Bell

El Dorado, Arkansas oil and gas fields

STATE OF ARKANSAS
Bureau of Mines, Manufactures and Agriculture
JIM G. FERGUSON, Commissioner

The El Dorado, Arkansas Oil and Gas Field

Geological Outline
Operation Methods
Conservation

* * *

By
H. W. Bell and J. B. Kerr of
the U. S. Bureau of Mines

* * *

Published Under the
Joint Auspices of the
UNITED STATES BUREAU OF MINES, THE UNITED STATES GEOLOGICAL SURVEY, THE UNIVERSITY OF ARKANSAS AND THE STATE BUREAU OF MINES, MANUFACTURES AND AGRICULTURE

LITTLE ROCK, ARKANSAS

1922

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DATA BY J. A. BRAKE,

State Oil and Gas Inspector

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Foreword

IN THE absence of a State Geological Survey, and without an appropriation of any kind for research work, the Bureau of Mines, Manufactures and Agriculture is fortunate in being able to give to the public this report on the petroleum and natural gas resources of the El Dorado field, together with the timely recommendations embraced therein for the guidance of drilling operations and for the conservation of these important minerals.

Publication of this material has been made possible by a prompt and cordial response to the State's call for co-operation upon the United States Bureau of Mines and by substantial aid from the University of Arkansas and the State Banking Department. The report also includes timely data on the geological features of the field previously issued in press bulletins by the United States Geological Survey.

It has been difficult to work out some of the problems met with, both in a study of the geology of the region and in the methods of drilling and controlling the wells, and the report has been delayed to await the settlement of some of these perplexing questions. It has been especially difficult to correlate the well logs, necessary to a correct understanding of the structure, due chiefly to the use of rotary equipment, which gives up few fossils. The report was held up some three months awaiting the geologic matter.

With this explanation, I am pleased to give the public the report as furnished by the co-operating agencies of the Federal Government, without change. The expense of publication is defrayed wholly by this department, out of its limited printing fund. A copy of the report may be obtained free by any citizen of Arkansas or person residing outside of the state who is actually interested in oil and gas development.

Jim G. Ferguson

Commissioner of Mines, Manufactures and Agriculture.

JOHN C. SMALL,
Editor of Publications.

Airplane View Showing Typical Topography of El Dorado, Arkansas, Oil Field

Drilling and Production

H. W. BELL* AND J. B. KERR†

The United States Geological Survey has compiled a report dealing with the geologic features, the accumulation of oil and gas and the possibilities of extending the producing area of the El Dorado Oil Field, Arkansas. The engineers of the Bureau of Mines have made a study and prepared the following data on methods of drilling and production. It is believed that if some of the suggestions in this report are adopted, the operator will enjoy a greater profit. These suggestions are primarily based upon the principles of the conservation of oil and gas.

The El Dorado Oil Field, Arkansas, has developed rapidly since January 10, 1921, when the first well that produced commercial quantities of oil was completed. The low prices for oil and lack of adequate pipe lines and tankage in the earlier months, did not apparently retard the rate of development to any extent. Up to November 1, 1921, the field had produced approximately 10,000,000 barrels of oil from a proven oil area of about 4,825 acres, which was an average of 2,150 barrels to the acre.

The maximum daily production of the field was about 77,000 barrels, which occurred for a few days in August, 1921. The production decreased to about 44,000 barrels per day by the middle of October, 1921. Since August, 1921, producing wells were completed at the average rate of about twenty per week for three months. By the end of October, 1921, about 460 commercial oil wells had been completed. The initial productions of the oil wells ranged from only a few barrels to 15,000 barrels of oil per day and the gas wells up to a maximum of about 40,000,000 cubic feet of gas per day. Unfortunately, some of the wells have been inefficiently handled, which has resulted in considerable waste.

The El Dorado field furnished the first commercial production of oil in the State of Arkansas. Gas has been produced since about 1905 in the Fort Smith gas field, which lies near the Oklahoma line and some 175 miles northwest of El Dorado. Because of this gas production, the Arkansas Legislature passed an Act in 1917 which dealt with the conservation of oil and gas. The situation for El Dorado was therefore unique, in that the first oil production of the State was immediately subject to the regulations of a conservation commission.

The excessive production of sand with the oil has been the source of much trouble to the operators and has caused them to give considerable attention to the handling of this problem.

The excessive production of water in some areas has curtailed or stopped the production of oil and gas. Several factors have contributed to a more rapid increase in water production than was necessary. One object of this report is to indicate the harmful effect of water and to discuss the most effective methods of excluding the water and operating the properties.

ACKNOWLEDGMENTS

This report was prepared at the request of and in co-operation with the State of Arkansas, whose financial aid made the work possible. The University of Arkansas, the Arkansas Bureau of Mines, Manufacture and Agriculture, and the State Banking Department provided funds.

The writers wish to acknowledge the assistance of the respective department chiefs, Dr. J. C. Futrall, Jim G. Ferugson and W. T. Maxwell. Assistance was also given by Messrs. J. A. Brake, State Oil and Gas Inspector; E. E. Winger, Oil and Gas Inspector and formerly expert driller for the Bureau of Mines, and John J. Doyle of the Margay Oil Company.

The operators and others familiar with local conditions kindly furnished logs of wells, production records and miscellaneous information. Messrs.

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L. W. Mosburg and H. W. Hoots of the U. S. Geological Survey co-operated in the collection of data. The El Dorado Chamber of Commerce furnished space and equipment for field headquarters.

Thanks are extended to the following, who co-operated in the preparation of the report: Eugene Holman, P. H. Walber, D. B. Harris and J. L. Finley of the Humble Oil & Refining Company; J. E. Todd, V. C. Megarity, W. C. O'Ferrell, S. C. Strathers, F. Ray McGrew, F. B. Bimmel, and Howard Murphy, of the Standard Oil Company of Louisiana; E. J. Raisch of the Federal Petroleum Company; H. Gandy and J. W. Westmoreland, of Gulf Refining Company; J. H. Mann and C. M. Palmer, of the Mann Oil Company and Imperial Oil Company; J. F. Wright, oil lease superintendent and deputy conservation agent; Roy Wilson, H. S. McGeath, E. D. Holcomb, of the Magnolia Petroleum Company; A. J. Jones, Kansas Gulf Company; E. E. Windsor Southwestern Oil Company; Bradford Hearn, Shreveport Producing and Refining Company; Elton Rhine and J. T. Lord, of the Amerada Petroleum Company; J. B. Sowell and W. M. Coats, of the El Dorado Natural Gas Company; George M. Sonfield and Jos. Parks, Sun Company; J. O. Nelson, J. P. Smoots, Arkansas Natural Gas Company; Blaine Johnston, White Oil Corporation; George McPherson, operator; H. W. Holland, El Dorado Petroleum Company; Charles Carter, drilling contractor; Ed Hollyfield of Hollyfield et al.; C. H. Kampeter of Parry Oil Company; D. J. & J. H. Johnson of Johnson Drilling Company; H. C. Eddy of Petroleum Rectifying Company; A. J. Graff, of Constantin Refining Company; H. N. Spofford, of Gladys Belle Oil Company; A. K. Gordon of Louisiana Oil & Refining Company; G. M. LeGrande of the Michigan-Arkansas Oil Company; C. E. Larder, of Sinclair Oil Syndicate.

The work was carried on under the general direction of Mr. A. W. Ambrose, Chief Petroleum Technologist of the Bureau of Mines. T. E. Swigart offered many helpful suggestions in the preparation of the manuscript, and W. W. Cutler assisted in the construction and preparation of the production declines and appraisal curves and data.

The writers wish to express appreciation for help and criticism to the following members of the Bureau of Mines; R. Van A. Mills, W. W. Scott, W. H. Strang, H. H. Hill, J. H. Wiggins and W. B. Lerch.

History of Development

First Wells:

The first successful well in the El Dorado field was a gas well brought in by the Constantin Oil & Refining Company, in Section 12-18-16 (see Map, Plate A), in April, 1920. This gasser had an initial open flow capacity of about 30,000,000 cubic feet per day and a rock pressure of 960 pounds per square inch. Several other gas wells were drilled in Section 12 and in the adjoining Section 1. Oil did not begin to appear in these wells in important quantities for some months and only shortly before the oil boom was initiated by the advent of the Busey well did they show oil at all. These first gas wells did not attract much attention from the public, probably because the Fort Smith gas field had produced no oil in fifteen years, and it was the general impression that there was little likelihood of finding oil at El Dorado.

During the latter part of August, 1920, drilling operations were started on the Armstrong farm in the NW¼ of Section 31-17-15 by Mitchell and Bonham. Considerable mechanical difficulty and financial trouble were encountered in drilling this well and it has been reported that the hole was twice abandoned and the derrick skidded a short distance for a fresh start. Dr. S. T. Busey became interested in the well and assisted in pushing the work to a successful conclusion. The well came in January 10, 1921, with a large amount of gas and an oil production probably exceeding 5,000 barrels per day. This well has since been known as the Busey well.

The Busey well was drilled with rotary tools and that practice has been followed for all other wells in the field. In a few instances, wells have been finished with cable tools. Adequate precautions were not taken and the Busey well blew wild for some time. The ground and foliage were sprayed with oil for a considerable area about the derrick. After about fifteen days blowing wild, water began to appear and the fluid turned to a brownish color. Efforts to control the well were unsuccessful. The water increased rapidly until the oil and gas were completely choked off, limiting the well's productive life to about forty-five days.

In drilling the Busey well, sand and lignite were logged at 1171-1180 feet and 1201-1211 feet. The log is not complete, but shows the lower formations as follows:

2052-2062 feet—shale.
2062-2072 feet—lime, rock, gas.
2072-2073 feet—gumbo.
2073-2176 feet—not logged.
2176 feet—top of sand.
2223 feet—total depth.

The well had either been drilled too deep or "drilled itself" into bottom water by the unrestrained flow of gas. It is likely also that the top water had not been excluded. After the oil production had been completely drowned out, plans were made to repair the well, in order to protect the surrounding territory and to make the well produce again. On account of the double source of water and the large quantity of formation that had been removed during the blowing period, E. E. Winger, then with the Conservation Commission of Arkansas, advised that the well be abandoned.

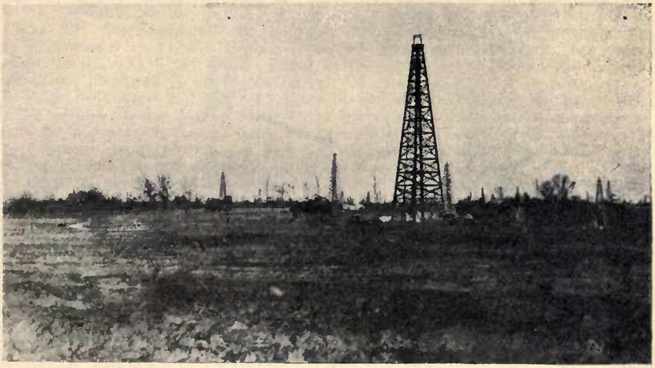

Plate I—Busey Well (shown in foreground) Section 31-17-15, the first oil well completed in the El Dorado Field. Well began producing January 10, 1921. Photo taken after abandonment of well.

Sept. '21

The well was abandoned during the latter part of April, 1921, under the direction of Mr. Winger and Mr. J. A. Brake, State Oil and Gas Inspector. The abandonment work included cleaning out to bottom, with the hole full of water, placing 90 sacks of thickly-mixed cement on bottom with a dump bailer, and filling the hole full of mud to the surface. The recommendation to apply extra pump pressure to the cement in the hole was not carried out, principally on account of the scarcity of suitable equipment at that time. Plate 1 shows the Busey well and surrounding wells (September, 1921). The scarcity of derricks in its immediate vicinity is noticeable.

Before the end of March, 1921, about twenty oil producers had been completed. The majority of these wells were drilled in a southerly direction from the Busey well. The second and third oil producers were located in Section 6-18-15, the next six in Section 31-17-15; then one in Section 5-18-15, one in Section 32-17-15, one in Section 25-17-16, two in Section 7-18-15, one in Section 30-17-15, four in Section 31-17-15, and one in Section 5-18-15. The development spread rapidly to the south as the productive area was found to extend only about a mile to the north of the discovery well.

Table 1 shows the number of producing wells, oil production and deliveries, stocks, and other data by months from January to October, 1921. The Total oil production of 10,380,000 barrels is estimated and meant to include evaporation losses, seepage and other lease losses, fuel burned in field, oil

TABLE I

Production, Deliveries and Stocks of Oil and Dry Holes and Gas Wells of El Dorado Oil Field, January to October, 1921

MONTH 1921	OIL PRODUCTION, BARRELS				DELIVERIES, BARRELS			STOCKS End of Month Barrels		Cumulative Number Dry Holes Drilled	Cumulative Number Dry Gas Wells
	Av. No. Wells Producing (for full Month)	Estimated Total	Estimated Daily Average	Estimated Daily Average Per Well	Total	Pipe Line	Tank Car	Steel	Field		
January	1	80,000	4,000	4,000	......	......	......	......	......	......	1
February	5	168,000	6,000	1,200	......	......	......	......	......	......	2
March	23	930,000	30,000	1,300	......	......	......	......	......	......	2
April	35	788,000	26,250	750	274,580	......	......	......	......	1	3
May	64	837,000	27,000	422	549,760	......	......	......	......	19	5
June	144	1,134,000	37,890	263	1,035,100	......	......	647,850	97,650	19	7
July	210	1,642,000	53,000	252	1,551,160	......	......	850,000	143,000	25	9
August	290	2,015,000	65,000	224	1,658,500	1,004,500	654,000	902,500	60,000	60	12
September	350	1,410,000	47,000	134	1,430,200	986,900	443,300	753,000	100,000	66	15
October	420	1,376,000	44,400	106	1,243,300	958,300	285,000	1,174,600	125,000	73	17
294 Days........	......	10,380,000	35,300	......	7,742,600						
		9,042,200	......	......	......						
		1,337,800	Oil unaccounted for								

used in local refineries, tank car deliveries, pipe-line deliveries and storage oil at the end of October. Some of the factors are admittedly difficult of estimation, but it is reasonably certain that at least 10,000,000 barrels of oil had been removed from the underground reservoir by November 1, 1921.

Acreage and Oil Prices:

Following the completion of the Busey well, which initiated the boom, the area within a radius of several miles from the discovery well, was leased by individuals and corporations. The prices paid for leases ranged from a few dollars to $5,000 per acre, depending primarily on the distance and amount of the nearest production.

The only outlet for the first production was by tank cars. It was fortunate that the discovery well was so close (about two miles) to El Dorado, a town of about 5,000 population and served by two railroads. Most of the first oil marketed brought as low as 30 cents per barrel. Some of it is reported to have been sold at that figure, even after The Louisiana Oil & Refining Company opened its 6-inch pipe line on June 24, 1921. This company paid 40 cents per barrel for oil below 34 degrees Baume gravity, and 50 cents per barrel for oil above that gravity. On June 17, the Standard Oil Company posted a schedule of 50 cents per barrel for oil less than 33° gravity, 60 cents for 33° to 35° gravity and 70 cents per barrel for oil above 35° gravity. On September 22 the price went to 80 cents and 90 cents for oils below and above 34° Baume gravity. The maximum limit for water and sediment was 3 per cent. Some of the small purchasers were paying a premium of about 10 cents per barrel.

Prior to August 15, 1921, considerable oil was sold at figures below the posted prices of the larger purchasers on account of the storage congestion. It is reported that a scale of 30, 40 and 45 cents per barrel was in effect simultaneously with the higher schedules and that the smaller purchasers often selected only the oil that exceeded 34 gravity and that ran less than 2.5 per cent B. S. and mud. These circumstances appear to have worked some discrimination against the small purchaser after the congestion was relieved. By the end of October, 1921, the top price per barrel had reached $1.50, and at present (January, 1922) the posted price is $1.75 for all oil under 34° Baume, and $2.00 per barrel for 34° Baume and above.

Storage and Marketing Facilities:

At the end of October, 1921, nearly 4,000,000 barrels of storage had been erected. It was composed of:

61—55,000 barrel steel tanks	3,355,000 barrels
9—37,500 barrel steel tanks	337,500 barrels
Miscellaneous	250,000 barrels
	3,942,500 barrels

The Louisiana Oil & Refining Company began pumping through its 6-inch line June 24, 1921. The Standard Oil Company of Louisiana started to operate its 8-inch line on June 26, 1921, and the Shreveport-El Dorado Pipe Line Company first moved oil through its 8-inch on August 9, 1921.

Seventeen loading racks with a total capacity of 401 tank cars, or about 80,000 barrels, of oil daily were in operation for tank car transportation by the middle of July, 1921.

There are twelve local refining plants of varying capacities and purpose. They have handled only a small proportion of the output of the field up to November, 1921. The following list covers those operating in January, 1922:

Name	Capacity Bbls. per Day
Airdale Oil & Refining Company	500
Arkansas P. & R. Company	2,000
Abner Davis Ref. Company	500
El Dorado Oil Ref. Company	2,000
Grison Ref. Company	5,000
Jones, R. C.	800
Lion O. & R. Company	5,000
New-Ark Pet. Corporation	2,500
Petroleum Products Company	2,000
Red River Refining Company	1,500
Shippers Petroleum Company	2,000
Union Pipe Line & Refining Company	3,000
	26,800

State Conservation Commission:

The original Arkansas law dealing with the conservation of oil and gas was passed by the Legislature in 1917. On February 18, 1921, thirty-nine days after the first commercial production of oil in the State, Act No. 144 was approved. This Act supplemented the basic law of 1917 and furnished a workable law for the Conservation Commission. The State laws relating to oil and gas are published in a State Report entitled "Minerals in Arkansas."

The Conservation Commission, headed by J. A. Brake, has been handicapped financially and has, therefore, been unable to extend supervision to all of the important features connected with development. However, it did good work insofar as its funds and personnel permitted.

The prnicipal regulations which the Commission attempted to enforce are, in substance, as follows:

(1) Wells that produce gas must be closed in and used for fuel purposes solely. The tendency was to waste enormous quantities of gas in an effort to "blow a well in" to oil production.

(2) The casinghead control fittings, usually known as a "Christmas Tree" (see Plate XV) equipment must be heavy enough to insure safety under the pressure obtaining and be constructed in a manner to insure control of the well in case of emergency.

(3) Each well shall be cased with at least two strings of pipe, the first landed and cemented with at least 25 sacks of cement at about 200 feet, and the second landed and cemented with at least 60 sacks of cement at a short distance above the oil sand.

(4) Abandonment of wells shall be accomplished with the use of mud or cement or both in a manner adaptable to the particular case and satisfactory to the Commission.

At present, there is no money appropriated or tax levied to carry on the conservation work in the State. Because of the treacherous nature of operating conditions, supervision by a commission of competent engineers should result in large savings of oil and gas. It would, therefore, be desirable to provide an adequate annual budget for such a commission, in order to insure a definite and complete program of conservation. This work is of great importance at this time, because of the opportunities to effect conservation in a new field. Once a field has been improperly drilled, it is usually difficult and expensive to repair the damage. If a new field is discovered in Arkansas a trained personnel would be equipped to meet the situation.

Co-operation by the U. S. Bureau of Mines:

By the middle of March, 1921, the situation at El Dorado had become a serious problem from the standpoint of conservation. Assistance from the Bureau of Mines was requested by the Conservation Commission, upon the advice of J. H. Mann of the Imperial Oil & Gas Company. Accordingly. E. E. Winger, consulting driller of the Dallas, Texas, office, was detailed to the work. J. B. Kerr, petroleum engineer, was later sent from Dallas to render further assistance.

The bureau men conferred with operators and did work on wells for the exclusion of water by means of cement, which had to be properly mixed and placed. At times, this involved the use of extra closed-in pressure. In some cases, cement was placed behind the casing to shut off top water, and again bottom water had to be shut off by cement.

About the middle of April, 1921, Mr. Winger resigned from the Bureau of Mines and joined the forces of the Conservation Commission of Arkansas. He made notable progress in introducing efficient methods of finishing wells and excluding water. J. B. Kerr made drawings illustrating methods and appliances and constructed a contour map, showing the shape of the top of the productive oil sand.

In August, 1921, the Bureau was able to assign the senior author to the El Dorado field and, with the assistance of J. B. Kerr, sufficient field work was done to warrant the compilation of this report.

Drilling Methods

Equipment and Power:

The use of rotary drilling is rapidly increasing, especially in loose formations, and it is now used in practically all loose or soft formations that are deep enough to justify the expense of its installation. Factors working against rotary installation are:

(1) Usually, a very poor well log is obtained, and many formations capable of production have been passed by without testing. In general, the contents of sands are not so well known in rotary drilled fields as in a cable tool drilled field,, and this results in more wells being drilled into water;

(2) When the formations are very porous, considerable expense is necessary for extra mud to mud off the porous-mud-absorbing formation and thus allow continuous circulation;

(3) When the formations are hard and stand up well without mudding, cable tools can be used to advantage, as long strings of casing can be inserted in the open hole;

(4) When there are frequent changes in formation, from such as hard rock to clay or gumbo, a continual change from rock bits to fish-tail bits is necessary because of the "gumming up" of the cone bits in soft, sticky material, and this causes delay.

The success of cable tools in the El Dorado field is not known, but it is probable that on account of the loosely consolidated formations, it would be more difficult and costly than the rotary method. The wells of the El Dorado field have been drilled to the last water shut-off point, in every case, with rotary tools. The rotary equipment used has varied in character from old style to new style rotaries. Four-inch drill pipe has been used throughout the greater portion of the hole. So far, no installations of high-power twin cylinder steam engine rotaries have been reported. A few wells have been drilled with gas engines and satisfactory results are reported. The comparatively easy drilling at El Dorado makes feasible the use of gas engines of ordinary sizes. The boiler installation can thereby be greatly reduced and of sufficient size to meet the needs of operating the pumps and forge. The gas engines are equipped with an electric magneto, an electric Wyco coil type or compression hot point system of ignition. The old system of hot tube ignition is not used in this work, because of its unreliability and the danger of an open flame in a gas-producing area. It is necessary to use an ignition system that can be correctly adjusted by the men available, because of the excessive strains in the engine and loss of power which results from improper timing.

Electric power for drilling has not been used at El Dorado, Arkansas. Although electric drilling has proven efficient and economical in other fields, its introduction in Southern Arkansas has been retarded by the absence of available power (unless private generating plants are constructed) and by the lack of familiarity of the local operators with the system. It is true that more energy can be developed with oil or gas by means of internal combustion engines than by generating steam with the same fuel. However, economy of power does not always dictate the practice in oil and gas fields, where gas is cheap and not marketable.

The generation of electricity by means of internal combustion engines has proven economical in many cases for drilling and general use on oil properties. This is especially true when cheap gas is not available and oil is used as the explosive fuel. Under certain conditions, it is more economical to generate electricity with steam turbines and transport it by power lines than to use the steam direct through long uninsulated pipe lines. There are many factors that determine the most practicable power to use for drilling. Mechanically, steam is well adapted to the work and because of the abundance of gas, with a limited market, it was used extensively in the El Dorado field.

In the fields where it has been tried, the electric motor for drilling has proven satisfactory from a mechanical standpoint for both standard and rotary work and very often reduces the cost of operations. A 75-horse-power motor is usually installed for drilling and a 40-horse-power motor for the mud-circulating pumps. The principal advantages over steam operation are the omission of boiler installations and repairs and almost complete elimination of water requirements.

Casing Programs:

Wells in this field are cased with at least two strings of pipe, the first being 12½-inch or 10-inch conductor pipe which is cemented at about 200 feet and the other a water string of usually 6-inch 8-thread pipe. In some wells, 8-inch pipe has been used as a second string, but probably in no case has it been used as the final water string. The general practice has been to check the hole and casing measurement with a steel tape. Some serious errors in measurements, however, are reported to have resulted in casing off oil or drilling into water. It is practically impossible to know the exact depth of the hole by adding the figures for lengths of joints of casing.

The smaller pipe used in El Dorado usually has 8 threads per inch. The larger sizes having 10 threads per inch are 12½-inch 40 pounds; 10-inch 32 and 35 pounds; 8¼-inch 32 pounds. Sizes of casing having 8 threads per inch are 8-inch 29.2 pounds and 6-inch 19.5 pounds. The liners are different weights of 4-inch to 4½-inch pipe.

There have been no cases of collapsed casing reported to the writers thus far, because El Dorado operators in most cases used good weights of casing for the depths. Comparatively shallow depths to the shut-off point and small sizes of casing used have also assisted in preventing collapse. In Table No. 2 (a), the collapsing depths of various casings are shown in connection with the other data. Table No. 3 (b) shows the amounts of cement required for different sizes of casings and holes. Both of these tables were prepared at the Denver, Colorado, office of the U. S. Bureau of Mines, under the direction of F. B. Tough.

In selecting casing for a water string, attention should be given to its weight in order to avoid collapse by outside water or mud pressure. However, collapsed casing cannot be prevented when formations shift. The best practice is to choose a string of casing that will stand the fluid pressure at the prescribed depth with a safety factor of two. If a given size and weight of casing is supposed to collapse by an external pressure due to 3,000 feet of effective water column (1,302 pounds per square inch), that casing should not be used to a depth greater than about 1,500 feet below the natural water level outside the casing unless enough cement is used to protect a considerable length of the lower portion of the casing. When rotary drilling is employed, the gravity of the mud and the full column outside the pipe to the surface, must be considered. For example, if the rotary mud back of the casing has an average specific gravity of 1.25 (25 per cent heavier than water) or 5/4 the weight of water, a given string of casing for safety should have an effective column of mud, on the outside of the pipe, of only 4/5 of the safe depth for clear water as recorded in Table II. Another way to arrive at the safe depth for casing in mud is to divide the safe water depth by 1.25, or whatever happens to be the specific gravity of the mud. If it could be assumed that the fluid standing outside of the casing would remain undisturbed, a factor of safety 1.5 or 1.4 might be considered. Earth tremors and shifting of formation may have considerable water-hammer effect, regardless of whether the walls actually squeeze the casing.

It is usually found economical for deep wells, to make up suitable combination strings with the heaviest pipe on the bottom and the lengths of the lighter weights proportioned according to their safe depths. In many oil fields, two different weights of pipe are often used, but a combination of three is less common. As far as is known by the writers, no combination strings have been used at El Dorado.

Testing Formations:

In at least the first work of developing underground deposits of oil and gas in any area, drilling methods should be modified in such manner as to give the most accurate knowledge of formations and their fluid content. There are many examples of wildcat wells condemning territory by passing through commercial deposits without testing them and, in some cases, without suspecting their presence. There are also many instances where high-pressure oil and gas have been found without any particular care being taken, but where the presence or capacity of upper deposits remain unknown, and the exact nature of the producing horizon was not learned. Oil

TABLE III

Table of Capacities Between Casing of Different Sizes and Weights

—Courtesy F. B. Tough

Inside Strings		NUMBER OF LINEAR FEET OF SPACE BETWEEN CASINGS FILLED BY ONE SACK OF CEMENT WHEN SET																									
		Outside Strings. Lower numbers refer to weights of casings (with couplings) in pounds per foot.																									
Nominal Diam.	Actual Outside Diam.	5 3/16 17	5⅝ 20	6¼ 17	6¼ 20	6¼ 24	6¼ 26	6¼ 28	6⅝ 17	6⅝ 20	6⅝ 24	6⅝ 26	6⅝ 28	6⅝ 30	7⅝ 26	8¼ 24	8¼ 28	8¼ 32	8¼ 36	8¼ 38	8¼ 43	9⅝ 33	10 35	10 40	10 45	10 48	10 54
4	4.25	3.4	19.1	10.3	10.9	11.9	12.4	13.0	8.2	8.5	9.1	9.5	9.8	10.2	5.5	4.2	4.4	4.5	4.7	4.8	5.0	2.9	2.4	2.4	2.5	2.5	2.6
4¼	4.5		24.0	11.6	12.3	13.6	14.4	15.2	9.0	9.4	10.1	10.5	11.0	11.4	5.9	4.5	4.6	4.7	4.9	5.0	5.3	3.0	2.4	2.5	2.6	2.6	2.7
4½	4.75			13.4	14.4	16.1	17.2	18.4	10.0	10.5	11.5	12.0	12.6	13.2	6.3	4.7	4.8	5.0	5.2	5.3	5.6	3.1	2.5	2.6	2.6	2.7	2.8
4¾	5.0			16.0	17.4	20.0	21.7	23.6	11.4	12.1	13.3	14.0	14.8	15.7	6.8	5.0	5.1	5.3	5.6	5.7	6.0	3.2	2.6	2.7	2.7	2.8	2.9
5 3/16	5.5								16.1	17.6	20.3	22.1	24.1	26.5	8.3	5.7	5.9	6.2	6.5	6.7	7.1	3.4	2.8	2.8	2.9	3.0	3.1
5⅝	6.0														10.9	6.8	7.1	7.5	8.0	8.2	8.9	3.9	3.0	3.1	3.2	3.3	3.4
6¼	6.625															9.3	9.9	10.7	11.6	12.2	13.8	4.6	3.4	3.5	3.6	3.7	3.9
6⅝	7.0	11 60	11⅝ 40	12½ 40	12½ 45	12½ 50	12½ 54	13½ 42	13½ 50	14½ 47						12.2	13.2	14.7	16.5	17.6	Will not go in	5.2	3.7	3.9	4.0	4.1	4.3
7⅝	8.0	3.9	3.1	2.2	2.3	2.3	2.4															8.4	5.2	5.4	5.6	5.9	6.4
8¼	8.625	4.8	3.7	2.5	2.6	2.6	2.7																7.1	7.6	8.1	8.5	9.5
9⅝	10.0		6.8	3.7	3.8	4.0	4.1	2.5	2.6	1.9	15½ 70	16 Hole	17 Hole	18 Hole	19 Hole	20 Hole	20 90										
10	10.75			5.2	5.4	5.7	6.0	3.1	3.2	2.2	1.7	1.4	1.2	.97	.82	.71	.80										
11	11.75							4.7	5.1	2.9	2.2	1.7	1.3	1.1	.90	.77	.88										
11⅝	12.0							5.5	5.9	3.2	2.3	1.8	1.4	1.1	.93	.79	.90										
12½	13.0									5.2	3.3	2.3	1.7	1.3	1.1	.87	1.0										
13½	14.0										5.8	3.4	2.2	1.6	1.2	.99	1.2										
14½	15.0												3.2	2.0	1.5	1.2	1.4										
15½	16.0													3.0	1.9	1.4	1.8										

deposits that are now commercially productive or that may become so within a reasonable period, should be protected from infiltrating water and from dissipation into other strata. Without a comprehensive knowledge of all of the formations penetrated, it is impossible to know whether and how to protect strata for future use.

