UNDERGROUND WASTES IN OIL AND GAS FIELDS
AND METHODS OF PREVENTION

BY

WILLIAM F. MCUMMURRAY AND JAMES O. LEWIS
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UNDERGROUND WASTES IN OIL AND GAS FIELDS AND METHODS OF PREVENTION.

By William F. McMurray and James O. Lewis.

INTRODUCTION.

By the term "underground waste," as used in this paper, is meant the unnecessary destruction or lessening of the value of underground supplies of oil, natural gas, and potable water.

Such waste results when oil, gas, or water is allowed to flow from its original strata and to dissipate into other strata, when water is allowed to invade oil or gas sands, when oil or mineral-bearing waters are allowed to pollute potable waters, or when any method of drilling or process of recovery is employed that does not permit the maximum extraction of oil, gas, or potable water.

For practical purposes the lessening of underground waste in oil and gas fields may be separated into two phases. One is the prevention of conditions that will reduce the recovery by methods of production now in ordinary use, the other is the increase of recovery by the employment of improved processes. Only the first phase is considered in this paper. The second phase is largely contingent on the first because, if the bodies of oil, gas, or water are not protected, new processes for increasing the recovery may not be applicable. How important this feature may be is indicated by the statement that only 15 to 75 per cent of the oil in a sand is extracted by ordinary methods of production.

Waste was defined as a "lessening of the value." Obviously, the price and market conditions of oil and gas can not properly be considered as phases of underground waste, but they have, nevertheless, the greatest practical bearing on waste prevention. The more valuable the oil and the gas, the greater is the incentive to the producer to protect them, and the greater the expense that he is justified in incurring in order to prevent waste. Moreover, the amount of oil and gas that can be economically recovered when prices are high is greater than when they are low, for the wells can be profitably operated at smaller productions, and additional expense for methods of increasing the percentage of extraction employed, and hence less oil

*Testimony before Corporate Commission of Oklahoma, August, 1915.
or gas need be left underground. These considerations are self-evident to the producer, and have been established time and again in the history of the business, but the consumer is apt to overlook the fact, in his desire for cheap oil and gas, that he is indirectly inducing waste and reducing the available supply. This is particularly true of gas, and the consumer must make his choice between cheap gas for a short time or higher priced gas for a longer time. The history of cheap gas in all States has been the same; waste from the well to the consumer. The amount of gas saved and brought to market will depend on prices. In many fields the supply will not be conserved properly at current prices. The producer should get enough for his gas so that he can afford to protect smaller volumes of it, and the pipe-line companies will be able to extend their gathering systems in the fields to take low-pressure gas in small volumes.

The producer on his part should not overlook the fact that yields of oil or gas that do not warrant the expense of conserving at the prices of to-day are likely to be valuable at the prices of to-morrow. This applies to oil in particular, for during the life of a property the price will fluctuate and there will be periods of high prices of which advantage can be taken.

The maximum usefulness could be derived from a pool of oil or gas by its being controlled by one competent management, as under such conditions it could be developed with the least waste and at the smallest cost. However, rarely is a pool under one control; ordinarily a pool is divided among many owners. To get the best results the operators should act in unison for the protection of their common sources of supply and for their mutual benefit. To make cooperation among the producers in a field effective, it seems necessary for them to organize with some central authority that can furnish protection against careless, inefficient, or even deliberately negligent acts of individuals. The center of this organization should be supplied with all the data affecting the common interests, which could be kept confidential if necessary, and from this information concerning conditions in the field, general policies for development and operation could be outlined. That would work to the best interests of all concerned.

There is no business to-day in which, by its very nature, there is more need for cooperation than among the oil and gas operators, yet they have been able to do practically nothing by themselves. Nearly all attempts at cooperation among oil and gas producers have failed, primarily because there was no authority to compel the ob-

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servance of the will of the majority by individuals who did not choose to follow the policies laid down.

In this paper the writers have endeavored to establish the manner and importance of underground waste by citing a few cases and to show the means whereby it can be prevented.

ACKNOWLEDGMENTS.

The material used in preparing this report was derived from many sources, and that which was not obtained by personal observation is known to be dependable. Many cases of alleged underground waste were investigated, and those that admitted of doubt or alternative explanations were rejected. The writers are particularly indebted to A. J. Diescher, F. P. Fisher, and H. R. Davis, of the Wichita Natural Gas Co.; J. A. Pollard, late of the Bureau of Mines; Harry D. Aggers, United States oil and gas inspector; Dorsey Hager, of Tulsa, Okla.; E. E. Yingling, of the Western Oklahoma Gas & Fuel Co.; and Glen T. Braden, of the Oklahoma Natural Gas Co.

FLOODING OF OIL DEPOSITS.

An important cause of underground waste of oil and gas is the flooding of productive sands with water. There are two ways in which water may encroach on a field.

