TECHNICAL DEVELOPMENTS IN PETROLEUM AND NATURAL-GAS PRODUCTION

By H. C. Fowler

Recent technical progress in the production of petroleum and natural gas has influenced, modified, and helped to solve many of the involved and at times almost indeterminate problems confronting the industry. In this review no attempt is made to differentiate between technical research and field applications of newly determined, fundamental data regarding physical laws. Today, engineering research is conducted as an integral part of complicated industrial operations, and frequently the results, even in pure science, soon are applied as the working tools of industry, so that an exact demarcation cannot be made between technical study and operating conditions that are changed and often controlled by the findings of the investigative work.

The discussion is not confined to technical and related developments in 1932 only. The significance of newly found engineering facts and resulting new departures in economic arrangements cannot be bounded by definite calendar limits. Several years of experiment may be required to bring a newly conceived idea to satisfactory practical application, although during the development stage it may exert an influence on the industry. Even after a new idea, resulting in a method of operation, device, or tool, is proved its ultimate effect is not easy to determine because of the appreciable "time-lag" required properly to evaluate cause and effect.

INTERRELATION OF OIL AND GAS PRODUCTION

Crystallization of thought has grown about the nucleus of the idea propounded by Bureau of Mines engineers prior to 1917–18 that oil and gas production cannot be treated as separate problems, because in addition to the economic factors controlling natural-gas production a large part of the natural gas produced in the United States (probably 60 percent) is dependently variable upon the production of oil. To the growing understanding of this interrelationship of natural hydrocarbons in the liquid and gaseous phases has been added a third phase—the energy attributes of oil-gas reservoirs.

Because of this knowledge the industry has been trying to adjust restricted oil and gas production during a period of depressed markets to conserve gas and its contained energy; devising means of operation that will cause the energy in the expanding gas to do its maximum useful work in bringing oil from the reservoir sands to the wells, and thence to the surface, and subsequently using this gas for fuel or other gainful purposes.
In studying oil-gas-energy relationships the engineer is dealing with two interdependent and connected flow systems: (1) Flow within the reservoir and (2) vertical flow in the column from the bottom of the well to the surface, including the well-head connections, flow lines, and oil-and-gas separators. Each system and its operation exert a definite and positive effect upon the other, and without knowledge of both reservoir energy will be dissipated; gas will be lost at the surface (if an adequate market outlet is not provided); an appreciable quantity of recoverable oil will remain in the reservoir until stimulative production methods bring it to the wells; and eventually mechanical means will have to be used to raise oil that otherwise could have been produced by natural flow at lower production costs.

PETROLEUM TECHNOLOGY AND ECONOMICS

The fluid and mobile characteristics of petroleum and natural gas have led to confusion in their production, technically and economically out of all proportion to the production of other natural resources. An erroneous concept of "capture and reduction to possession" has spread and permeated the whole oil-and-gas structure since 1875 when a court decision was rendered that put the search for these hydrocarbon companions in the same category as the hunting of wild game. Many efforts toward a wiser and more efficient use of oil and gas have been hindered by the legal and economic conditions compelling highly competitive drilling and production methods in a common pool. These uncontrolled practices, engendered by human traits and interpretations rather than by physical laws and desirable economic considerations, have led to physical and economic losses.

The actual physical losses of oil at the surface are relatively small compared with the total production of oil. The proximate and contributing causes of these surface losses are well known, and in general engineering methods have been devised to bring them under good control. The quantity of oil lost through spillage now is almost negligible, although the disposal of oil-field (also refinery and tanker) waste has been costly to the petroleum industry. In the absence of steel storage earthen pits have been and still are used. Confronted by highly competitive drilling and production practices some operators hold that it is better to lose an appreciable quantity of oil through seepage than to lose their oil through underground drainage across property lines. It has been estimated that the total evaporation and leakage losses for 1 year in the handling of oil from the wells to the ultimate consumer of gasoline is about 3½ percent. This percentage probably can be reduced appreciably if the best-known engineering practices are applied to keep the oil in the ground until needed.