In some fields, cable tool drilling is generally the best adapted to the accurate determination of underground conditions. Unfortunately, this method cannot be used in many fields, because of the soft and caving nature of the formations. Satisfactory results can be obtained with the rotary system if sufficient care is exercised. In order to obtain adequate knowledge with rotary, samples should be taken from the ditch at least every ten feet of hole made. The speed of the upward current of mud should be figured and the samples checked back, through the time interval, against the feel of the tools and action of the pumps. As the driller relies mainly on the feel, to detect a change of formations, cuttings should be studied with relation to changes noted by the feel. Samples of porous material should be carefully examined to determine the fluid content. When practicable, the core barrel should be used repeatedly when nearing the productive horizons. The core is a correct sample of the formation and will usually disclose the presence of any oil in the stratum. The future of accurate information obtained from rotary-drilled wells is dependent to a large extent on a practicable method of sampling formations and, at present, the core barrel seems to have the most promise.

It is advisable to test a sample from the ditch with chloroform, ether or carbon tetrachloride, in order to indicate the presence or absence of oil. In making this test, the sample should be thoroughly shaken with the solvent and allowed to settle for some time and the liquid then run through white filter paper. If petroleum is present in appreciable quantities, a dark ring will appear on the filter paper.

In general, ditch samples are obtained in two ways. Some drillers thin the mud, while others thicken it and increase the speed of circulation. Both methods possess merit and are usable for the same general purpose, though the principles are somewhat different. Thinning the mud lightens the weight of the column of liquid in the hole and decreases the pressure opposite the sand, so that any oil or gas can come into the hole more easily.

Gas is somewhat soluble in water. Methane, the largest constituent of natural gas, is 3.9 per cent (*) soluble in water at ordinary temperature and pressure. It is probably much more soluble at the increased pressures obtaining underground on account of the compressibility of gas and the non-compressibility of water. The solubility of gas in water assists it in traveling from the formation to the hole, because when a substance is dissolved in a liquid, it tends to diffuse equally to all parts of the liquid. Hence, solubility and diffusion help to explain why a gas is able "to show" when the fluid pressure exceeds the rock pressure. Such a condition may exist when the sand is not taking water and a condition of stability exists. When the gas enters the hole, it rises through the water on account of the difference in weight and the high fluidity of the water. Thin mud then gives the gas and oil a better opportunity to enter the hole. There are, however, many deposits that will not "show" against a hole full of muddy water or even clear water. If light gravity oil shows under such conditions, it is manifest that there is considerable pressure to force it into the hole.

When mud is thickened and the speed of circulation increased, larger particles of formation are buoyed up and discharged at the surface. In this way, particles as large as peas may be obtained in the samples. If the thick mud does not wash through such pieces, they will, in some cases, indicate the presence or absence of oil by solvent test or by more inspection. This method oftentimes gives an indication of the presence of gas as well, for the gas will "show on the ditch" in the form of bubbles which rise to the surface of the mud and burst.

When the rock-pressure is not sufficient to expel the mud and water from the hole, the only means of estimating the productivity of the sand is to lower or remove the drilling fluid from the hole by bailing. Even that is sometimes not sufficient to prove commercial production, and swabbing

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* *Hill, H. H. Supt., U. S. Bureau of Mines Experiment Station, Bartlesville, Oklahoma—personal communication.*

or rewashing is resorted to in order to bring in the oil or gas. It is, of course, necessary to fully protect the walls of the hole from caving while making a bailing test. The usual procedure in such a test is to remove the drill stem and insert the pipe with a packer and with a suitable amount of perforation so placed as to be opposite the formation to be tested when the pipe is set.

If complete data of other wells are collected and compiled by the engineer for the purpose of selecting depths to test, it becomes relatively easy to test at those depths. For instance, if it is desired to make a test of the formation between 1,160 and 1,200 feet, the drill hole can be stopped at about 1,150 feet in a tapered hole and the casing set without perforations. A small hole can then be drilled ahead to the desired depth and the mud bailed from the casing without much danger of disturbing the mud and formations on the outside of the casing. When the oil-bearing formation has already been passed through, which is often the case, the pipe is usually set on bottom and some sort of suitable packer attached above the perforated portion in order to retain the mud. The so-called mother-hubbard packer of the inverted umbrella type and made of canvas, burlap, rope or leather, has been used with success and economy for such work. In many cases, such a packer does not effectively exclude top water, and in that event the test is of little or no value. Enough packing material should be used to insure against buckling past and down the casing. **The telescoping packers,** carying rubber or hemp, also are used. For their successful use, the bore-hole should be circular and smooth and of about the diameter expected. A hard shell to set this type of packer in is also desirable.

If a temporaray shut-off can be effected, the mud should be slowly bailed from the casing, after providing the proper control fittings. Obviously, these appliances are likely to be of little use for high-pressure unless means are provided for retaining the pressure on the outside of the casing. It is desirable to braden-head the casing to the conductor pipe or other string of casing, else there will be danger of a well blowing wild outside of the casing.

Plate II shows a crew in the El Dorado field bailing down the mud in a well that is expected to come in any minute. Gas has already appeared in this well. The "Christmas Tree' is fitted with a valve below and one above the lead lines. In case the well should blow in with high gas pressure, both valves can be closed on the sand line. The only waste would be a spray around the line, but the main flow of oil would be diverted through the lead lines shown in the foreground.

Plate II—Bailing Down to Bring in Well. Connections Made for Flowing Well.

The practice at El Dorado of cementing a conductor string at about 200 feet, is an excellent one. If this is done, any formation can be safetly tested by braden-heading or packing off between the testing string and the conductor. It may be argued that the upper showings at El Dorado are known to be of low pressure and of little commercial importance, because a few tests have indicated that condition. The main oil zone in the field is apparently not uniform and the upper strata in general are also irregular in occurrence. It is quite possible, then, that upper horizons may occur which are commercially productive in certain areas and that the few tests have not been conclusive.

The mad scramble with which operators conducted their rotary drilling, in order to reach the known productive zone has resulted in meager information concerning the nature of the upper deposits. A number of wells have logged showings of oil or gas. For instance, a strong showing of gas and oil in twenty feet of good sand was reported at 1,800 feet depth in a well on Section 8-18-15. This deposit was mudded off in the usual way. If the correct gravity of the upper oil could be obtained, it would aid in an estimation of its value. It is obvious that if a bed of tar or very heavy oil is penetrated, it will probably be noted on the ditch, for the reason that it is not readily driven back into the strata by the mud and water and sticks together better than lighter oil. When light oil shows in the presence of a full column of mud, there is apt to be considerable pressure behind it and it is worth testing to determine its productivity.

If there are upper oil and gas deposits of present or near-future commercial value, that fact should be known before the wells are finished, and adequate provision made to protect them. Before the wells in a certain district are abandoned, enough tests should be made to determine the possibility of utilizing the upper sands. It is obvious that if upper production is obtained, it must be protected from any top water lying below about 200 feet. So far, no special attention has been given to the protection of any upper oil sands from top water, and on this account it may be impossible later to get a fair test of the upper sands until the upper water is excluded.

In this connection it should be mentioned that the mud-fluid column cannot always be relied upon to protect upper oil sands against water infiltration, especially with the common method of circulation with no extra closed-in pump pressure. In older fields, gas is often found issuing from behind casings landed with rotary. As time elapses, even thick rotary mud may gradually settle out and allow gas to blow out and water to travel from its native formation. The results of such action are illustrated in A and B of Plate III. Thus a valuable deposit of oil may be somewhat flooded with water before production is attempted. The time to protect oil deposits from water and from dissipation into low-pressure porous strata is during the drilling of the wells.

This discussion is not a prediction that extensive valuable upper deposits exist. The possibility exists and a more thorough inventory should be made by conducting tests whenever possible. When drilling is done by contractors, a qualified representative of the company should keep almost constant watch of the samples and should be able, under the contract, to make a complete test at any point desired.

Completing Wells:

In order to avoid serious mistakes, when drilling in a territory lacking easily recognizable marker formations, considerable care must be exercised in determining the final point for excluding top water and in selecting the final depth to drill the well.

It is, of course, necessary to shut off low enough to get below all top water and to stay above the oil sand. There is considerable leeway for the shut-off point at El Dorado, as a number of tests have indicated that there is no water nearer than about 100 feet above the top of the oil sand.

In drilling into the oil formation, it is important to use great care (1) to avoid drilling to a point within short range of edge water, (2) to avoid drilling into bottom water, and (3) to avoid permanently mudding off or seriously injuring low-pressure oil and gas.

If it is known that in certain locations, edge water lies under the oil and along the bottom of the oil sand, the hole should merely penetrate the top of the sand or extend into the sand only a small percentage of its thickness. In this way considerable oil will be allowed to drain laterally, before the water can overcome friction and gravity and crowd the oil back. This means of conservation fails if the production is not controlled to a certain degree. If too great an output of fluid is allowed, the water will soon find its way into the well, on account of its low viscosity (high fluidity) and will "cone" the oil back, as shown in Plate IV. Quite a number of El Dorado wells have gone to water prematurely on account of drilling too deep into the sand or by not sufficiently restraining production, thereby causing the well to drill itself deeper or causing the water from below to be sucked up through the intervening sand.

The term "bottom water" is here used to mean water that underlies the oil sand and is separated from it by a more or less impervious parting. Plate IV shows the apparent relationship of the oil and water. Some of the wells in the southern portion of the field have no doubt drilled into bottom water on account of finding no cap above the oil sand. The cap at the bottom of the sand was sometimes mistaken for the cap above the oil sand and the well was drilled into bottom water. Sufficient care was not used in determining the character of the formation, the presence of oil was noted too late and its exact source was misinterpreted. Other wells have been drilled into bottom water through lack of proper direction. Much of that could have been avoided by the application of ordinary engineering methods, which allowed conclusions to be reached from a study based largely on the data of neighboring wells. Full consideration should be given to the elevation of the wells, the pitch of formation in different directions as shown by logs (see cross sections of Plates V and VI) and the known intervals between marker formations, the top of sand and bottom water. Failure to consider these factors has cost the operators dearly. A study of the well logs of these two cross-sections shows that in most cases the oil sand is the principal marker.

Considerable harm is likely to be done by allowing excessive mud and water to penetrate low-pressure oil and gas strata. When the formation is not very porous, it may be better to plaster it up with thick mud and avoid mudding a great distance. When the formation is quite porous, it would appear better to drill in with water rather than mud. The water would be more readily expelled into the hole again and would act as a less effective choke. The wells of El Dorado have to date had fairly high pressure with which to free themselves of rotary mud. Because of declining gas pressure, however, future wells will not clean themselves so readily. In other fields, wells have been drilled with rotary and called dry, after which some of the formations penetrated have been proven highly productive. There may possibly have been such cases in the El Dorado field also.

Certain operators report that there is little opportunity to determine the top of the oil sand by taking core barrel samples of the formations when approaching the oil sand, on account of the incoherence of the porous material. The writers believe, however, that too little attention has been given to core-barreling in El Dorado, because such work has been very successful in other fields where conditions are somewhat similar.

A few of the wells have been finished with cable tools and that method is more satisfactory than the rotary tools, for the following reasons: (1) in order to pump the well, it must be partially equipped with standard cable tool equipment and, therefore, the work of changing the rig to suit cable tools is not lost; (2) the drilling may be done without mud and usually with much less fluid in the hole; (3) running the bailer to clean out the drill cuttings gives accurate formation samples every few feet, and a sample can be obtained at any depth desired with little delay. In some fields with loose caving oil sand, only a small amount of open hole can be drilled in cable tool work, ahead of the pipe, but at El Dorado it is not advisable to drill more than a few feet into the oil sand, so that the liner can be placed with cable tool equipment.

Mr. Winger, who initiated the finishing of wells with cable tools at El Dorado, has communicated the following information on the rotary method of completing wells:

"In drilling with a rotary it is frequently impossible to determine the exact nature of the formation being drilled, for the reason that it takes some thirty minutes to get cuttings from the bottom of a 2,000-foot hole and there is also good opportunity for samples being mixtures of different formations. I know of an instance in this field, where the drillers thought they were in shale and decided to test it out and see if it was bearing any water. They ran the bailer four or five times and the well came in, one of the best in the field. No liner had been set or other necessary preparations made.

"Another instance: A certain company in this field drilled an offset to a well, the sand depth of which was known. This depth was reached, but there was absolutely no showing—not a rainbow, gas bubble, or cutting that indicated anything. But the neighboring well had been drilled too deep and it was necessary to plug back to shut off salt water before making a well of it. So this company stopped there where the "pay" should be and after bailing about twelve hours brought in their well. This test would not have been made at that point had they not known the exact depth to the "pay" in their neighbor's well. In cable tool drilling, the cuttings are brought out of the bottom of the hole each time with the bailer and there is not so much guess work.

"If the rig is standardized, the expensive rotary equipment does not have to remain idle ten days waiting for the cement to set, but is released to another location. A number of big wells in this field, brought in by rotaries, have bridged and sanded up soon after the machinery was moved off. The owners lost enough production, waiting to get machinery back on the well to clean out, to pay for standardizing. It takes several days to rig up a rotary and get it back on the job, if one is available, whereas if the well is standardized the tools and sand pump can be run and production resumed in a few hours."

The operators of El Dorado who have tried completing wells with cable tools, have found it highly satisfactory and express their intention to continue the practice.

When finishing wells with cable tools in high-pressure territory, it is sometimes necessary to use care in removing the tools from the hole, lest the well blow in. The "lubricator" shown in Figure 1, when properly used, will prevent blowouts. In at least one instance at El Dorado it was used with success. Usually a short string of drilling tools can be used for finishing, as speed is not so necessary at this place in the work. The drilling is done through the control head (a) and the master gate (k). The assembled lubricator parts (a), (b) and (c) are hung above the beam with the drilling line passing through them. When the drilling is finished, the lubricator is lowered and screwed into the lower control head (a). The upper control head (a) and oil saver (b) are then closed somewhat on the line and the tools are pulled up to the position shown. The master gate and lower control head can then be closed, the lubricator removed and preparations made for bringing in production.

Although careful rotary drilling gives good results in many instances, it appears certain that the field would be making less bottom water today if all of the wells had been finished with cable tools in the hands of competent drillers.

There is probably not a well in the El Dorado field that has used a full oil string for producing. Perforated liners or screen pipe or a combination of both are generally used. The loose sand problem is difficult of solution and greatly retards production. It will be discussed under "Production methods."

Labor Conditions:

The nation-wide rush for oil, with high prices for oil, which was initiated by the demands of the World War, resulted in much wildcatting and the opening of many new fields. In order to handle the vast amount of work, it was necessary that men with little oil field experience be entrusted with important phases of development and production. A competent oil man cannot be developed in a few months or even years, and hence there has been much mismanagement and poor workmanship. The El Dorado field has suffered considerably from this condition, which probably cannot be righted for some time.

The following example of poor handling was furnished by a driller familiar with the work on the particular well: A well was drilled with rotary tools to the depth estimated from the logs of neighboring wells, as sufficient to encounter the oil sand. The mud was thinned considerably and a show of gas appeared. Without thickening the muddy water and without keep-

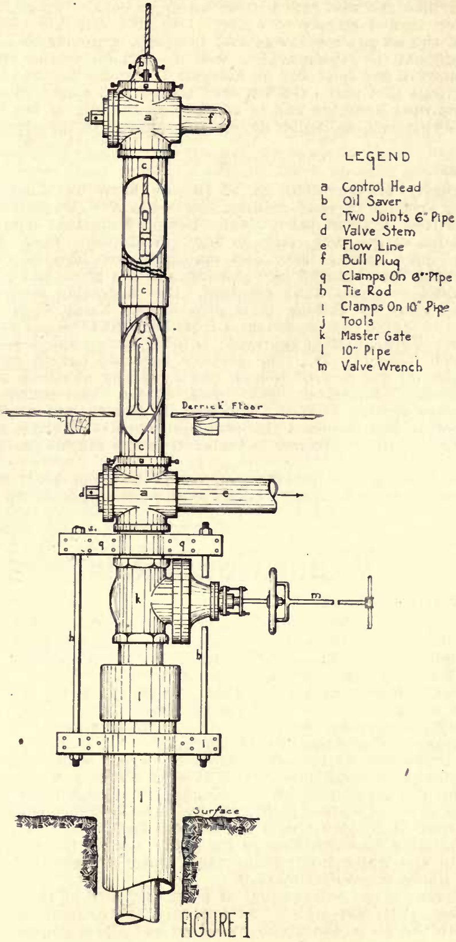

Fig. 1. Cable Tool Lubricator for High Pressure Walls.

ing the hole full of fluid, the drill stem was withdrawn from the hole as rapidly as possible. The driller stated that this was done in order to get the casing in as soon as possible. The removal of the drill stem lowered the fluid in the hole and the well blew out before the drill stem was withdrawn. About 1,300 feet of drill pipe was dropped to the bottom. The wild flow either drilled the well into bottom water or sucked up edge water and the production turned largely to water. The fluid ran into earthen sumps and much of the oil produced was lost in spray, evaporation and seepage. It becomes difficult to repair such a well on account of the large cavities formed by blowing out sand and on account of the damage done to thin impervious partings that may exist between the oil and water. This well was ruined by improper handling and in addition to the loss of the hole and resultant expense it has, no doubt, done great damage to the surrounding territory.

Drilling Costs:

The majority of the wells at El Dorado have been drilled by contractors. On account of easy drilling, the wells are completed at approximately 2,200 feet in about thirty days. Some of the first contracts called for a completion of the well, ready to flow, for $25,000. These were known as "turn-key" jobs. Since labor and material have become cheaper, and more competition has entered into contracting, the price has been reduced to about $12,000 or about $5.50 per foot. One operating company reports considerable saving by drilling their own wells. Using $5.50 as the contract basis, it is stated that a saving of from $0.59 to $3.90 per foot has been accomplished. These figures represent a total saving range of $1,300 and $8,490 per well, respectively. The average reported saving was $2.81 per foot. The cost for 200 feet of 10-inch and 2,100 feet of 6-inch 8-thread line pipe is at present (November, 1921) about $3,000. The contract price for a 112-foot rotary derrick is $800. The cost of derrick and combination rig (rotary timbering and standard rig irons and wheels) is about $1,500. The cost of casing and rotary derrick is included in the $12,000 for a "turn-key" job.

The prevailing wages for rotary crews in October, 1921, was $10 per 12-hour period for drillers and $5 each for the remainder of the well crew.

Water Conditions

Amount of Water Produced:

The amount of water produced in the Ed Dorado field is difficult to approximate, because of the failure of operators to gauge the water production as a whole or from individual wells. A large proportion of the water produced is bled from the separators as free water. As the water comes from the bleeder lines through "cracked" valves, it is under considerable pressure and is, therefore, in the form of small high-velocity streams and spray, rendering estimation very uncertain. Much water escapes by running into streams and sinking into the ground.

A large proportion of the water from numerous wells passes into the first storage tanks as emulsions. After this emulsion is broken up by special treatment, the amount of water present is not usually measured.

Estimates of total water production by those familiar with field conditions, range from 25 to 50 per cent of the total fluid raised. Operators who are more familiar with conditions in the north end of the field are apt to under-estimate the water production, while those of mostly south-end experience are likely to over-estimate it.

It is believed by the writers that at least one-third of the gross production in October, 1921, was water. At any rate, the amount of water being recovered with the oil is enough to cause serious alarm concerning the life of the field.

Harmful Effects of Water:

The very rapid decline of production in this field is no doubt caused by water, more than by any other factor. All operators of wide experience with production of this character realize the harmful effects of water under certain conditions, and so much has been written on the subject that only general references are given to some publications of the U. S. Bureau of Mines.*

The physical properties of oil and water are widely different. Water is considerably heavier than El Dorado oil, is more fluid (less viscous) at ordinary temperatures, and has greater surface tension. Each of these characteristics of water gives it an advantage over oil when the two liquids are competing for passage through the reservoir rocks toward the wells. Water is also very effective in "killing" gas action, especially when the sediments are of close texture.

The weight of water standing in a well exerts a back-pressure on the oil in the formations and tends to hold it there. When oil once reaches the well there is, of course, nothing to prevent it from rising to the top of the fluid column, it being lighter than water.

Viscosities of liquids are measured by means of a viscosimeter, and this instrument demonstrates that water is more fluid than oil. For the benefit of the field man, a brief description is given. It is essentially a tall cylindrical vessel with a small standard spout opening in the side at the bottom. The viscosity of liquids are compared by the time it takes to empty the vessel through the orifice. It is thus shown that water will move through small openings much more freely than will oil.

If water and oil are present in a stratum penetrated by a well, although the water will occupy the bottom portion, drilling too deep or removing the fluid too rapidly, will allow the water to rush into the well and crowd at least some of the oil back. Gas pressure is, in general, the principal force that carries oil toward a well, the force of gravity being of only minor importance, especially in strata of low inclination and small thickness. Excessive water will reduce or "drown out" all but high-pressure gas with disastrous effects on production.

Water has greater surface tension and is attracted more strongly by the formations than is oil. The force, known as capillary attraction will draw water upward in much the same way that a wick supplies oil to a flame. The water tends to "grip" the formation particles and thereby retards the movement of oil and gas. That force is strongest in fine-grained material or in minute crevices and the greatest retardation of movement by water can, therefore, prevail in such material. As an illustration, consider two sands that are each composed of spherical grains. The grains of sand A have a diameter of .005 inch, while those of sand B measure .050 inch, or ten times greater. Each sand has the same percentage porosity and will hold the same amount of fluid. Movement can occur more easily in B than in A, because there is less frictional resistance and less capillarity on account of the larger space between the grains.

Source of Water:

There is little doubt that over 90 per cent of the water produced at El Dorado is a combination of bottom water, which underlies the oil-bearing strata and appears to be uniformly separated from it by a cap rock, and edge water which is present in the down-dip and lower portion of the oil-bearing strata.

It is not unlikely that some faulty shut-offs are letting in top water, but from the data at hand this source appears insignificant. The minimum requirements of the Conservation Commission for water strings, are twenty-five sacks of cement to set thirty-six hours for 170 feet of shallow string and sixty sacks of cement to set ten days in the case of the final string, which is usually 6-inch 19½-pounds pipe. A test of water shut-off is required on the main water string. If the test is not satisfactory, the condition must be remedied before drilling into the oil. The operator should be more anxious to exclude the water than any one else, but as he cannot always be present at such tests, the responsibility may be left with the foreman, driller or contractor, who is often careless about such work. It would be desirable for a Conservation Commission officer to witness all tests for

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**Bulletin No. 134, The Use of Mud-Laden Fluid in Oil and Gas Wells, by J. O. Lewis and W. F. McMurray, 1916.*

**Bulletin No. 163, Methods of Shutting Off Water in Oil and Gas Wells, by F. B. Tough, 1918.*

**Bulletin No. 195, Underground Conditions in Oil Fields, by A. W. Ambrose, 1921.*

water shut-offs. The results of each test could then be reported and an adequate record kept by both the operator and the Commission, which would be of value in future work.

A number of circumstances may arise that cause water shut-offs to leak. They will be mentioned as of possible value in determining upon the source of water in this field:

(1)—Running casing in hole may loosen threads and cause leaks. This is not so apt to happen with mud back of the casing as with water. Oftentimes, casing is not screwed up tightly and by putting on tongs and screwing up, the water may be shut out. Source of leak can be determined by running casing tester or by setting a packer on tubing. Before drilling out cement for test of shut-off, the tightness of the casing itself should be ascertained by bailing out the mud or water and letting the well stand undisturbed for about five hours. If nothing collects in the bottom, other than that reasonably expected as drain-back, the casing may be considered tight. If a large quantity of cement has been used and a large proportion of it sets inside the casing, it may become necessary to test the lower portion of the casing after the cement is drilled out.

(2)—Casing may be imperfect in places or may develop breaks while running in. If second-hand pipe is used in high-pressure territory, it is well to test each joint with hydraulic pressure before using. In the Monroe, Louisiana, gas field some of the operators test their casing and fittings with a special apparatus. A description and photograph of such apparatus can be found in Bulletin No. 9 (pp. 55, 56) of the State of Louisiana, Department of Conservation, a co-operative report written by H. W. Bell and R. A. Cattell of the Bureau of Mines. In testing one string of 6-inch, 19½-pound pipe, at the factory, twenty out of the sixty joints leaked, and one joint split about fifteen inches on one end under an internal pressure of less than 1,200 pounds per square inch.

(3)—After determining that the casing does not leak, the cement should be drilled out and the well drilled to the formation in place. For safety, drilling should be stopped when about one foot into the formation. If a new water or oil and gas stratum is encountered at the shoe, it will be impossible to test the effectiveness of the shut-off.

(4)—After drilling out cement and bailing down for test, drilling mud and water may rise to a high level, due to being returned from porous formations adjacent to the shoe. Indeed, it may require a number of tests to show that such inflow is decreasing and is exhaustible and that the cementing operation was a success.

(5)—If too much hole is made for the test and new water is encountered below, that fact may not be recognized until after considerable work is done. The shoe may be in the middle of a water-bearing formation, a very short distance above it, or a considerable distance above it. In the first case, it may be impossible to demonstrate the source. In rotary wells it should, in all cases, be noted whether mud is coming in, and in every case whether known upper deposits are supplying oil or gas around the shoes. If a good dye is placed behind the water string and shows up at the shoe, the test indicates the water string is leaking, but if it does not appear, nothing is proved. In the second case, it may not be possible to set a cement or other plug to exclude the water from below and, at the same time, leave a little open space below the shoe. If the dye test fails, the source might be proven, as has been done elsewhere, by plugging the formation with cement and up to about two feet into the shoe; then perforating the water string a few feet above the shoe, until formation comes in. The kind and amount of fluid that enters will probably indicate the source of water. It is a dangerous thing, however, to punch holes in a water string and this should be done only as a last resort. In the third case, the source could be demonstrated by placing a cement bridge just below the shoe or possibly by setting a packer in formation just below the shoe, and making a bailing test.

In some fields, where cable tools are used samples of each water encountered, or at least a composite sample of all top water, are obtained and analyzed. In this way the source of water is usually easily determinable by comparison with the analysis of water in question, as the chemical characteristics of the mineral content of oil-field water usually change considerably with depth. A comparison of fluid levels and of amounts of the known and unknown water is often sufficient evidence of the source. With rotary drilling, these methods are impossible, except in rare cases.

(6)—Besides making sure that the cement has been drilled through for a test, no shut-off should be passed unless the hole can be kept cleaned out to bottom. Heaving formation may bridge and hold back water.

(7)—In drilling out a considerable distance below the shoe of a water string, oil-bearing formations may be penetrated or re-exposed and the test of shut-off thereby rendered more difficult or inconclusive, due to the oil or gas coming into the hole. In such cases, it is usually not possible to plug off the oil or gas without also sealing the shoe of the water string. The only recourse then is to make a production test in an effort to determine the condition of the shut-off, either by producing from present depth or after deepening for more production. The former method, that is, before deepeneing, is more reliable because deeper drilling may encounter lower water. Obviously, the production test is not conclusive unless the well settles down to a clean production and it should, therefore, be avoided, except as a last resort.

The liability of error in measuring the depth of the shoe is believed by some to be sufficient reason for drilling out an excessive amount below the shoe. However, there is no call for such procedure if broken cement and formation are brought to the surface.

In general, the determination of the source of water in a well or group of wells, can be indicated by the use of the following:

(1)—Formation, production and casing records of wells.
(2)—Graphic means to visualize complex data.
(3)—Comparison of physical characteristics of water produced.
(4)—Amounts of water producible by wells.
(5)—Comparison of fluid levels.
(6)—Bridges and plugs of cement or other impervious material.
(7)—Dyes or colorless substances for tracing underground flow of water.
(8)—Packers used in casing or in formation.
(9)—Muddy water to indicate point of entry.
(10)—Relation of sequence of wells "going to water" to geologic structure.
(11)—Comparison of chemical analyses of waters.
(12)—Oil and emulsions accompanying water.

When water appears after a well has been producing clean oil, it is usually more difficult to determine its source than at the time of a test of shut-off, because the possible sources of the water have increased. It is one thing to determine through what channel or stratum water is entering a well, and another to ascertain how the water came to be in that particular stratum. When water is native to a certain stratum, it is here called "primary water;" when it obtains access through the agency of a well, to other formations, it is termed "secondary water" with respect to those formations. The waters of the typical oil field can be classified with respect to position under the three headings, upper, lower and intermediate water. It is, therefore, possible, in general, that water found in production may be from either of these sources and may be primary or secondary in character. The possible contributory combinations of these six elements are many. In dealing with water conditions in a group of wells, all of these possibilities may demand consideration. The problem is probably best attacked by first paying attention to the wells producing most water and having the highest fluid levels. In order to make reliable comparison, each pumping well should be tubed near the bottom and the lifting of the fluid conducted under similar conditions. It is safe to assume at the start and in the absence of more convincing data, that the largest water producers, or the wells with highest fluid levels, are the offenders.

An outline is given of the various means of determining the source of water in oil and gas wells. In dealing with this phase of the subject, general material was drawn from a paper entitled "Source of Water in Oil Wells," which was written by the senior author and appeared in the February, 1920, issue of "Summary of Operations" of the California State Mining Bureau.

(1)—Formation, Production and Casing Records of Wells:

In order to save time and money in dealing with water problems, it is necessary to assemble accurate and exhaustive data on each well and to record these in convenient and readable form. Those in authority should standardize as far as practicable for a given area the nomenclature of formations encountered in drilling. It is desirable that the driller's designation of samples should be confirmed before the final log is made. With one person determining all samples from several drilling wells on a property, uniformity of formation names can be accomplished. For instance, drillers in the same field often name the same formation differently. Some samples which are inspected with different degrees of scrutiny and under varying conditions of moisture, light, etc., may give diverse impressions to different people.