1. Water rises from the lower depths of a producing stratum to replace the oil and gas extracted from it.

2. Water from strata above or below may enter and flood the unexhausted oil-bearing stratum.

Flooding in the first way usually follows the depletion of those oil pools "backed up by water" in volume and under pressure, and could possibly be prevented. Flooding from other strata is avoidable, and is due to faulty drilling methods or other preventable causes. The following discussion applies only to the second type:

Premature flooding may result from water infiltrating from higher strata through leaky casing, from water cutting under the casing, from unsystematic casing, or from improperly plugged wells. Other ways are by drilling into water, which is often found in the same stratum below the oil or gas, or in lower strata, or by allowing unnecessary escape of the gas, which if saved would have delayed the flooding. Instances of the drowning of individual wells are so common that it is not necessary to cite them in this paper. Also, in many instances whole properties and fields have been prematurely flooded, with great resulting loss. The writers believe that the number of instances in which the drowning of wells, attributed to natural exhaustion, could have been prevented or delayed is much greater than is commonly supposed. Whenever water makes its appearance
in either an oil or gas sand it should never be assumed that the advance of the water is the natural, and possibly unpreventable, invasion that marks the depletion of the field. A careful and systematic study should be made of the field, including the geologic structure, the history of the invasion, the movements of the water, and the conditions of all the wells in the field. By these means it may be determined whether the invasion is the beginning of the natural end or whether it is a premature flooding that can be prevented.

The damage caused by flooding varies according to local conditions—that is, according to the volume and head of the water, the volume and pressure of the oil and gas, and the character of the oil and of the oil sand. Under some conditions water has been known to make the producing of oil impossible, whereas under other conditions the producers consider small amounts of water with the oil to be desirable. In fields with high-gas pressures the water may "cut the oil" and make an emulsion that is expensive to treat. It has been estimated on reliable authority that at a time when the Cushing field was producing 174,000 barrels daily, some 25,000 barrels was "cut" oil, much of which was allowed to run into the Cimarron River. Single wells in California have produced thousands of barrels of "cut" oil daily.

In some California fields the water seems to "set" the sands, and it is difficult to get them to produce, once water has ever been on them. So marked is this tendency that it has been the practice of some California operators to drill into the oil sand with oil in the hole instead of water. Usually the water can be pumped out faster than it comes in, but generally it increases the cost of production, especially in deep wells, because a greater amount of fluid must be lifted to the surface, the wells pumped for longer hours, more repairs are required, and more "B. S." (sludge) is formed.

It is usually impossible to shut down the wells when prices are low, because the water would gain such headway that the wells could not be made productive again. Consequently the producer may have to keep pumping at a loss in order to protect his property. Not only are the profits lessened by the increased cost of production but the lives of the wells are shortened, because they can not be pumped with profit at as small productions as when there is no water in them. Furthermore the water may make it impossible to take advantage of improved processes for increasing the recovery of the oil.

Figure 1 shows how oil may be trapped by an invasion of water. Figure 2 shows the effect of difference in porosity of the many layers of a sand on the extraction of gas and the invasion of water. Although this figure is used to illustrate the trapping of gas, the same principle holds true for oil. The ordinary oil or gas sand is a combination of porous and tight layers. The outcrops show this
clearly, and drillers know that most oil and gas sands are in layers, with "breaks," thin streaks of shale, etc., between, some layers being fine-textured or hard and others coarse-textured or loose. Many of these partings are so thin that they are not detected in drilling. A few feet, or even inches, in depth may make a tremendous dif-

![Diagram of oil and water layers](image)

**Figure 1.**—Effect of water encroachment.

ference in the capacity of a well, because of the drill penetrating a porous streak. These layers make it far more difficult for oil and gas to move across the bedding than along it and increase the amount of oil and gas that may be trapped by flooding.

Huntley\(^a\) discusses the flooding of oil sands and the effect on the recovery of the oil. He describes the method of flushing oil from

a sand by flooding with water, and is inclined to believe that the theory is sound but that, on account of the general conditions that prevail in most fields, flushing has not been, and in general will not be, a success. The method is based on the supposition that more of

the oil can be brought to the surface by flushing with water than by the usual methods of recovery. Water is let into certain wells, and drives the oil ahead of it through the sands to other wells, where the oil is pumped to the surface. By this means effort is made to flush out that portion of the oil retained in the sands by capillarity,
and to concentrate it so that it can be recovered. Usually the porosity of the oil sands is not uniform, so that the water advances irregularly, the more porous streaks being the first to be flooded, trapping the oil in less porous layers. In general, the operators do not consider flushing to have been a success where it has been used. The Bradford field in Pennsylvania is a conspicuous exception, and there a majority of the operators consider that the method has been successful. Bradford is an old field and has nearly reached the limit of economic pumping. The sands are claimed to be unusually uniform in texture, yet even here there is evidence of oil being trapped. Once the sand has been flooded, there is no probability of getting more production and the oil trapped is irrecoverable by any known methods. For this reason, and because there are other successful methods for economically extracting the oil retained in the sands by capillarity, involving less risk and leaving the field in a condition for the employment of other processes, it is believed that flooding should be used with extreme caution.

**FLOODING OF GAS DEPOSITS.**

Water may invade a gas sand by infiltrating from sands above or below, by the encroachment of "edge water," by the drawing in of water underlying the gas in the same sand, or from improperly plugged wells.  