Although calculation of the actual surface losses of natural gas up to now would reach astronomical dimensions if it were possible to measure them in cubic feet, an active and well-defined movement has been made by industry and government (State and Federal) to control factors contributing to natural-gas losses. Some engineering factors of natural-gas conservation are discussed in report V of the Federal Oil Conservation Board to the President of the United States, 1932, pages 47 to 56.

Underground losses of oil, dissipated gas energy, and economic losses resulting from highly competitive development programs and
from unwarranted withdrawal of oil from the reservoirs in excess of what the market will absorb at a reasonable price are more vital at present than the surface losses just described.

From the preceding paragraphs it will be recognized that no discussion of engineering methods to prevent underground losses caused by premature and irregular water encroachment, dissipation of gas energy, changes in the physical characteristics of the oil (making it more difficult to recover because of gas liberation), and others is complete without a discussion of attendant economic losses.

At present, when the current language noticeably reflects such phraseology as "distress oil", "depressed prices", "inventories above and below ground", and "waste", studied consideration is being given to the related technical and economic problems to mitigate existing conditions. The petroleum and natural-gas industry of its own volition has taken the active lead, knowing that unwarranted and wasteful depletion of reserves destroys the raw material on which the industry depends for its continued existence and that the marginal profit whereby the business can continue frequently depends upon the reduction of losses through engineering efforts. The technical, economic, legal, executive, and other representative organizations of the industry have met in various open forums and considered such problems as proration, unit operation, the part played by gas in producing oil, and the oil-gas-energy relationships in the reservoir. These topics have proved to be so interrelated that it has been difficult to confine the discussions on the agenda to any one definite subject.

Proration.—The history of proration, with a treatment of its many engineering factors and its effects upon conservation and stabilization, has too many ramifications to be included in this résumé. It is sufficient to state that proration as applied to individual fields has been and is being used as a necessary but temporary expedient to balance supply with market demand. There are nearly as many proration programs as there are oil fields to be prorated, and the whole gamut of technical, economic, and legal controversy has been run in attempting to determine methods for the equitable production of oil and gas.

Some persons claim that proration has failed in its entirety, others concede that proration as practiced has many limitations, but no one can estimate what the demoralization of market demand would have been if these attempts to give each producer a ratable share of the market outlet had not been made. Proration in the broader sense, without the implication of price maintenance, has helped to curtail wasteful physical and economic conditions. As an example, engineering data prove that water encroachment along the western edge of the East Texas field has been retarded through restricted methods of production, and thus the ultimate recovery from that field has been increased.

Careful estimates of unbiased engineers "indicate that the displacement of oil by water in the East Texas field has been efficient, and only small quantities of oil have been trapped and left behind in the water-flooded area."1

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1 Lindley, Ben E., A Study of "Bottom-Hole" Samples of East Texas Crude Oil: Rept. of Investigations 3212, Bureau of Mines, 1933, p. 22. (Read before Am. Petrol. Inst. Division of Production, Tulsa, Okla., May 19, 1933.)
The greatest hindrance to the solution of the petroleum industry's problems solely by proration within a pool is that this method is not directed toward the fundamental concept of developing a pool as a unit, and no proration plan has yet been devised whereby many of the evils of highly competitive off-set drilling and production in a common pool have been eliminated.

Unit operation.—The subject of unit operation is not new, but the industry generally has been slow in giving favorable consideration to proposed plans while individualistic ideas of capture (sometimes referred to as "legalized piracy") have predominated.

The term "unitization" is subject to several definitions, depending upon the viewpoint, but fundamentally it refers "to the practice of unifying the ownership and control of an actual or prospective oil and/or gas pool by the issuance or assignment of units or undivided interests in the entire area with provision for development and operation by an agent, trustee, or committee representing all holders of undivided interests therein." Unitization is to be distinguished from cooperative development and operation.

