upon each person associated with the oil business to do his utmost to have those practices employed that will assure that the most oil is recovered from each newly discovered field.