Gas sands are theoretically less liable to be permanently damaged by water than oil sands, because gas separates from water more readily. If sufficient time is given, the gas in a flooded deposit will rise through the water and reaccumulate in the higher parts of the sand, as has been demonstrated in some of the older fields. But this fact should not be considered an excuse for not taking precautions, because the gas may not all reaccumulate, or at any rate, within such time or under such conditions that it can be economically recovered. Moreover, flooding will be accompanied by serious economic loss, because it will increase the expense of recovery and special treatment of the wet wells will be required, causing an additional waste of gas.  

If water is allowed to enter a well in sufficient volume, or under a large enough head, it will force the gas back into the sand and away from the hole so that no gas can be produced. Sometimes the gas can be brought back by continuously pumping the water, but often this can not be done (see p. 15). A group of wells may be ruined in this manner and the gas driven away from the property, or much gas may be left in the sand between the wells and can not be recovered without drilling new wells or waiting for it to reaccumu-

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late. An instance is reported from Montgomery County, Kans., where five wells were drilled around the edges of a 240-acre tract. Within four or five years the wells were considered exhausted and the property was abandoned. Two years later another company took up the tract, drilled several wells in the center, and obtained a good supply of gas with a rock pressure of 200 pounds.

Figure 3 illustrates how gas is driven from a hole by water. If the well contains water under pressure from whatever source, this water will keep forcing the gas away from the hole and recompressing the gas until the pressure on the gas equals that of the water and a balance is established. Where the sand is in layers separated by thin "breaks" and streaks of shale, the reaccumulation will be greatly hindered and may never take place.

The encroachment of "edge water" is unavoidable in those fields "backed up by water" in quantity and under pressure. As rapidly as the gas is extracted, water rises from the edge of the pool and fills the spaces previously occupied by gas. However, the encroachment is likely to be in such manner as to trap much gas and place it beyond economical recovery. Figures 1 and 2 show the characteristic formation of most gas sands. With the conditions shown in figure 1, gas can be trapped in the same manner as oil. With the conditions shown in figure 2, the gas will naturally flow much more rapidly from the layers of sand of open texture than from the tight layers; therefore, if the well is drawn upon too fast the pressure in the open layers will tend to decrease faster than in the harder layers, thus permitting water to invade the well through the more porous layers before the others are exhausted. The more porous layers may contain only a minor proportion of the gas. Once water enters the well through the more porous layers, it will drive the gas in the other layers back from the hole.

WASTE OF GAS BY MIGRATION AND DISSIPATION.

The manner in which gas is wasted by diffusion through other strata is explained by Pollard and Heggem, as follows:

To place a casing properly, the drill hole must be large enough to allow the couplings to slip freely down the hole. There is, therefore, the space of an inch or more between the casing and the walls of the hole. This makes a free path around the casing, which allows water, oil, or gas to pass from one formation to another. The water may drown out the oil or gas, the gas may escape into the porous strata, reducing the pressure below commercial value, and the fresh water in any formation penetrated may be spoiled by salt water.

Much of the gas enters the more permeable strata, sometimes forcing its way to great distances and is lost, so that when the well is opened at a later day the available supply of gas has decreased to such an extent that it is of practically

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no value to the owner. This subterranean movement of natural gas sometimes leads to the rejuvenation of exhausted gas sands, which has been observed in some of the older fields, and in other instances has constituted a formidable danger by establishing a "stray sand," the unexpected encountering of which at another well may result in a gas fire with all the attendant loss of life and property.
The amount of gas that can be taken up by the strata commonly found in an oil and gas field is usually underestimated by the operators. There is seldom any considerable thickness of beds which does not include some porous formation. Even though strayed gas remains underground, experience teaches that it can seldom be recovered from the new locations, because it has become diffused through many strata, or because the pressure in the original strata and in the strata to which some of the gas has moved, has become too low to make recovery practicable.

It has become an axiom among gas producers that once a gas sand is tapped the gas must be utilized quickly, because it will not remain stored, but in some manner escapes. It is their practice to case or pack as closely as possible above the gas sand, which shows an acceptance of the fact of widespread underground waste in considerable amount. Furthermore, in the older gas-producing States the purchasing companies insist that the gas must not have access to much open hole.

The underground waste of gas is not a recent discovery, as is shown by the following extract from the first report of the supervisor of natural gas in Indiana for the year 1891:

The gas, after its release from the Trenton rock, permeates every portion of porous rock that forms the wall of the well below the point at which the well is packed. It spreads itself laterally through every crevice and opening that is found, and thus an enormous waste is maintained.

In many parts of the field we find gas escaping through the earth and bubbling up through the water in the streams and in water wells. In some instances the escape into water wells has been so strong that the wells have been closed in and the gas piped into the houses adjoining and found sufficient for domestic consumption.

All this may be attributed to the insufficient packing of the wells in the vicinity. The great upheaval of earth and rocks, and the explosion which followed in the vicinity of Waldron, Shelby County, which occurred August 11, 1890, was due to the gas escaping through the shales and below the packers from the wells at Waldron and St. Paul. The gas escaping laterally through the shales collected in subterranean reservoirs until the pressure became so great as to cause the upheaval.