The complete record of public hearings of the Federal Oil Conservation Board, February 10 and 11, 1926, and later symposiums in the publications of the American Institute of Mining and Metallurgical Engineers and the American Petroleum Institute, the Handbook on Unitization of Oil Pools published by the Mid-Continent Oil and Gas Association in 1930, and many other public writings in the petroleum and legal press set forth the principles of unitization and unit development and operation. The North Dome of the Kettleman Hills (Calif.) field is the outstanding example in this country at present of a working unit plan effected through efforts of the operators and the Federal Government.

Many legal considerations have complicated the problem of unit operation, but from the technical standpoint only the general consensus of opinion expressed among engineers is that development and operation of pools as units accord with desirable economic considerations and the best-known principles of physical laws, and there is no technical reason why the quantity of oil and gas originally within the structural confines of the respective original properties in a common pool cannot be estimated and allocated with fair accuracy.

Within the last year the energy factor of the reservoir has been under consideration in the open meetings of various technical organizations. It has been postulated, without serious contradiction, that to obtain maximum extraction of oil and gas from a reservoir without waste the energy in the pool must be used for the common benefit. Whether or not the reservoir energy is divisible and subject to allocation is still under debate.

ENGINEERING RESEARCH

Among the most important recent production-engineering developments, which have been prompted by the economic conditions already mentioned, and others, or which will influence the future technique of controlled production, are methods for obtaining and interpreting data that pertain to the following:

* Mid-Continent Oil and Gas Association, Handbook on Unitization of Oil Pools: Tulsa, Okla., 1930, p. 15.
1. Subsurface pressures and temperatures in wells, involving problems of reservoir and vertical flow (more frequently referred to as "bottom-hole" problems).

2. Solubility of gas in oil and the phenomena attending the liberation of natural gas from solution in oil under conditions approximating those of the reservoir.

3. The flow of oil, gas, and oil-gas mixtures through porous media, to which the complicated problem of well spacing is directly related.

Subsurface pressures and temperatures.—The evolution of equitable methods of production control by means of precise information regarding conditions at the bottoms of wells has been rapid.

In 1928 Sclater gave one of the first technical papers on the subject, and about the same time K. B. Nowels (then an engineer of the Bureau of Mines and now chief petroleum engineer, Forest Oil Corporation, Bradford, Pa.) began development of an instrument to obtain subsurface data needed in the study of energy requirements of vertical flow in wells.

Hawthorn states that 8 or 10 different instruments have been developed to the practical stage. He gives the following classification, based upon the manner in which the pressures are recorded: (1) Maximum recording, (2) indicating, (3) selective recording, (4) continuous recording, and (5) continuous recording and indicating.

The various recording devices are interesting as examples of unique instrument making, and the several designers have overcome great obstacles in developing sensitive mechanisms that will withstand shock and temperature changes and yet give the required accuracy; however, these devices are only the means to an end, and the primary concern is the interpretation of data obtained with them.

Reistle and Hayes in a cooperative study in East Texas with an instrument of the continuous-recording type having, in addition, a continuous temperature-recording mechanism, recently obtained data from which they computed the minimum reservoir pressure necessary to maintain natural flow through 2½-inch tubing for existing energy conditions.

Knowledge of the gas-oil-energy relationships not only makes it possible to determine correct sizes of flow strings, limiting flowing pressures and other production methods and operations, but also well data pertaining to reservoir conditions should assist materially in determining rational and equitable production programs for a field.

Extensive reservoir-pressure surveys have been made in East Texas, and during the early part of 1933 the railroad commission of Texas based the allowable production from the various leases in that field partly upon subsurface pressure data.