Without a uniform system of logging formations, it is, in the absence of unmistakable markers, difficult to correlate the well logs. Errors in correlation lead to incorrect methods of combating water troubles, and also to non-uniform water shut-offs. By this means, top water behind a water string may be allowed to enter any porous formation and travel through this channel to a nearby well in which this porous formation is exposed in the hole.

There is, as yet, no evidence that non-uniform shut-offs are responsible for any water production at El Dorado. Such is not likely to be the case, if the cement used has properly bonded with the casing and walls of the hole, for 100 feet or so, above the shoes of the water strings.

The need for accurate figures for production of oil and water is too often overlooked. Erroneous ideas concerning the source of water in production are likely to be developed to the end of misdirected remedial effort. This is particularly true when two or more wells produce into the same tank. Suitable equipment for the accurate determination of amounts of oil, water and emulsion produced by each well will be found a sound business investment in many cases.

Full records of all casing put into and removed from each well should be available for use in case of water troubles or abandonment. The amount and location of any side-tracked and perforated casing should also be recorded. Side-tracked casing may be left in such a position and condition as to afford a passageway for water down past a shut-off point or upward past a plug or bridge, and thus prevent a determination of the true source of the water.

(2)—Graphic Means to Visualize Complex Data:

In dealing with oil field problems, it is important to know the underground structure and to obtain all possible information relative to the occurrence and production of oil, gas and water. Ambrose* has pointed out that the best use of field data can be made when presented in graphic form, by cross sections, underground contour maps, production curves and peg models.

Until the geologic structure is accurately known, it will not be apparent where to make the water shut-offs in order to establish a stratigraphic uniformity. Peg models and cross-sections are used especially to determine structure and to indicate sources of water due to haphazard drilling campaigns.

With the aid of models and sections, the location of water that may lie in or below the oil measures can also be determined with more or less accuracy and drilling governed accordingly.

The comparison of the behavior of neighboring wells often gives criteria regarding underground connections and source of water. Charts that show graphically the average daily amounts of oil and water produced by each well during each month, and the number of days the well produced during the month, together with the reasons for any non-producing days, are valuable to indicate the effect of certain conditions or operations at one well upon the production of another.

In considering the data of more than two wells, the problem becomes complicated and graphical representation of data is necessary, in order to make a reliable study of the several features, such as time and volume of producible water.

**Ambrose, Underground Conditions in Oil Fields, Bull. 195 U. S. Bureau of Mines, pp. 26-68.*

(3)—Comparison of Physical Characteristics of Water:

The easily distinguishable non-chemical properties of water, such as taste, temperature and odor, are often serviceable in indicating source of water entering a well. If one or more of these properties are known for the different waters encountered in drilling a well, an idea of the source of the water appearing in production can sometimes be had. It is usually not practicable to observe these conditions, due to the contamination of added water, or of new water encountered in the well, or due to rotary drilling. However, it is well to note, when possible, the taste, temperature and odor of first water or its resultant combination with other waters cased off behind a water string. The value of this feature is greater when the well is drilled "dry" with cable tools or when no drilling water whatever has to be added from the surface.

Ordinarily, the hotter water comes from the deeper levels. Water that is salty to the taste usually comes from deeper levels than fresher water. Sulphur gas is the principal source of odor in water, and its presence can be substantiated by its blackening effect on silver. The writers have not noticed any sulphur water at El Dorado.

Although such observations for a particular well may indicate that the well is making top water. it would remain to determine whether top water was entering the productive formations as a result of the faulty condition of some other well. Similarly, it should be determined whether any supposed lower water was of secondary origin.

(4)—Amounts of Water Produced by Wells:

The terms "amount" and "quantity" used here refer to actual volumes rather than percentages. Often in groups of producing wells, the well which makes the most water can be singled out as the probable offender. This is true of pumping wells when they produce all of the fluid that comes into the hole.

Stratigraphically non-uniform shut-offs may make it difficult to designate the well letting water into the oil sand. Due to a low shut-off, well No. 1 may allow considerable top water to infiltrate into the production of well No. 2. Well No. 2 may thereby become the largest water producer of a group of wells, but could not rightly be called the offending well. On the other hand, well No. 1 may produce the least water of the group and its status would have to be determined by other means.

The amounts of water produced by pumping wells are of little significance in indicating the source of water when the fluid levels are continually and uniformly high. In such cases, the productions do not represent the fluid capacities of the wells and the amounts of production obviously depend then on such features as size of pump and tubing, efficiency of pump, length of stroke and number of strokes per minute. It is evident that under such conditions the offending wells may be producing less water than a well or wells not letting water into the sand.

An increase or decrease in the amount of water a well produces is an important item to consider for indicating the source of the water. The sudden appearance of considerable water in a well or wells would indicate possible sources, and these would be dependent largely on the conditions obtaining in that area. Under average conditions such a sudden increase of water would appear more likely to be due to causes immediately connected with the well itself.

A sudden increase in water production would point to such things as a sudden development of large casing leak; the failure of shut-off; the breaking in of water through thin formation or past a plug in the bottom of the well; or the water pressure overcoming the effect of oil and gas pressure. It is quite possible also that edge water or water due to the drilling or to the fault of some other producing well, could manifest itself suddenly when conditions of porosity are favorable.

After conditions have been remedied in the well in question, or in neighboring wells, it may require considerable time to exhaust the accumulated secondary water from the formations. The rate of exhaustion would. of course, depend again on the porosity of exposed strata. A gradual decrease in amount would indicate that the water was let into the sand, and not native to it.

(5)—Comparison of Fluid Levels:

Fluid levels may be classified as follows:

(1)—Those compared on a basis of distance from sea level will be termed "absolute."

(2) Those compared with reference to distance from a stratigraphic horizon or stratum will be termed "stratigraphic."

High fluid levels usually indicate large productive possibilities of oil or water. They also indicate the offending wells when the fluid level is due to an excess of water. It is out of the ordinary to find a condition, for a group of wells with settled production that have gone to water, whereby the offending wells would not show the highest fluid levels. This is noticeable in several cases at El Dorado. Exceptions to this general rule are found when water is entering the lower portion of a well and is restrained from seeking its own level in that well by a bridge or by a plug, the lower portion of which was defective. In such cases, the confined water will travel across to other wells through any porous strata available. In an area of markedly inclined strata; water which enters a well at any point may be conducted rapidly away by an unsaturated or partially drained porous stratum to another well and the conditions of porosity may be such that the secondary water will attain a higher stratigraphic fluid level in the down-dip well.

The fluid levels should be taken, when possible, for idle as well as for producing wells. It is, of course, necessary to obtain these data under similar conditions for the different producing wells. The levels should be taken at a certain time after production was stopped. It is also advisable to conduct an investigation of fluid levels after a period of uniform producing conditions for all wells has elapsed. If a well has been pumping only a few days after a considerable period of idleness, the figure obtained may be misleading. It is apparent that an idle well will probably have a high fluid level. If its level is considerably higher than those of neighboring wells, it should be made the object of further investigation as, under ordinary circumstances, such a condition could not exist in a non-offending well.

A comparison of fluid levels should be considered on the same stratigraphic plane, although if the formations have a gentle dip, sea level basis will usually suffice. The greater the resistance to the passage of water from one well to another, the greater will be the difference in fluid levels of the offending and non-offending wells.

When infiltrating water travels up the dip of fairly steeply inclined beds, a stratigraphic comparison of fluid levels will tend to exaggerate the comparison, because the up-dip non-offending well could never attain the same stratigraphic fluid level, due to water pressure, as the offending down-dip well. The opposite is, of course, true when the water travels down the dip.

It is felt that the operators in El Dorado have not studied fluid levels to the extent that should be done and it is believed that such a study would often be helpful in determining the repair of wells. The preceding data on fluid levels was given in considerable detail in the hope that such information might be useful in later work in this field.

(6)—Bridges and Plugs of Cement or Other Impervious Material:

The terms "bridge" and "plugs" are sometimes used synonymously. "Bridge" is here used when the impervious filling is not in contact with the bottom of the well; while "plug" designates a filling, part of which is impervious, which is in contact with the formation at the bottom of the well.

The proper manipulation of bridges and plugs of cement is frequently employed and is one of the most reliable means of determining source of water. If plugging the bottom of the hole shows that the water has been entering the well at that point, the demonstration may constitute the remedy.

If a study of all available information does not sufficiently indicate the point of entry of water in a well, the following is a proposed outline of work:

(a)—Retest the shut-off by placing a substantial cement bridge under the shoe and conduct a bailing test. It often happens that a bridge does not form a water-tight bond with the walls of the hole, in which case water may come from below. If the bridge is tight, water may come from defective casing, defective shut-off, or from any porous formation existing between the top of the bridge and the shoe of the water string. The general conditions governing such a test are outlined in the previous discussion of original tests of shut-off (pp. 19-21).

(b)—If water is found to be entering the well above the bridge, retest the casing for leaks.

(c)—If test (a) shows that the well still makes water, or does not account for all of the water that was being produced, the bottom of the well may be plugged with cement for a certain distance. After the cement has set, a bailing test should be made. If the well still makes water, continue plugging and testing in stages until the source of the water is determined and the water is shut off.

(7)—Use of Dye or Colorless Substance for Tracing Underground Flow of Water:

Suitable dyes can sometimes be used to good advantage for indicating underground fluid connections and the direction of movement. Dye can also be used for testing the efficiency of a water string.

The World War has greatly retarded the use of dyes since 1914, due to scarcity and prohibitive prices. Varying degrees of success have accompanied experiments in connection with oil field conditions. Some dyes are decolorized by the reducing action of petroleum compounds and by hydrogen sulphide, or are absorbed by mud and formations. Such dyes are usualy unsuitable for oil well purposes.

The subject has not received the attention it merits, and it is believed that experimental work would point to a means of using dyes more advantageously in tracing water. Some of the dyes that are absorbed or reduced by crude oil may be used successfully when the fluid carries a large percentage of water.

It is said that the dye eosin is not affected by hydrogen sulphide, nitric acid, magnesium sulphate, sodium hydroxide, alcohol or gasoline. The price and supply, however, prohibit its use at present.

The United States Geological Survey has used fluorescein for tracing the flow of underground waters in connection with water supply problems. It is said to be a delicate dye which is only slightly affected by the normal ingredients of natural waters; to be decolorized by acids and affected by some forms of unstable organic matter. A loss of color due to acidity can be restored by making the sample alkaline. Stabler* points out that fluorescein can be noted with the eye in solutions as weak as one part in 40,000,000 parts of water and that one part in 10,000,000,000 can be detected with the aid of a long glass tube. He considers it the most efficient dye for tracing underground flows of water. In a personal interview, Mr. Stabler stated that this dye can be obtained from the Eastman Kodak Company, Rochester, N. Y., at a price of about $10.00 per pound and that, regardless of its price, it is probably the most desirable dye to use.

The chemical nature and intensity of a dye will influence the amount that should be used for a given set of conditions. In testing the efficiency of a water string, two to five pounds of good dye would probably suffice, while for use to show underground flow, ten pounds or more would be advisable. When testing a water string, the dye is put behind such casing and washed down with a stream of water. The pumping of the well should not be suspended. The appearance of dye in the production will indicate a casing leak or defective shut-off. When testing for underground connection, the dye should be released at the bottom of the suspected well and this well should remain shut down during the time of test. It is important to remember that dye placed in the bottom of well No. 1 and showing in well No. 2 is not conclusive proof that well No. 1 is at fault. The current of water, flowing in the general direction No. 1-No. 2, may be due to imperfections in one or more other wells.

**Stabler, Herman (Chief Engineer, Land Classification Board, U. S. Geological Survey), Engineering Investigations, The Reclamation Record (Department of the Interior) Vol. 12, No. 3, March, 1921.*

It is stated by A. W. Ambrose, chief petroleum technologist of the Bureau of Mines, that "acid orange" is a cheap and reliable dye for average sub-surface conditions. The cost of this dye is about 90 cents per pound and is obtained from Hemingway & Company, New York. A Prussian blue is reported to have been successfully used in a number of cases, and it seems to meet the general requirements of oil field conditions. It is a cyanide of iron, and the writers are not fully advised as to the effect that sulphur compounds may have upon it. It is, however, probably one of the most reliable and available dyes for present use.

It is understood that the underground flow of water has been traced by colorless substances which the water did not originally contain except in comparatively small quantities. For instance, one of the rare elements, such as lithium, may be added in small quantity and samples from some other point tested by spectroscopic analyses. Or an excess of a compound, such as chlorides or sulphates, may be added and the samples tested by measuring the resistance to an electric current, or by chemical means.

(8)—Packers Used in Casing or in Formation:

Packers run into the wells on tubing or casing and set in casing or formation are used to good advantage for testing the source of the water. The packer is supposed to form a tight bond between the wall of the hole or the inside of the casing and the tubing or casing on which it is set and thus retards the fluid moving past the point at which the packer is set. The subsequent testing by bailing or pumping is done below the packer, whereas in the case of a bridge, the reverse is true.

A packer is usually employed for testing and with the idea that if it excludes the water, it will remain in the hole. The common packer makes use of an expanding rubber or canvas to effect a seal. Although the rubber is decomposed in time by oil and water, such packers have frequently been left in wells of other fields for permanent correction of water troubles. Hemp has been used successfully in this connection, and will probably last longer than rubber. The efficiency of a packer may sometimes be increased by caving formation or by the addition of mud or sand put in from the surface. Experience has shown in some fields that packers should not be used against the formation, if a permanent water shut-off is to be expected.

(9)—Use of Muddy Water to Indicate Point of Entry:

The point of entry of water into a well may sometimes be determined by using thin mud fluid or muddy water. The well should be filled as high as practicable with muddy water, with the hole open to bottom or otherwise. The fluid should then be bailed off the top and a careful watch kept to note the thinning of the mud and the appearance of clear water. As the fluid level is lowered in the hole, the head of infiltrating water will again over-balance the fluid column in the well, with the result of thinning up the mud with clear water. As soon as the bailer has reached the point of inflow, it will pick up practically clear water. The point of inflow is thereby approximately located.

(10)—Relation of Sequence of Wells "Going to Water" to Geologic Structure:

Water which occurs in the down-dip portion of an oil-bearing stratum is called "edge-water." As the oil is removed by producing wells, the water will replace it. The head of the encroaching water will be a factor in its rate of progress, as will the off-setting oil and gas pressure. In strata of low inclination, such as at El Dorado, the line of encroachment will be quite irregular and will be controlled largely by the porosity and texture of the edge-water sand.

The classification of a water as edge-water would usually be based solely upon the evidence of down-dip wells going to water first. The available means of determining the stratum through which encroachment is taking place are not usually different from those described elsewhere for locating the point of entry of water into a well. It may occasionally happen that a clue is readily available owing to the fact that some of the down-dip wells are not as deep stratigraphically as the others. This condition would probably eliminate some of the strata as edge-water-bearing possibilities.

(11)—Comparison of Chemical Analyses of Waters:

It has been demonstrated that a careful investigation of numerous chemical analyses will usually disclose identical characteristics of the waters of each horizon; and that these characteristics are apt to persist in general over the area of an oil field. It is reasonable to assume that, if the waters of different depths are restrained from mixing, different conditions will obtain and render them dissimilar. Some of the controlling factors affecting the mineral contents of the water are temperature, pressure, time of contact with formation, distance traveled through formations, chemical nature of the reservoir formations, quantity of water, and the accessibility of meteoric water to the point of sampling. The best results from water analyses can be expected where the structural movements have not permanently destroyed the impervious character of interzonal formations. The intermingling of waters along fault planes and through crushed zones will, of course, minimize the possibility of a definite conclusion from analyses.

Chemical analyses have been used in several fields to determine the source of the water produced by oil wells. This work has shown that the engineer can not use analyses of one field as an indication of the chemical properties of the water of another field. Any attempt to use chemical analyses of waters at El Dorado must be carried on as an investigation entirely independent of the findings in other fields. Samples of water from definite, known sands should be analyzed and then later when a well makes water whose source is unknown, a sample can be collected for analysis. The analysis of this water can then be compared with the known samples, so as to determine the origin of the water.

Analyes of Underground Waters of the El Dorado Field:

Table No. 4 gives the results of analyses of four samples of water from El Dorado wells (probably edge or so-called bottom water) and of two samples of known top water from shallow water wells. The analyses were made by W. F. Fulton of the Louisiana Oil & Refining Company at Shreveport, Louisiana, and by W. B. Lerch of the U. S. Bureau of Mines at Bartlesville, Oklahoma.

Lack of time prevented a complete collection of water and compilation of their analyses. The few samples examined showed a very marked difference in the chemical properties of upper and lower waters. The general differences adhere rather closely to the differences in waters of some other fields as pointed out by Rogers* The difference in total solids is the most notable and it has an important influence on the percentage figures shown in Table No. 4. For instance, the first analysis shows 48.52 per cent chlorine and the last shows 40.01 per cent. There is, however, about 628 times more chlorine in the first sample (bottom water) than in the last (top water). The samples of top water were taken from comparatively shallow depths and the character of any deeper top water is, therefore, uncertain. Because all wells have been drilled with rotary tools, it has been impossible to obtain any samples of lower top waters. The bottom or edge water at El Dorado has a distinctly salty taste. The fact that the large producers of water also make water with a similar taste indicates that the large water producers are making edge or bottom water. As remedial work is undertaken, chemical analysis may be found useful.

(12)—Accompanying Oil and Emulsion:

When water and oil are intimately mixed by agitation, an emulsion is formed. It is known to be formed by such conditions as the sudden expansion of gas in the presence of oil and water and by the passage of oil and water through small openings, such as leak-back past a worn ball and seat of a pump, between tight-fitting liner or screen and oil string, past defective bottom plug and through the oil-bearing formations. It appears likely that emulsion may be formed at the surface as well as underground.

**Rogers, G. S., Chemical Relations of the Oil Field Waters in San Joaquin Valley, California, U. S. G. S. Bull. 653, 1917.*

TABLE 4

WATER ANALYSES OF EL DORADO OIL FIELD

WELL	PERCENTAGE COMPOSITION								Tot. solid parts per million of water	ANALYST
	Section	SiO2	Na	Ca	Mg	C1	SO4	CO3		
Mich.-Ark. No. 1	33-18-15	......	41.21	9.47	0.79	48.52	0	0.01	59,500	W. B. Lerch, U. S. Bureau of Mines
Lucas Tomberlin, Crawford No. 1	31-17-15	......	36.20	2.80	......	61.00	0	......	53,200	W. F. Fulton, La. Oil & Refg. Co.
Chew Oil & Gas, Rowland No. 1	5-18-15	......	37.20	1.90	......	60.9	0	......	74,650	“
Rowe & Rowe, Pratt No. 1	7-18-15	......	38.40	0.90	......	60.7	0	......	65,600	“
City Water Well, 175 feet deep	32-17-15	7.13	13.19	22.49	......	31.85	23.09	2.25	89	W. B. Lerch, U. S. Bureau of Mines
City Water Well, 636 feet deep	32-17-15	3.23	24.90	24.84	......	40.01	3.55	3.47	115	“

Association of Oil and Water:

A correct idea of the underground relation existing between the oil and water appearing in production, is essential to establish the best practice for the removal of the maximum amount of oil and gas. In studying this phase of the subject, the evidence was found to be rather meager on account of poor logging or slight distance drilled into the oil sand.

Plate VII was constructed from thirty-eight well logs for the purpose of estimating the character of the oil and water zones. Plate IV was presented to generalize the conclusions drawn from information at hand.

The north-south generalized section of Plate IV represents conditions along the high portions of the structure and also the variance in certain features from north to south. The convolutions of the strata represent saddles along the axes of the structure. It is assumed that the oil zone proper is free from edge water along the higher portion. The dip is exaggerated fifty times in both sections, the horizontal scale being 1,000 feet to the inch and the vertical scale being twenty feet to the inch. These scales are used for proportioning the thickness of sand and its change in elevation, but the remaining features are necessarily generalized.

The fault shown in Plate IV is assumed for the reason that it makes a rather sudden change from productive to practically non-productive territory, and from light oil to heavy oil.

The oil sand proper varies in texture from sand to sandy shale and in thickness from about sixteen feet at the north end to about ten feet at the south end. The sand is less prolific in some parts of the field than in others. The logs show that a hard cap rock, one to two feet in thickness, is encountered uniformly just above the oil sand in the north end of the field. South of about the middle of Section 8-18-15, such a cap rock is not generally logged. It appears likely that a hard rock layer does not overlie the oil sand in the southern portion of the field and that some of the wells, logging a cap rock, have encountered the lower cap rock instead. A cap rock below the oil sand proper appears to persist throughout the field. Below this cap is a zone of variable texture that appears to carry both oil and water. Deposits of oil have been retained under the highest portions of the persistent second cap rock and in places apparently under local impervious partings.

Below the second zone, which is about twenty feet thick, a third cap rock was logged in a number of wells, under which occurs another sandy zone that carries salt water. The sands between the first and third cap rocks are usually designated in the well logs as the oil sand.

Wells that are drilled just into the sand, below the second cap rock on high points of the structure, may make clean oil if they are sufficiently controlled (i. e., their flow restricted) to avoid water coning. Wells located far down on the structure within range of edge water, should also produce clean oil if drilled only a few feet into the main oil sand and restricted so that they will not produce too fast from the bottom of the sand. The east-west section of Plate IV illustrates the underground conditions to be dealt with.

Some operators believe that the lifting of excessive water must be taken as a matter of course in cases of this kind. In the higher portions of the structure, there was probably little or no water originally in the first oil zone. As the pressure was reduced and oil removed, edge water encroached further up the dip. Moreover, when wells are drilled far enough down slope, edge water may easily be drawn into them from the bottom of the sand, if they are pumped hard or allowed to flow full capacity, even though they have barely penetrated the oil sand.

In this field, when the top of the oil sand lies as low as 1,935 feet below sea level, the sand should be barely touched when drilling in and the output restrained considerably below the full capacity of the well. This should not be interpreted to mean that wells in which the oil sand was found at shallow depths below sea level, such as 1,930 or 1,925 feet, can be drilled deep into the sand and "pulled hard," without danger of drawing in edge water. All high-pressure wells must be controlled in this field, not only to avoid the "drawing in" of edge water, but to prevent them from drilling themselves deeper into the soft and consolidated sand body.

Thus the evidence indicates that clean production can be expected from wells that are fairly high on the structure, that are drilled only a few feet below the top of the oil sand and that are kept under proper control. Exceptions to this rule would be due to the letting in of water by neighboring wells or the production of top water.

The wells shown in Plate IV are hypothetical wells, drawn to represent the following conditions which exist in various parts of El Dorado field:

Wells A and I: Low on the flanks of the structure. Drilled too deep or produced too rapidly, resulting in the drawing in of edge water.

Wells B and G: Bottom of hole rather close to edge water level in the sand, but can produce large quantities of clean oil by "pinching down."

Wells C, M and S: Drilled too deep and penetrated second sand at points where it carries water. These wells are flooding the upper productive sand with water.

Wells D, F, N and R: Drilled to proper depth and cased properly, but making water let into the sand by other wells.

Well E: Drilled through third cap into bottom water, plugged back but not high enough to catch **second cap,** flooding oil sand with water.

Well H: Low on structure and originally made edge water. Plugged part way back to cut off entrance of water. This well should make considerable oil if properly controlled.

Well J: East of probable fault, oil low gravity and a great deal of water, entered deposits of heavy oil, non-commercial at present.

Wells K, P and T: High on structure, producing clean oil and no water.

Wells L and U: Drilled through second cap rock, but properly plugged to exclude water.

Wells O and V: Drilled just below second cap into underlying oil on structural highs, produced too rapidly, causing water coning.

Well Q: Drilled into bottom water and not plugged, flooding oil sand.

In the case of Well N, it will pay to plug with cement to a point several feet above the contact between the water and oil, providing the sand is reasonably consolidated. If water with a high head has access to a hole, the water will soon prevent the entry of oil into the hole. Where there is no parting between the water and oil, a plug cannot be expected to hold the water back indefinitely. However, the water cannot enter the hole as freely as in the case of open hole, because it must pass upward through a greater thickness of formation, with a resulting increased resistance from the formation. In doing so, some of the oil is pushed ahead of the water, also the oil has a longer period for draining laterally into the hole which often results in an increased extraction of oil.

An example of the harmful effect that an improperly drilled well can have on a correctly drilled well, is here given. In El Dorado, Well A was drilled too deep with rotary and produced a large amount of salt water with the oil. Well B, about 300 feet away, was carefully finished about one foot below the top of the oil sand with cable tools shortly after A came in. Well A had been flowing an oil-water fluid vigorously and B also flowed oil for a short time. Muddy salt water then appeared in B, which was strong evidence that rotary mud and water had entered from A, as these two wells were practically isolated at that time. The flow in B quickly subsided and it was then pumped. The oil production was comparatively small and the water continued to appear in large quantities. Neither Well A nor B will show a profit unless A is repaired properly and promptly.

Use of Cement

In the history of the oil industry, many methods have been devised for the exclusion of water. For shutting off top water with casing, the formation shut-off, seed bag or other material that will swell behind the pipe, tamping method, various types of packers, mud-fluid in combination with formation shut-offs, and cement have been used. For bottom water, the tamping of various substances, mechanical plugs and cement (sometimes in combination with mud) have been used. Of these several methods of excluding water, in many cases, cement has proved to be highly satisfactory for both classes of work. Mud fluid is in many fields of considerable use, particularly in top water shut-offs. It is not serviceable when used alone for high-pressure bottom water. It is often necessary to use mechanical devices or mud-fluid in connection with cement for the purpose of clogging porous formations and stopping the movement of water, oil or gas.

The use of cement behind water strings has been quite diverse in application. Detailed descriptions of cementing methods have been described by Tough.*

A brief description of the various ways of cementing in different fields is here given. Cement has been placed behind casing (1) by dumping it outside of the casing at the surface; (2) by lowering the casing into the mixed cement which has been placed at the bottom of the hole and effecting no change in the height of the cement inside and outside the casing; (3) by placing the cement in the bottom of the hole by pouring it in dry or mixed, or with a dart bailer (adapted) or dump bailer and then lowering the casing into the cement with a plug in the bottom of the casing or with a head on top, having the casing full of water, thus leaving little or no cement in the shoe joint; (4) by pumping the cement through tubing, with or without the aid of one or two wooden plugs to determine the travel of the cement, following with water or mud, and using a packer at bottom or a packing head at top; (5) by pumping cement through the casing and following it with water or mud, using no plugs to determine the travel of the cement and to prevent its mixing with other fluids; (6) by the same method as number 5, except using one plug after the cement; (7) by the same method as number 5, except using one plug before and one plug after the cement.

Method 1 is unreliable and has not been attempted to any extent. Indeed, the conditions allowing its use are not frequently met. Method 2 is not reliable, especially for rotary holes, because there is little or no cleaning action on the walls by the cement. The more cement that is used, the more it is necessary to drill out. In method 3, good work has been done with the dump bailer, using small amounts of cement, but it is not suitable for rotary holes, unless the formation will stand washing, on account of probable inability to properly free the walls of mud with a large amount of cement. Method 4 has been used to good advantage, especially when a small quantity of cement or a quick-setting cement is used. The cement can be put away in quicker time with tubing than with casing. The method, however, is now practically obsolete for casing jobs. Method 5, although used in some fields, is not considered reliable, as there is danger of diluting the cement or of leaving too much cement in the casing. By method 6, it becomes known when the cement is all out of the casing, but unless a large quantity of cement is used, the excessive dilution of the first of the cement column may render the work unsuccessful. Method 7 is considered the most reliable cementing practice that has been developed. There are various modifications of this practice, but in principle the first plug prevents the dilution of the cement with the fluid in the pipe and allows its passage after that plug reaches bottom, while the second plug protects the upper part of the cement column and indicates when the cement is all out of the casing, by stopping or slowing the pump. The first plug remains in the bottom of the casing and the last plug cannot leave the casing. The most efficient plugs are made of wood with circular pieces of belting to fill out the full diameter of the pipe, except that an inverted leather cup should be placed on top of the second plug.

Probably the most improved practice in connection with the two-plug system of cementing water strings is found in the patented Halliburton and Perkins methods. In the former, the exact position of the last plug, which follows the cement, is always known by reading a steel tape. The

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**Tough, F. B., Methods of Shutting off Water in Oil and Gas Wells, Bulletin 163, U. S. Bureau of Mines, 1918.*

tape is attached to the plug, runs through a packing device and is fed from a reel and over a pulley. This apparatus is coming into extensive use in various fields of the country, particularly in southern Oklahoma. A full description is given by Swigart and Schwarzenbek.* The position of the plugs is checked by reading a water meeter.

At El Dorado the general practice has been to use only one wooden plug with a sack of shale placed on top of it, to follow the cement. The sack of shale is meant to act in the same manner as an inverted cup, i. e., stall the pump when the plug reached bottom. This practice, although apparently successful, is not always as reliable as the two-plug method.

The use of a loosely-filled sack of fine shale following a plain wooden plug, is no doubt an efficient method of stopping the pump at the end point, provided the shale is retained in the sack. The sack may become torn before it travels very far and the particles of shale separated from the top of the plug. If this happens, circulation may obtain between the plug and the casing, when the plug reaches bottom, and thus carry the cement up above the casing shoe. As a matter of fact, if the plug is almost the same diameter as that of the casing, the pumps will be slowed up so appreciably when the plug reaches bottom, that it would be distinctly noticeable.