**Cases of underground waste of gas.**

Actual instances of underground waste, of which conclusive proof can be found, are not common. Ordinarily, there is no way of telling how much of the gas from a depleted deposit has been brought to the surface and how much has been wasted underground because there is no accurate method of determining the quantity of gas originally present in the field, nor the quantity that has migrated. The circumstances and conditions are exceptional under which this underground waste becomes known in such manner that there remains no

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*Geology and natural history, seventeenth report of the State geologist, 1891, p. 338.*
other satisfactory explanation. The writers present a few typical cases that have come to their attention, in which the evidence seems clear. These prove the existence and importance of underground waste of gas and indicate that such waste has been a large contributory factor in the depletion of many sands.

Near Loco, Okla., a well was drilled into gas at a depth of approximately 750 feet. The initial open flow was 15,000,000 cubic feet a day, and the initial rock pressure was 310 pounds per square inch, a pressure shown by other gas wells not far distant. The well was finished with two packers on the inner string of casing; one packer was to shut off the water and the other or bottom packer was set in or above the gas sand, apparently to confine the gas. The lower packer was clearly defective, because in two weeks the pressure had decreased to 155 pounds, in two more weeks to 120 pounds, and two months later to 90 pounds. Meanwhile, wells about 1,000 feet distant in the same sand held a pressure of 300 pounds. The well was then repaired by seating the casing in cement. Within a day the pressure increased 6 pounds, in 2 days 13 pounds, in 3 days 17 pounds, in 5 days 25 pounds, and in about 45 days the pressure had risen from 90 to 210 pounds, an increase of 120 pounds.

In this case the gas did not escape to the surface, neither was the depletion due to drawing on the sand by other wells, as the other wells were not in use, and the pressure in them held at about 300 pounds. The pressure built up again when the defects were repaired. Evidently the waste was underground and was remarkably rapid, because with an initial open flow volume of 15,000,000 cubic feet the pressure fell off in 14 days at the rate of 10 pounds a day.

The condition of a well in the Osage Nation is shown in Plate I and figure 4. In this well a flow of 22,000,000 cubic feet of gas was obtained in the Bartlesville sand and the original rock pressure is reported to have been about 900 pounds. Bradenheads were placed on all but the outer casing, and all the gas except that outside the 12½-inch casing was shut in. The high pressure caused the gas to cut under the 8½, 10, and 12½ inch casings and come up between the 12½ and 16 inch casings to the surface. Wooden plugs were driven between the 12½ and 16 inch casings to hold back the gas, and cement was placed between the 16-inch casing and the walls of the hole. As a result the gas was forced out into overlying formations and came to the surface away from the well. When the authors visited this well in August, 1915, gas was issuing in large volumes from many places within a radius of 300 feet from the well. Six hundred feet distant a small flow of gas was escaping from the bottom of a creek. This condition had existed for 15 months. In time the gas pressure would decrease until the pressure of the water would overcome it, and then the direction of flow would be reversed and the water would
drown out the remaining gas. In Plate I the designations of the different formations penetrated are those recorded by the driller.

A similar case was observed in the Cushing field. Through improper operating methods, gas of high pressure reached gas of less pressure and shallow water-bearing sands. The high-pressure gas forced its way into the water-bearing sands and within a few days water and gas began to erupt from two drilling wells 500 feet away, and from crevices in the bottom of a ravine still farther distant. The gas could be detected only where it was accompanied by water, but doubtless it was escaping in many places other than those observed. The fresh water forced to the surface was used for field purposes. A few months later, in another well that was being drilled 500 feet from the offending well, gas was unexpectedly encountered in the shallow water-bearing sands and the rig was burned down.

Other instances are known in the same field and elsewhere in Oklahoma where the high-pressure gas had gained access to upper strata and affected the wells near by. Except where its movement may be traced in some such manner, there is no knowing how far gas may migrate underground, nor how great the waste may be.

In an instance reported by G. T. Braden of the Oklahoma Natural Gas Co., two wells being drilled in virgin territory struck gas and were carefully shut in with packers set above the gas sands. One of the wells when shut in had an open flow of 16,000,000 cubic feet

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**Figure 4.**—Surface conditions at well shown in Plate I, gas escaping with water at crosses. Where there was no water the gas was not easy to detect. The pond is about 200 feet from the well.
DIAGRAM OF WELL IN OSAGE COUNTY, OKLA.

Shows condition of well and way in which gas escaped to the surface. This well was completed May 8, 1916, with an open flow of gas estimated at 22,000,000 cubic feet per day. When shut in, the gas had reached the surface as far as 600 feet from the well and for a radius of 200 feet was issuing from the ground in large volumes, when inspected on August 7, 1917.
of dry gas, yet when the well was opened six months later the hole was full of water. The water was pumped out and every effort made to bring back the gas, but without success. The other well, in which the packer was set directly above the gas sand, was opened up later and this hole was also found to be filled with water. In the case of this well the gas did not escape to the surface nor was it withdrawn through other wells in the field. The only possible explanation seems to be that the casing or the packer became defective, and that either the water was in sufficient volume and under such pressure as to immediately overcome the gas, or the gas wasted until its pressure was less than that of the water, whereupon the water came in and drowned out the gas. In the case of the first well mentioned it is not known where the casing and the packer were set in relation to the gas sand. The explanation may be similar to that given above, or the gas may have escaped into other strata until the water was drawn in from lower parts of the gas sand.