Surveys are in progress in Kettleman Hills, Calif. Clark and Kimberlin of the Kettleman Hills North Dome Association made the
following timely statement regarding the value of "bottom-hole" pressure data:

The use of bottom-hole pressure instruments affords a splendid means of securing data to determine the rate at which drainage is affecting not only the various areas immediately involved, but areas removed from them by considerable distance. The periodic taking of shut-in pressures in all the wells available, and a correlation of the results obtained with the production data at hand, should give accurate information on drainage conditions. This information will apply as between the wells of the area being produced and the extent to which the concentration of production in a few small areas is affecting the field as a whole. The difference between the shut-in pressure readings from available points in the field will indicate the degree of drainage, and subsequent readings will indicate its rate and the areas that are being affected most.

They also point out that the method may be used in establishing "potentials" and in planning future development programs. Referring to well spacing, they say:

As pressure-survey data accumulate and the results are correlated and plotted on pressure-contour maps, a long step will have been taken toward removing the problem of correct well spacing from the realm of theory and placing it on a basis of determinable fact.

Solubility of gas in oil.—The relationships of dry gas dissolved in relatively stable samples of oil, as stated in Henry's law, and the attending phenomena of change in viscosity, surface tension, and gravity of the oil have been common knowledge in the industry for some years. The work of Lacey 7 at the California Institute of Technology, conducted as American Petroleum Institute Research Project 37, has increased this knowledge in an exceptional and practical way.

Engineers have recognized for some time that the relationships of fluid movement in the reservoir and in the wells cannot be understood thoroughly and applied in rational production programs, with a maximum recovery of oil and gas, without knowledge of the character of naturally dissolved gas in crude oil, as these mixtures occur under reservoir conditions, and of the effects to be expected when gas is liberated from solution upon diminution of pressure as the fluid travels from the reservoir to the bottom of the well and up the flow column to the surface. Nevertheless, very little experimental work has been done in this country to determine these natural solubility or "liberation" factors.

In this connection, Sir John Cadman 8 in his recent paper on Persia wrote:

Certain problems, which have only recently attracted general interest, have been under investigation in the Persian fields for several years.

Among the problems which he named was determination of the physical characteristics and dissolved-gas content of crude oil under reservoir conditions and their relationship to pressure and temperature and determination of the permissible bottom-hole pressure drop during flow before unnecessary gas is produced with the oil. In writing of the special instruments developed by the Anglo-Persian Oil Co., Ltd., to obtain the necessary data, he said:

These include instruments for use at any point in a well: Pressure indicators—the first accurate bottom-hole pressures having been observed in 1928; tempera-

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ture recorder and sample taker for collecting samples of reservoir crude under full pressure.

The Bureau of Mines in January 1930 began a specific study of this phase of gas-solubility and gas-liberation research. The initial work was on well-head samples, from which valuable data were obtained, and a technique of operation was developed. A sampling device then was constructed which made it possible to take samples in wells at or near reservoir conditions and bring them to the surface for subsequent analysis in the laboratory. This instrument, devised by Lindsly, had its initial trial in March 1932 in the Seminole (Oklahoma) field, and later a series of tests was made in the East Texas field with the financial assistance of a majority of the oil companies operating in that field.

Although technical and economic conditions are unique in the East Texas field the results of the cooperative work indicate a satisfactory method for determining the maximum amount of energy in a given volume of reservoir oil. Data of this type can be used to design flow strings properly and, possibly, in the equitable valuation of properties if a pool is to be operated as a unit.

The data on shrinkage of oil caused by liberation of gas give workable figures with which to make reasonable estimates of the fluid content of the reservoir, and fair approximations of the quantity of recoverable oil can be determined.

The studies established an important technical fact influencing economic conditions, namely, that the gas begins to be liberated from solution in the East Texas reservoir oil only when the pressure reaches 755 pounds per square inch absolute. Incidental experiments were made on the compressibility of East Texas oil which showed that the over-all lifting effect caused by this phenomenon is relatively minor as a source of energy in raising the oil to the surface.