Because of the large amount of bottom hole plugging which will eventually have to be done in El Dorado oil field, a brief discussion of plugging with cement will be included. Cement for bottom water jobs in other fields has been handled in different ways; (1) by pouring dry or mixed cement into the casing at the surface; (2) by placing mixed cement on the bottom with a dart or dump bailer; (3) by dropping cement-filled metal containers to bottom and breaking these up with the tools; (4) by pumping cement through tubing and holding a pressure. Method 1 is almost certain of failure. With Method 2, small quantities of cement can be successfully placed on bottom with a dart bailer and more can be added if some device is used to hold the dart open after it trips. The use of a dump rod attachment injures the cement. The dump bailer is a thoroughly reliable tool for such work and should always be used in preference to other bailers. Fig. 2 shows one of the common types of dump bailer. This device can be used very successfully when the walls of the hole to be cemented are fairly clean, when all gas, oil or water movement has been stopped and when it is not necessary to force cement into the pores of the formation. Method 3 has been used quite successfully in different fields. It offers opportunity for quieting very weak fluid movement by the tamping effect and thus allowing the cement to set on top of the tamp. It is a convenient method to try where apparatus for better methods is lacking.

Method 4 is a very satisfactory way to cement off bottom water with a high head. As shown, C of Plate III, the tubing is run nearly to bottom of the hole through a casinghead packer, which has an outlet valve. The tubing should first be run to bottom and circulation of mud started to clean out collected debris. After circulation is gained, the cement is then started through the pump with or without preceding it with a wooden plug. When a plug is not used, the cubic contents of the tubing are calculated. The progress of the cement can be checked by a water meter. In this method it is important to know when the first cement reaches bottom and it becomes impracticable to measure mixed cement from a tank.

If a plug is used, the pump will be checked when the first cement reaches bottom, because the tubing is not held high enough to allow the plug to pass entirely out. In any event, when the cement reaches bottom, the tubing should be raised slightly above the required depth for the top of the cement plug, and the outlet valve on the casing should be closed. The cement is then forced against the walls of the hole and into the pores of the formation. If the cement is readily absorbed by the formations, it

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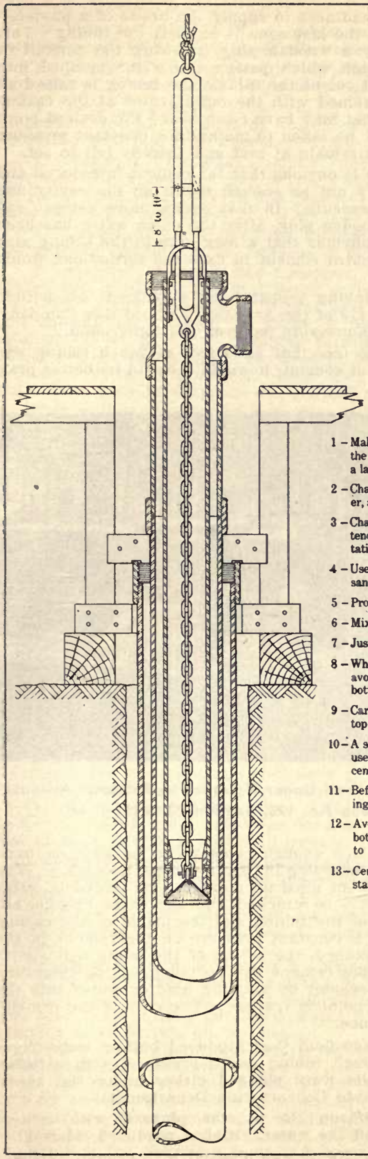
**Swigart, T. E., and Schwarzenbek, F. X., Petroleum Engineering in the Hewitt Oil Field, Oklahoma—Co-operative Report of State of Oklahoma and U. S. Bureau of Mines, January, 1921. Distributed by Ardmore Chamber of Commerce. Price, $1.00.*



SPECIFICATIONS AND USE

1 – Make reins of 1¼-inch square iron as far as 6-inches below the latch and ¾-inch square iron below that point, allowing a larger space for filling with cement.

2 – Chains should be ⅜-inch Swedish steel for 6⅝-inch, or smaller, and ⅝-inch material for larger than 6⅝-inch bailer.

3 – Chains should be fastened to removable eye-bolt which extends through the valve, facilitating repairs and transportation.

4 – Use only neat cement and fresh water, i.e. cement without sand, rock or other material.

5 – Proper mix about 45 pounds water to 100 pounds cement.

6 – Mix thoroughly and rapidly.

7 – Just sufficient cement to fill bailer should be mixed at once.

8 – When lowering cement-filled bailer, run slowly enough to avoid latch moving below bail and dumping cement above bottom when slow motion is resumed.

9 – Care should be taken not to trip the latch when bailer hits top of water.

10 – A sectional bailer; made of several joints of pipe, should be used when it is desired to dump a considerable quantity of cement.

11 – Before cementing, stop gas or water movement at cementing point with a sufficient head of water, or with mud.

12 – Avoid dilution of cement, after opening valve, by holding bottom of bailer at top of loose cement a sufficient time to finish emptying cement from bailer.

13 – Cement should be allowed 10 days to set. Maintain a constant head of water during that time.

U. S. BUREAU OF MINES
PETROLEUM DIVISION
DALLAS, TEXAS.

SKETCH SHOWING
DUMP BAILER FOR
CEMENTING OIL WELLS

Drawn by J. G. Shumate | Date Ac.. 11, 1921
Scale, Diagrammatic

Fig. 11. Dump Bailer, p. 102.

is necessary to have enough in readiness to supply the needs of a predetermined pressure or to know when the last cement has left the tubing. This can be ascertained accurately by a wooden plug following the cement or by reading a water meter, through which passes the water pumped into the well. When the cement is all out of the tubing, the tubing is raised off the plug, and the pumping is resumed with the outlet valve at the casing-head partly open. Any cement that may have risen above the desired point can be circulated out. Care must be taken to maintain a constant pressure or otherwise the cement may not remain at rest and thereby fail to set.

In using the above method, it is obvious that the cement introduced and followed by the second plug, may not be enough to fill up the cavity and pore spaces under the desired pressure. In that event, more cement can be added, followed by another wooden plug, after the extra water has been circulated out of the way. It is obvious that a long plug in the tubing may cause trouble in circulating out extra cement in case the formations would take no more cement.

Plate VIII shows a crew making preparations to cement off bottom water (through tubing) in Wood 119 of the Arkansas Natural Gas Company. Notice both low-pressure and high-pressure pump in the foreground.

In view of the above and the fact that 2,200 feet of 2-inch tubing will hold only about forty-eight sacks of cement, it would seem to be better practice to omit the second plug. Then enough cement can be kept on hand and mixed in time for continuous pumping in of the cement necessary. The tubing should be kept full of cement until no more can be forced in, after which the circulating valve should be cracked and the extra cement circulated out between the outside of the tubing and the inside of the casing, at a sufficient speed to maintain a constant pressure on the cement in the well. After a certain point is reached, the action of the pump will give a good idea of about how much more cement will be taken. It is, therefore, possible to reduce the waste of cement by starting mud or water into the tubing somewhat before the end point is reached. The cost of the cement, however, is of secondary importance.

Plate VIII. Preparing to Cement Well Under Pressure in Bottom. Arkansas Natural Gas Company, Wood No. 199, Section 20-18-15, p. 110.

Several wells in the El Dorado field that produced bottom water have been plugged by cementing through tubing under pressure, with satisfactory results. The following wells were plugged either under the supervision or at the request of the State Conservation Department:

1. Foster Oil Company, Hinson No. 4, was plugged with cement (amount unknown), which shut off the water. It then produced clean oil.

2. Guffey-Gillespie, Steadman No. 3, was plugged with cement (amount unknown), which shut off water.

3. Standard Oil Company, Robertson "B" No. 3, was plugged with thirteen sacks of cement, materially reducing the production of water.

4. Busey, Armstrong No. 1, was plugged with ninety sacks of cement and shut off bottom water. This well has been abandoned.

5. Lucas Tomberlin, Crawford No. 1, was plugged with eighteen feet of cement, for the purpose of abandonment. This work was done in co-operation with the U. S. Bureau of Mines.

6. Magnolia Petroleum Company, McKinney No. 3, was plugged nine feet with cement, but the plug is now being drilled out. This well produced oil for a short time after it was plugged. The cement may have shut off most of the productive portion of the sand.

7. Constantin Oil & Refining Company, Hill No. 3, was plugged with 300 sacks of cement, for the purpose of abandonment.

8. Arkansas Natural Gas Company, Wood No. 199, was plugged by stages with cement. The first batch of 160 sacks filled the hole only two feet. There was 180 sacks of cement next pumped in, filling the hole three and one-half feet. Then 120 sacks of cement was pumped in, making a total of 460 sacks. After pumping in nine wagon loads of fine sand and empty cement sacks, eighty more sacks of cement was added. This made a total of 540 sacks of cement. Soon after this, the well started flowing oil, but it soon drew in water, as no "chokes" were inserted in the flow line.

This well is reported to have been drilled only two feet below the top of the oil sand. When first opened up, it produced about ten days through a ¾-inch choke. The rate of flow was even then too rapid, for large quantities of sand and water were expelled, and the flow was finally cut off by water. Measurements showed the well had drilled itself at least two feet deeper. Probably it had drilled itself much deeper than the measurements indicated and had subsequently filled in with loose sand. The well is no doubt located where edge water occurs in the bottom of the main oil sand, and, therefore, great care should have been exercised in regulating its flow. The fact that the well flowed again after plugging, illustrates the point that plugs are beneficial even when it is probable there is no parting between the oil and water. If this well had been sufficiently controlled after the plugging, there is little doubt that it would have produced considerable oil.

Some wells were plugged by means of an improvised dump bailer with a rod attached to the dart for dumping the cement. This method was adopted because a regular dump bailer was not available. The washing of the cement and its picking up in the return of the bailer to the surface were minimized by first attaching only a few feet of dump rod. Additional lengths were screwed on, as the cement filled up the hole. The idea was to have the bottom of the bailer dump each time only a few feet above the top of the cement. The engineers of the Bureau of Mines worked on the abandonment of two wells: the Abner Davis, Cornish No. 1, and the Crosby Syndicate, Jackson No. 1. The former was plugged with eight sacks of cement which filled the hole about sixty-six feet, and the latter was plugged up sixteen feet with cement.

Operators plugged the following wells by dump bailer method, resulting in increase of oil production and decrease of water production:

Hickman & Baird, McKinney A-1, plugged six feet with cement.

Hickman & Baird, McKinney A-2, plugged three feet with cement.

Hickman & Baird, McKinney 1, plugged nine and one-half feet with cement.

Hickman & Baird, McKinney 3, plugged with twenty sacks of cement.

White Oil Corporation, Armstrong N-2, plugged twenty-four feet with cement. This well then made eighty-four barrels oil. Drilled out one foot at a time, it then produced water. Plugged back second time, now pumping sixty barrels oil, no water.

White Oil Corporation, Armstrong S-1, plugged with twenty sacks cement and shut off bottom water.

It has been repeatedly proved at El Dorado, that proper plugging will shut off or materially reduce the production of water, and because this is the most important remedial work that can be done in this field it should be concentrated upon by operators.

Some of the operators have had apparent success in excluding bottom water by tamping empty cement sacks in the bottom of the hole with the drill pipe. The sacks are rolled tightly, placed in the top of the drill pipe and are then forced to bottom by the pump. The sacks are wedged into a very compact mass by "spudding" the drill pipe on them. It is very doubtful if the tamped sacks can be relied on to permanently retain sufficient rigidity to hold back the water. The apparent success may be only temporary. Time and an increasing differential between the water pressure and the fluid pressure above the plug, is apt to wreck such a plug.

Handling of Cement:

The following is taken in part from "Engineers' Survey of Burkburnett," Wichita County, Texas, by the present authors, appearing in the Oil & Gas Journal, issues March 24 to April 20, 1922, inclusive.

Pure cement should be used and mixed with as little water as is possible for handling in the pump or bailer. It should not be unnecessarily diluted with water or with mud, after it is placed in the well. Cement is a definite mixture of compounds, some of which are soluble in water. The soluble portions should not be separated from the insoluble. Therefore, a diluting or "washing" of the cement will seriously, if not wholly, destroy its hardening qualities. Likewise, a dilution with an excess of other material, such as mud, will reduce its strength.

Cement will set readily under salt water and many other foul or highly mineralized waters, providing sufficient care is taken in handling it.

Ten feet of settling through water is too much washing for a small quantity of cement. The unsuccessful use of the ordinary bailer with a rod attached to the dart, which adaptation was originally designed for dumping drilling water, has led many operators to assume that cement will not set in oil field water. It has been proven that the dump rod is the cause of many failures, due to the washing of the cement while settling through the water from the dart to bottom.

The cement should be placed directly from the bailer at the bottom of the hole with as little agitation as possible. This can be done by a suitable dump bailer, such as is shown in Figure 2. It will pay an operator to possess a reliable tool of this kind, if he expects to use that method for cementing casings or for plugging off bottom water. Some of the patented dump bailers are dependable; one makes trips and holds the valve open by means of a latch near the bottom.

After the first bailer is dumped, care should always be taken to raise the bottom of the bailer to the top of the cement and allow ample time for draining the cement from the bailer, for, otherwise, the cement will drain from the bailer as it is drawn upward. This is undesirable, because it means a considerable settling of the cement, through the water. It should be made certain that all commotion, such as action of gas or water, is eliminated before the cement is placed, or very shortly thereafter.

When cement can be made to bond with the walls of the hole, there is no better method than a good cementing job for shutting off top water with casing or for plugging off bottom water. When handled properly, it will set under nearly all conditions; in foul water and in oil. Age, moisture and improper storage may render a good quality of cement unfit for use. Failures of cement to set in oil wells have resulted from poor cement, and these can probably be prevented by the use of simple tests made in advance. The following procedure is recommended: Take three small average samples of the cement; mix one with water from the well, and the other with distilled or very pure water. Place the stiffly mixed samples in tall containers and finish filling the first two with the foul water, taking care to avoid commotion and washing. On the third sample, the same water may be added to the container that was mixed with the cement. After a day or so, notice the condition of the samples. If none of them have set hard, experiments should be made with other lots of cement until it is certain that a reliable lot has been found.

It is common practice, in some fields of other states, to use from 100 to 500 sacks of cement and to pump it through casings with or without the use of separating plugs. In some of these instances, the casings have been cemented solid with cement from the shoe to the surface. This confines each fluid to its original stratum, assuming the cement sets hard all the way and completely jackets to the casing.

The advantages of using large quantities of cement are:

1. When the mud of rotary wells cannot be washed with water, on account of caving formations, the first cement that is pumped out of the shoe scours the mud from the lower formations and casing. This allows

the final cement to properly bond with them. The first cement will not harden, due to the dilution with mud, but this portion will be on top and its condition will not affect the shut-off.

2. The cement may seal off water and oil-bearing strata of shallow depth. In the case of rotary wells, it will prevent, as far as it bonds with casing and formation, washing of the absorbed mud and establishment of water infiltration into oil and gas deposits that lie above the shoe.

3. The casing seat will have additional strength. Large amounts of cement have been used to hold casings that could not be supported by the formation adjacent to the shoe. Also, the possibility of high-pressure oil or gas blowing past the shoe and outside of the casing is lessened.

4. The casings are protected over a larger surface from corrosive water. The mud fluid of rotary wells is also good protection, provided water does not wash its way to the casing. (See also No. 2.)

5. The danger of collapsing water strings, due to water pressure, is lessened by reinforcing the casing on the bottom where the greatest pressure occurs. When cement is used in this manner, a shallow water deposit may not exert as high a maximum pressure on the casing as a deeper water, although the two waters would stand at the same level. Suppose, for instance, that a water string is cemented at 2,100 feet and that a good jacket of cement extends to a depth of 1,500 feet. If no water exists in the formations between 1,500 feet and 2,100 feet, the top water cannot exert a pressure at a point lower than 1,500 feet, or no greater than about 700 pounds per square inch, for salt water. A thin jacket of cement would suffice to prevent this water from following down the casing and exerting the full hydrostatic pressure on the bottom of the casing. Assume now that a water stratum exists at 1,800 feet and that this water, like the shallow water, would rise to the surface if not obstructed by the cement. It will, therefore, exert a pressure of about 850 pounds per square inch for salt water. When high-head water is sealed with cement alone, it will exert pressure directly on the cement and casing so that thick walls of cement will be necessary to lend substantial reinforcement to the casing.

The final necessity of thick cement walls will also depend upon the rigidity of the water stratum and upon the amount of cement that hardened in its pore spaces. These considerations, and the possibility of low-head porous strata becoming converted to high-head by secondary water, argue forcibly for thick walls of cement around the lower portions of the casings, especially when the factor of safety against collapse is small. When cement is used in rotary wells, this feature is taken care of usually, as the water strings have a large clearance in most cases.

6. When the water in the hole is too foul to allow the cement to set, an excess of cement mixed with good water may displace the foul water sufficiently to allow hardening for a certain distance above the shoe .

The use of large quantities of cement may appear to be a waste, when considering the future recovery of casings in the process of repairs or abandonment. However, a portion of the casing is a small item compared to the total cost of drilling a well, and is very small compared to the possible waste of oil and gas due to water infiltration. These statements, of course, are not strictly true in the case of "wildcat" wells, where underground conditions and possibilities have to be learned first.

Abandonment of Wells:

It is always expensive and sometimes impossible to re-enter and re pair an improperly abandoned well, and for those reasons it is highly desirable to use particular care in the abandonment operations. In this work, each fluid near the oil and gas horizons should be confined, as far as practicable, to its own stratum. If this idea is followed, the recovery of oil and gas from other wells will be increased and, at the same time, valuable deposits of potable water may be protected from contamination by brines or sulphur water.

A well may be properly drilled and tested, but prove to have no commercial production of oil. If such a well is not properly abandoned, however, it may allow water with a high head to travel across the formations to neighboring wells. The improper abandonment of wells in proved areas is usually inexcusable and constitutes a deplorable crime against our natural resources.

Too much reliance should not be placed on an entire water string left in a well, inasmuch as the rotary-mud protection from corrosion may be overcome by water action after subsistence of the mud, unless the mud was subjected to a considerable closed-in pump pressure.

The proper use of cement and of mud-laden fluid afford the best means for the proper abandonment of wells. The technique of properly placing cement has been discussed previously. The use of cement for this purpose usually calls for a study of the fluid content of the different formations, the probable future worth of present non-commercial deposits and the possible danger of leaving two or more oil strata open together between cement bridges.

In general, an adequate cement plug should be placed in the bottom of the hole, if necessary, with substantial cement bridges between each pair of water, oil or gas strata. Obviously, the present and possible future conditions of the area determine the size and extent of these plugs. The problem would, on first thought, appear to be simplified by cleaning out the well to bottom and filling it with cement to a considerable distance above the oil zone or possible oil zones. Such would be the case, but if the hardness of the cement were not tested at the vital points, efficiency of the work would not be assured. When a well has many showings of oil, with no intervening water, there is a temptation to leave some of the sands open together, with possibly a cement bridge below the bottom showing and one above the top oil deposit. If water appeared in one of these, the other sands might be flooded from a well improperly abandoned.

In general, long cement plugs and bridges should be set opposite oil sands when a well is abandoned, but they should be tested for hardness at proper depths during their construction.

The proper method of abandoning wells will vary somewhat according to local conditions. Mud fluid has been used to good advantage in El Dorado for such work. The well should first be cleaned out to bottom, mud pumped through the tubing or extra casing which is then lowered nearly to bottom. The mud should be pumped in until returns of mud have been established at the surface, for several hours. The casing is then packed off and mud forced in under extra pump pressure, using as much heavy mud as possible.

Some formations will take enormous quantities of thick mud. It is, therefore, occasionally found expedient to introduce sawdust, chopped rope or straw, etc., into the fluid, in order to assist in clogging the pore spaces. After the lower part of the hole is well mudded, the water strings can be removed and mudding continued up the hole by moving the mudding string upward as the work is accomplished. If there is a conductor string, this can be removed, but the final mudding at the top of the hole should also be done under extra pump pressure in order to seal off the top water. Heavy mud which is free from grit should be used in all of this work. The top of the hole should be protected from debris, and an occasional inspection made to determine whether the mud has receded, in which event more should be added to the top of the column.

The caving and bridging of formations, as the casings are removed, should be avoided as far as possible, in order to be sure that the mud gets into all porous formations. In this way, each fluid can be kept sealed in its original stratum and a reliable abandonment accomplished.

Another satisfactory way to abandon a well is to force mud into the formations under considerable pump pressure between cement plugs and bridges. If only the usual pressure due to circulation, or weight of the mud, is used for filling the space between cement bridges, it is possible that a gradual absorption of the fluid by the formation, may occur. This would tend to break the column of mud between the bridges. It might result in a washing of the mud with water and a harmful migration of one or more of the fluids under consideration. It is obvious that this "slack" between bridges cannot be taken up by adding more mud at the surface. A slow movement of mud into the formation may easily appear to be no movement at all. However, as time elapses, a column of mud may undergo considerable further absorption.

The Conservation Commission of Arkansas requires that the producing sands be protected with cement and that the hole then be filled to the surface with mud. If the bottom of a well is plugged with cement to a point above the oil sand, and thick mud is then filled in to the surface, the abandonment would most likely be effective, if more mud could be added in case it receded down the hole. It is, of course, quite possible that a portion of the mud fluid would be held at the surface by the bridging of caved formations, while subsidence took place below that point. The migration of oil, gas or water might then occur below the bridge. In introducing mud into a well, it is also possible to fail to get mud into all parts of the well, on account of bridging formation. It is therefore necessary to mud a well with a string of pipe, starting at bottom and mudding and applying pressure opposite each porous formation which may contain oil, gas or potable water, as the casing is raised.

Protection in Case of Deeper Production

The present producing zone of El Dorado has been definitely assigned by the U. S. Geological Survey, to the Nacatoch subdivision of the Upper-Cretaceous period. It is the history of some neighboring oil fields with Nacatoch production that they have also obtained deeper production and it may be that deeper production will be found at El Dorado. This paper deals with deeper production, only in connection with conservation. With this possibility in mind, adequate means of protecting the various oil deposits should be considered in case deeper drilling is carried on.

If a commercial quantity of deeper oil is discovered, there would be general activity toward its exploitation. Either oil wells would be deepened or new wells drilled. For the sake of convenience in discussion, the zones of interest will be designated as follows: Zone A, above a depth of 1,900 feet below sea level; Zone B, present productive zone; Zone C, hypothetical deeper production. Zones B and C would be produced from at the same time and through the same or separate wells, depending upon the distance between sands and the character and content of the intermediate formations. Suitable methods for bringing in deeper production are outlined below.

1. A well can be deepened for lower production (a) by cementing the next smaller casing just above the new production and producing with or without a liner; (b) by recovering all possible of the original water string, side-tracking the remainder and carrying the same size for a deeper shut-off. In (a) enough cement should be used to reach above the shoe of the first water string; in (b) the discarded casing should be plugged with cement before sidetracking in order to prevent its becoming a water channel, mud should be forced into the strata under an extra pump pressure of at least 500 pounds per square inch, and enough cement should be used on the deeper casing to reach at least 300 feet above the top of Zone B. Most of the present water strings are 6-inch and plan (a) would reduce the hole to 4-inch, or smaller if a liner were used. Such a plan, however, may be found feasible. The general disadvantages of reducing the hole to such small size are, small area of face of hole for oil to drain to, and the excessive danger of sticking tools, bailer or tubing and the difficulty of conducting fishing operations in such a small hole.

Plan (b) may not prove desirable for the reason that it may be impossible to reclaim more than 1,200 feet of the water string and that sidetracking with rotary may prove difficult.

2. New wells could be drilled to obtain lower production. This would involve the question as to the number of strings of casing to use. With a suitable practice already established for production at the present depth, the drilling of new wells for deeper production can be done as follows: (a) cement about 170 feet to 200 feet of 10-inch or 12½-inch casing (as usual), cement second string a short distance above Zone b (as usual), cement third string just above Zone C, using enough cement to reach above the shoe of the next string: (b) omit the second string of (a), put at least 500 pounds extra pump pressure on the mud and cement lower string of casing with enough cement to reach at least 300 feet above the top of Zone B.

By the methods outlined above, adequate protection could be afforded the several oil deposits. The cementing should be carefully done, employing the best practice of the two-plug system. Method (b) has the advantage of saving a string of casing.

High and low-pressure deposits should not be left open together in the same well on account of probably dissipation of the high-pressure into the low-pressure strata. It is possible that, before abandoning the wells, Zones B and C could be produced simultaneously, by perforating the water string with a long-knife perforator opposite the top of the present production (Zone B). The cement jacket should protect this oil from both top and lower water. If such was not the case, cement could be forced out through the perforation by means of a bridge, tubing and packing head and production then resumed from Zone C, or tests made of Zone A.

Production Record

Oil Produced, Proven Acreage, Well Spacing:

As shown in Table No. 1, the El Dorado field had produced something in excess of 10,000,000 barrels of oil by the end of October, 1921. These production figures are shown graphically in Figure 3 (in pocket). At that date there were about 460 producing wells and an estimated proved acreage of oil and gas territory of 6,825. The average spacing was about fifteen acres per well.

The figures on proved acreage and spacing are misleading, however, on account of some 2,000 acres of the area being gas bearing to a high degree, thus rendering it undesirable for present exploitation for oil. This leaves about 4,825 acres of territory that may be considered as proved oil territory. Considering the oil area alone, the average spacing of wells at the end of October, 1921, was about 10.3 acres per well (average of 670 feet distance). By the end of November, the average spacing for the entire field had decreased to approximately 8.8 acres per well (619 feet distant). Completions were made at the rate of about eighteen or twenty wells per week during October and November, 1921.

In the estimate of 4,825 acres of proven oil-producing area, 100 acres were assigned to Section 33-17-15. This may be, as many believe, a separate structure from the main field and its probable further development is necessarily omitted from the accompanying estimates.

Section 17-18-15 has been drilled more intensively than any other section in the field. By December 1, 1921, the average spacing in the productive part of that area was about six acres per well (wells 511 feet apart). There are small tracts in this and other sections of the field where the spacing will approximate three acres per well (362 feet distance). Plate IX gives an idea of the close spacing of wells near the southern boundary of Section 17-18-15.

The general ruling of the State Conservation Commission provides that interior wells shall not be closer together than 400 feet, and that wells shall not be nearer than 200 feet to property lines. In the case of so-called "shoe string" properties, the Commission is more lenient, and may consider a group of properties as a whole and stagger the wells. An average spacing of 400 feet allows only 3.67 acres per well. In the light of present information, it is safe to say this spacing is undoubtedly too close.

The following figures, while approximate, are presented to show that, in view of conditions prevailing at El Dorado, an average spacing of seven acres per well is no doubt too close, for this field.

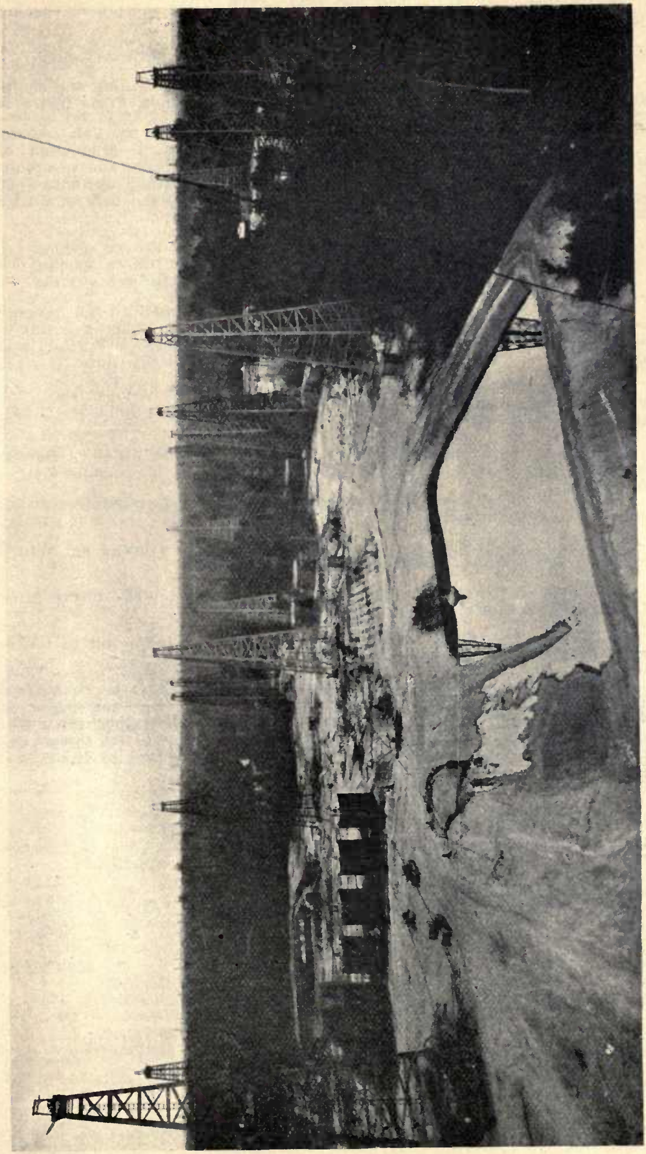


Plate IX. Intensive Drilling Near South Boundary of Section 17-18-15. Shows Open Earthen Sump for Oil Storage.

The principal factors to be considered in estimating the proper spacing are:

(1) Acreage—a proven oil area of 4,825 acres has been estimated.

(2) Cost of Drilling—$15,000 is taken as the cost of drilling and equipping a well, including its pro-rated general lease expense. This figure is probably too low.

(3) Total Production—From the production data, a production of 20,640,000 barrels is assumed for the present proven acreage and reservoir. It is assumed that the wells will not be spaced closer than ten acres per well (average spacing as of October, 1921). Guided by the data of Cutler and Clute* for other fields, it is assumed that:

9-acre spacing will yield per well 95.0% of yield for 10-acre spacing
8-acre spacing will yield per well 89.5% of yield for 10-acre spacing
7-acre spacing will yield per well 84.0% of yield for 10-acre spacing

(4) Production Cost—35 cents per barrel is assumed as the average cost of production during the productive life of the field. This is meant to include all expenses incurred in production, and includes "overhead" and general charges. This figure is difficult of estimation at this time.

(5) Lease Prices—The figure of $500 per acre for the average price of leases is based on rather meager data, but it will serve for general purposes. It is probably low.

(6) Loss of Oil—As indicated by Table I, the loss of oil at El Dorado may be as high as 12 per cent. The figure of 7 per cent is no doubt low.