In the north end of the Cushing pool a number of wells in the Layton sand were deepened to the Bartlesville sand, and the gas between the two sands was cased in with that from the Layton. In this manner high-pressure gas had access to the Layton sand and forced the oil ahead into wells still producing from that sand, thereby temporarily increasing their production.

Near Duncan, Okla., two wells 800 feet apart were drilled to the 800-foot gas sand. Well No. 1 had an initial open flow of 3,000,000 cubic feet, and well No. 2 an initial flow of 10,500,000 cubic feet. In each well the rock pressure was 280 pounds. When these wells were shut in, the pressure dropped rapidly. At the end of a year it was down to 60 pounds, and the open flow in well No. 1 was 300,000 cubic feet. At this time well No. 2 was deepened to the 900-foot sand, which showed an open flow of 20,000,000 cubic feet and a rock pressure of 310 pounds. The casing was landed in a “shell” between the two sands. Four days later at this well the pressure in the 900-foot sand had decreased to 245 pounds, and the pressure in the upper sand had increased from 60 pounds to 220 pounds. The casing seat had given way and the gas could be plainly heard “feeding” into the upper sand. A gage on well No. 1 showed that the pressure in that well had increased from 60 to 100 pounds. The casing in No. 2 was reset in cement, an operation which consumed eight days’ time, and during this period the pressure increased in well No. 1 to 135 pounds, and the open flow increased to 1,500,000 cubic feet. When well No. 2 was shut in once more, the pressure in well No. 1 gradually dropped to 60 pounds and the open flow decreased to 300,000 cubic feet.

There was no gas escaping to the surface and the field was not drawn upon sufficiently to account for the decrease. The effect on well No. 1 shows clearly the result of unsystematic casing.
Attention has been called to the fact that, from experience, gas producers have adopted the practice of confining the gas to its original strata as closely as practicable. Recent experience in producing oil by forcing air under pressure into an oil sand has demonstrated the same fact. It has been found that unless, in each well to the oil sand, the sand is securely shut off from the strata above and below, except where unusually dense beds of shale directly overlie or underlie the sand, the pressure in the sand can not be maintained. This shows that the air forced into the sand may enter other strata in large volume. In these circumstances the quantity of air forced into the sand is known, and it is possible to obtain more definite information of the magnitude of underground waste than in a gas-producing field.

CONNECTING GAS SANDS.

Sands of different depths in a new pool will have different gas pressures, and in general, the deeper the sand the greater is the pressure of the gas in it. When different sands are connected in any way the gas under higher pressure will have access to the gas under lower pressure, and in some cases the difference in pressure will be great. Different gas-bearing sands may be connected in many ways—through an open hole, behind a casing, by defective casing, through connections from braden-heads without back-pressure valves, or by reason of other imperfect operating methods. The effect is the same in all cases, but it may take longer to become evident in some than in others. The gas pressures between the different sands will tend to equalize the gas flowing from the high-pressure into the low-pressure sand, gas will become exposed to much open formation and wasted thereby, and the pressure of the gas may exert a strain on the upper strings of casing greater than they were intended to hold, and consequently defects will develop. Such a well is shown in Plate I. A number of similar instances have been called to the attention of the writers.

The practice of connecting all the gas wells on a property or in a field should be adopted with great caution, because the wells may be producing from different sands, or even if all the wells are producing from the same sand, as a rule one or more wells in a field are defective and consequently will waste gas from the others.

REASONS FOR CONSERVING GAS IN OIL FIELDS.

In addition to the direct value of the gas wasted in drilling for and recovering oil, there are other reasons for conserving gas in oil fields that should receive the serious consideration of the producers.

To exhaust the gas from a sand that overlies an oil sand may endanger the oil, because water is likely to enter the gas sand and incidentally flood the oil sand. In the early history of a field the
operators might see no reason to protect the oil from an overlying gas sand, and hence, if the gas sand became flooded, the water would have access to the underlying oil and might cause much damage. In the north end of the Cushing field this has actually happened, and it has been one cause of the encroachment of water in the Bartlesville oil sand (see p. 18). Maintaining the gas pressure is one means of delaying the ingress of water.

In an article in the Oil and Gas Journal of May 6, 1915, R. H. Johnson and L. G. Huntley consider the effect of the gas on the productivity of oil wells. The principle is simple. The pressure of the gas is the motive force that expels the oil from the sand and causes it to flow to the surface; therefore, every well should be so operated that the maximum quantity of oil will be moved by the gas that is found with the oil. In some of the California fields wells capable of producing as much as 10,000 to 15,000 barrels of oil a day, and making in addition several million feet of gas, are restricted to a flow of 1,000 barrels a day or less, with a comparatively small flow of gas, by closing the well to a $\frac{1}{8}$-inch or 1-inch opening. It has been found that the ultimate flush production from such restricted wells has almost invariably been more than the unrestricted flow from neighboring wells.