Fluid movement.—All production problems of the reservoir, the flow column, and pipe-line transportation problems are concerned with fluid movement caused by differential pressures. The results of recent research strengthen the consensus of opinion among engineers that the same physical laws of flow pertain to oil, gas, and oil-gas mixtures, whether the travel is in horizontal pipes, vertical pipes, or through the interconnected pore spaces of the oil-and-gas reservoirs. Naturally, the type of conductor and physical characteristics of the moving fluid change the character of flow, but various investigators have interpreted many of these conditions mathematically with reasonable accuracy. The flow of oil and gas, or mixtures of these substances, through sands and other porous media is more complicated than horizontal or vertical pipe-line flow, requiring more factors in the equations to be supplied empirically.

The work on this problem is closely related to that on well spacing.

Well spacing, also dependent upon the relationships of reservoir pressure and the solubility of gas in oil, has been an engineering and economic problem from the early days of the industry. Engineers are concentrating on this phase of petroleum production, and the petroleum literature contains numerous references to the many technical and economic factors connected with the problems. In fact, as recently as May 1933 a symposium on well spacing was held under the auspices of the American Petroleum Institute, and the subjects

* Lindsly, Ben E., work cited.
of "determination of permeability from field data" and "approximate comparative ultimate yield from varied well spacings" were considered. Except in some special fields where underground conditions are well known and the structure is under a unified plan of operation no definite criteria for well spacing have yet been determined, although a suggested method for determining the average permeability of a producing zone through knowledge of well performance is an important forward step.

Unfortunately, even when engineering facts regarding the reservoir have been known, it frequently has been impossible to work out rational spacing programs due to conditions of competitive drilling calling for a multiplicity of "off-set" wells in place of a few carefully selected wells which would have recovered the oil and gas effectively from the reservoir and would have prevented attendant physical losses.

The influence of porosity (or space between the sand grains) upon oil and gas production is well known. Recent scientific investigation has shown that the sand characteristic of permeability (broadly defined, the quality of allowing passage of fluids) is even more important than porosity if definite knowledge regarding fluid movement is to be obtained. The characteristics of porosity and permeability are related, but it is possible for a sand of high porosity to have a low permeability factor. One of the greatest advancements to the science of oil recovery will be the general acceptance of a definite meaning for the term "permeability." Discussions of fluid flow through porous media have been hampered because various investigators have presented their data on noncomparable bases. In 1932, the Bureau of Mines determined experimentally permeability factors in terms of "mean effective pore diameter" for a wide range of grain sizes and pressure differentials. Not only do these data apply in oil flow and well spacing, but they have been used practically in the natural-gas industry in gaging the ability of gas wells to produce gas, in calculating gas reserves, and in solving other gas-production problems.

In May 1933 the eastern district committee on development and production research, K. B. Nowels, chairman, of the American Petroleum Institute, issued a report on Proposed Standardization of Laboratory Technique and Nomenclature in the Determination of Permeabilities and Porosities of Oil Bearing Structures. This report was reviewed carefully by petroleum engineers at the midyear meeting of the institute, Tulsa, Okla. Although there was general agreement with most of the conclusions of the report, definite action was postponed until the subject can be given further study by the industry. A suggestion of the Tulsa meeting was that the unit of permeability be called the "perm" and that provision be made for both the C.G.S. (metric) and English system of units.

Water flooding.—Although data on the water-flooding problems in the Bradford (Pa.) district involve stimulative methods of oil recovery, nevertheless they augment and assist in the further understanding of fluid movement in other areas, particularly in those fields where a natural "flood", or encroachment of edgewater, is supplying part of the energy required to produce the oil. The knowledge regarding water displacement of partly depleted oil sands has been augmented to a noteworthy degree during the last year or so.
Improved production practices in water-flooding areas, superseding the older "circle-flood" and "line-flood" methods, include special well-spacing patterns, for example, the "five-spot" and hexagonal or "seven-spot" patterns; the use of pumps to increase the flooding pressure caused by the hydrostatic head of water; and delayed drilling, whereby the water is forced to move through the beds of low permeability, making it possible to recover more oil at faster rates when the producing well is drilled in the central portion of the flood zone.