(7) Interest—A total of 21 per cent is here assumed, regardless of the time of receiving the oil.

(8) Salvage—$1,000 per well is meant to be the average net return from sale and re-use of casing and surface equipment.

(9) Price of Oil—$1.35 per barrel is here assumed. The future price of oil is, of course, a matter of speculation.

(10) Royalty—12½%, which leaves the selling price of oil to be received by the lessee as $1.18 per barrel.

The following estimates (slide rule computation) must be considered as only approximate. They at least prove that an average spacing of as low as four acres per well, is unprofitable. From Plate X (in pocket) it will be seen that wells with an initial average daily production of 480 barrels the first month, will produce during their entire life, an average of 42,800 barrels.

Ten Acres Per Well

4825 acres÷10 acres=482 wells—		
482 wells @ $15,000 drilling and equipment cost		$ 7,230,000
482 wells @ 42,800 bbls. each, 20,640,000 bbls. @ 35c production-cost		7,225,000
4825 acres @ $500 for leases		2,412,000
Loss of oil (7%) 1,445,000 bbls. @ $1.18		1,706,000
Interest, 21% of investment		3,900,000
		$22,473,000
Oil sold, 19,195,000 bbls. @ $1.18	$22,640,000	
Salvage of casing and surface equipment, $1,000 per well	482,000	
	$23,122,000	
	22,473,000	
Gain	$649,000	

Cutler, W. W., and Clute, Walker S., Relation of Drilling Campaign to Income from Oil Properties—Reports of Investigations, U. S. Bureau of Mines, August, 1921.

Nine Acres Per Well.

4825 acres÷9 acres= 536 wells—

536 wells @ $15,000 drilling and equipment cost		$ 8,040,000
536 wells @ 40,600 bbls. each, 21,800,000 bbls. @ 35c production cost		7,640,000
4825 acres @ $500 for leases		2,412,000
Loss of oil (7%) 1,525,000 bbls. @ $1.18		1,800,000
Interest, 21% of investment		4,175,000
		$24,067,000
Oil sold, 20,275,000 bbls. @ $1.18	$23,920,000	
Salvage of casing and surface equipment, $1,000 per well	536,000	
	$24,456,000	
	24,067,000	
Gain	$389,000	

Eight Acres Per Well.

4825 acres÷8 acres=603 wells—

603 wells @ $15,000 drilling and equipment cost		$ 9,045,000
603 wells @ 38,300 bbls. each, 23,100,000 bbls. @ 35c production cost		8,090,000
4825 acres @ $500 for leases		2,412,000
Loss of oil (7%) 1,616,000 bbls. @ $1.18		1,907,000
Interest, roughly 21%		4,510,000
		$25,964,000
Oil sold, 21,484,000 bbls, @ $1.18	$25,380,000	
Salvage of casing and surface equipment, $1,000 per well	603,000	
	$25,983,000	
	25,964,000	
Gain	$19,000	

Seven Acres Per Well

4825 acres÷7 acres=689 wells—

689 wells @ $15,000 drilling and equipment cost		$10,335,000
689 wells @ 35,960 bbls., 24,790,000 bbls, @ 35c production cost		8,675,000
4825 acres @ $500 for leases		2,412,000
Loss of oil (7%) 1,734,000 bbls. @ $1.18		2,046,000
Interest about 21%		4,933,000
		$28,401,000
Oil sold, 23,056,000 bbls., @ $1.18	$27,220,000	
Salvage of casing and surface equipment, $1,000 per well	689,000	27,909,000
Loss		$ 492,000

It may be interesting to note that approximately 22,400,000 barrels of oil would be produced with the following factors:

(1) A proven acreage of 4,825. This does not mean that extensions to the field will not be made.

(2) An average thickness of twelve feet for the saturated portion of the reservoir formation. The data is rather meager on this point.

(3) An average porosity of 25 per cent. On account of the incoherence of the sand, no samples have been obtained on which porosity tests could be made. In an uncemented sand, the porosity may be rather high.

(4) An ultimate recovery of 20 per cent of the total oil underground.

Either of the last three factors or the production from the 4,825 acres, may have a different value, in which case one or more of the other factors would be affected.

Several factors that will influence the spacing of wells, are: Possible profits that can be derived, estimated amount of oil recoverable with different spacings, porosity and size of grain of reservoir formation, gravity of oil, gas pressure and depth. The relation of well spacing to possible profits derivable from production, is one of the most important factors and has not, in general, received much attention. It is apparent that a larger ultimate net profit expected on operations will justify a larger expenditure by drilling more wells, in order to extract more oil in a shorter period, thereby decreasing the total interest charges on the money invested. Expected profits can easily be swallowed up when close-spacing is used, by excessive total cost and attendant interest, depreciation and amortization charges.

The individual productions of wells vary considerably at El Dorado. The records show that numerous wells have increased their production temporarily at different points during the general decline of production. This condition is, no doubt, due primarily to sand trouble. After a well frees itself of sand or is cleaned out, the production usually increases. The accumulation of sand and waxy sediment in the liner or screen, or the lower portions of the tubing, may seriously retard production.

Like most oil fields, El Dorado has some so-called "spotted" territory. For example, a well of 2,200 barrels initial flow was located in the midst of small producers. Its decline was abnormally rapid, however. The rock pressure is said to have been low and not well sustained, and it was apparently an isolated prolific spot.

Quality of Oil:

Some of the oil runs as high as 37.5 degrees Baume gravity. It averages about 35.5 degrees Baume gravity and is placed in the class of paraffin base oils. Analyses from various parts of the field indicate that the crude averages about 31 per cent gasoline and 15 per cent distillate. The sulphur content is rather large, frequently exceeding one per cent.

Surface Wastage:

In developing an oil field, it is impossible to avoid all waste, especially during the pioneer period. It is possible, however, to curtail waste to a greater extent than is usually done. There is much oil lost, due to the rush in completing wells that could be prevented with little extra time and expense.

Evaporation losses are field losses that will probably never be entirely eliminated, but remarkable economy can be effected. Wiggins* has shown by numerous experiments and data that the average evaporation loss for the Mid-Continent fields is 6.2 per cent, divided among the various operations as follows:

APPORTIONMENT OF THE EVAPORATION LOSS SUSTAINED BY CRUDE OIL ON ITS JOURNEY FROM THE WELL TO THE REFINERY

Location of Loss—	Per Cent Volume Evaporated Summer	Spring	Winter	Avg.	Source of Information
Flow tank	1.2	1.0	0.8	1.0	Estimate plus test on filling lease tank
Filling lease tank	1.2	1.0	0.8	1.0	Test
Lease storage	1.8	1.4	1.2	1.5	Test
Gathering	1.3	0.9	0.8	1.0	Test
Transportation	1.2	0.9	0.8	1.0	Estimate plus tank tests Test on filling large tank
Tank farm	0.9	0.7	0.6	0.7	Test
Total	7.6	5.9	4.9	6.2	(By addition)

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*Wiggins, J. H., *Evaporation Losses of Crude Oil in Storage in the Mid-Continent*, Bulletin No. 200, Bureau of Mines (in press). Advance chapters in trade journals.

The conclusion as drawn by him is: "This figure of 6.2 per cent when applied to the 196,000,000 barrels produced in the Mid-Continent fields shows that 12,152,000 barrels is the yearly evaporation bill. In gallons, it equals 510,000,000, which is just about the total gasoline produced by the natural gas-gasoline industry in the United States in 1919."

Gasoline, the most valuable portion of the crude, sustains the entire loss, and the money value lost is much higher than the 6.2 per cent volume loss. Wiggins has proved that air contact with, and movement over, the surface of the oil, is responsible for the large evaporation losses. If storage tanks have covers actually tight and arrangement is made to relieve pressure through a liquid seal, evaporation will be greatly reduced. After a tank has been provided with a tight cover, an efficient combination safety valve and air excluder can be made by connecting one or more goose-neck pipes to the cover in such a manner that about four inches of oil or water can stand in the bend. Such protection will pay for itself in a short time, even though the producers' loss is in volume only. If an oil is of sufficiently high gravity to remain in the top price division after loss by evaporation, the producer actually loses only in proportion to the volume. The refiner's losses are in gasoline.

One operator at El Dorado reports that 7,000 barrels of oil stored in a tank with a steel top lost 4 degrees Baume gravity in six months. The gravity was decreased from 36 to 32 degrees. The loss in barrels of oil was not ascertained.

Table 5

Table 5 gives an analysis of typical El Dorado crude oil, made in the Pittsburgh laboratory of the Bureau of Mines:

Specific gravity, 0.852	Baume gravity, 34.30°
Per cent sulphur, 0.83	Per cent water, 0.1
Saybolt Univeral viscosity at 70° F.—57.0	Pour test, below 5° F.
Saybolt Universal viscosity at 100° F.—46.6	

Distillation, Bureau of Mines Hempel Method

Air distillation, Barometer 749 mm. First drop, 31° C. (88° F.)

Temperature °C	Per cent cut	Sum per cent	Sp. Gr. cut	°B cut	Viscosity	Cloud test °F.	Temperature °F
Up to 50							Up to 122
50 to 75	4.5	4.5	0.680	75.9			122 to 167
75 to 100	4.2	8.7	.701	69.7			167 to 212
100 to 125	7.1	15.8	.722	63.9			212 to 257
125 to 150	6.2	22.0	.746	57.7			257 to 302
150 to 175	5.1	27.1	.772	51.3			302 to 347
175 to 200	3.6	30.7	.795	46.1			347 to 392
200 to 225	3.5	34.2	.810	42.8			392 to 437
225 to 250	4.4	38.6	.823	40.1			437 to 482
250 to 275	5.1	43.7	.833	38.1			482 to 527

Vacuum distillation at 40 mm.

Temperature °C	Per cent cut	Sum per cent	Sp. Gr. cut	°B cut	Viscosity	Cloud test °F.	Temperature °F
Up to 200	5.5	5.5	.853	34.1	40	18	Up to 392
200 to 225	6.5	12.0	.860	32.8	45	30	392 to 437
225 to 250	5.9	17.9	.874	30.2	60	52	437 to 482
250 to 275	5.4	23.3	.890	27.3	81	72	482 to 527
275 to 300	4.6	27.9	.903	25.0	132	91	527 to 572

Carbon residue of residuum—10.3%.

Approximate Summary

	Per cent.	Sp. Gr.	°B.
Gasoline and naphtha	30.7	0.735	60.5
Kerosene	13.0	.823	40.1
Gas oil	12.0	.857	33.4
Light lubricating distillate	11.3	.882	28.7
Medium lubricating distillate	4.6	.903	25.0

The senior author developed a formula in 1916, for use in estimating mixtures of light and heavy oils to make up tank car shipments of a certain desired gravity and to use a minimum of light oil in the mixture. This formula was developed mathematically and assumes that there is no volume shrinkage after two oils are mixed.

It is interesting to note that the results from the use of this formula give results of oil lost by evaporation which check closely with an estimate of J. H. Wiggins, of the volume lost in the case cited above. Mr. Wiggins has been working for two years on evaporation losses of Mid-Continent crudes. The formula is as follows:

$$As=\frac{Ax\,(Ba-Bx)\,(Bs+130)}{(Bx-Bs)\,(Ba+130)+(Ba-Bx)\,(Bs+130)}$$

Where "A" is amount of oil, "B" is Baume gravity of oil, "a" refers to portion added, "s" refers to portion at start and "x" refers to the mixture. In solving the problem given above, it can be assumed that 70 degree gasoline was added to the remaining 32 gravity oil to make up 7,000 barrels of 36 gravity oil. Assume that the average gravity of the evaporated portion was 70 degrees (corresponds to oil analyses). Then Ax=7,000, Ba=70, Bs=32, Bx=36. Substituting in the formula,

$$As=\frac{7000\times34\times162}{(4\times200)+(34\times162)}=6112\text{ barrels,}$$

which was the amount of oil remaining after evaporation. The amount evaporated was then 888 barrels, or 12.7 per cent. The efficiency of this cover in excluding air circulation is not known and the same is true of the determination of the loss of gravity. A small additional expenditure in proper design of the tank cover would have reduced the evaporation losses greatly.

Besides evaporation, there has been a great deal of oil lost at El Dorado by spray, poor separation from water, inadequate storage for uncontrolled wells, seepage and fire. Plate XI shows a rapidly constructed sump for an uncontrolled well. A great deal of oil ran along the natural surface drainage channels, where much of it was lost by evaporation, seepage and fire. Some of it has been reclaimed by the operating companies and by individuals. The oil thus reclaimed by impounding and skimming has usually lost most of its gasoline. Because of the recent increase in the price of crude oil, operators will, no doubt, exert more effort toward conservation of their oil

Plate XI. Waste of Oil by Storage in Earthen Sump.

As a protection against the spread of fire, all steel-storage tanks should each be surrounded by earthen walls of suitable height and distance from the tank. Bowie* gives detailed information on this subect. A portion of a 55,000-barrel steel tank with a suitable fire wall is shown in Plate XII. It is located on the Standard Oil tank farm at El Dorado. Such tanks should also be protected by a complete fire foam equipment.

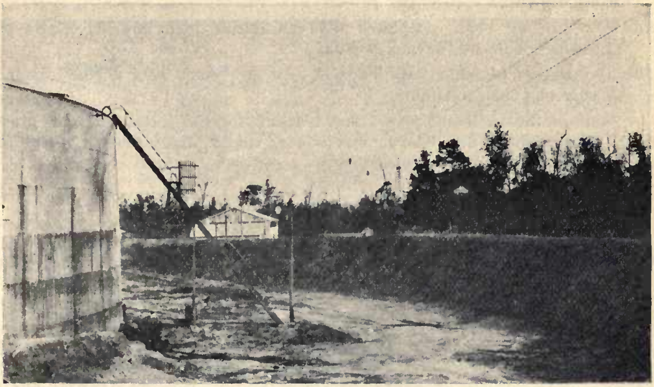


Plate XII. A 55,000-Barrel Steel Tank on the Standard Oil Tank Farm. Shows Portion of Adequate Fire Wall which Centers the Tank in a Closed Basin.

The waste of gas at the surface has not been unusually large. The principal losses have occurred from blowing wild. In certain areas, the gas waste may be sufficient to reduce the total recovery of oil by ordinary methods. If gas is allowed to escape in large quantities, it by-passes oil in the sand and cuts down the ultimate recovery. This is due to the gas being much more fluid than the oil and it, therefore, encounters less resistance to passage through the reservoir. The sand then becomes too rapidly impoverished of gas and the oil recovery is diminished.

For other oil fields, production statistics and physical measurements of underground factors, such as sand thickness and porosity, indicate that there is always more oil left underground that is raised to the surface. Estimates of the total recovery of oil by ordinary means, vary from 10 per cent to 40 per cent of total oil underground. With this in mind, it is not difficult to realize how necessary it is to consider every possible means of aiding recovery. A few additional per cent of ultimate extraction may represent millions of barrels of oil.

Production of Gas:

As pointed out previously, there are about 2,000 acres of proved gas producing area in the El Dorado field. This area is being developed only enough to supply the local needs for gas. As the gas is depleted from the oil deposits of the same strata, there will no doubt be some transfer of gas to them from the gas area. The conservation of gas is urged, therefore, as it may assist in the recovery of the oil in adjacent areas.

An estimation of the total amount of gas used and wasted is not attempted on account of incomplete information.

Up to about September 10, 1921.

At least 50 wells had been completed with an initial open flow in excess of 5,000,000 cubic feet of gas per day;

At least 33 wells had been completed with an initial open flow in excess of 10,000,000 cubic feet of gas per day;

**Bowie, C. P., Oil Storage Tanks and Reservoirs, Bulletin No. 155. U. S. Bureau of Mines, 1918. Extinguishing and Preventing Oil and Gas Fires, Bulletin No. 170, U. S. Bureau of Mines, 1920.*

At least 24 wells had been completed with an initial open flow in excess of 15,000,000 cubic feet of gas per day;

At least 12 wells had been completed with an initial open flow in excess of 20,000,000 cubic feet of gas per day;

And 5 wells had been completed with an initial open flow in excess of 25,000,000 cubic feet of gas per day.

These statistics, together with Table 6, will give some idea of the amount of gas that has been available.

Some of the wells show very rapid decline of gas production and pressure. Water infiltration has, in many cases, undoubtedly been a factor in shortening the life of these wells.

Table 6

DECLINE IN GAS PRESSURE AND PRODUCTION OF SOME OF THE WELLS OF EL DORADO

1921

WELL	Section	Completed Date	Rock Pressure Lbs. per Sq. In.				Working Pressure			Open Flow Capacity Thousands of Cubic Ft.			
			Initial	Aug. 27	Sept. 3	Sept. 10	Aug. 27	Sept. 3	Sept. 10	Initial	Aug. 27	Sept. 3	Sept. 10
McCauldin 1 (?)	31-17-15	6-'21	700	140	120	110	100	90	90	35,000	18,000	15,000	13,500
Lacy No. 1	31-17-15	5-12-'21	960	115	115	115	100	85	85	35,000	16,000	13,000	13,000
Chal Daniels	6-18-15	2- 8-'21	720	140	140	120	100	85	70	25,000	15,000	10,000	6,000
Woodly et al., 1	6-18-15	8-11-'21	......	140	140	120	100	70	70	15,000	10,000	6,000	5,000
Miles No. 1	36-17-16		......	150	150	150	115	115	115	....	2,500	2,500	1,500
Heartstone	26-17-16		600	480	320	315	300	190	190	13,000	11,000	11,000	10,000
Burns No. 1	31-17-15	2-20-'21	......	120	120	110	90	80	70	25,000	15,000	15,000	13,000
Reynolds	6-18-15		......	110	110	110	90	90	90	....	6,000	6,000	6,000
"Home" Well	1-18-16		900	Killed by salt water						31,000	Dead		
Constantin	12-18-16	4-'20	960	......	......	......	......	......	......	30,000	Dead		

The active gas wells listed above are blown daily, tri-weekly or weekly for ten or fifteen minutes, for the purpose of freeing them of water. This procedure has probably drilled some of the wells, in the unconsolidated sand, deeper, which may increase the inflow of water. As the gas occurs on the higher portions of the structure, edge-water could hardly be expected to appear there during the early life of the field. The blowing of gas wells to full capacity is a practice that should be reduced to the minimum whenever possible. If water is not already present in some cases, this will aid in drawing it in rapidly. When wells are producing gas with a large quantity of water, the well should be repaired or at least plugged high enough to retard the inflow of water, if it is coming through the gas sand.

Besides blowing wells to free them of accumulated water, they are also blown "open" to ascertain their mechanical condition, to clean out the pore spaces of the formation, to allow the wells to be repaired, and to make open-flow tests. Water can be removed from gas wells by a gas syphon line, which does not interrupt the gas service of the well. There is some loss of gas incurred when a syphon line is used, but the amount required to lift the water to the surface is relatively small. The frequency of open flow tests can well be deduced by a study of the data of pressure readings and calculation of capacities therefrom. When a well must be blown, it should be done by an experienced man who is familiar with the physical condition of that well.

The National Committee on Natural Gas Conservation adopted the following resolution on June 11, 1920:

> "Resolved, That the practice of 'blowing heads' off wells for long periods to get open-flow tests at stated intervals be discontinued. That pressure tests by closing 'side gates' or the use of other practical measuring schemes be used. That wells should only be 'blowed' when practical men know it to be necessary."

El Dorado natural gas is at present used for power, lighting and heating in the field, by the local refineries and industries and by the city of El Dorado. The El Dorado Natural Gas Company distributes most of the gas and reports an average daily consumption of about 19,500,000 cubic feet. The wells are drawn on to about 20 per cent of their capacity.

Some tests made by operating companies show that the gravity of the casinghead gas varies from .74 to .92 and the dry gas runs about .60. Reliable data on gasoline content of the gas were not obtained.

Production Decline Curves for Oil Wells:

The production records of practically every well in the El Dorado field were obtained and used in making the production decline and future production curves. The production records of certain individual wells were available, but in general the average production per well of each group was used. On most producing properties, the oil from several wells is run into the same tank. Because the correct water content may not have been deducted in every case and the date each well started to produce was not always available, there may be some inaccuracies in certain of the records. However, it is likely that these inaccuracies are compensating. Some records of groups of wells were rejected on account of being too greatly affected by the unknown flush production of new wells.

The production figures of each well, or average of a group, were tabulated in terms of average barrels per day by months. These data, as shown in Table 7, include October, 1921. In arranging these figures, the "mathematical method" described on page 88 of the 1921 Manual for the Oil and

Table 7

Estimated Future and Ultimate Production for an Average Well in the El Dorado Field.

I Estimated Remaining Life of Well Months	II Est. Average Daily Prod. Per Well Per Month Barrels	III Estimated Monthly Production Col. IIx30.4 Barrels	IV Est. Future Production of Average Well Barrels	V Est. Total Ultimate Prod. of Average Well Col. III+IV Barrels
23	10,000	304,000	305,864	609,864
22	4,600	139,840	166,024	305,864
21	2,300	69,920	96,104	166,024
20	1,250	38,000	58,104	96,104
19	700	21,280	36,824	58,104
18	420	12,768	24,056	36,824
17	255	7,752	16,304	24,056
16	165	5,016	11,288	16,304
15	106	3,222	8,065	11,287
14	74	2,250	5,816	8,066
13	52	1,581	4,235	5,816
12	37	1,125	3,110	4,235
11	26	790	2,320	3,110
10	19	578	1,742	2,320
9	14.5	441	1,301	1,742
8	11	334	967	1,301
7	8.5	258	708	966
6	6.5	198	511	709
5	5	152	359	511
4	4	122	237	359
3	3.2	97	140	237
2	2.6	79	61	140
1	2	61	0	61

Gas Industry (issued by the Treasury Department) was used. W. W. Cutler, petroleum engineer of the Bureau of Mines, co-operated in the work of preparing production figures for El Dorado.

The first month's production of each well or group was tabulated in the column whose average approximated that production, and subsequent monthly productions were placed in successive columns. The averages of the columns were then taken as the basis for the average production decline curve shown in Plate XIII. In this way, the old wells of small initial production served to extend the curve some months in the future. This method is used in accordance with the law of Beal and Lewis (Bureau of Mines), which states that when wells are producing under similar conditions and have the same present rate of production, they will, on the average, decline at the same rate, regardless of their relative ages. In extending the average future production to the assumed economic limit of two barrels per day, logarithmic cross-section paper was used. The curve was straightened and projected in the manner described in the Treasury Manual.

When wells came in as strong gassers and made very little oil at first, the month of maximum oil production was assumed as the first month. There were not many cases of this character.

After the field began producing, it was soon evident that the use of "chokes" was advisable and their use became general. The effect of "chokes" on production has been, of course, to make the decline more gradual. This is accomplished by holding back the oil and gas from a rapid discharge and this, in turn, delays a water-coning effect in the sand. The average decline curve is, therefore, somewhat modified by this factor during the flush production period.

The production decline curve here presented was constructed mainly from the records of flowing wells. It may be that when pumping becomes the common method of operation throughout the field, the production decline curve will be more sustained.

After preparing the average production decline curve, the records were divided into groups: (1) those of wells whose first month's productions were greater than 500 barrels per day, and (2) those of wells whose first month's productions were greater than 500 barrels per day. This showed that both large and small wells conformed in decline with the average production decline curve. Decline curves for the northern and southern parts of the field were also constructed, but were so near alike that they are omitted and only the average curve is shown in Plate XIII.

Table No. 7 is based on the average production decline curve shown in Plate XIII. Column II shows the estimated average daily production per well per month. The figures were obtained from the ordinates of the average decline curve (Plate XIII) at the points representing the various months. For any particular case, these figures can be considered as first month's production or as the production of any other month. Column III represents the corresponding total monthly production, the figure 30.4 being used as the average number of days in a month. Column IV shows the sum of the monthly production subsequent to that shown in Column III, if the average well is produced down to an assumed economic minimum of two barrels per day.

Column V is the sum of columns III and IV and represents the sum of the present month's total production and the estimated future production of an average well.

It is likely that the economic limit of commercial production will be somewhat higher than for most oil fields on account of the large quantities of water that will probably have to be lifted with the oil. Sand trouble is also a factor that may cause an earlier abandonment. At present, many of the small producing wells are off production a large part of the time on account of sand troubles. One probable compensating feature of the continuous sand movement is the elimination of deposits of paraffin and other clogging material on the walls of the hole.

It must not be inferred from Table 7 that the field will produce commercially no longer than twenty-three months. The average well with a first month's production of 10,000 barrels, for instance, will produce for twenty-three months to an economic limit of two barrels per day, or will produce for twenty-three months longer after it has declined to an average monthly production of 10,000 barrels per day. New wells may be drilled after the first producers are abandoned and the actual life of the field would thus be extended. The curves and table apply to the present producing oil zone only.

The curves of Plate X were prepared from the data of Table No. 7 and are for the purpose of interpolation as well as graphic representation.

Production Methods

When drilling in high-pressure gas areas, such as the El Dorado field, it is essential that the control equipment at the surface be of sufficient strength to be safe. In this field, special valves and fittings must be used, as there is considerable sand produced with the oil and the wear is excessive. Plate XIV shows a steel choke badly worn by sand.

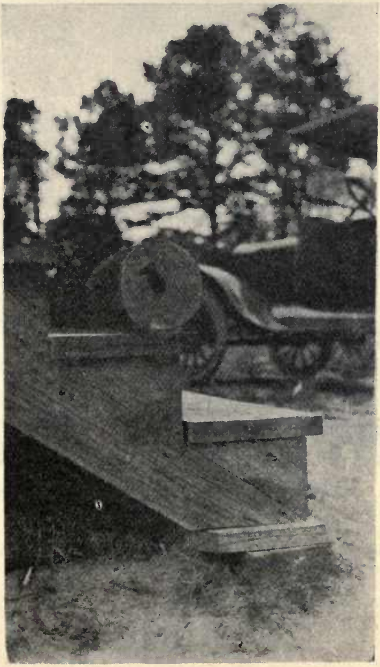


Plate XIV. A Steel Choke Worn by the Passage of Sand with Oil.

Safety Devices:

The usual casinghead fittings which are commonly used in the El Dorado field (see Plate XV) are made up as follows:

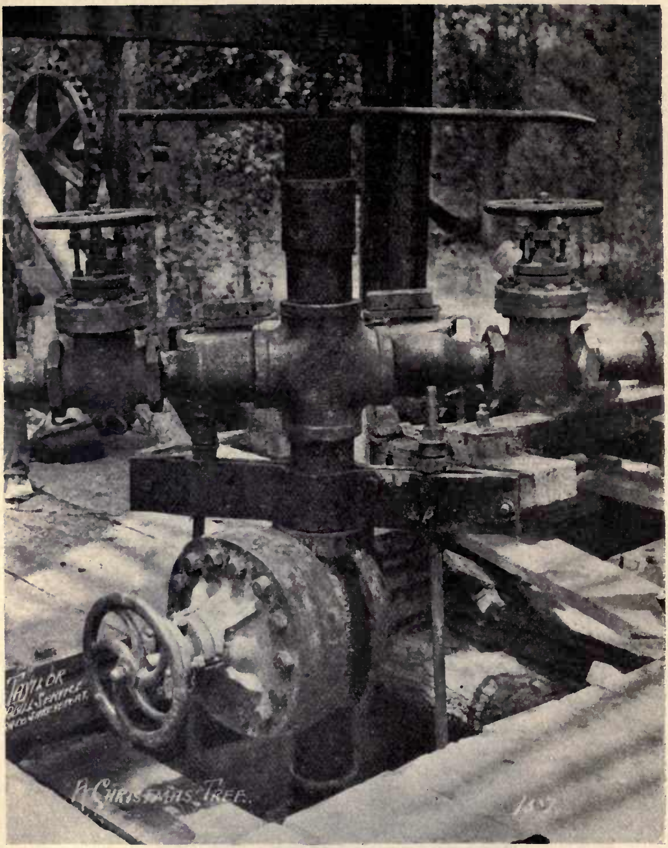


Plate XV. "Christmas Tree" Equipment of About Average Design.

(1) Master Valve—A heavy gate valve attached to the 6-inch water string, preferably placed below the derrick floor and operated by an extension arm in case of emergency, such as fire or blow-out. In order to ob-

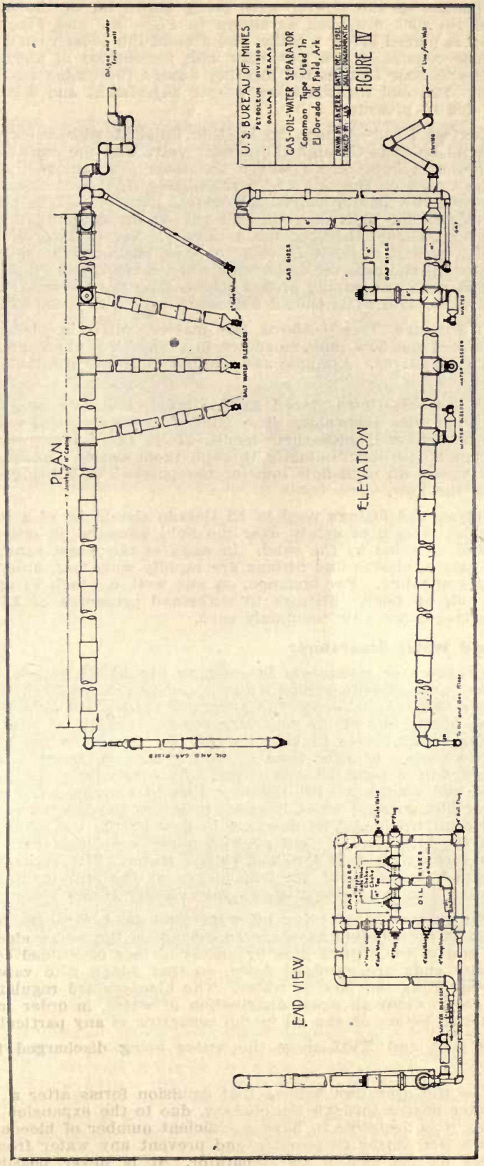


Figure 4. Gas-Oil-Water Separator.

viate the danger of the master gate being blown off of the 6-inch pipe, clamps and tie rods are used as shown in Plate XV and Figure 4. The lower clamp is placed below a collar and around the 10-inch conductor pipe. These clamps consist of two iron bars with dimensions of about one inch by six inches by four feet, bolted together around the casing and connected by tie rods. The end threads allow proper adjustment and distribution of the strain due to pressure.