When a fresh pool of oil is opened, an excessive quantity of gas is generally produced with the oil. In a short time the flow of gas is greatly reduced in volume and pressure, because the gas tends to separate from the oil and escape more rapidly. The custom is to make no effort to control this excessive flow of gas, for to hold it back will temporarily retard the oil production also, and the gas can not be marketed without special treatment. Apart from considerations of immediate gain, it is to the operator's advantage to hold back and conserve the gas, for not only will he aid in protecting his property from water by so doing, but the total amount of oil raised to the surface by flowing will be greater, and it is likely that the total recovery from the property will be increased, as pointed out by Johnson and Huntley. In addition, the gas will be a valuable asset in the later life of the property when all wells must be pumped. In deep wells the saving because of the increased proportion of oil that can be made to flow will be a factor of considerable economic importance.

**WASTE OF OIL BY MIGRATION AND DISSIPATION.**

The waste of oil by migration to and dissipation in other strata is less general than the waste of gas; yet it is the belief of the writers that it has not received the attention that it merits. The movements of oil underground are much slower than those of gas, wastes are easier to detect and control, and oil is more closely watched by the
operator. The principal waste results when the oil enters a sand that previously had never contained oil. It is well known that a large proportion of the oil will not drain out of a sand but is held in the pores by capillarity. It has been estimated that from 25 to 85 per cent of the original content of an oil pool remains in the earth when the field has been drained by customary methods. Although the proportion will vary and no accurate figures of actual cases are known, it is evident that much oil is left in the sand and lost. The oil that migrates is oil that could all have been brought to the surface, and of this also a large proportion is lost.

Probably the commonest waste of oil by migration is by allowing oil to enter a gas sand. In most fields gas is closely associated with oil, either in the same sand at higher levels or in sands closely overlying the oil. As the gas is usually depleted much faster than the oil, the oil tends to move toward the gas sand in a field that is being developed. It has been not uncommon for an operator to blow a gas well to bring in the oil. In such cases there has been not only great waste of gas, but much oil has been lost also. An instance in which the oil was allowed to enter an overlying gas sand is given below.

In the north end of the Cushing field in drilling the first wells a thin "break" was found that separated the gas from the oil in the Bartlesville sand. The gas was allowed to waste rapidly with the result that the pressure was soon so low that the oil could enter the gas sand more easily than it could flow to the surface. Six months after this pool was opened in the Bartlesville sand, oil was being found in the gas horizon close to wells that formerly had found gas in it. The loss must have been very great. The gas sand is 30 to 40 feet thick, and the amount of oil that entered it may be judged by the fact that very large flows of oil were obtained from it from wells drilled subsequently. Those operators who wasted the gas or cased the oil and gas together in order to cause the oil to flow more rapidly gained only a temporary advantage, for much of the oil was sucked into the gas sand, and of such oil, all of which could have been brought to the surface, possibly 75 per cent will be lost. A later phase of the waste cited above is that about three months after oil appeared in the gas sand some wells near by found this sand flooded with water. Figure 6 illustrates this case.

Figure 5, after Hager, illustrates a case with similar results, where oil was allowed to enter a dry sand, the plugging of which greatly increased the yield of oil.

WASTE AND POLLUTION OF POTABLE WATER.

In many oil fields water that is suitable for domestic use or for boilers is scarce or of inferior quality, and is usually limited to sur-
face water or that from shallow wells. Deep waters in the oil fields are generally strongly mineralized. Surface water is apt to be polluted from the oil-field waste, and this condition, although serious, is not permanent, as when the cause is removed the quality of the water soon improves. If well water becomes contaminated it is difficult to remove the cause of pollution, and underground water, once polluted, requires a long time to purify itself.

Underground water should be protected both from the field waste, which will seep down from the surface around the casing, and from underlying oil and salt water. This can be done without great expense.

Fresh water will also be wasted where it is allowed to communicate with underlying dry sands or sands containing oil, gas, or salt water under less pressure than the fresh water. This will occur when the water-bearing formation is cased in with these formations or when the casing is not tight or properly placed.

A noteworthy case of wasting of fresh water is in the Kern River field, California. Early operators found a shallow sand 300 feet thick containing an abundance of water, Between the water and the oil sands were a series of gas and tar sands. Some wells were cased just below the water, and other wells were cased below the gas and tar sands. The water entered the gas and tar sands by some wells and from them got into the oil sands by the wells that had been cased just below the water. The result was that the water disappeared from the original water-bearing sand, the gas and tar sands became flooded, and in many parts of the field the oil sands were seriously damaged by water.
UNSYSTEMATIC CASING OF WELLS.

Typical examples of the results of unsystematic casing of wells are presented in figures 6 and 7. These diagrams show that the oper-

ator, to protect his oil and gas, must consider not only his own wells but also the relations between all of his wells and those on neighbor-
ing ground. Two operators on adjacent lands may each be making conscientious efforts to protect their properties, yet fail in that pur-

pose because they did not consider other wells. Oil, gas, and water are mobile and do not stop at property lines, consequently all operators in a field are interdependent, and one can not develop his property with-
out taking into account what his neighbors are doing. The effects of not observing this policy may not be evident at first, as it will take some time for the water to move back and forth between the wells and from sand to sand. Once the harm is done, it is difficult and expensive to correct. Each operator will claim that his method was right, and, in fact, in so far as his own property is concerned, his method might be satisfactory.