A seemingly anomaly has developed out of the fact that, coincident with these newer methods making possible the extraction of more oil, a definite program of production control has been practiced in the Bradford area.

Oil recovery.—With special emphasis being laid on practices and methods that will help bring production and demand into balance, so-called "increased recovery methods" are not being studied and practiced as assiduously as before, when the then discovered reserves of oil were appreciably less than they are known to be today. Nevertheless, the total reserves are subject to exhaustion, and no method of oil production that leaves large quantities of oil in the ground unrecovered is economically sound. Therefore, the forward-looking viewpoint is to devise methods that will make it possible to increase the recovery from sands by stimulative methods.

The Bureau of Mines, the American Petroleum Institute cooperative project, and a few oil companies are about the only agencies that have maintained active work during the last year on this phase of production. The work at the California Institute of Technology has been mentioned. In the oil-recovery laboratory at the Petroleum Experiment Station of the Bureau of Mines data of a fundamental nature on repressuring, pressure maintenance, air and gas drive, and the complementary fluid-flow problem have been obtained and compiled. These data give evidence of practical application when the industry and the Nation again concentrate on diminishing reserves and maximum recovery of oil from the reservoirs.

Acid treatment.—During the latter part of 1932 and the early part of 1933 interest throughout the industry was directed to the new application of an old method of oil-production stimulation. This method is generally referred to as the acid treatment of wells. Several applications for patents on this method have been filed in the United States Patent Office. United States Patent 556669 (granted to Herman Frasch on March 17, 1896) describes a method by which the flow of an oil well in a limestone formation may be increased by treatment with a quantity of acid such as hydrochloric acid. In United States Patent 1877504 (granted to Dow Chemical Co. of Midland, Mich., assignee, on September 13, 1932) an improved method is disclosed wherein certain inhibitors such as arsenic compounds soluble in acid solution and aniline derivatives are used in conjunction with the acid to prevent excessive deterioration of the metal and other equipment in wells.

It is understood that this method was first tried in fields of Michigan with apparent success, and today acid-treatment methods, patented or otherwise, have been tried in almost all fields having limestone, chalk-rock, or dolomitic formations. According to reports, dolomitic formations do not respond as readily to acid treatment as those con-
taining a higher percentage of calcium carbonate. The method also has been tried in sandstones where the cementing material is of a calcareous composition.

Probably the Zwolle (La.) field has been the largest proving ground for this method. Up to May 1, 1933, 157 treatments had been made in the Zwolle area, a number of which were second treatments, and it is recorded that at least one well has been treated three times. The first treatment in the Zwolle field is reported to have been on December 5, 1932, although it appears that some other wells were treated in Louisiana before that date.

The procedure in treating the wells has technical interest, but this subject has been well covered in the literature and in the patents. A treatment usually consists of 1,000 gallons of solvent, with accompanying inhibitor.

According to computations, 1,000 gallons of the solvent should dissolve 10 to 11 cubic feet of chalk rock. This dissolving action appears to take place laterally rather than vertically. Suitable pressures (as high as 600 pounds per square inch in some wells) are maintained at the casing head, and the well may be allowed to stand for 12 to 48 hours. The cost of one treatment is about $250.

Some very spectacular results have been reported. For example, two wells in the Zwolle area before treatment were producing 8 and 6 barrels per day. These wells were treated, and after 120 days they were producing 295 and 435 barrels, respectively. It should not be inferred, however, that all wells are successfully stimulated. Some wells have failed to respond; others have an increased production for a short time only; and still others, which made no water before treatment, have increased in water production to as much as 50 percent of the total fluid produced. This variation in successful treatment is the natural result of the complicated reservoir conditions, particularly in the Zwolle area, and each well is a separate problem.

A detailed study of the results of acid treatment in the Zwolle field to determine the total increase in production caused by this stimulative method has not been completed. In time, an analysis of the production figures should show with reasonable accuracy results obtained for the field as a whole. It is likely that a creditable increase will be indicated.