(2) Control Head—When the well is finished with cable tools, the drilling should be done through the master valve and the control head. In case gas becomes bothersome before the tools are removed, the control head can be closed on the line and a reasonably tight seal effected. A tee placed between the master valve and control head should be connectd up and in readiness for delivering oil and gas or for mudding the well and killing the flow, should that become necessary. When the wells are being finished with rotary tools, it is well to have packing clamps or a blow-out preventer in readiness for emergency when removing the drill stem. By using such devices and paying proper attention to the thickness and height of the mud fluid, wild wells should not occur, except in cases of accident.

(3) "Christmas Tree"—Above the master valve is placed a cross from which lead the flow lines as shown in Plate XV. These lines are provided with gate valves. A nipple and another gate valve is installed above the cross.

Chokes are sometimes placed at this point, but they are, in general, needed only on the separator. The chokes are cylindrical steel blocks, threaded on each end, with their length about twice their diameter and having a small hole longitudinally through their center. Substantial gate valves are placed on each flow line for the purpose of shifting, regulating or stopping the flow.

The valves and fittings used in El Dorado should be of a heavy type, with sufficient margin of safety over the field pressure, in order to allow for wear and abrasion by the sand. In some of the worst sand producing wells, the valves, chokes and fittings are rapidly worn out, unless the flow is properly controlled. For instance, on one well, a 6-inch valve seat was ruined in half an hour. Fittings to withstand pressures of 2,500 pounds per square inches are now commonly used.

Oil, Gas and Water Separators:

The oil-gas-water separators in common use at El Dorado, consist of about seven joints of 10-inch pipe with oil and gas risers at each end. Figure 4 shows the type of separator generally used at El Dorado. The oil riser at the higher end of the separator consists usually of two 4-inch vertical nipples about 6 feet in height, each having at the top a 4-way tee connected to chokes of sizes from ⅜ to 1 inch. The number and size of chokes used will depend on conditions. Another nipple extends from a central tee and connects with the flow line to storage. The chokes are required for high-presure wells, in order to lessen the flow and thus reduce water and sand trouble. The decrease in flow by the use of chokes tends to prevent the formation of "cut oil." A more complete separation of gas and oil is accomplished in the last (high) risers. The separator is generally inclined, being about six feet higher at the end farther from the well, in order that the water may separate readily at the lower end.

For the purpose of bleeding off water and sand, three or four lateral 6-inch lines of three joints each are connected on the under side and near the lower end of the 10-inch pipe by means of tees or welded connections. The opposite ends are swedged down, so that 2-inch gate valves can be used for regulating the flow of water. The bleeders are regulated so that each will carry about an equal distribution of water, in order to avoid excessive suction action on the oil in the separator at any particular point.

Plates XVI and XVII show the water being discharged from separators.

Some of the operators believe that emulsion forms after a mixture of oil and water passes through the chokers, due to the expansion of gas. If this is true, it is desirable to have a sufficient number of bleeders to draw off as much free water as possible and prevent any water from reaching the chokers at the end of the separator. It is never possible to separate all the water, but some of the oil is freed of water in this way and the amount of emulsion which can form is thus cut down. In the event of emulsions forming before the oil reaches the surface, the separators will not cut down that which had already been formed, but may assist in preventing the formation of additional emulsions. The exclusion of water is the only certain means of preventing the formation of emulsion, although

Plate XVI. Discharge of Water and Some Oil from Separator. Gas and Oil Risers at Ends of Separator not shown. Some Oil being Wasted with the Water through the Bleeders.

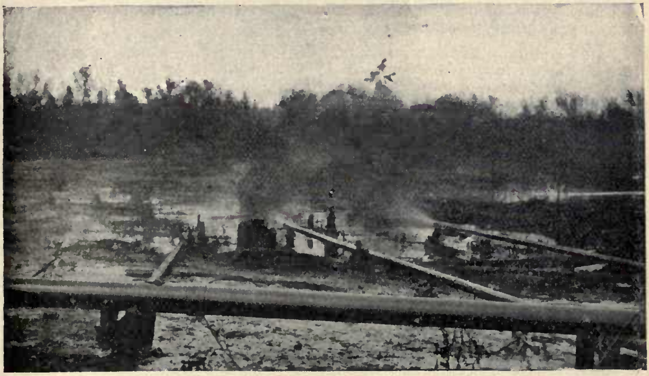


Plate XVII. Discharge of Water from Separator, Clear Water being Discharged from the Bleeders.

when the gas pressure is reduced, gas expansion will not be so serious a factor in forming emulsified oil. The large quantities of gas acompanying oil in the El Dorado field is one of the chief factors in creating an intimate mixture of oil and water. This point is illustrated by the action of fluid in a pumping well in the north end of the field. The superintendent stated that with the valve on the casinghead open (allowing gas to escape) no emulsion was produced. With that valve closed, 60 per cent emulsion resulted.

It appears likely that the quantity of emulsion formed in wells with high pressure will be reduced by diminishing the output, but this, if true, would not be of economic importance in all instances. For example, an operator stated that the production of one well making 16,700 barrels per day through a 4-inch flow pipe, was reduced to 3,400 barrels per day by inserting a ¾-inch choke.

Dehydration:

In most cases, El Dorado oil must be treated after it leaves the separator before the pipe line companies will accept it. At least four general methods of treating emulsion have been tried in the El Dorado field with satisfactory results: They are (1) the Tret-O-Lite System, (2) Centrifugal machines, (3) Electric Dehydration, (4) the so-called "gun-barrel" tank.

(1) The most common method of treating emulsion in the El Dorado field is by the addition of chemical compounds. The best known of these is Tret-O-Lite. This is a chemical which, when mixed with some oil-water emulsion, causes the water to settle out, leaving clean oil. The cost of treatment varies from 3 cents to 18 cents per barrel of clean oil, according to the percentage of emulsion. Tret-O-Lite compounds are usually understood to be essentially crude soaps or compounds of sodium and sulfonic acid. The average cost is about 9 cents per barrel of oil treated. The amount of Tret-O-Lite used varies from 10 to 70 gallons to every 1,000 barrels of oil. Different methods are used to mix the Tret-O-Lite with the oil. One company uses about 1,000 feet of 2-inch coil pipe through which the emulsion and Tret-O-Lite mixture is pumped before being run into the settling tank. The amount of Tret-O-Lite running into the coils can be gauged by means of a glass indicator, before the mixing occurs. The water settles into the bottom of the tank, where the water level is usually kept about seven feet from bottom. A steam pipe open at its lower end extends almost to the bottom of the tank and maintains the temperature at from 100 degrees to 110 degrees Fahrenheit. The introduction of live steam into the settling tank should, however, be avoided, because it agitates the oil, thereby retarding settling, and also increases evaporation. The clean oil is drawn from an outlet pipe about two feet from the top of the tank and runs into storage tanks by gravity.

One company uses an additional device to insure a more thorough mixing of the chemicals and emulsion. This consists of two joints of 8-inch pipe, about forty feet long and laid on the ground, with two unjointed pieces of 2-inch perforated pipe placed inside from each end. The emulsion and Tret-O-Lite mixture is pumped through one of the 2-inch pipes and inside the 8-inch pipe and is forced out through perforations in the other small pipe. The more uniform mixture is then pumped through coils on the ground, to increase time of contact, before being run into settling tanks. Steam coils are generally used to raise the temperature of the emulsion to about 120° Fahrenheit. In order to maintain a constant feeding pressure, it has been found desirable to feed the emulsion from the stock tank into a 25-barrel tank at about the same level as the pump. By this method, a reasonably uniform mixture with Tret-O-Lite is maintained.

(2) Centrifuge System is used to some extent in the El Dorado field. Centrifuges or supercentrifuges, as the oil field types are commonly called, are really enlargements of the cream separator with certain modifications which adapt them to oil field use. They rotate at speeds which reach a maximum of 17,500 revolutions per minute and develop tremendous separating forces.

In the El Dorado field the Magnolia Petroleum Company has installed a 5-unit Sharples plant for treating their emulsions. The total cost of installation, including equipment, labor and freight, is approximately $18,200. The operating cost on this plant is not known, but on a similar plant in another field, it is said to have amounted to $62 per day. This figure is believed to be the minimum cost at which such a plant could be operated. and it is probable that such a low average could not be expected over a great length of time.

In this installation Tret-O-Lite is used in combination with the centrifuge process when the percentage of emulsion is greater than 10. The plant is 5-unit and the capacity ranges from fifteen to twenty-five barrels per hour for each machine when treating oil averaging about 80 per cent emulsion. When using Tret-O-Lite in combination with the centrifuge, four quarts are used to 100 barrels fluid. The following description is given in a report by the Sharples Specialty Company:

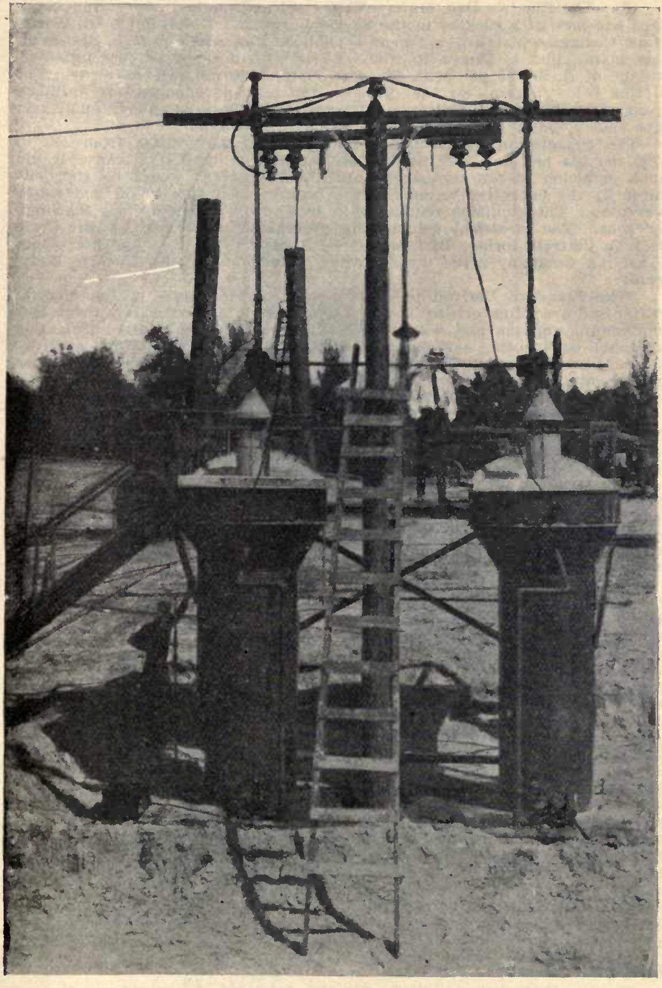


Plate XVIII. The Two-Unit Electric Dehydrator on the Hearin Lease of the Humble Oil Company.

"The emulsion is pumped from storage to the bottom of an elevated supply tank which is equipped with a steam coil and Sarco Regulator for heating. As the emulsion enters the bottom of the tank it rises through such salt water as may have accumulated from the emulsion and gradually fills the tank, during which period it is brought up to a standard temperature of from 160 to 170 degrees Fahrenheit. The pre-treatment of emulsion is essential and in fact, some emulsions may require the addition of suitable chemicals, in order to give greater plant efficiency.

(3) The Electric Dehydrator—This electrical method of treating emulsions has met with success in the El Dorado field. The Humble Oil & Refining Company installed a two-unit plant in the south part of the field. This installation is shown in Plate XVIII. On account of the high percentage of B. S. (85 per cent, in some instances), the rate of recovery of oil was below normal for that process, the average capacity for ordinary emulsions being 450 barrels per unit per day. Tests on these emulsions have shown that they average about 68 per cent water.

The capacity of an electrical dehydrator usually varies from 300 to 1,200 barrels per day, per unit. The capacity is limited, because if too much emulsion is run through the plant, the current would be short-circuited by the excessive water and the proper separation of oil and water prevented. The emulsion remaining in treated oil is usually less than one per cent. The electrical dehydrating process was invented by Dr. Frederick G. Cottrell, former Director of the Bureau of Mines. The Petroleum Rectifying Company gives the following description of the Electric Dehydrator:

"The Standard Cottrell apparatus consists essentially of the electric treater and a settling or trap tank. The treater is approximately three feet in diameter and ten and one-half feet high, made of galvanized iron, this tank shell constituting one electrode that is 'grounded.' The other, or 'live,' electrode consists of several circular discs, generally four discs eight inches apart, mounted on a vertical shaft concentric with the treater shell. These are slowly revolved by gearing from a small moter. This electrode carries a voltage of approximately 11,000 and is properly insulated from the gearing and the rest of the treater * * * *. Within the treater is a steam coil for controlling the temperature of the emulsion undergoing treatment." (This is usually about 135 degrees Fahrenheit.)

The emulsion is run through an electric field set up in the annular space between the edges of the discs and the treater shell, where it is broken up by the electric current. The water forms in large drops and settles to the bottom by gravity, where it is automatically drawn off in a continuous stream. The clean oil rises to the top and flows out to the storage tanks.

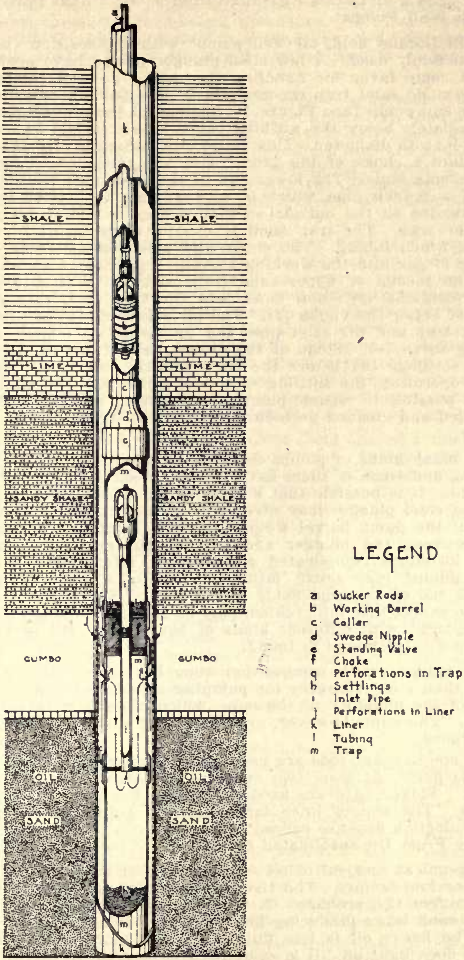
The electric power-requirement for the two-unit installation mentioned was about 2.76 kilowatts. The probable cost of generating electricity on the lease is about 4 cents per K. W. H., making a total cost of about 11 cents per hour for the electricity needed to operate the two units. The total cost of treating oil, considering various items such as steam, electricity, royalty, labor, repairs, interest and depreciation, has been found to be from one to three cents per barrel of net oil, according to the report issued by the Petroleum Rectifying Company.

(4) The so-called "gun barrel" tank which is sometimes used to dehydrate oil, is not satisfactory for use in the case of highly emulsified oil. It is suited for settling out water held more loosely in suspension.

The apparatus consists essentially of a tank fitted with steam coils on the bottom, a vertical wooden flume from top to bottom, a swing pipe connected near the bottom, and an overflow connection near the top of the tank. The oil is run into the flume at the top. It is conducted to the bottom of the tank and comes in contact with the hot steam cores before mixing with the other fluid. The oil-water mixture is broken up when passing up through the hot fluid, the oil rising to the top and the water settling to the bottom. The clean oil runs to storage through the overflow pipe. The height of the water can be regulated by raising or lowering the swing pipe. The excessive heating of the oil by this process results in considerable loss by evaporation.

Natural Gas Gasoline:

As yet, there are no plants for the recovery of natural gasoline at El Dorado. As the richness of gasoline in natural gas increases as the gas pressure decreases, it would be desirable for operators who produce quantities of gas to have tests made, and should they warrant it, install gasoline plants. One operator reports that he extracts a portion of the gasoline from the gas in a unique way. Gas is blows through the crude oil while



Note
Both Liner and Trap closed at bottom

FIGURE V

Fig. 5. Sand Trap Used in Some of the Pumping Wells.

in a tight tank. He claims gasoline from the gas is absorbed by the oil and thus silghtly raises the gravity of the crude. In some cases, a comparatively "dry" gas would absorb gasoline from a fairly light gravity oil.

Types of Oil Well Pumps:

In the El Dorado field, oil well pumps with composition cup plungers are most commonly used. A few steel plunger pumps have been tried and have gained some favor for handling the sand. Several companies have used a home-made sand trap successfully in this field in combination with the ordinary cup pump (see Figure 5) Instead of the standing valve being placed immediately below the working valve, it is attached to a stand pipe, generally ¾-inch in diameter. This stand pipe, which is also the inlet pipe, is screwed into a choke of the proper size and threaded to receive a ¾-inch pipe on both ends. The lower end of the inlet pipe consists of about one joint of a ¾-inch pipe which is screwed into the choke below. The choke is threaded on the outside so that it may be inserted between two collars on the trap. The trap shell is usually made up of 3-inch pipe, if for use with 2-inch tubing. The choke and pipe below it tend to prevent the entrance of gas into the working barrel. The choke also serves as the bottom of the second or upper sand trap. The oil first enters the liner through perforations (j), then flows into the trap (m), through perforations (g) just below the choke (f). The oil passes downward between the walls of the trap and the inlet pipe and up through the inlet pipe (i) to the standing valve (e). Some of the coarse sand drops to the bottom of the trap as settlings (h) before the oil enters the inlet pipe. In case the pump stops operating, the settling sand will settle past the standing valve and make it possible to resume pumping without a "wet job." These traps must be pulled and cleaned periodically, but they are known to reduce the sand trouble.

A great many kinds of pumps designed to handle sand have been tried at El Dorado, and some of them have given fair satisfaction under the trying conditions. It is possible that a combination of the sand trap principle and a packed steel plunger may give economical service. A packing gland at the top of the pump barrel would probably lessen the amount of sand that gets between the plunger and barrel. However, it is not always feasible to introduce complicated contrivances into wells. Theoretically serviceable pumps may prove failures, when tried out. Much sand is pumped with the oil in some fields of the United States and it is not unreasonable to expect that the problem may be solved in this field. Operators should experiment with different kinds of equipment until the most satisfactory pump or attachment is found.

Pumps equipped with composition cups have generally proved more satisfactory than steel plungers for pumping sand-free oil of light gravity, on account of the pliability of the cups, which allow less leak-back of low viscosity oil. The cups, however, are short-lived when considerable coarse sand is produced.

Regular steel sucker rods are used by most of the operating companies in El Dorado field. At least two concerns use wire lines instead of rods for pumping. Sinker bars are used just above the pump to facilitate the down stroke. The use of lines facilitates the pulling of cups and cuts down the production expense caused by pulling.

Oil Recovery From Unconsolidated Sands:

The economical removal of oil from incoherent sands will vary considerably with several factors. The viscosity of the oil is one of the main conditions that affect the problem. It is necessary to remove a larger quantity of loose sand when producing heavy oil than is essential for producing light oil. The heavy oil is less fluid and drags more sand into the well with it than does light oil. It is sometimes impossible to extract heavy oil without also lifting large quantities of sand.

This subject has been discussed at length, in the case of heavy oils, by Kobbe* and Suman.† In the case of light oil, it is probably better to remove only enough sand with the oil to keep the oil stratum fairly free from mud and waxy deposits.

**Kobbe, Wm., Recovering Oil from Unconsolidated Sands, Vol. LVI, Transactions American Institute of Mining Engineers.*

†Suman, John R., Petroleum Production Methods, pp. 282, 283.

It is no doubt true in general that a large removal of sand with the oil will increase the extraction of oil by lessening the friction offered to its reaching the well. The cost of handling the sand must, of course, be a large factor in determining the economical procedure. A considerable removal of the sand with the oil may result in a small inverted cone-shaped cavity forming at the well and in a slightly decreased density of sand near the well.

The overlying formations at El Dorado appear to be rather loosely consolidated, with the exception of some minor lime strata and the roof of the oil reservoir, therefore, may not stand up definitely above an extensive cavity. The roof may generally follow the sand downward and maintain a fairly constant sand density, or it may stand up for a while and suddenly collapse. Such collapse of the rock overlying the oil sand has been known to cause serious mechanical difficulty and decrease of production in fields producing heavy oil.

Experimentation in each particular area or field is the only reliable means of drawing correct conclusions, but in view of the known conditions in El Dorado, it would seem inadvisable to remove any more sand than is necessary to keep the sand around the well reasonably clean. Some operators have become disgusted with screens and liners and have allowed the sand to "heave" into the hole. When the production drops off considerably, tools or bailer are run to clean out. There is no definite information at hand with which to compare the effectiveness of this practice with the use of liners or screens. The amount of open hole below the shoe of the water string would influence this practice, as cavings from the walls of the hole may be a serious consideration in the case of high shut-offs.

It is believed that the gathering of clean sand around a liner will probably not offer much resistance to fluid movement. In fact, the loose sand should be the more porous for the reason that it has no cementing material in its pore spaces. Clean sand does not clog the perforations so that oil cannot enter the liner, even though it bridges in them. Perforations up to ¼-inch have been used in the El Dorado field.

Perforated Liners and Screen Pipe:

Perforated liners and screen pipe have been used in various ways at El Dorado. A home-made screen was devised by close wrapping by machine of No. 10 gauge wire around a perforated pipe. One of these, after being in a well only a short time, became plastered over with fine sand and mud which shut out the production. Such a device will not give satisfaction unless it is certain that no impervious material, such as mud, can accumulate on it. The spaces between the wire wrappings were first clogged with fine sand and then with mud. Liners with inserted screens have been tried and are used by some of the operators. These are not, in general, satisfactory.

Practically all screens now manufactured have a wrapping of slots which are keystone-shaped, in order to minimize the wedging of sand and pebbles in the openings. Two makes of patented screen used at El Dorado are made by wrapping "Keystone" wire around and soldering the wire to perforated pipe. Another make has slotted "buttons" inserted flush into large perforations in the pipe. The matter of selecting a suitable size for screen mesh must be given considerable attention and it may vary somewhat in different localities of the field and in any well as the gas pressure declines. The size of the openings is, of course, a matter of experiment in the different areas. The finer meshes of screen have been the the rule and will probably continue in use, as long as screens are considered useful.

At El Dorado, the liners and screens, when inserted very far below the top of the sand, should be closed on the bottom to prevent the sand and mud from "heaving" up into the liner. It may sometimes be advisable to have the liner or screen blank for a certain distance above the bottom of the hole.

Considerable difference of opinion exists among the operators regarding a seal for the top of the liner. Although it is difficult to effect a tight mechanical seal between a liner and water string, it is not difficult to exclude the coarser sand by that means. A seal may also be of service in holding the liner in place. In one case, where the perforations had been clogged, an unsealed liner resulted in practically all of the oil passing up between the liner and casing. If a liner can be sealed at the top without bridging sand above the perforations, it would be good practice to aid in the easy removal of the liner when necessary to clean out. A canvas packer is used at the top of the liner in some wells. One operator has decided that the best system is to use a perforated liner fitted with a bell nipple on top.

It is believed that the finer sand and mud content of the oil stratum should be allowed to have fairly free entrance into the wells, in order that the clogging effect will be reduced. Any tendency of this oil to deposit paraffin in formation or tubing, is evidently counteracted by the scouring action of the sand.

In the declining period of a well's life, it may be found feasible to stimulate the movement of fine sand and sludge through the liner or screen and into the well. Several methods are known for stimulating wells. They include steaming, positive and negative swabbing and the introduction of hot oil. Washing with hot or cold water is sometimes done but the method should be used with great care, if at all. Excessive water is not beneficial. Hot water, put in from the surface, may drive waxy sediment back into the sand and redeposit them along a ring of sufficient cooling. Vigorous swabbing is not recommended on account of the ever present danger of drawing in top, edge or bottom water and the danger of caving formations. The use of hot oil or distillate is probably best adapted to the removal of any waxy sediment forming under conditions as found at El Dorado. The introduction of hot oil melts the waxy sediment and also tends to render the oil less viscous and thus permits a freer movement of oil sand into the well.

If an abnormal quantity of sand flows into a well, it may become necessary to temporarily raise the pump to prevent its sanding up or cutting out of the plunger.

Flow Oil Through Tubing:

The general practice at El Dorado has been to "flow" wells as long as they could produce reasonably large quantities of oil by this method. Some of them flow as low as fifty barrels per day before being put on the pump. A few operators are taking advantage of the gas pressure and are flowing the oil through small tubing which is packed off at the surface or near the shoe of the water string. This practice is economical and generally keeps wells flowing for an additional period. Some operators put their wells on the pump when the output has declined to 100 barrels per day because pumps will increase the production. The high cost of pumping more oil with large quantities of sand must be balanced against a quicker return on the investment, but has the advantage of better protection against drainage by neighboring wells.

Air Lifts for Raising Oil:

Lifting oil by means of compressed air jets is common practice in some fields. When the fluid level in a well is high, due principally to water, any lowering of fluid will aid in the recovery of oil, as discussed under Water Conditions. Because compressing air is rather expensive and because air lifts in wells tend to emulsify oil, the method may not always be adaptable. The production of water-free sandy oil by air would no doubt be economical if there was a sufficient quantity of oil to allow of fairly continuous operation. The efficient lifting of liquids by compressed air calls for about 35 per cent submergence, which would not be likely to exist for a period long enough to justify air installations to produce clean oil. In U. S. Bureau of Mines Bulletin 195, by A. W. Ambrose (referred to previously), a portion of an unpublished paper by E. W. Wagy gives some interesting data on compressed air lifting practice, to which the reader is referred.

A well making sufficient water to cause an air lift to appear feasible, should be repaired, if possible, in order to increase the oil production, decrease the water production and reduce the cost of lifting so much fluid. An air lift must operate continuously to be practicable. When water is shut off, pumping of oil with air "by heads" is not practicable. There are so many factors opposed to the lifting of several thousand barrels of water with air, in order to obtain several hundred barrels of oil, that, first of all, the possibility of shutting off the water without decreasing the oil production should be considered. In other fields, much water was produced for several years, in order to produce some oil, after which the water was shut off, with a resulting increase in oil production. Water often aggravates sand trouble by settling and packing the sand. Incoming sand will not be floated out by a water current as well as by an oil current of the same velocity, because the oil is more viscous—it has more "body."

The presence of dissolved air in the oil and gas lowers the gravity of the oil by carrying off the lighter fractions. Air also dilutes the gas and may ruin it for fuel use, and the energy necessary to extract a given amount of gasoline from gas is thereby increased.

The air lift has been tried in only a few wells at El Dorado. The Clark & Greer well on Section 17-18-15 started to make water and decreased in oil production. The well was put on air and the oil production was increased, due no doubt to a lowering of the fluid level in the hole. Although several thousand barrels of fluid per day was removed, the fluid level was apparently not greatly reduced. The water soon "killed" the gas and the oil production stopped. Even though the water could have been removed to a low level as fast as it entered the well, its steady flow through the oil stratum would have prematurely cut off the oil supply.

Vacuum Pumping:

In some fields, vacuum pumps are applied to the well in order to stimulate production and to enrich the casinghead gas. The vacuum pump is attached to a lead line from the casinghead and is set where the application of power is convenient. This system of pumping is only employed in fields where the production has declined to such a point that it is unprofitable to pump the wells without some stimulation of production or an enrichment and increase in casinghead gas.

Although vacuum pumping has not as yet been tried at El Dorado, the subject is here mentioned as of possible future importance in that field. Its application may not be found feasible, but if used it should be applied cautiously in accordance with well-directed experiments. The haphazard use of vacuum has created ill feeling among operators in certain fields. Vacuum has drawn water into wells, with harmful results.

Regardless of the generally incoherent condition of the sand at El Dorado, vacuum pumping may possibly find useful application, inasmuch as a suction of fourteen pounds per square inch would probably influence sand movement no more than a positive gas pressure of fifty or one hundred pounds per square inch. This principle does not apply to water infiltration, however, and high vacuums may rapidly draw in water. The vacuum shown on the gauge at the surface is not the actual vacuum applied to the movement of oil, as friction reduces the vacuum by the time it is applied to the sand. In applying vacuum, it is probably best to start with a low vacuum and increase gradually. Each well, however, may be a special problem. It is reported that in some cases high vacuums draw less oil than low ones, and wells can occasionally be increased by lowering the vacuum to a certain point. The rapid by passing and loss of gas reduces the total assistance of its expansive force for oil extraction.

It is sometimes found that vacuum pumping does not materially increase production. When the productive sand is coarse and heavy, the wells will not "sand up" so readily by vacuum pumping. Some very diverse phenomena have been noted under apparently similar conditions in vacuum pumping. There is, no doubt, much to be learned of the action of vacuum under varying underground conditions. While the use of vacuum pumping will increase the ultimate extraction of oil in some fields, where conditions are suitable, its successful application is doubtful at El Dorado.

Power for Pumping:

The power most extensively used in the El Dorado oil field for pumping purposes is the gas engine. Various types of gas engines are used. They are equipped with magneto. "wyco" and hot point ignition systems, which are discussed under the subject of "Drilling Methods." The steam engine is too expensive for pumping individual wells, unless the central power of a jack line system is operated by that means. It should be used in such a manner only when gas engines, oil engines and electric motors are not economically usable.

The central power system with jacks has not as yet been installed in the El Dorado field. The use of jacks is usually practicable in depleted fields where there is very little trouble from sand. It does not now appear likely that groups of wells will be operated by jack lines from central powers, on account of the frequent necessary work on the wells due to sand troubles. If this condition is overcome sufficiently, jack systems may be profitably operated in conjunction with a cheap portable power unit for pulling, such as a tractor fitted with a hoisting drum, or even by individual engines which are left at the well. In this connection, full consideration must be given to the probable life of El Dorado wells. If the wells produce only a short time, it might not pay to change from individual power to jacks. In general, the principal factors governing the selection of suitable pumping systems are amount of production, depth of wells, size of tubing, gravity of oil, topography of the country, relative location of the wells and the speed of pumping desired.