Through unsystematic casing the upper waters are given access to the deeper oil or gas sands, or lower waters can invade upper productive sands, salt water can contaminate fresh water, or fresh water migrate down into lower sands and become lost or polluted. In addition, the hydrostatic pressure and volume of the lower waters may be increased so as to develop defects in the wells. As all the water-bearing beds will be connected, the volume of water that may flood the productive strata will be greatly increased and the ultimate pressure developed in the field will equal that from the highest water-bearing sand. Even water-bearing strata which elsewhere in the field contain oil and gas should be protected from the surface waters, because the volume and hydrostatic head will be increased. Furthermore, not only may water invade productive strata, but gas and oil may migrate into other strata. Figure 6 shows how oil may invade a gas sand.

Where there is no water, or the gas is in sufficient volume and its pressure is great enough to overcome the pressure of the water, the gas will flow back and forth between wells and from sand to sand, and in this way it may reach the surface, or, in any event, will become dissipated through formations from which it can not be recovered. When the point is reached where the volume and pressure of the gas are no longer great enough to force back the water, the direction of migration will be reversed, and the water will flow down into the depleted gas and oil strata. Any defective wells in a field will aid in spreading the evils into all parts of the field and into every sand.

Figures 6 and 7 are drawn from conditions in the Cushing field. Although all these casing conditions are not known in any two wells, they are known to exist in three wells not widely separated, and the evils of nonuniform operation are widespread throughout the field. On pages 15 to 19 the effects of unsystematic casing are shown.

Figure 8 shows that packers or similar devices for protecting gas may be worthless if not set with regard to conditions. One strong argument for setting casing in mud-laden fluid is that such setting eliminates all dangers of this kind.

**METHODS OF PREVENTING UNDERGROUND WASTE.**

To provide full protection for oil, gas, or fresh water, it is necessary to confine each to its original strata until such time as it can be
brought to the surface and used without waste. Unfortunately many fields are now beyond recovery, or if not, the expense of putting the wells in repair is prohibitive. The writers believe that much can

**Figure 8.**—Diagram showing results of unsystematic use of packers. Operators shut gas in between packers to save it for future use, but at different wells the best gas may not be in the same sand, so that different sands are packed off. Even if the packers are set successfully the benefit is only temporary, as the gas can work from well to well and up outside the casings, and thus gain access to the different formations penetrated by the well. If the upper sand is not systematically packed off, the gas may escape to the surface.
be done to correct existing conditions, but it is principally in regard
to future development work that their recommendations are made.

Both oil and gas men recognize that the prevailing methods cause
unnecessary waste and that ultimate profits would be increased by
greater efficiency in preventing the underground wastes. They are
willing to take up other methods if it can be demonstrated that
such methods are more effective, the cost not prohibitive, and that
they are simple and capable of general adaptation. The writers
believe that the mud-laden fluid method meets these requirements
most fully, and in addition to preventing underground waste, poss-
sesses certain other advantages that make it desirable for the
operators.

The commonest methods of protecting oil, gas, or water-bearing
sands when a well is drilled through them to a lower sand, are to
use casing with or without shoes and casing with or without packers;
sometimes also cement is forced behind the casing. When casing
alone is used, it is necessary to seat securely one string immediately
above and another immediately below each oil, gas, or water-bearing
stratum to fully protect it. Ordinarily a secure seat can not be made
without using shoes on the casing, and frequently the nature of the
adjacent strata will not permit secure seats, even with shoes.

When packers are used, the casing can be seated immediately below
the oil or gas sand and a packer set above it, or packers can be set
above and below and the casing seated at greater depth. As many as
four packers have been used on the same string of casing, and by
this means two or more productive sands could be shut in behind
one size of casing. But the same limitations apply to the use of
packers as to casing alone. The nature of the strata will not always
permit a secure seat for the packers at the desired points, and a
high degree of technical skill is required. Packers often become
defective soon after being placed, and in any event can not be con-
sidered as permanent fixtures. Furthermore there is no way known
to the writers of satisfactorily testing for leaks more than one packer
on a string of casing. With cement the casing can usually be seated
securely, and in some wells the cement can be forced back far enough
to seal off a porous formation. Often, however, the cement will not
set properly because of interference by gas or from other causes.

The three methods mentioned are not always effective and where
it is not desired to produce from a formation, or where there are a
number of formations that should be protected, the cost may be very
great or even prohibitive, and in such cases the practice in the past
has been to sacrifice all other bodies of oil or gas to the one of great-
est immediate value.
When a new pool is opened, the oil and gas are found in porous strata interlaid with strata of impervious clay, shale, or limestone that prevent the contents of one porous layer from intermingling with the contents of any other. This condition, which has existed for countless thousands of years, has kept the oil and gas intact. In the same stratum, however, there may be gas, oil, or water arranged in different levels according to their relative specific gravities and not separated from each other by any natural barriers. There is thus a fundamental distinction between protecting a body of oil, gas, or water from the contents of other strata and from the contents of the same stratum found at a different level. The latter problem is principally one of production, which has been touched upon elsewhere in this paper; the former relates to the technique of well drilling.