The general economic effect of this method of stimulation is not yet known. If the method continues to be used extensively it appears that recoverable reserves will be increased. Naturally, the market outlet in a given area and the attending price of the oil will determine whether or not the method can be used to economic advantage by an operator in any given field.

Natural gas.—Although attention has been directed to the fact that oil and gas production are too closely related to be treated as separate subjects certain problems and developments pertain individually to natural gas. Cooperative research by the natural-gas industry and the Bureau of Mines has culminated in a method for gaging the capacity of natural-gas wells without the need for blowing large quantities of gas to the air in open-flow tests. This method and some of the results of its growing application are given in report V of the Federal Oil Conservation Board to the President of the United States, 1932, pages 53 and 54.
Other cooperative research by the natural-gas industry and Federal agencies has resulted in the working out of a new set of orifice coefficients and related facts that will make it possible to gage delivered gas with greater accuracy than heretofore.

In pipe-line transportation a definite criterion for designing and operating natural-gas transmission lines has been established. This criterion is based upon the results of experimental work lasting more than 5 years on representative commercial lines in all parts of the country.

The problem of combating external corrosion of pipe lines, both oil and gas, has been studied as a cooperative research by the industry and the Bureau of Standards. Many long-time tests of buried specimens, treated with various types of coating materials, have led to the development of suitable external corrosion preventive measures.

A recent study of the Bureau of Mines has determined many valuable facts regarding internal corrosion of gas pipe lines caused by traces of hydrogen sulphide, oxygen, and moisture. A report on some of the conditions contributing to "modified gaseous corrosion" in natural-gas pipe lines is in press. These studies are being extended with a view to determining more exactly the experience of companies in removing the causes that reduce the operating life of their lines.

In the construction of many of the longer natural-gas pipe lines (1929 to 1931), machinery largely supplanted the older hand methods of laying the lines. Mileage of line construction per day was increased to almost unbelievable figures compared with that of the older methods of construction. Recently, in an effort to help the unemployment situation generally prevailing throughout the country, some companies, for the present at least, have returned to the older manual methods of trenching, laying, and back filling.

DEEP WELLS

For several years the object has been to reach depths of 10,000 feet. In 1931 three wells were drilled to this depth. The first was the Chanslor-Canfield-Midway Oil Co.'s well near the Rincon (Calif.) field in June. Logan 10 has given a very complete record of deep wells drilled throughout the world, but deep-well records are subject to frequent change.

On May 10, 1933, the North Kettleman Oil & Gas Co. (Ed McAdams) Lillis-Welsh No. 1 well (Kettleman Hills, Calif.) reached a depth of 10,927 feet, with a reported gas pressure of 6,400 pounds per square inch—the highest ever recorded for a well. The full significance of this recent discovery of oil sand and high gas pressure below the Kreyenhagen shale, in what is believed to be a formation of Eocene age, has not been determined, but it indicates future oil and gas production at depths exceeding 2 miles. Previously, a well has been producing from a depth of 9,710 feet in the Ventura Avenue (Calif.) field. Some indication of the changed viewpoint regarding estimates of known reserves as influenced by deep drilling is discussed in report IV of the Federal Oil Conservation Board to the President of the United States, 1930, pages 6 to 8.

Well equipment.—Improvements in design and materials, stronger derricks and their appurtenances, the use of hard-facing alloys for bits, and better technique have made deep drilling possible. In this report it is impractical to mention and impossible to discuss the many new developments that have helped to bring about this changed condition of deeper drilling. Every new field is a proving ground for new equipment. For example, innovations in the Seminole (Okla.) field were improved upon and added to in the drilling of the Oklahoma City field. The problem of keeping holes straight was met, and ways were found to correct this condition. Some form of weight indicator is now considered an essential part of the drilling equipment of a well. The technique of casing practice has changed materially in the last few years. With wells reaching depths of 10,000 feet suitable clearance between strings of pipe must be maintained. Recently, a new type of flush-joint casing (both inside and outside) has been tried and found to have several advantages over older styles of casing joints. It is claimed that the efficiency of this type of joint is satisfactory and that, for the same size of flow string, less earth need be removed by the drill with an attendant lessening of drilling time and costs.