Counterbalances and Tail Pumps :

Counterbalances on the beams of pumping wells have not as yet been used in the El Dorado field. It is well known that they can be used to advantage in any field, and it is recommended that operators install them.

Counterbalances are used to balance the dead load and assist in maintaining uniform turning motion. This cuts down idle time due to parted rods. The primary object of installing them is to decrease the power consumption, idle time and rod breakage. Where the cost of gas is only of secondary importance, suitable counterbalance will soon pay for itself by decreasing the wear on the gas engine and rods. The counterbalance also tends to reduce the amount of emulsion in production, by causing the rods to move more smoothly. Emulsion is, in some cases, formed by the churning action produced by leak-backs past damaged cups and valves and a portion of the damage is due to the vibration of the rods.

One of the most efficient counterbalances is a concrete block, supported from an extension of the walking beam by a stirrup. The position of the stirrup on the beam may be changed, in order that the leverage may suit the conditions of the load. Guides must be provided to prevent the concrete block from swinging.

Except in the case of a few line pumps, beam-operated pumps have not yet been installed. The tail pump is usually installed between the "sampson post" and "pittman," or on an extension of the beam, so that the same power pumping the well operates the tail pump. The upstroke of the tail pump is actuated by the weight of the descending rods, but its down stroke does not assist in the lifting of the rods. Some of the lead lines are long and the frictional resistance is considerable. Some flow tanks are considerably higher than the wells and additional power is required to force oil to the tank. The load on the well pump can be appreciably decreased by the use of a tail pump which requires little or no extra power to operate.

Conclusion

In studying conditions at El Dorado, it was found that the character of the reservoir strata is somewhat different from the average field. With respect to the association of oil and lower water, it is hoped that the ideas expressed herein will form the basis of continued investigation by others. The underground relation between the two liquids is one of the most important questions to solve. Without some accurate knowledge on this subject, the handling of wells becomes largely a matter of guess work. "Cut and try" methods are necessary to gain information as well as production, but experiments in blowing and deepening wells should not go beyond reasonable limits. The drilling and production practices in the El Dorado field have been generally wasteful, much of which could have been avoided by the application of good engineering.

The two main factors affecting the recovery of oil in the El Dorado field are water and loose sand. Wells that make considerable lower water should be plugged in the bottom with cement. regardless of whether there is a known impervious parting between the oil and bottom water. The top of the plug should be at least two feet above the probable top of the water. Best results with cement will be obtained by the tubing method, under a pump pressure of at least 500 pounds per square inch. It is recommended that a wooden plug be used in the tubing ahead of the cement and that a packing head with a relief valve, be used at the surface.

At El Dorado, rotary drilling has failed to determine the safe depth to drill wells. Core-barrelling has been unsuccessful in this field, on account of the unconsolidated character of the oil sand. It is believed, however, that as core-barreling is successful in soft sands in other fields, that better results with core barrels can be accomplished at El Dorado. It is recommended to drill wells in with cable tools after cementing the water string. The driller may "feel his way" into the sand and avoid drilling too deep.

The position of each well with respect to the structure should be borne in mind and down-dip wells with a contour-control as low as 1,935 feet below sea level, should barely penetrate the top oil stratum, lest the water-bearing portions of the strata be opened up after producing a short time.

The problem of handling sand in pumping wells may be solved to a great extent by experimenting with steel plunger working barrels designed to handle sand and by the use of sand traps. The control of flowing wells is a matter of utmost importance. Wells must be restricted in their flow, in order to avoid "self deepening" and premature entry of water.

Production methods used by various operators in the field differ widely. It is suggested that operators study the results obtained by other producers who are trying new methods. Informal discussions between production men of the various companies should be encouraged. It was found that some operators were not fully informed as to the methods in successful use by their neighbors.

Uniform systems of cost accounting should be adopted in order to correctly compare the efficiencies of different operations and appliances. The free exchange of ideas and open discussion in a spirit of co-operation cannot fail to be of mutual benefit.

Sufficient funds should be provided for a Conservation Commission composed of experienced and competent oil men, with ability to cover all of the important inspection work of the field. The present system of raising money by collecting fees is inadequate and unsatisfactory. The amount of money necessary to support an adequate conservation force will be insignificant as compared to the gain to the industry.

The Commission should inspect and record all vital operations in wells, such as test of water shut-off, special mudding operations, plugging bottom to shut off water, or plugging to abandon. Cement plugs should be tested for hardness, thickness, and location. The Commission should make underground studies and render decisions in writing to the operators, with respect to where water should be shut off and the depths of wells. When the companies employ engineers to study underground conditions, they, in consultation with the state representatives, can discuss matters of dispute and reach satisfactory and logical conclusions.

Operators should welcome such a plan, as they would be protected from flooding with water by inefficient and inexperienced operators, and at the same time there should be preserved certain valuable facts regarding the wells that might overwise be lost.

The possibility of shallower and deeper oil sands of importance should be considered before a definite plan is adopted for drilling up the field. As outlined in the body of the report, the proper use of mud fluid and cement is recommended. It appears logical to test these possibilities before abandoning present wells on account of depletion.

Efforts should be made to reduce the formation of emulsion both underground and at the surface. If the wells and pumps are in good mechanical condition, emulsions will not form so readily. Wells that flow water with oil and gas are likely to emulsify, despite all efforts, but properly designed separators will aid in keeping down the amount of emulsion formed.

Swabbing is not adaptable to El Dorado field, because of the loose sands. It should be limited to the few instances where wells can only be rid of mud and water and their flow started by swabbing.

It is very doubtful if vacuum pumping would be successful at El Dorado.

The spacing of wells should be about nine acres per well (627 feet distance), in view of the present (November, 1921) price of oil.

Other production economies, such as tail pumps, counterbalances, multiple pumping with jack lines, use of tubing catchers, use of low-pressure burners to conserve the rapidly diminishing gas supply, and discard of steam power or proper installation and insulation of boilers and steam lines are recommended for use where adaptable.

Concerted efforts should be made to reduce oil losses due to evaporation, seepage and other mechanical means. Practically no gas should be allowed to waste. Its use for moving oils into the wells and its use for fuel, render it highly important in the recovery of oil. Surface conservation is second in importance only to underground conservation.

El Dorado Oil Field in Arkansas--Discovery and Development

The El Dorado oil field in Arkansas was discovered by the Constantine Refining Company when their Armstrong No. 1 well in Sec. 1, T. 18 S., R. 16 W., struck an immense flow of gas, estimated at 40,000,000 cubic feet a day, and a small quantity of oil. The oil men of the mid-continent region paid comparatively little attention to this discovery for several months, although a few companies, acting on the advice of geologists, leased some land near the gas well, but when a well drilled by Mitchell & Busey in Sec. 31, T. 17 S., R. 15 W., came in on January 10, 1921, with a flow of about 1,500 barrels of oil a day and perhaps ten times that much water, there was a stampede for the field. Leasing and drilling were pushed with an intensity so tremendous that, in spite of several months' delay in getting an adequate pipe line outlet for the oil produced, the field was developed with remarkable rapidity. The oil sand is only about 2,150 feet below the surface, and the rocks above it are mostly beds of shale and clay that are easily penetrated by the rotary drill. Wells that gave a large output were the rule rather than the exception, several yielding more than 10,000 barrels a day, although most of these wells produced much salt water with the oil. The output reached about 82,000 barrels a day during the week ending August 20, 1921, but declined rapidly to about 32,000 barrels a day during the week ending March 11, 1922. Since then the output has increased slightly.

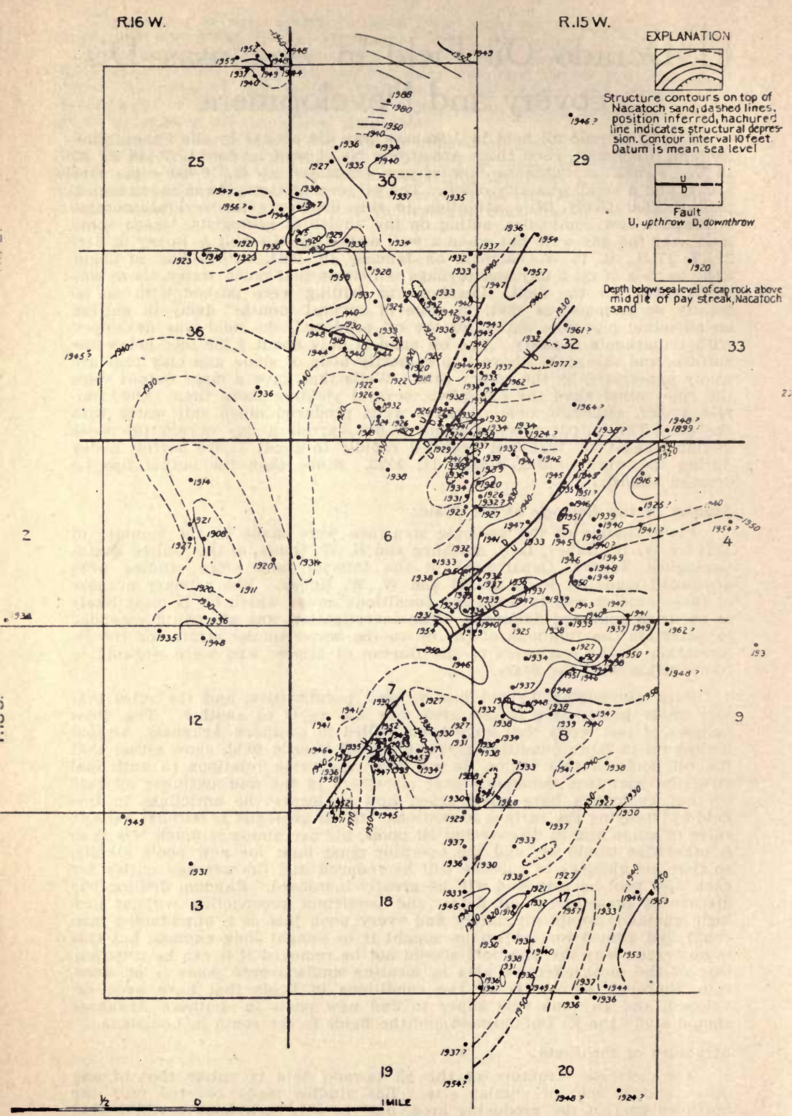
Studies of the Geology of the Field:

Field studies of the geologic structure were made in the summer of 1921 by W. W. Rubey, L. G. Mosburg and H. W. Hoots, of the United States Geological Survey, Department of the Interior, and office studies were afterward made by K. C. Heald and W. W. Rubey. The primary purpose of these studies was to learn the conditions under which oil is most likely to occur in southern Arkansas. The investigation was afterward extended to ascertain the relations of the oil to the water in the strata for the information of the engineers of the Bureau of Mines, who were working in co-operation with the State.

Each oil-yielding district has its own peculiarities, and the rules that may guide prospecting in one area may not apply to another. The great number of test wells that have been drilled in southern Arkansas without finding oil in large quantity except in the El Dorado field, show either that the oil pools in this region do not bear the same relations to anticlinal structure that they commonly bear elsewhere in the mid-continent oil field or that geologists have not learned how to locate the anticlines in this field by studying the surface formations. If the geologist is without definite rules to guide him in discovering oil pools, his usefulness is much less than it otherwise would be, and the operator must hunt for new pools blindly, so that his chances of success will be reduced and the average outlay for each now pool he may find will be greatly increased. Random drilling has discovered many great oil fields, and persistent prospecting without geologic guidance would ultimately find every pool, just as a blind-folded man could find almost any object he sought if he sought long enough, but this is no reason why the blindfold should not be removed if it can be removed. One of the most effective aids in locating undiscovered pools is an accurate, thorough knowledge of the conditions in fields that have been developed, and any one who hopes to find new pools in southern Arkansas should study the El Dorado field and the fields to the south in Louisiana.

Structure of the Field:

The geologic structure of the El Dorado field is unlike that of any other known field of similar size. The studies made covered only the northern part of the producing area, but there is no reason to think that the structure of the southern part is materially different. If the sand, clay and gumbo could be stripped off the producing bed in the area covered by the map no large dome or great anticlinal arch would be seen. The surface of the oil sand is so nearly level that it might remind one of gently



U. S. GEOLOGICAL SURVEY

GEOLOGIC STRUCTURE OF NORTHERN PART OF EL DORADO OIL FIELD, ARKANSAS

BY K. C. HEALD AND W. W. RUBEY

rolling prairies or of meadows made up in part of smoothly rounded knolls and swales or hollows whose slopes rise in even, sweeping curves. The evenness is interrupted by a number of low, almost vertical cliffs that mark faults where the rock has been broken and one side of the break has risen from one to thirty feet above the other. There are probably a great many more of these breaks than are shown on the map. Almost without exception they trend northeastward, forming a sharp angle with the longer axis of the field, and most of the low folds that vary the flatness of the surface of the oil sands also trend northeastward.

The oil sand rises higher in Sec. 1, T. 18 S., R. 16 W., than elsewhere in the part of the field that has been mapped. Not enough wells have been drilled in this part of the field to enable the geologist to work out its structure in detail, but it seems more nearly anticlinal than the narrow oil-yielding area that borders it on the northeast, east, and southeast. The few well records available indicate that in this part of the field there is a real dome on which the beds dip gently to the east and more abruptly to west and southwest. The wells on the dome yield gas and a little oil. Between this dome and the oil-yielding belt to the east there is a rather broad area over which the structure has not been worked out, so that the impression of flatness in that area given by the map is unjustified.

The structure in the area west and south of the gas-yielding dome, in Sec. 1, is not known, but the few records that are available show that the oil sand there is fully as high as it is in the productive part of the oil field.

A study of well records in areas east and west of the El Dorado field shows that this field is not upon a pronounced regional uplift, although there may be a slight bulge or gentle arch in the El Dorado region. The strata dip gently to the east and southeast over most of southern Arkansas. If the El Dorado field is on a regional bulge or uplift there is a synclinal depression west or northwest of it. A flattening of the regional dip was detected but no true syncline. Furthermore, if the field were an uplift the strata immediately east of it would probably show steeper dips than are common in this region, but no suggestion of such steep dips was found. The location of this field is therefore not controlled by the manner in which the rocks are folded. There is no true major anticline here, and the minor folds did not control the distribution of the oil, although the gas in this pool does tend to concentrate in arched or domed areas. The parts of the field in which, as shown by the map, the structure is anticlinal lie in a sinuous belt that trends in general northward through the center of Sec 31, T. 17 S., R. 15 W., including about 40 acres in the NW¼, Sec. 5. T. 18 S., R. 15 W.; about 60 acres in the northeast corner of the same section; about 60 acres in the north-central part of Sec. 8, T. 18 S., R. 15 W.; and about 100 acres in the southeast corner of Sec. 7. T. 18 S., R. 15 W., besides the gas-yielding dome in Sec. 1, T. 18 S., R. 16 W. In no one of these areas are there oil wells that show productivity above the average or the freedom from water trouble that might be expected if the segregation of oil were controlled by anticlinal structure. If the dates of completion and of average decline in initial production are taken into consideration in order to compensate for interference from adjacent producers, the wells in these anticlinal areas are perhaps a little above the average for the entire field, but this initial production is not higher than that of wells in adjoining synclinal areas.

On the other hand it can not be said that in this field there is no relation between geologic structure and the accumulation of oil, for structure includes both folds and faults, and the faults were probably influential in forming the pool. Nearly every area of high productivity in the oil-yielding belt here considered is traversed by one or more faults. A strip of richly productive territory does not border each fault shown on the map, but here and there along almost every fault there is a spot of unusual richness.

The direction and arranegment of the faults, and the shapes of the low folds that accompany some of them, probably indicate the presence of a large fault or zone of faulting in the beds deep below the Nacatoch sand, trending about N. 15° W. The structure shown by the oil sand there must have been produced by lateral movement along this fault, the strata east of it moving northward relative to the strata west of it.

How the Pool Was Formed:

The Marlbrook marl is believed to be the source of the oil in this field, and the accumulation of enough oil in the Nacatoch above the Marlbrook to form a commercial field is probably due to a happy association of a source of oil, channels through which it could migrate, and a good reservoir bed. Oil was probably not formed everywhere in the Marlbrook, at least not in great volume, but in favored spots where it was laid down in shallow water, and possibly raised above the sea from time to time, the conditions were right for the deposition and preservation of oil-forming matter. In any event, in some places the Marlbrook appears to have supplied large amounts of oil to the overlying Nacatoch sand, and in others, where the structure is seemingly quite as favorable, it has supplied little or none. At El Dorado the zone of faults crossed a productive area in the marl. The oil moved up along the fault planes and accumulated in the upper part of the Nacatoch sand. Pronounced anticlinal folding and faulting and a rich spot in the Marlbrook would together have produced ideal conditions for the accumulation of oil, and under such conditions the water trouble that has been the curse of the El Dorado field would not have appeared. The beds of sandstone lie so flat, however, that the oil they contain does not saturate them to any great thickness; but instead it is found in thin layers at the tops of several beds in the upper part of the Nacatoch, and the remaining parts of these beds are filled with salt water. The gas being more mobile than the oil has migrated to the more prominent domes and has excluded most of the oil and the water from certain thin beds of sandstone under the arched areas.

If the formations just above the Nacatoch had contained porous sandstones the oil, as it moved upward along the fault planes, would probably have formed small pools in them, for the faults are not limited to the beds below the top of the Nacatoch, but certainly cut the Arkadelphia clays, although these beds contain few sands. The faults may cut also the Midway beds, although this supposition can not be definitely verified by the well records, but no evidence was found to indicate that they cut the Wilcox.

Instead of originating in the Marlbrook the oil possibly may come from a much deeper formation, such as the Brownstown marl, the Eagle Ford shale, or the Lower Cretaceous beds. The depth of these formations below the Nacatoch is no obstacle to the migration of the oil, for the faulting that cuts the Marlbrook must also cut them, and if it could furnish channels for upward migration from the Marlbrook to the Nacatoch it could almost as easily furnish channels for migration from the deeper beds. If the oil came from the Brownstown marl, there may be chances of finding oil reservoir beds in this formation or adjacent to it, and if it came from the Eagle Ford shale there is a good chance of obtaining it from the Blossom and Woodbine sands.

If the oil came from the Marlbrook marl, however, the chances of obtaining it from underlying formations are not exceptionally good, although these lower formations should not be utterly condemned. The records of other fields that draw oil from Upper Cretaceous formations prohibit such a blanket condemnation, for practically all fields that have yielded either oil or gas in notable amounts from the Nacatoch sand and have yielded much greater amounts from either the Blossom or the Woodbine sands, or both. The lack of anticlinal structure at El Dorado, however, offsets this favorable feature. Where oil is found in the Blossom or the Woodbine there is either pronounced regional uplift or strong anticlinal folding. In the Caddo and De Soto-Red River districts there are both. In the El Dorado district there is neither. The conditions that are associated with oil pools in northern Louisiana, and to which the formation of those pools is presumably due, are therefore lacking here, and production from the deep beds can not be counted on. Nevertheless, the deep sands should be tested. The most promising locality for a deep test well, so far as the map shows, is on the west side of the gas-yielding dome in Sec. 1, T. 18 S., R. 16 W. The very center of the section seems to be a good location for such a test well, but as it is desirable to make a test for oil in the Nacatoch at a place west of the gas-bearing area, a location 800 feet west of the center of the section would probably be preferable.

Oil and Gas Above the Principal "Pay" Sand:

A few wells in the El Dorado field have reported "showings" of oil or gas in beds in the Midway formation. The few reports that traces of oil have been found in these beds might be discredited, for enough oil to give a rainbow-colored film on the drilling water might accidentally get into a well, but not traces of gas, and it therefore seems evident that at least one bed in the Midway formation carries some oil and gas. This bed may lie about 1,150 feet below the surface over most of the field, or about 970 feet above the Nacatoch sand. A number of sands in a zone 200-300 feet thick may carry this shallow oil. The wells in which it is reported do not lie on any of the faults that have been mapped or very near them, a fact which indicates that the oil probably did not rise along those faults.

Reported showings of oil or gas in a number of wells that have been drilled within a radius of forty miles of the El Dorado field suggest that an oil-bearing sand may lie at the base of the Midway formation, which in the El Dorado field is from 575 to 625 feet above the Nacatoch. No careful tests of these shallow beds seem to have been made in the field, in spite of the very apparent need for such tests. Small water-free wells that would draw oil from a bed not more than 1,200 feet below the surface would probably yield greater net profits than the more spectacular but less reliable wells that get oil from the underlying Nacatoch sand. Tests of the shallow sands should be made very carefully, for the gas in them is evidently low pressure, and it would be easy for one to drill through a thin oil or gas-bearing sand without suspecting its presence.

Possible Extensions of the Field.

In the part of the field covered by this study the location of highly productive wells near faults suggests the desirability of drilling in the southwest corner of Sec. 7, T. 18 S., R. 15 W., and in the adjoining territory in Secs. 12 and 13, T. 18 S., R. 16 W. The field may probably also be extended in the SE¼ SE¼ Sec. 32, T. 17 S., R. 15 W., and there seems to be no indication that the producing territory will not also include parts at least of the SW¼ Sec. 33, T. 17 S., R. 15 W., and of the NW¼, NW¼, Sec. 4, T. 18 S., R. 15 W. A well in the NW¼ Sec. 7, T. 18 S., R. 15 W., should yield either oil or gas, particularly in the eastern part of the quarter section. The same is true of Sections 18 and 19 in the same township.

A number of test wells should be drilled west of the gas-bearing area, for oil-bearing beds may possibly border the gas-bearing beds on the west and south as they do on the north and east. Suggested locations for test wells are the northeast corner of Sec. 2, T. 18 S., R. 16 W., the center of the N½ Sec. 2, T. 18 S., R. 16 W., and the center of the N½ Sec. 12, T. 18 S., R. 16 W.

The extension of the field to the south of its present limits is to be expected, and determined prospecting to discover a northward extension is also justified by the peculiar type of structure. Operators should not accept a single dry hole as limiting the field in these directions. The producing territory at the present north margin of the field can probably be extended westward.

Possibility of Similar Fields Elsewhere in Southern Arkansas.

Parallel belts of faults separated by areas almost unfaulted may occur in southern Arkansas as they do elsewhere in the mid-continent region, notably in northern Oklahoma and southern Kansas. If such a belt exists within a few miles of El Dorado the other favorable conditions that combined to produce the El Dorado pool probably also exist there and a field much like the El Dorado field may be developed. Because of this probability the following suggestions are made.

1. If gas in volume is encountered in a wildcat well the search for oil should be continued by wells drilled east, northeast, or southeast of the gasser.

2. If oil is encountered in a wildcat well the extension of the oil-yielding area should be sought by other wells drilled either north or south of the discovery well.

3. Gas pressure should be conserved by shutting in gas wells. The maintenance of the high gas pressure will help to promote greater extraction of oil and to prevent water trouble.

The chances for finding new fields are not limited to zones of faulting, for there are probably anticlines in southern Arkansas fully as strongly developed as those on which the Homer and Bellevue fields of Louisiana are located. Even if some of the conclusions here presented may be questioned, other oil fields will no doubt sooner or later be discovered in southern Arkansas, for in view of the showings of oil obtained in widely scattered wells in this broad region it would be unreasonable to believe that there is only one place in it where the conditions are favorable to the formation of an oil pool.

Description of the Producing Bed:

The Nacatoch sand in the El Dorado field is about 180 to 190 feet thick. The upper part is principally sand, but the formation also includes shaly sandstone and streaks of gumbo and shale. The lower part varies from slightly calcareous shale to hard limestone, although it generally contains some thin sandy layers.

The top of the sand is commonly marked by hard streaks called "rock" by the drillers. At some places these hard streaks are absent, and drillers who depended on them to indicate the top of the pay sand drilled deep into the sand before they realized that they had reached the oil-bearing bed. In fact, the drillers of the Busey well, commonly considered the discovery well of the field, drilled through the bed that yields most of the oil produced from the surrounding wells without recognizing it and obtained oil from a lower pay streak in the sand.

There are at least three pay streaks in the upper part of the Nacatoch. No one of these three streaks appears to extend through the field but the middle one, which is about forty feet below the top of the sand, is nearly continuous and yields most of the oil. Producing beds both higher and lower than the middle one have made good wells, but these other producing beds appear to be very patchy or perhaps they have not been adequately tested, for comparatively few drew oil from them. The gas well drilled by the Constantine Refining Company, which was the real discovery well of the field, obtained its gas from a bed that lies about forty feet below the bed which is yielding oil in wells to the east.

In all the pay streaks oil seems to be present only in the topmost few feet of the sand and is everywhere underlain by salt water. Salt water is also closely associated with the gas in the gas-yielding part of the field. Unless a well is completed with the utmost care this water flows from it with the oil and gas from the day it is completed until water flooding causes its abandonment. This water is much more difficult to combat than the water in most pools, because there is no such thing in this field as "edge water," which is restricted to the margins of the producing area. So far as salt water is concerned this field may be said to be all "edge" and each well is a problem in itself.

There is no evidence that the Nacatoch is either thinner or more shaly near the edges of the field than elsewhere. It is undoubtedly much more shaly in some places than in others, but no relation between the yield of oil and the percentage of clean sand could be determined.

Methods Used in Constructing the Map:

The records of wells drilled with rotary tools are notoriously poor and afford very unreliable correlations. In the El Dorado field comparisons and correlations are particularly hard to make, because the top of the Nacatoch sand varies so little in evelation throughout the field and because no single bed can be easily and certainly recognized everywhere. The results presented on the map are admittedly open to challenge, but they represent very careful and painstaking work—the best that can be done with the data available.

The correlation of the beds struck in different wells was first attempted solely by noting the relative positions of the beds of sandstone, limestone chalk, and gypsum recorded by the drillers. The results of these correlations were not satisfactory. Next, the "rocks" recorded by the drillers were colored distinctively on the plotted well logs and were found to furnish a good tie between many of the wells. However, to make satisfactory correlations it was found necesary to assign characteristic symbols or colors to every term employed by the drillers. The record of hardness was helpful. "Boulders" were in places distinctive. Some of the "pack sands" could be correlated between two or more wells. Shale and gumbo were distinguished, and although the usage of the drillers was not uniform their use of these terms furnished a valuable clue for many areas.

The work thus done permitted the recognition of small faults shown on the map. These faults would have been indicated by the evidence afforded by the oil sands, but this indication had to be confirmed in the upper part of the section. In a record of a well drilled across a normal fault a part of the stratigraphic section is missing, and, conversely, in a record of one drilled across a reverse fault a part of the section is repeated. In parts of the map that are based on comparatively few well records the structure appears to be much smoother and simpler than it is elsewhere, but if more records had been available these apparently simple areas would no doubt prove to be much more complex.

Character of the Oil:

Detailed analyses of the oil from the El Dorado field, published by the United States Bureau of Mines November, 1921, show that its gravity is about 34.2 Baume, and it contains about 30 per cent of gasoline and naphtha and 13 per cent of kerosene, the remainder being gas oil and lubricating oil.

ELEVATIONS OF NACATOCH SAND AND INTERVALS BETWEEN NACATOCH SAND AND BLOSSOM (?) SAND AT SOME WELLS DRILLED IN SOUTH-CENTRAL ARKANSAS

COMPANY AND LEASE	Well No.	LOCATION			County	Reported total depth of well	Depth to top of Nacatoch sand	Elevation of wel	Depth of top of Nacatoch sand below sea level	Interval betwee top of Nacatoch sand and top of Blossom (?) sand
		Section	T. S.	R. W.		Feet	Feet	Feet	Feet	Feet
Carlton & Owens, McGough lease	1	SW¼ SW¼ 16	17	13	Union	2136	*2350	†262	*2088?	......
Penn-Wyoming Oil Co., Union Sawmill Co. lease	1	21	18	13	Union	3089	‡2386?	†209	‡2177?	......
E. M. Brown, Goodwin lease	1	NE¼ SW¼ 16	16	14	Union	2634	2160	†213	1947	......
Wilson Oil Co., Moody lease	1	NW¼ SW¼ 16	17	14	Union	2815	2220	†252	1968	......
South Arkansas Oil & Gas Co., McCurry lease	1	NW¼ SW¼ 19	17	14	Union	2190	2165	†210	1955	......
E. M. Brown, Grace lease	1	SW¼ NE¼ 3	18	14	Union	2160	*2250	†253	*1997?	......
Quaker City Petroleum Co., Mittendorf lease	1	SW¼ SW¼ 15	17	15	Union	3010	2141	†192	1949	834
Cooper & Henderson, Hammond lease	1	SE¼ SW¼ 19	17	15	Union	3200	2111	†204	1907	828
Carter & Morgan Syndicate, McKinney lease	1	SE¼ NW¼ 4	18	15	Union	2881	2115	†206	1909	......
Mountz et al., Tillman lease	1	NW¼ NE¼ 9	18	15	Union	2580	2140	†232	1908	......
Congress Oil Co., Swilley lease	1	SE¼ NE¼ 8	19	15	Union	2522	‡2120?	†227	‡1893?	......
White Oil Corp., Murphy Land or Edgar lease	1	NW¼ SW¼ 22	18	16	Union	3025	2045	†159	1886	830
Milo Drilling Co., Robins or Trimble lease	1	1	19	16	Union	2586	2094	†182	1912	......
Nebraska Oil Co., Gallagher lease	1	NE¼ SE¼ 3	17	17	Union	2110	1938	†178	1760	......
Walker Drilling Co., Flourney lease	1	5	17	17	Union	2533	1980	†°220	°1760?	......
Love Petroleum Co., Darden or Edgar lease	1	SE¼ NW¼ 23	17	17	Union	2505	2112	†256	1856	......
Forest Oil Co., Mayfield lease	1	NE¼ NE¼ 21	18	17	Union	2914	‡2098?	¶300	‡¶1798?	812
Hinton & Mattocks, Murphy lease	1	SW¼ SE¼ 29	19	17	Union	3008	2110	†234	1876	§(?)
Carter Oil Co., at Hadnett, Ark.		NE¼ NE¼ 28	14	18	Ouachita	3240	‡1790?	¶200	‡¶1590?	‖856?
Trinity Petroleum Co., Realty Colonial lease	1	NW¼ 21	18	18	Union	2800	1967	¶275	¶1692?	‖809?
Louisiana Oil Refining Co., Allen lease	B-1	NW¼ SE¼ 13	15	19	Ouachita	2777	1720	†170	1550	842

* Nacatoch sand not reached. Depth to top estimated.