In repairing a field, the first thing to be determined is whether the source of the trouble is in the same stratum or in other strata. Essentially, the problem of protecting against other strata is the repairing of the barriers established by nature. To do this it is necessary to run the casing to the top of the sand which is to produce, for leaving open hole is comparable to having leaking joints in a gas line or to running oil from a well in an earthen ditch. Also the space between the casing and the walls of the hole should be filled with impervious material which will reseal each porous strata and restore the natural barriers. To interpose an occasional obstruction, such as a packer or a casing seat, can hardly be considered more than a make-shift; the history of the oil and gas business shows conclusively that tremendous wastes will result from their use.

MUD-LADEN FLUID METHOD.

The mud-laden fluid method and its application has been fully described by Pollard and Heggem.4

When the mud-laden fluid is used, the fluid must be placed behind the casing and kept at a height sufficient to overcome the pressure of any oil, gas, or water behind the same string of casing. The casing must also be securely seated in order to retain the fluid. In order to protect a sand from which it is not desired to produce, or to protect a number of sands above the producing one, it is believed that this method will generally prove to be the simplest and cheapest, and by means of it gas under high pressure can be handled with greatest efficiency and safety. These sands will stay sealed as long as a

column of mud-laden fluid is maintained behind the casing, and the operator, if he so desires, can usually unseal a sand by removing the fluid, provided the rock pressure is great enough to force the mud out of the sand after the restraining pressure of the column of fluid has been taken off. By means of this system, any oil, gas, or water-bearing sand penetrated by the well can be sealed off, whether of immediate value or not, and preserved for use. Furthermore, danger from corroded casing is lessened and the danger from the unsystematic use of either casing or packers, is eliminated.

ADVANTAGE OF MUD-LADEN FLUID METHOD.

The cost of applying the method, which must be added to the first cost of drilling the well, can be kept low and is compensated by the probably greater cost of satisfactory alternative methods of drilling, more casing can be recovered after the well is finished, and casing left in the hole is protected from corrosion by water. The method is simple and is easily applied; it can be used under almost any conditions, the materials for making the mud can in most places be obtained near the well, and little extra equipment is necessary. The formations penetrated can be permanently sealed off; ordinarily a formation can be unsealed if so desired, and all strata are sealed in whether they are of value at the time of drilling or not.

The method is self-testing; that is, if mud-laden fluid is placed behind a casing and a defect develops, it makes itself evident at once, and the operator can always know whether the hole is in good condition or not. In this respect the method has an especial advantage over other methods and in particular over sealing with packers. The mud-laden fluid will not work through loosely screwed joints in the casing as readily as water, which will not only seep through, but will enlarge the leak and weaken the joint by rusting the threads.

All danger from unsystematic casing or the use of packers is eliminated, and the field is left more nearly as it was before development than by any other system; that is, practically as a sealed reservoir. If it is desired to drill a well through an oil or gas sand, the lower part of which carries water not separated by a break or parting from the oil or gas, drilling with mud-laden fluid is usually the only way to protect the sand. For drilling into a sand containing gas under high pressure, the mud-laden fluid is often the only method that can be employed to drill in and complete the well without first reducing the rock pressure by permitting the gas to waste either into the atmosphere or into porous underground formations. Furthermore, the well can be handled with less danger, expense, waste, or chance of losing control. In no other way now known can a well be drilled through a gas sand without waste or damage. By the use of mud
fluid strong flows of water, which are difficult or impossible to handle in any other way, and heaving or running sands which can not be handled by other standard-tool methods can be controlled. Also, caving of soft or friable formations can ordinarily be overcome. Filling a well with thick mud is the cheapest and most effective way of abandoning the well, and sometimes is the only method by which adjacent properties can be protected.

The mud-laden fluid method has been in use long enough to demonstrate its practicability. Believing this method of protecting oil and gas sands to be the most practicable and efficient of those so far called to its attention, the Bureau of Mines recommends its use.

PUBLICATIONS ON PETROLEUM TECHNOLOGY.

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TECHNICAL PAPER 32. The cementing process of excluding water from oil wells as practiced in California, by Ralph Arnold and V. R. Garfias. 1913. 12 pp., 1 fig.


TECHNICAL PAPER 42. The prevention of waste of oil and gas from flowing wells in California, with a discussion of special methods used by J. A. Pollard, by Ralph Arnold and V. R. Garfias. 1913. 15 pp., 2 pls., 4 figs.

TECHNICAL PAPER 45. Waste of oil and gas in the Mid-Continent fields, by R. S. Blatchley. 1914. 54 pp., 2 pls., 15 figs.

TECHNICAL PAPER 49. The flash point of oils; methods and apparatus for its determination, by I. C. Allen and A. S. Crossfield. 1913. 31 pp., 2 figs.


TECHNICAL PAPER 68. Drilling wells in Oklahoma by the mud-laden fluid method, by A. G. Heggem and J. A. Pollard. 1914. 27 pp., 5 figs.

TECHNICAL PAPER 70. Methods of oil recovery as practiced in California, by Ralph Arnold and V. R. Garfias. 1914. 57 pp., 7 figs.
TECHNICAL PAPER 72. Problems of the petroleum industry; results of conferences at Pittsburgh, Pa., August 1 and September 10, 1913, by I. C. Allen. 1914. 20 pp.

TECHNICAL PAPER 74. Physical and chemical properties of the petroleum of California, by I. C. Allen, W. A. Jacobs, A. S. Crossfield, and R. R. Matthews. 1914. 38 pp., 1 fig.