The invention of equipment suitable for drilling through high-pressure areas and for running tubing in wells under high pressures has been an important engineering achievement. By the use of snubbing equipment and hydraulic cylinders, drill pipe or tubing may be forced into a well under pressure through a suitable casing-head stuffing box or packer. Not many years ago, if a well encountered high pressures, a “blow-out” was likely to occur.

“Christmas-tree” connections at the well head now are manifolding systems of high-pressure pipe and fittings that make the wellhead fittings of a few years ago appear to be exceedingly insecure.

The limit of deep drilling has not been reached. In fact, it has been reported that a new type of rotary table and draw works has been designed and developed for drilling to 15,000 feet. The machine has no headboards, and there are 4 shafts instead of 3 (the usual practice in heavy-drilling equipment). Two speeds are provided for the rotary drive, one for drilling and the other for coring operations.

Deep-well pumping.—With the increased depths of wells, it has been necessary to devise equipment by which the oil may be lifted mechanically after the natural flowing life has ceased. Even now in the Oklahoma City field several wells have ceased their natural flow, and the gas-lift method, used so generally in the Seminole area, is being used to lift the oil from these deep wells. The indications are that the gas-lift method will again be used extensively, especially in producing oil from deep sands in various parts of the country when “flush” production no longer supplies a large part of current market needs.

A number of deep-well pumps have been devised, and slow-speed pumping has increased over-all efficiency. A positive displacement pump of the rotary type, motivated by electrical energy conducted to the bottom of the well through insulated cables, has attracted attention. The fluid-plunger pump is another recent development. These and other pumping methods are making it possible to lift oil when the natural energy of the reservoir no longer brings oil to the surface.
MOVING EQUIPMENT

One of the essentials of intensive drilling campaigns in fields of diversified ownership is speed in setting up and dismantling equipment. As the equipment at one well is used in drilling several others and the time required to move the equipment, although necessary, is nonproductive, close study has been given to developing a plan which will reduce this time to a minimum, especially in the East Texas and Conroe fields. The layouts of the drilling rigs have been standardized and a high degree of organization and team work in the moving schedule has been developed.

By having adequate transportation facilities, including caterpillars and trucks provided with crane equipment, by having the draw works, engine, feed pumps, and other appurtenances on welded-steel skids, and by providing flange or flexible couplings for all pipe connections, it is possible to dismantle completely and set up a drilling rig in approximately 3 days. According to Teague,11 the Humble Oil & Refining Co. has been able to make 15 moves of equipment at an average cost of $230, including the movement of machinery and drill pipe. Although this development is largely one of organization, nevertheless many technical factors are involved, and the economies effected by this plan of organization are far-reaching.

CONCLUSION

Industry, Government, and the public are vitally concerned in the resources of oil and gas and in their continued supply without evident shortage. The growth of the petroleum and natural-gas industry has been remarkable, and the ability of the industry to meet the demands placed upon it has been the result largely of technical knowledge, most of it attained recently. Production methods conceived only a few years ago now supply a large part of the crude oil from which the refined products are made. The research agencies of the industry and Government have been responsible for most of this technical progress, with some outstanding individual contributions. In the past the public generally has failed to understand the significance of technical research, but more is becoming known about the effects on social economy of an orderly recovery of oil and gas and the proper utilization of the manufactured products.

Recent engineering advancement has complicated many of the economic problems during a period when all industries have been depressed, but statements that technical research and its resulting practical applications in the petroleum and natural-gas industry have acted as a retarding agent in the stabilization of economic conditions have been made by persons who have failed to learn that the best attainable engineering practices and sound economic principles cannot be dealt with separately in industry because the two are synonymous.