† Well elevations obtaned from the oil companies; fairly reliable and, except for isolated wells far from the railroads, are probably correct within 20 feet. Elevations near El Dorado are based on the bench mark at the El Dorado Court House, the true elevation of which is about 3½ feet above that used for it.

‡ The upper surface of the Nacatoch sand could not be recognized definitely from the driller's log.

° Two well elevations are given in this section. Uncertainty exists as to which is the proper one.

¶ Well elevations determined by estimation and from map in U. S. Geol. Survey Bulletin 429 (Pl. 12). May be as much as 100 feet in error.

§ Blossom (?) sand could not be recognized from the driller's log.

‖ The upper surface of neither the Nacatoch nor Blossom (?) sand could be recognized definitely from the driller's log.

Geology of the El Dorado Field and Some Mistakes in Drilling Methods

(Prepared by the U. S. Geological Survey)

Of the many wells that have been drilled in south-central Arkansas for oil, several apparently stopped short of the sand that yields the oil at El Dorado, in Union County, and the greater number did not reach the sand that yields oil in the Haynesville field, in Claiborne Parish, La., is the opinion of the United States Geological Survey, Department of the Interior. Furthermore, practically all drilling has been done with rotary tools, a method which not only yields inaccurate records of the formation penetrated but which also requently prevents the recognition and testing of oil sands that may be drilled through.

Several sands in northern Louisiana, below the Nacatoch, have produced much more oil than the Nacatoch, and in some of the fields the Nacatoch is practically barren, in spite of the immense volume of oil in the underlying sands. The deepest formation in this region that now seems worth testing is estimated to lie 4,000 or 5,000 feet below the surface and may be below profitable drilling depth. This formation is the Trinity, which in Pike and Sevier counties, Arkansas, contains asphalt deposits that represent the meager remains of what were once rather large bodies of oil.

Although the character of the formations in southern Arkansas may require the use of the rotary drill, operators should realize its shortcomings and employ methods that will insure, so far as possible, detection of showings of oil and gas. Cores should be cut from all beds penetrated that yield showings, and particularly from a sand near the base of the Midway formation and from sands in the Nacatoch, Marlbrook, Brownstown, Blossom, Eagle Ford, Woodbine, and Trinity formations, whether or not oil showings are observed in the sludge.

The ages, relative positions, and thicknesses of the formations encountered in drilling in south-central Arkansas must be determined if the search for oil is to be carried out effectively and economically. These determinations are difficult because of the similarity of the beds of the several formations, and can be made precise only with the aid of fossils. The approximate boundaries of the larger units, however, may be determined from the character of the beds as shown by well records. The following descriptions of formations encountered by drillers in Union County, Arkansas, are the result of a detailed study of many well records by W. W. Rubey, of the U. S. Geological Survey, Department of the Interior. Inaccuracies in the well records may have caused like inaccuracies in the interpretation of the stratigraphy.

Probably all the rocks that cover the surface of Union County belong to the Claiborne group of the Eocene series of the Tertiary system, which in this general region is divided into two formations, the Yegua above and the St. Maurice below.

Yegua (?) Formation:

Recent determinations of fossil plants by E. W. Berry indicate that the Yegua (?) formation is probably present in Union County, and that it comprises the surface beds over most of the county. The beds that are probably to be assigned to the Yegua ("Cockfield") formation are recorded in well records as alternating layers of sand and gumbo, some shale and calcareous material ("boulders" and "rocks"), and a little lignite. They may be distinguished from the underlying beds by their dominant sandiness. These beds probably attain a maximum of slightly more than 450 feet in the southeastern part of the county.

St. Maurice Formation:

The strata in this area which are here identified as the St. Maurice formation are commonly recorded in drillers' logs as layers of shale and gumbo with many "boulders" and "rocks" and some sandy material. The St. Maurice is much freer from sand than the formations above and below it. It probably ranges in thickness from 90 feet in the northwest corner of the county to about 200 feet in the southeastern part .

Wilcox Formation:

The Wilcox formation is generally shown in logs as thick alternating layers of sand, sandy gumbo, and shale, with some zones marked by "rocks" and "boulders," although subordinate amounts of gravel and lignite are occasionally noted. This formation can be recognized by an upper sandy group and a lower shaly group which contain less sand. Its thickness averages about 600 feet throughout Union County, but increases slightly toward the east.

Formations similar in composition to the Wilcox have yielded small quantities of oil in Louisiana and Texas, and the expectation that some oil may be obtained from this formation in restricted areas is not unreasonable. A careful watch should therefore be kept for indications of oil or gas while wells are penetrating these beds.

Midway Formation:

The beds referred to as the Midway formation are recorded by the drillers as "boulders," "rocks," and layers of sand, gumbo, and shale, with more or less chalk, limestone, and gypsum. Recent microscopic studies of cuttings from wells in the El Dorado field by James Gilluly, of the U. S. Geological Survey, have shown these beds to include some lignite. This occurrence of carbonaceous material in the Midway, although by no means widespread, is nevertheless not unusual. This formation is characterized throughout by its relative hardness.

The greatest known thickness of the Midway at its outcrop is about 260 feet* but this measurement was taken near the shore line of the embayment in which the formation was deposited. The character of the strata penetrated indicates that the formation probably attains a maximum thickness of slightly more than 500 feet in Union County.

Many wells drilled in south-central Arkansas have obtained showings of oil or gas or flows of water in a sandy bed near the base of this formation. At only a few wells, however, have tests been made to ascertain the true value of these showings. Especially in the El Dorado field has this bed remained untested.

Arkadelphia Clay:

The Arkadelphia clay of the Upper Cretaceous or Gulf series is in general easily recognized by its thickness and its freedom from sand. The strata recorded are mainly shale and gumbo, which are generally accompanied by many layers of "boulders," "rocks." chalk, limestone, and gypsum, and in a few wells layers of sandy shale. A very noticeable group of chalky or calcareous beds makes up the lower 175 or 200 feet of the Arkadelphia. The thickness of this formation averages about 550 feet in the western part of Union County and increases eastward, possibly to as much as 600 feet near the eastern boundary.

Nacatoch Sand:

The drillers' logs record the Nacatoch sand as beds of hard sand, shale, and limestone with may layers of "rocks," "boulders," and "pyrite" and some gumbo and chalky material. The upper part is commonly hard and sandy; the lower varies from slightly calcareous shale to hard limestone, although it usually includes thin sandy layers. The thickness ranges from 150 to 200 feet.

The Nacatoch has been identified by its fossils as the producing sand at El Dorado.† The oil there is obtained from three or four discontinuous layers of sandstone in the upper fifty feet of the formation.

Marlbrook Marl:

The Marlbrook marl is recorded as shale, chalk, "boulders," limestone, and lesser amounts of gumbo, "rocks," and "pyrite," and some sandy shale. This formation consists typically of shale and varying amounts of calcareous material. It ranges in thickness from about 300 to nearly 350 feet.

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†*U. S. Geol. Survey Press Notice: Oil from the Nacatoch Sand, El Dorado, Ark., Feb. 7, 1922.*

**Kennedy, William. A section from Terrell, Kaufman County, to Sabine Pass on the Gulf of Mexico: Texas Geol. Survey, Third Annual Report, p. 49, 1892.*

A group of sandy shales between 400 and 500 feet below the top of the Nacatoch usually yields water wherever it is penetrated. The beds at this horizon may contain oil or gas where the structure is favorable.

Annona Tongue of the Austin Chalk (?):

Fossils obtained from one of the wells† indicate the Marlbrook age of strata at least 250 feet below the base of the Nacatoch sand, and as no marked change in the character of the sediments down to the Brownstown marl is recorded, the Annona tongue of Austin chalk may be absent here. However, as this tongue, in its area of outcrop, varies from typical chalks to calcareous clays, it is probably present in Union County, but because of this lithologic variation it may not be easily distinguished from the overlying Marlbrook marl. The boundary between the Marlbrook marl and the Annona tongue of the Austin is provisionally drawn at the upper surface of a persistent limy or chalky series. As thus identified the Annona tongue in Union County consists of strata recorded in logs as limy shale, gypsum, and gumbo, with some "rocks," sandy shale, or chalk; its thickness ranges from 60 to 100 feet .

Brownstown Marl:

The strata referred to the Brownstown marl are dominantly calcareous sandy shales. They are usually called sandy shale, hard shale, "rock," sand, and gumbo in drillers' logs. Subordinate amounts of lime stone, "boulders," "pyrite," gypsum, and chalk are frequently noted. The thickness of the Brownstown ranges from about 200 to nearly 300 feet and apparently increases westward.

The formation is unique among those penetrated in that its thickness seems to decrease eastward across Union County. This fact is doubtless associated with a marked increase in sandiness of the Brownstown from its outcrop in Hempstead County southeastward through Union County. Any conclusions as to the cause of these changes would be unwarranted if based entirely on evidence furnished by records of rotary-drilled wells, but the presence of these sandy layers may well justify a thorough test of this formation.

Blossom (?) Sand:

A group of beds below the Brownstown marl, consisting of about 65 feet of sandstone, shale, and some calcareous layers, is probably to be correlated with the upper part of the Bingen formation of southwestern Arkansas and is therefore tentatively referred to as the Blossom sand. The Bingen formation is considered by L. W. Stephenson "as the probable near-shore equivalent of the Blossom sand, the Eagle Ford clay, and part of the Woodbine sand, but these formations are probably represented in part by unconformities within the Bingen and at its base. Indeed, it is possible that the Woodbine sand is entirely represented by the unconformity at the base of the Bingen." Sandy layers in the upper part of the Blossom (?) sand commonly carry water and are thought to correspond to the oil sand or sands in the Haynesville field, in Louisiana, although the formations there have not been positively identified. The Blossom (?) sand lies from 800 to 850 feet below the top of the Nacatoch sand over most of Union County and probably about 810 to 830 feet in the productive part of the El Dorado field.

Eagle Ford (?) Clay:

The several hundred feet of calcareous or limy shales below the Blossom (?) sand that have been penetrated in Union County probably belong to the Eagle Ford (?) clay of Upper Cretaceous age. In the logs of some wells in and near Union County a few red layers are recorded from these shales (see the accompanying cross section), and in parts of the Bingen formation of southwestern Arkansas that are presumably to be correlated with the true Eagle Ford clay much reddish material has been noted, both at the outcrop* and in wells.‡

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*Miser, H. D., and Purdue, A. H., *Gravel Deposits of the Caddo Gap and De Queen Quadrangles, Ark.: U. S. Geol. Survey Bull. 690, pp. 22-24, 1919.*

‡*Miser, H. D., and Purdue, A. H., Asphalt Deposits and Oil Conditions in Southwestern Ark.: U. S. Geol. Survey Bull. 691, pp. 282-291, 1919.*

†*U. S. Geol. Survey Press Notice: Oil from the Nacatoch Sand, El Dorado, Ark., Feb. 7, 1922.*

The principal oil sands of the Caddo and DeSoto-Red River districts, in Louisiana (which are commonly but erroneously called the Woodbine sand), are probably of Eagle Ford age.¶ The horizon of these oil-bearing strata in Louisiana is estimated to lie 500 feet more or less, below the top of the Blossom (?) sand in Union County, Ark., and from about 1,300 to 1,400 feet below the upper surface of the Nacatoch. So far as known, this horizon has not been reached in Union County.

RECORD OF DEEP WELL NEAR EL DORADO

Detailed information regarding the nature of the beds penetrated may be obtained from the following record of one of the deepest wells in Union County, Hammond well No. 1 of Cooper & Henderson Oil Company, in SE¼ SW¼, Sec. 19, T. 17 S., R. 15W.:

(Elevation above sea level about 204 feet. Geologic correlations by U. S. Geological Survey. All formational boundaries are fixed tentatively except that between the Arkadelphia and Nacatoch.)

Material	Thickness	Depth
Eocene series:		
Claiborne group:		
Yegua (?) formation:		
Surface sand	30	30
Sand	20	50
Gumbo	11	61
Packed sand	6	67
Rock	3	70
Packed sand	40	110
Hard sand	45	155
Rock	2	157
Hard sand	20	177
Gumbo; set 12½-inch casing	4	181
Gumbo	6	187
Sand and boulders	6	193
Packed sand and boulders	20	213
Gumbo	25	238
Rock and sand	2	240
Packed sand	10	250
Sandrock	5	255
Sand and boulders	3	258
Sand boulders and gumbo	100	358
St. Maurice formation (position of contact doubtful; lies above in the 100 feet of sand, boulders and gumbo):		
Sand and boulders	18	376
Rock	2	378
Packed sand	9	387
Rock	3	390
Gumbo	10	400
Sand and gumbo	20	420
Gumbo	22	442
Wilcox formation:		
Boulders	20	462
Boulders	42	504
Sand and boulders	14	518
Packed sand	18	536
Boulders	36	572
Sand and boulders	107	679
Sand and boulders	23	702
Gumbo	6	708
Sand and boulders	43	751
Gumbo	26	777
Gumbo	28	805
Gumbo and boulders	8	813

¶*Watson, G. C., and Hopkins, O. B., The De Soto-Red River Oil and Gas Field, Louisiana: U. S. Geol. Survey Bull. 661, pp. 113-116, 1918.*

Rock	4	817
Gumbo	7	824
Gumbo	41	865
Rock	3	868
Gumbo and boulders	8	876
Gumbo and boulders	30	906
Gumbo	5	911
Gumbo and boulders	42	953
Packed sand	10	963
Broken sandrock	6	969
Gumbo	20	989
Sand	16	1,005
Sandrock	19	1,024
Midway formation:		
Hard sand	6	1,030
Gumbo	6	1,036
Gummy shale	20	1,056
Sand and boulders	27	1,083
Gumbo	15	1,098
Sand and, sandrock	7	1,105
Broken formation	23	1,128
Broken formation	13	1,141
Sandy gumbo	15	1,156
Gumbo	71	1,227
Shale	12	1,239
Sand and boulders	11	1,250
Gumbo	20	1,270
Gumbo	14	1,284
Rock	1	1,285
Rock	2	1,287
Gumbo	14	1,301
Lignite	5	1,306
Gumbo	14	1,320
Gumbo	20	1,340
Rock	1	1,341
Sand	12	1,353
Sand and boulders	8	1,361
Gypsum	31	1,392
Gumbo	8	1,400
Gumbo	86	1,486
Gumbo	25	1,511
Rock	3	1,514
Rock	3	1,517
Upper Cretaceous or Gulf series:		
Arkadelphia Clay:		
Gumbo	10	1,527
Gumbo	23	1,550
Hard shale	5	1,555
Gumbo	8	1,563
Gumbo	12	1,575
Gumbo	20	1,595
Shale	5	1,600
Gumbo	30	1,630
Gummy shale	4	1,634
Gummy shale	60	1,694
Gumbo	52	1,746
Shale and gumbo	65	1,811
Shale and boulders	10	1,821
Shale	23	1,844
Gummy shale	18	1,862
Shale and gumbo	30	1,892
Gumbo	27	1,919
Gypsum	10	1,929
Hard shale	20	1,949
Gumbo	27	1,976
Gumbo and shale	44	2,020
Hard shale and gumbo; set 8¼-inch casing	25	2,045
Gumbo	5	2,050

Gumbo and shale	32	2,082
Gumbo and shale	14	2,096
Shale and gumbo	15	2,111
Nacatoch sand:		
Hard lime and shale	6	2,117
Gumbo	20	2,137
Broken rock	3	2,140
Sand	6	2,146
Sand	2	2,148
Broken rock	2	2,150
Sand	6	2,156
Sand	4	2,160
Rock	4	2,164
Sand	2	2,166
Sand	4	2,170
Shale and boulders	14	2,184
Gumbo	5	2,189
Gummy shale	24	2,213
Shale and gumbo	48	2,261
Gummy shale	26	2,287
Shale and lime	14	2,301
Marlbrook marl:		
Shale and boulders	45	2,346
Gummy shale	41	2,387
Shale and boulders	14	2,401
Hard shale	95	2,496
Hard shale	15	2,511
Salt-water sand	8	2,519
Rock	2	2,521
Sandrock	2	2,523
Sandrock	5	2,528
Sandy shale	2	2,530
Gummy shale	5	2,535
Rock	2	2,537
Gummy shale	7	2,544
Shale	4	2,548
*Sandy shale	4	2,552
Hard shale	13	2,565
Rock	2	2,567
Gumbo	12	2,579
Gumbo	15	2,594
Gumbo	10	2,604
Gumbo	20	2,624
Hard shale	5	2,629
Annona tongue of Austin chalk (?):		
Broken sandrock	4	2,633
Broken sandrock	4	2,637
Hard shale	13	2,650
Gumbo	3	2,653
Gumbo	9	2,662
Hard sand	3	2,665
Rock	4	2,669
Gumbo	6	2,675
Lime and shale	25	2,700
Rock	2	2,702
Lime and shale	25	2,727
Brownstown marl:		
Gumbo	7	2,734
Rock	6	2,740
Gumbo	1	2,741
Gumbo	14	2,755
Hard sandy shale	10	2,765
Gumbo	5	2,770
Gumbo	4	2,774
Sand, showing salt water	6	2,780
Gumbo	12	2,792
Hard gummy shale	22	2,814
Rock	8	2,822

Rock	3	2,825
Rock	5	2,830
Hard sandy shale	26	2,856
Hard sandy shale	21	2,877
Gumbo	5	2,882
Hard shale	3	2,885
Hard shale	9	2,894
Rock	1	2,895
Rock	3	2,898
Shale	3	2,901
Shale and gumbo	5	2,906
Hard sandy chalk	4	2,910
Sandy chalk	14	2,924
Hard shale	15	2,939
Blossom (?) sand:		
Sand	2	2,941
Sand	14	2,955
Rock	3	2,958
Sand	2	2,960
Sandrock	2	2,962
Gumbo	20	2,982
Sandy shale	8	2,990
Shale and boulders	1	2,991
Rock	1	2,992
Sand	6	2,998
Sand and gravel	7	3,005
Eagle Ford (?) clay:		
Gumbo	14	3,019
Gummy shale	7	3,026
Gumbo	22	3,048
Gummy shale	9	3,057
Broken limerock	28	3,085
Shale	7	3,092
Broken limerock and shale	22	3,114
Shale	6	3,120
Broken limerock	20	3,140
Shale	6	3,146
Broken limerock and shale	17	3,163
Broken lime and shale	37	3,200

Geologic Structure in the Region:

The accompanying cross section, from the vicinity of Centerpoint, Howard County, Ark., in the Caddo Gap quadrangle, to a point about ten miles east of El Dorado, Union County, shows the general structural conditions in south central Arkansas. The diminishing slope and the general increase of thickness of the formations as the center of the embayment is approached is readily apparent.

The elevation of the surface as shown is based on a partial revision of a map previously published by the Survey*, and is included in this diagram to show the relation of outcrops to formation below the surface and the depth of the oil and gas bearing sands. Topographic details near the wells are necessarily obscured because of the exaggerated width of the graphic logs. The records of the Nashville, Hope, and Bodcaw wells with correlations‡ and the outcrops of the formations¶ were taken from published reports.

**Harris, G. D., Oil and Gas in Louisiana: U. S. Geol. Survey Bulletin 429, pl. 12, 1910.*

**A small fossil obtained from this depth indicates that these beds are no older than the Marlbrook marl.—U. S. Geol. Survey Press Notice: Oil from the Nacatoch Sand, El Dorado, Ark., Feb. 7, 1922.*

The strata recorded in a number of the available logs of wells drilled in and near Union County were also correlated and the results are given in the descriptions of the formations. Maps showing the structure of the Nacatoch and other formations in south central Arkansas have been prepared by Veatch§. A general structural contour map of Union County has not been made, as a sufficient number of well logs for that purpose has not been obtained, but the position relative to sea level of the upper surface of the Nacatoch sand and other interesting features of the wells studied are given in the following tabulation.

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‡*Miser, H. D., and Purdue, A. H., Asphalt Deposits and Oil Conditions in Southwestern Arkansas: U. S. Geol. Survey Bulletin 691, pp. 282-292, pl. 33, 1919.*

¶*Harris, G. D., Oil and Gas in Louisiana: U. S. Geol. Survey Bulletin 429, pl. 12, 1910.*

§*Veatch, A. C., Geology and Underground Water Resources of Northern Louisiana and Southern Arkansas: U. S. Geol. Survey Prof. Paper 46, 1906.*

PART III

New Wells Show Extension of El Dorado Field

On the eve of going to press with the final forms of this report, information was received by the department of the bringing in of several new wells, indicating a considerable extension of the El Dorado Field, especially in a north and east direction. Mr. J. A. Brake, State Oil and Gas Inspector, El Dorado, Ark., has kindly furnished the department with logs and photographs of these new wells, and this information is supplemented to that which had already been prepared by the authors of this report, with the explanation that there was no opportunity for these authors to make comment upon the new wells or the bearing of these important discoveries upon future developments in the field. Mr. Brake says: "The new wells are a revelation. The log of the deep sand, which shows the new field, and the log of the north field, which shows still another formation, I think are better than any we have yet found."

East Field Four Miles East of El Dorado.

Six big gas wells have been brought in in the East Field, two of them making 45,000,000 cubic feet each with a rock pressure of 1,050 pounds. The other four wells are two and one-half miles farther north and they are making 20,000,000 cubic feet with a rock pressure of 850 pounds.

Four oil wells have been brought in in this same territory, one of them making 2,000 barrels and still is producing at the rate of 1,200 barrels. About twenty wells are now being drilled in this east field.

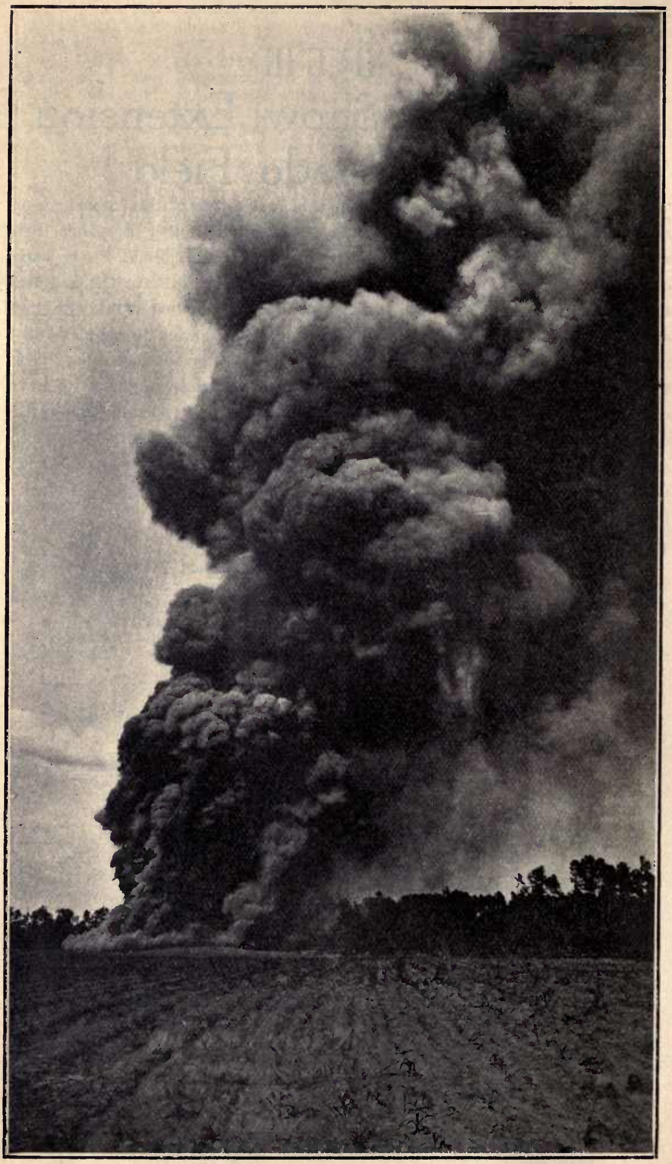
North Field, Eight Miles North of El Dorado.

Murphy No. 1, in 8-16-15, shows a different log, with much more shale, than any of the other wells, and the sand is found 176 feet higher than in the old field of Union county.

Log of Murphy No. 1—the Wild Well

Elevation 218 feet. Location SW Corner of NE¼ of SE¼:

0 to 25, sand
183, sand and clay (set 10-in. casing
190, gumbo
255, sand and shale
288, gumbo and boulders
300, boulders
333, sand and shale
475, shale and gumbo
500, hard sand
608, gumbo and boulders
651, gumbo
652, rock
700, shale and gumbo
746, gumbo and boulders
748, rock
788, black shale
842, gumbo and boulders
895, shale, black
960 gumbo and boulders
1036, packed sand and boulders
1060, sticky shale
1061, rock
1062, rock
1080, shale, black
1081, rock
1082, rock
1140, gumbo
1150, sand, lignite and boulders
1163, gumbo
1165, rock
1167, gumbo
1200, gumbo
1229, shale
1232, rock
1269, tough blue gumbo
1309, gumbo, blue
1445, gumbo, blue
1490, gumbo, black
1581, gumbo and shale, black
1600, gumbo, black
1668, black shale and boulders
1728, shale and boulders
1740, gumbo, black
1760, shale, black
1781, gumbo
1795, gumbo, black
1805, shale
1841, gumbo and boulders
1865, gumbo
1909, gumbo, black
1960, gumbo and shale
1975, gumbo
2000, shale
2012, gumbo
2023, shale
2024, sand



—Photo by Taylor

Burning Well by Day—Murphy No. 1, Sec. 8-16-15

West Field, Three Miles West of El Dorado.

On May 7, 1922, the El Dorado Natural Gas & Petroleum Corporation brought in a well on the Frazier lease in 1-18-16, making 4,000,000 feet of dry gas. After blowing for a short time it increased to 45,000,000 and blew off all the fittings and went wild. The first day after being wild it commenced making oil. This well came from the deep, or new, sand at 2,529 feet. The well was successfully capped and closed in and was at that time making 50,000,000 feet of gas and 300 barrels of oil.. Three or four deep test wells are being drilled in the field at this time.

Log of Frazier Well

0 to 6, surface sand
6 to 12, sand and gravel
12 to 65, clay.
65 to 160, sand clay
160 to 175, sand
175 to 185, clay, cemented 10" casing
185 to 190, sand
190 to 225, sand with clay and lime chalk
225 to 235, gumbo
235 to 265, sand
265 to 285, shale
285 to 300, gumbo
300 to 335, sand
335 to 355, white sand
355 to 380, gumbo
380 to 395, sand
395 to 415, shale
415 to 435, gumbo
435 to 445, clay
445 to 500, gumbo
500 to 525, sand
525 to 555, gumbo, brown
555 to 580, rock
580 to 635, gumbo
635 to 655, sand
655 to 665, gumbo
665 to 730, clay
730 to 760, loose and gumbo
760 to 775, sand and gumbo
775 to 785, gumbo
785 to 815, sand
815 to 825, clay
825 to 860, gumbo
860 to 885, sand
885 to 960, shale
960 to 965, rock
965 to 970, gumbo
970 to 980, sand
980 to 985, rock
985 to 990, lime rock
990 to 1000, gumbo
1000 to 1035, shale
1035 to 1038, rock
1038 to 1055, gumbo
1055 to 1090, shale and boulders
1090 to 1105, sand
1105 to 1120, gumbo
1120 to 1160, shale
1160 to 1175, gumbo and boulders
1175 to 1195, shale
1195 to 1198, rock
1198 to 1235, shale and boulders
1235 to 1238, sand with streaks of gumbo
1238 to 1285, gumbo
1285 to 1330, sand
1330 to 1340, shale
1340 to 1344, sand
1344 to 1355, shale and sand
1355 to 1375, gumbo
1375 to 1408, hard lime rock
1408 to 1412, gumbo
1412 to 1416, rock
1416 to 1455, sand
1455 to 1465, shale
1465 to 1470, rock
1470 to 1474, sand
1474 to 1495, jipsy chalk
1495 to 1498, gumbo
1498 to 1530, rock
1530 to 1570, sand
1570 to 1580, gumbo
1580 to 1665, shale
1665 to 1705, gumbo and sand
1705 to 1735, rock
1735 to 1885, sand
1885 to 1920, gumbo
1920 to 2005, shale
2005 to 2025, rock
2025 to 2035, sand
2035 to 2040, gumbo
2040 to 2050, shale
2050 to 2080, boulders
2080 to 2105, gummy shale
2105 to 2125, gumbo
2125 to 2155, hard shale
2155 to 2160, sand, shale
2160 to 2165, gumbo—2165—8-inch casing
2165 to 2365, broken sand and shale, showing little gas
2365, 500 feet of oil stand in hole. Well bailed dry. Drilling commenced at 2377 sand
2365 to 2377, sand
2377 to 2425, sand and shale
2425 to 2440, gumbo
2440 to 2462, shale and gumbo (most shale)
2462 to 2470, shale
2470 to 2475, hard sand
2475 to 2498, gumbo
2498 to 2506, gumbo and lime
2506 to 2524, tough gumbo
2524 to 2529, soft shale
2529, Hard gas rock and 2-in. core taken; 5 3-16 liner was set. Well came in making dry gas after bailing

South Field, Nine Miles South of El Dorado.

They are still bringing in 1,000-barrel wells in the south field, and there is quite a good deal of activity there at present. Much of the oil in the south field runs 42 and 43 gravity. This oil commands a premium.

There is being produced at the present time about 40,000 barrels of oil per day at a price ranging from $1.75 to $2.00 and $2.10 per barrel.

—Photo by Taylor

Burning Well by Night—"Arkansas Lighting the World"

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